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Critical and Californium Source-Driven Noise Analysis Subcritical Measurements with an Unreflected Cylindrical Tank of Mixed Uranium-Plutonium Nitrate Solution

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OAK RIDGE National Laboratory

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Physics Division

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ABSTRACT

The reported experiments were performed by Oak Ridge National Laboratory (ORNL) at the Battelle Northwest Laboratory's (now Pacific Northwest National Laboratory) critical experiments facility at Hanford, Washington in 1981 and used 16 days of critical facility time, not including 10 days for setup and removal of ORNL equipment. These measurements were to assess the capability of the Cf source-driven noise analysis (CSDNA) method to measure the subcriticality (keff) of mixed U-Pu nitrate solutions. In addition to the CSNDA measurements, measurements were also performed near delayed criticality where CSDNA measurements cannot be performed. This report documents the experiments that were not reported at that time by presenting the ORNL experimental results and any online analysis performed during and shortly after the measurements. The mixed nitrate solution had a U concentration at 188 grams per liter (g/L), a Pu concentration of 280 g/L, free acid normality of 2.80, H ion molarity of 5.9 and a specific gravity of 1.754 g/cm^3, a ^{240}Pu isotopic content of 7.981 wt. %, and a ^{235}U isotopic content of 0.724 wt. %. The stainless-steel tank for the solution had an inside diameter of 35.38 cm, an outside diameter of 35.53 cm, a height of 56.72 cm, and bottom thickness of 0.9525 cm. A Zircaloy pipe with a 3.1496 cm outside diameter, a 2.7788 cm inside diameter, and bottom thickness of 0.635 cm was available for insertion of the Cf source in the center of the fissile solution. The Cf source was also located at the outside surface of the tank (solution height varied from 10 to 53 cm) and in the center of the solution (solution height varied from 10 to 60.7 cm). The CSDNA measurements were not analyzed online to determine the subcritical neutron multiplication factors. At all subcritical states, the break frequency noise analysis data was fitted to obtain the prompt neutron decay constant. The neutron multiplication factors were determined for the two configurations of the measurements near delayed criticality. The subcritical neutron multiplication factors from the CNSDA measurements can be obtained with further analysis. However, the near delayed critical configuration, the prompt neutron decay constants, the count rates, and the measured cross and auto power spectral densities can be calculated directly for benchmarking. Much of data presented in this report are from ORNL notes—not in the ORNL logbooks. For the final benchmark analysis, the data from the Battelle Northwest Laboratory (which operated the critical facility in 1981) critical facility logbook should be consulted and be incorporated where appropriate. The purpose of this report is to document the experimental information for the measurements performed so that at a later date researchers could perform the required uncertainty and calculational analyses and documentation to use these data for an International Criticality Safety Benchmark Program (ICSBEP) or Nuclear Energy Agency benchmark. The data from these measurements are available from the ORNL Records Management Services Department, and the logbook is available from ICSBEP at Idaho National Laboratory.

Preparation of the present report is part of a larger cooperative effort between Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL) to document more than 15 undocumented critical and subcritical experiments enumerated in ORNL/TM-2019/18 and performed by ORNL at ORCEF and other USDOE critical experiments facilities using more than 500 operational days of critical facility time.

1. INTRODUCTION

The applicability of the Cf source driven noise analysis method (CSDNA) [1] to determine the subcriticality of mixed U-Pu nitrate solutions was evaluated in 1981 in a series of measurements at the critical experiment facility of the Battelle Northwest Laboratory (now Pacific Northwest National Laboratory) [2]. In addition to the CSNDA measurements, inverse kinetic rod drop (IKRD) measurements [3] were also performed close to delayed criticality where CSDNA measurements cannot be performed. Because of funding limitations at the time, the results of the measurements were not documented and only limited online analyses were performed. This report, although written much later, documents some of the preliminary online results. These measurements were performed with a mixed U-Pu nitrate solution and

had a U concentration at 188 grams per liter (g/L), a Pu concentration of 280 g/L, free acid normality of 2.80, H ion molarity of 5.90 and specific gravity of 1.754 g/cm^3, ^{240}Pu isotopic content of 7.981 wt. %, and ^{235}U isotopic content of 0.724 wt. %. The stainless-steel tank for the solution had an inside diameter (ID) of 35.38 cm, an outside diameter (OD) of 35.53 cm, a height of 56.72 cm, and bottom thickness of 0.9525 cm. A Zircaloy pipe with a 3.1496 cm OD, a 2.7788 cm ID, and bottom thickness of 0.635 cm was available for insertion of the Cf source on the axis the cylindrical fissile solution. The Cf source was also located at the outside surface of the tank (solution height varied from 10 to 53 cm) and in the center of the solution (solution height varied from 10 to 60.7 cm). At all subcritical states, the break frequency noise analysis data was fitted to obtain the prompt neutron decay constant [4]. The neutron multiplication factors were determined for the two configurations of the measurements near delayed criticality. Without further analysis of the CSDNA measurements to obtain the subcritical neutron multiplication factors, only the near delayed critical, the prompt neutron decay constants obtained, the measured count rates, and the measured cross and auto power spectral densities can be benchmarked by direct calculation of the measured data. Most data presented in this report are from Oak Ridge National Laboratory (ORNL) notes and memory and are not in the ORNL logbook. The purpose of this report is to document the experimental information for the measurements performed so that a later date researchers could perform the required interpretation of the experimental data, the required uncertainty and calculational analyses, and documentation to use these data for an International Criticality Safety Benchmark Program (ICSBEP) or Nuclear Energy Agency (NEA) benchmark. The data from these measurements are available from ORNL's Records Management Services Department, and the logbook [2] is available from ICSBEP at Idaho National Laboratory.

Preparation of the present report is part of a larger cooperative effort between Idaho National Laboratory (INL) and Oak Ridge National Laboratory (ORNL) to document more than 15 undocumented critical and subcritical experiments enumerated in ORNL/TM-2019/18 [5] and performed by ORNL at ORCEF and other USDOE critical experiments facilities using more than 500 operational days of critical facility time.

2. DESCRIPTION OF MATERIALS

The main materials in these experiments were the fissile solution, the tank, and the location in the room.

2.1 FISSILE SOLUTION

The properties of the fissile solution are given in Table 2.1. The isotopic contents of the fissile material are given in Table 2.2.

Table 2.1. Properties of fissile solution.

Property	Values
Pu content	280.4 g/L
U content	188.4 g/L
Free acid content	2.80
Specific gravity	1.7537 g/cm^3
H ion molarity	5.90
Chemical composition of nitrate	$Pu(NO_3)_4$ and $U(NO_3)_2$

Table 2.2. Isotopic analysis of fissile material.

Isotope	Weight percent
^{238}Pu	0.030 ± 0.004
^{239}Pu	91.50 ± 0.050
^{240}Pu	7.891 ± 0.050
^{241}Pu	0.509 ± 0.050
^{242}Pu	0.060 ± 0.001
^{233}U	0.013 ± 0.002
^{234}U	0.010 ± 0.002
^{235}U	0.724 ± 0.007
^{236}U	0.030 ± 0.002
^{238}U	99.223 ± 0.010

2.2 EXPERIMENTAL TANK AND LOCATION IN THE ROOM

The experiment tank was of stainless steel with a height of 56.72 cm, a diameter of 35.38 cm, an OD of 35.54 cm, and a height of 56.72 cm. The thickness of the bottom of the stainless-steel tank was 0.9525 cm. The reentrant tube into the solution for the Cf source was Zircaloy with a density of 6.57-g/cm^3. The ID of the reentrant tube was 2.7788 cm; the OD was 3.1496 cm, and the bottom thickness was 0.635 cm. The bottom of the solution tank was 15.87 cm. above the bottom of the large empty reflector tank that surrounded the cylindrical solution tank. The reflector tank side dimensions were 160 and 179 cm. The bottom of the source tube was 1.587 cm above the bottom of the stainless-steel solution tank and in the axis of the tank. A section of moderator (designated as the safety blade) was adjacent to the radial surface of the experimental tank for configurations close to delayed criticality. This provided an emergency shutdown mechanism, which was a requirement for operations near delayed criticality. Quick removal of this moderator allowed the determination of the reactivity in dollars for the system close to delayed criticality without the moderator in place using the IKRD method. The location of the cylindrical tank in the critical facility cell is shown in Figure 2.1.

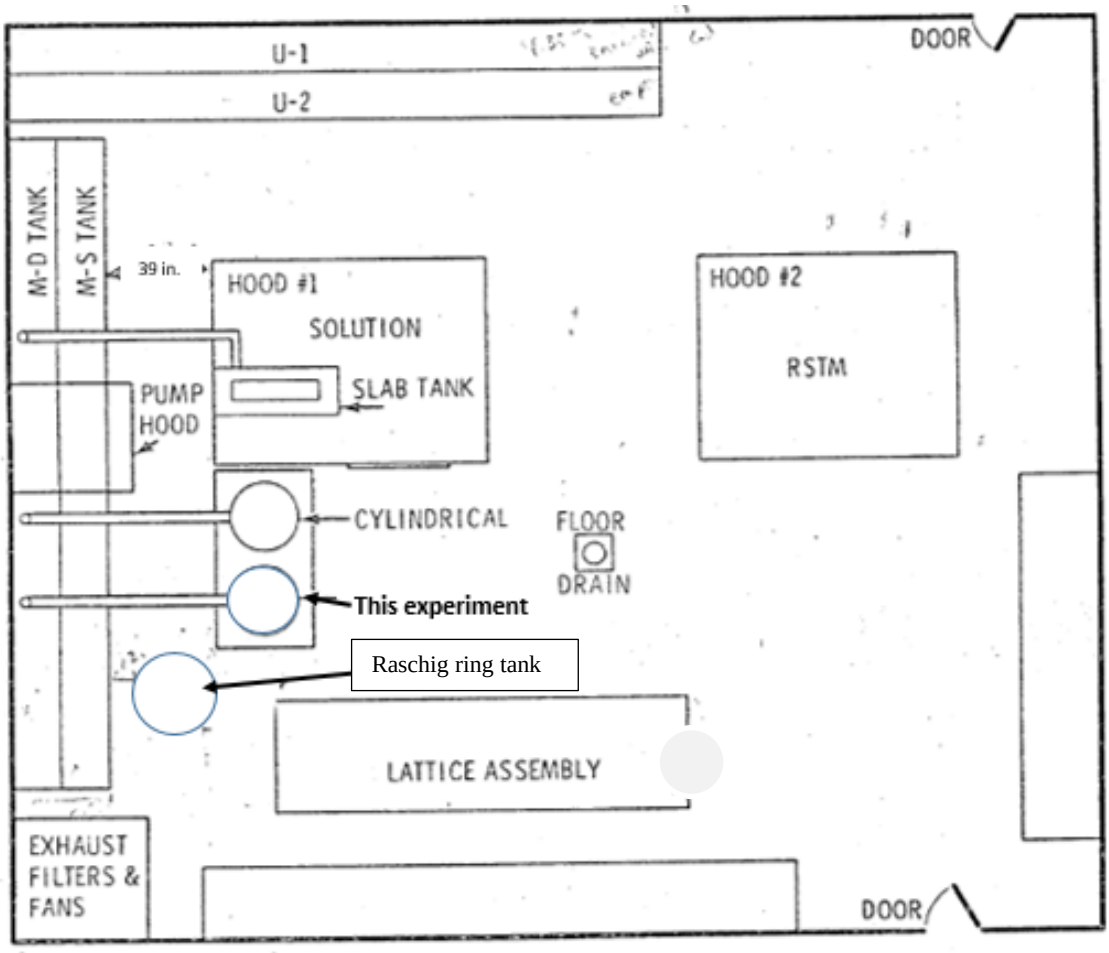

Figure 2.1. Location of the cylindrical solution tank in the experimental cell (raschig ring tank 12 in. from storage tanks).

2.3 CALIFORNIUM SOURCES

Two Cf sources designated as CF 16 and CF 17 were primarily used for measurements. Additionally, a much lower neutron intensity source designated as Cf 11 was also used for limited measurements. The output of the source-emission detection electronics was input to channel 1 of the Fourier processor. On June 19, 1981, the smaller source (Cf 11) had a detected (with the discriminator threshold) fission rate of 41,338 fission per second.

The Cf sources were electroplated on one plate of a parallel plate ionization chamber. The use of a source in an ionization chamber allowed the time tagging of the emission of neutrons from the source, which is essential for the CSDNA method. The configuration of the ionization chamber is shown in Figure 2.2. The typical composition of one of the sources is given in Table 2.3. The fraction of neutrons from ^{252}Cf was 0.99761, as measured at the source fabrication facility on April 25, 1981, and the measured Cf amount was 14.3 µg. A detailed Monte Carlo model of this source is given in NEA benchmark report SUB-HEU-SOL-THERM-002 [6], and a detailed sketch of the Monte Carlo model from this benchmark is given in Appendix A.

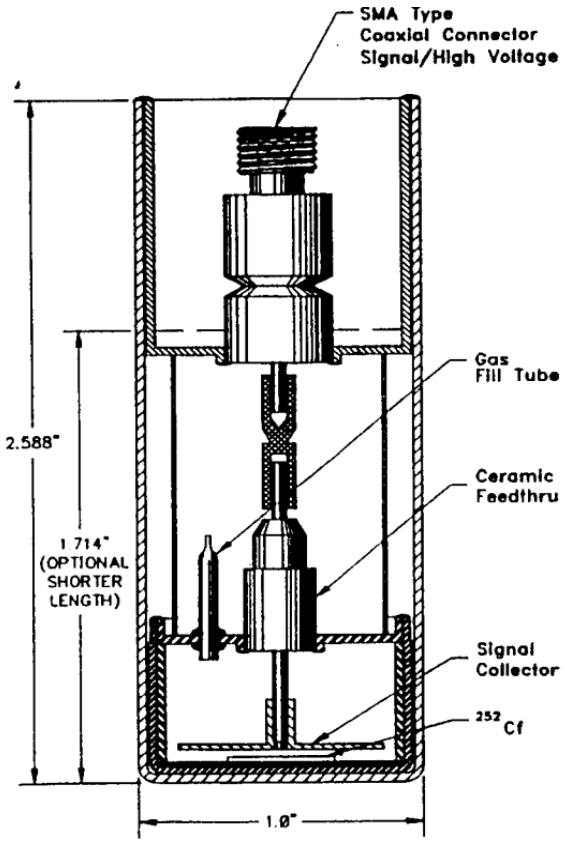

Figure 2.2. Configuration of the doubly contained stainless steel ionization chamber (1 cm diameter Cf deposit not to scale).

Table 2.3. Typical composition of the Cf source.

Isotope	Wt. percent
249	11.54
250	21.37
251	8.58
252	58.51
253	< 0.001
254	< 0.001

The count rate of Cf 11 as a function of discriminator threshold is given in Table 2.4 and plotted in Figure 2.3. A discriminator threshold of 170 mV was chosen as the threshold with a count rate of 74,570 fissions per second on March 21, 1979.

The source intensities for Cf 16 and 17 were determined when the system was returned to ORNL on November 16, 1981 by comparison to Cf 11 whose intensity was better known. In particular, the intensities of Cf 16 and 17 were determined by comparing neutron count rates to those of Cf source 11 for a common source geometry. This procedure was required for these larger sources because of the inability to distinguish the fission pulses from some of the alpha pulses (30 times more numerous than the fission pulses) due to alpha pulse pile up. Instead, the rates of helium proportional counters in paraffin moderator detected thermal neutrons and unmoderated fast neutrons.

Table 2.4. Detection rate vs discrimination threshold for Cf-11 on March 21, 1979.

Threshold (mV)	Counts per s
50	3,083,000
60	1,599,000
70	623,200
80	235,700
90	117,000
100	87,080
110	78,740
120	76,380
130	76,330
140	75,150
150	74,790
160	74,650
170	74,570
180	74,550
190	74,580
200	74,340
210	74,180
220	73,620
230	72,970
240	72,100
250	70,920
300	61,890
350	52,590
400	45,740
450	40,220
500	35,780
550	32,010
600	28,970
650	26,220
700	23,540

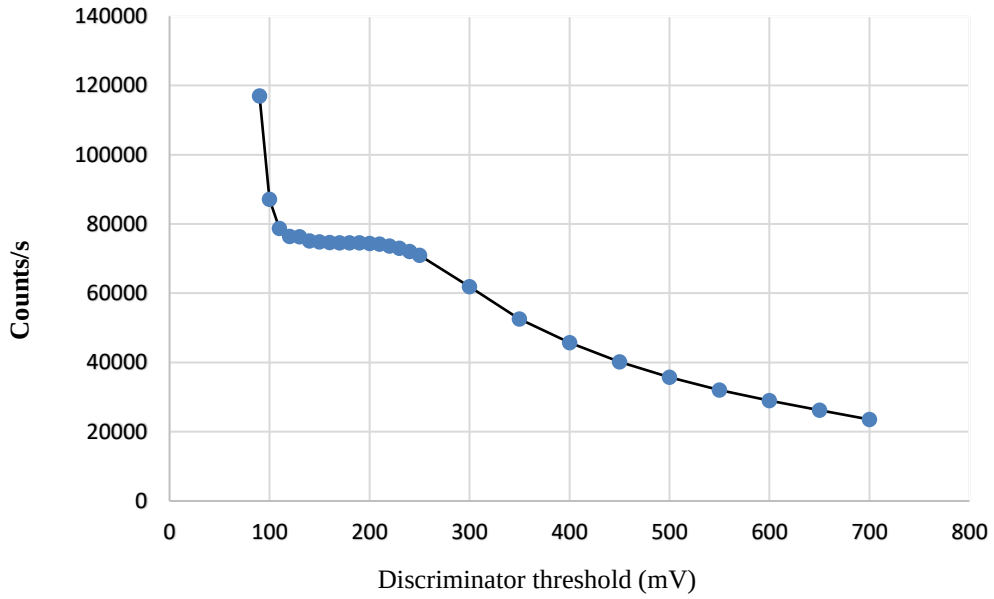

Figure 2.3. Counts per second as a function of discriminator setting for Cf source 11 on March 21, 1979.

The ratio of count rates for Cf 16 and 17 to Cf 11 on November 21, 1981, are given in Table 2.5. Measurement was performed with unmoderated proportional counters (fast neutron detection) and moderated proportional counters (thermal neutron detection)

Table 2.5. Relative Cf source intensity ratios.

Ratio	Fast neutron counting	Thermal neutron counting	Average
Cf 17/Cf 11	63.6	68.6	66.1
Cf 16/Cf 11	157.8	160.3	159.0

The average ratios were 66.1 and 159 for Cf sources 17 and 16, respectively.

2.4 DETECTORS

Two types of neutron detectors were used: Li glass scintillators and ^{3}He proportional counters. The Li glass scintillators were 1.5 in. in diameter and 1 in. thick and were used for the ratio of spectral density measurements. The Li glass scintillator identification numbers were 237 (used as input for channel two of the Fourier processor) and 239 (for channel three). The glass contained 6.6 wt. % Li with 95 wt. % ^{6}Li. These detectors had 0.635-cm-thick lead on the front and sides to reduce the sensitivity to gamma rays. These detectors are described in Reference 7.

The moderated ^{3}He proportional counter was located on the surface of the cylindrical solution tank in the direction away from the solution storage tank (Reuter Stokes model P4-0810-251) and was used for Feynman measurements. The other one was about 6 ft from the solution tank (P4-0810-207) and was used for IKRD measurements to determine the initial and final reactivity for configurations closer to critical.

In addition to the ORNL detectors, three neutron counters were associated with the critical facility cell. These counters were located inside and adjacent to the walls of the reflector tank in which the cylindrical

experimental solution tank was located. One (#3) was on adjacent to the side of the reflector tank that viewed the Cf source directly when it was located on the outside surface of the cylindrical tank. This detector was in the direction of the facility's small-diameter horizontal storage tanks. The other two (1 and 2) were located on the opposite side of the reflector tank with the experimental solution tank between the source and the detectors when the source was on the outside adjacent to the radial surface of the experimental tank. The bottoms of these moderated thermal neutron detectors were 16, 14.5, and 0 in. above the bottom of the tank for detectors 1, 2, and 3, respectively, for the measurements with the source pipe inserted. For the measurement with the source external, the bottom of detector 2 was 21 in. above the bottom of the reflector tank. These detectors were used to determine the ratio of total fission to those inherent source fissions. These ratios were determined from the count rate with the Cf source inserted to that with the Cf source removed. For ratios with the source, external counters 1 and 2 were used, and for measurements with the source pipe inserted in the center of the solution, all three counters were used. These detectors normally have a background count rate of a few counts per second. The background count rate could not be measured because of the Pu solution in the experimental cell, so it was assumed that the background for an isolated detector was negligible.

However, there were considerable counts from the solution in the storage tanks which was measured. For low solution heights and with measurements with the source on top, there may be counts in the detector from neutrons directly from the source.

3. MEASURED RESULTS

Two configurations of the experimental cylindrical solution tank existed: one with a cylindrical tube on the axis of the cylindrical tank and the other without the axial tube. The tube was used for location of the Cf source in the solution.

3.1 MEASUREMENTS NEAR DELAYED CRITICAL

The measurements near delayed criticality were performed for both configurations of the experimental tank—one without the axial source insertion pipe and the other with the axial source insertion pipe that could contain the Cf source.

3.1.1 Measurement without the Axial Pipe

The reactivity of this configuration with a solution height of 53.18 cm was determined by IKRD measurements. On July 21, 1981, this measurement was performed with the detectors and source adjacent to the outer surface of the tank and 120° apart. The safety rod was a hydrocarbon reflector adjacent to the solution tank. For the IKRD measurement, the reflector was removed rapidly from the position adjacent to the tank. The final reactivity with the reflector removed was minus 2.98 dollars and the effective delayed neutron fraction of 0.00283 corresponds to a neutron multiplication factor, $k_{eff} = 0.9916$. Inverse count rate measurements and ratio of spectral density as a function of solution height measurements resulted in extrapolated critical heights of 56.7 cm for the ratio extrapolation, 56.1 for the extrapolation of inverse count rates from the ORNL detectors, and 56.1 for the extrapolation of the inverse count rated from the Pacific Northwest laboratory detectors. The count rates as a function time in the IKRD measurements slightly below delayed critical are given in Appendix B. These data will have to be reanalyzed with present-day delayed neutron parameters for the final benchmark analysis. The value of the effective delayed neutron fraction will also have to be recalculated for conversion of the reactivity in dollars to neutron multiplication factor units for the final benchmark values.

3.1.2 Measurement with the Axial Pipe

Similar measurements were performed for the tank with the central pipe. The subcritical reactivity from the IKRD measurements was 2.85 dollars for a solution height of 60.68 cm, and with the same value of the delayed neutron fraction, gives a k_{eff} = 0.9920. The count rates as a function time in the IKRD measurements are given in Appendix B. These data will have to be reanalyzed with present-day delayed neutron parameters for the final benchmark analysis. The value of the effective delayed neutron fraction will also have to be recalculated for conversion of the reactivity in dollars to neutron multiplication factor units for the final benchmark values.

3.2 SUBCRITICAL MEASUREMENTS

CSDNA subcritical measurements were performed for a variety of configurations. Fitting these data can provide the break frequency, which is related to the prompt neutron decay constant. Close to delayed criticality, IKRD measurements were performed to obtain the final reactivity after the safety blades were removed. Additionally, for some of the configurations, the response of external detectors to the insertion of the Cf source was measured.

3.2.1 Ratio of Spectral Densities

The measured ratios of online spectral densities are given in Tables 3.1 and 3.2 with their uncertainties for all subcritical measurements. These values were obtained at the time of the measurements by visual observation of the plots of the ratio of spectral densities as a function of frequency. These values are the constant values at low frequency and were averaged over the region at low frequencies visually chosen where they were constant. For final analyses of these measurements, a more quantitative choice of the frequency range where the values are constant should be made. This is usually done varying the upper limit of the frequency range for the averaging and choosing the average value with the lowest standard deviation. Where there are blanks or experimental runs are not listed, the data were bad or lost at the measurement site. These tables also contain the break frequency obtained by only fitting the cross power spectral densities between the two detectors where the break frequency is related to the prompt neutron decay constants by the relationship that the prompt neutron decay constant equals 2π times the break frequency. For the final determination of the break frequency, the data for the auto power spectral densities for the two detectors and the real and imaginary parts of the cross power spectral densities between the detectors and the source and that between the two detectors (eight functions) should be fitted simultaneously, as illustrated in Appendix D. Once these break frequencies are determined, break frequency noise analysis methods can be used to determine the neutron multiplication factor accurately down to k_{eff} = 0.80.

Table 3.1. Ratio of spectral densities with the source CF 16 and detectors outside.

Run number	Solution height (in.)	Cf source height (in.)	Detector height (in.)	Ratio of spectral densities ($\times 10^{-3}$)[a]	Source detector separation (degrees)	Break frequency (s^{-1})[a]	Ratio source in to out
AA	20.90	10.45	10.45	1.2046 ± 0.0400	120	464 (489)	
AB	20.90	10.45	10.45	1.0720 ± 0.0400	120	468 ± 1 (480)	
AC	19.44	9.72	9.72	2.188 ± 0.008	120	806 ±2 (870)	
AD	17.52	8.76	8.76	3.668 ± 0.100	120	1,348 ± 10 (1,429)	4.03
AE	17.52	8.75	8.75	4.106 ± 0.130	120	1,324 ± 12 (1,381)	
AF	14.50	7.25	7.25	NA	120	2,522 ± 22	4.28

Run number	Solution height (in.)	Cf source height (in.)	Detector height (in.)	Ratio of spectral densities ($\times 10^{-3}$)[a]	Source detector separation (degrees)	Break frequency (s^{-1})[a]	Ratio source in to out
BA	17.50	8.75	8.75	NA	adjacent	363 ± 9.5	
BB	15.87	8.0	8.0	5.064 ± 0.200	120	1,875 ± 16 (1,918)	4.13
BC	14.50	7.25	7.25	6.256 ± 0.360	120	2,478 ± 41 (2,566)	4.31
BD	13.05	6.525	6.525	7.608 ± 0.140	120	3,172 ± 17 (3,091)	
CA	15.87	7.93	7.93	2.450 ± 0.16	adjacent	1,907 ± 36	4.26
CB	15.87	12.0	8.0	3.838	120	1,889 ± 14	3.66
CC	15.87	10.0	4.0	3.263	120	1,805 ±35	
CD	15.87	4.0	4.0	4.109 ± 0.2	120	1,849 ± 26	
CE	15.87	8.0	8.0	4.977 ± 0.20	120	1,782 ± 26 (1,927)	
CF	11.2	5.5	5.5	10.55 ± 0.30	120	4,107 ± 49 (4,152)	4.28
DA	19.27	10.0	10.0	1.356 ± 0.07	120	50 ± 2	
DB	21.05	10.53	10.53	0.542 ± 0.04	120	NA	
DC	20.59	10.30	10.30	1.347 ± 0.04	120	605 ± 4 (595)	
DD	10.0	5.0	5.0	11.77± 0.30	120	4,770 ± 190 (5,077)	4.18
EA	9.8	5.0	5.0	6.755	adjacent	3,444	
EB	8.91	4.5	4.5	10.28	120	7,190 ± 326	
FA	8.0	4.0	4.0	11.13	120	7,209 (7,049)	4.39
FB	7.06	3.5	3.5	10.55 ± 2.0	120	8,086 (9,285)	

[a]Where uncertainties are not given, they were not recorded online.

Table 3.2. Ratio of spectral densities for measurements with the central Zircaloy source tube with the source CF 17 and 16 with detectors outside.

Run number	Solution height (in.)	Cf source	Cf source height (in.)	Detector height (in.)	Source detector separation (degrees)	Ratio of spectral densities ($\times 10^{-2}$)[a]	Break frequency (s^{-1})[a]	Ratio of Cf source response in to out
GA	17.8	17c	9.0	9.0	180	4.061 ± 0.05	1,543 ± 16 (1,661)	7.85
GB	17.8	17c	9.0	9.0	180	5.473 ± 0.06	1,531 ±16	
GC	17.8	16c	9.0	9.0	180	3.859 ± 0.05	1,566 ± 268 (1,662)	17.60
GD	17.8	16c	9.0	9.0	180	2.570 ±0.05	1,653 ± 374 (1,873)	
GE	17.8	17c	9.0	9.0	180	3.771 ± 0.06	1,610 ± 6.9 (1,695)	
GF	9.91	17c	5.0	5.0	180	18.105 ± 0.20	5,339 ± 97 (7,271)	
HA	16	17c	8.0	8.0	180	6.279 ± 0.070	1,705 ±10	
HB	16	17c	8.0	8.0	180	7.62 ± 0.060	2,190 ±20 (2,523)	
HC	16	17c	16	8.0	180	0.9446 ± 0.04	2,312 ± 52 (2,312)	2.15
HD	14	17c	7.0	7.0	180	11.48 ± 0.3	3,721 ± 209	5.7
HE	14	17c	7	7	180	10.44 ± 0.24	3,002.6 ± 36 (3,512)	
HF	14	17c	14	7	180	2.94 ± 0.1	3,109 ±88 (3,325)	
HG	12	17c	6	6	180	13.88 ± 0.2	4,023 ± 89 (4,949)	
HH	8	17c	4	4	180	22.57 ± 0.20	7,163 ± 190 (11,114)	
IA	16	17s	8	8	120	0.753 ± 0.03	2,308 ± 25 (2,254)	
IB	16	17c	16	8	180	1.566 ± 0.04	2,298 ± 23 (2,321)	2.27
IC	14	17c	7	7	adjacent	8.56 ± 0.20	3,966 ± 9 (4,519)	7.35
ID	14	17s	7	7	120	0.912 ± 0.05	3,228 ± 67	2.27
IE	14	17c	7	7	adjacent	10.12 ± 0.15	3,495 ± 58	7.62
IF	14	17c	7	7	?	9.62 ± 0.2	3,608 ± 60	3.537
IG	12	17c	12	6	180	4.084 ± 0.10	3,988 ± 88 (3,988)	
IH	9.92	17c	9.92	5.0	180	6.743 ± 0.20	6,359 ± 256 (7,527)	4.06
II	6	17c	3	3	180	25.8 ± 0.8	16,813 ±960 (20,755)	
JA	14	17c	7	3.5, 10.5	0	8.7 ± 0.12	3,285 ±59	7.58
JB	14	17c	7	7	180	NA	NA	
JC	14	16c	7	7	180	6.93 ± 0.1	3,063 ± 39	
JD	14	16c	7	7	180	9.00 ± 0.2	NA	
JE	14	16c	7	7	180	4.69 ± 0.1	3,086 ± 35	
JF	14	17c	7	7	180	7.46 ± 0.2	3,109 ± 44	
JG	12	17s	6	6	120	1.281 ± 0.05	4,156 ± 87 (4,156)	2.25, 206
JH	8	17c	4	4	180	21.7 ±0.3	7,394 ±221	10.2
KA	17.9	17c	17.9	8.95	180	1.0736 ± 0.03	1,635 ± 23 (1,763)	3.217
KB	17.9	17s	8.98	8.95	120	0.577 ± 0.02	1,664 ± 14.7 (1,751)	3.10
KC	17.9	none	-	8.95	180	NA	NA	
KD	14	none	-	7	180	NA	NA	
KE	8	17c	8	4	180	12.2 ± 0.7	11,115 ± 632	2.507, 1.95
LA	10	17c	10	5	180	7.14	NA	10.06
LB	6	17t	6	3	180	14.8 ± 0.7	18,227 ± 1,359	

Run number	Solution height (in.)	Cf source	Cf source height (in.)	Detector height (in.)	Source detector separation (degrees)	Ratio of spectral densities ($\times 10^{-2}$)[a]	Break frequency (s^{-1})[a]	Ratio of Cf source response in to out
MA	5	17c	2.5	2.5	180	29.2 ± 1.0	19,250 ±1,314	
MB	4	17c	2	2	180	NA	NA	
NA	23.89	17c	11.95	11.95	180	1.309 ± 0.01	475 ± 2	
NB	21.8	17c	11.5	11.5	180	2.713 ± 0.03	828 ± 2.5	
NC	21.8	17c	21.8	10.9	180	3.766 ±0.01	846 ± 2	
ND	21.8	17s	10.9	10.9	180	2.639 ± 0.01	853 ± 24	2.06
NE	19.94	17c	9.97	9.97	180	4.155 ± 0.04	NA (1254)	
NF	19.94	17t	19.94	9.97	180	6.03 ± 0.02	NA (1280)	
NG	19.94	17s	9.97	9.97	120	0.4628	1,288 ± 5.6 (1,232)	
NH	4	17c	2	2	180	NA	NA	
OA	16	17c	8	8	180	8.20 ± 0.1	2,425 ± 39	
OB	16	17c	8	8	180	8.29 ± 0.1	2,409 ± 27	
OC	16	17c	8	8	180	4.764 ± 0.06	NA	
OD	14	17c	7	7	180	10.8 ± 0.1	NA	
OE	12	17c	6	6	180	Not available	NA	

[a] The entries in parentheses are from the fitting described in Appendix D where all auto and cross power spectral densities are fitted simultaneously after the measurements were completed. The values not in parentheses are from only fitting the magnitude of the cross power spectral density where uncertainties are not given they were not recorded online.

The ratio of spectral densities for a limited range of heights is plotted in Figure 3.1 as a function of height with the source centrally located in the axial Zircaloy pipe. The detectors at the vertical center and the break frequency as a function of height for the same source and detector locations are plotted in Figure 3.2. The break frequencies were fitted online in a nonoptimum way. The values given are from fitting the cross power spectral density between the two detectors. The proper fitting should be done by fitting all auto and cross power spectral densities as is illustrated in Appendix D. This location of the central source and detector on the outside of the tank 180° apart favor the applicability of point kinetics interpretation of the ratio of spectral densities for determination of the neutron multiplication factors. These locations also ensure that most of the coincidences come from extremely large fission chains distributed over the entire cylindrical fissile solution.

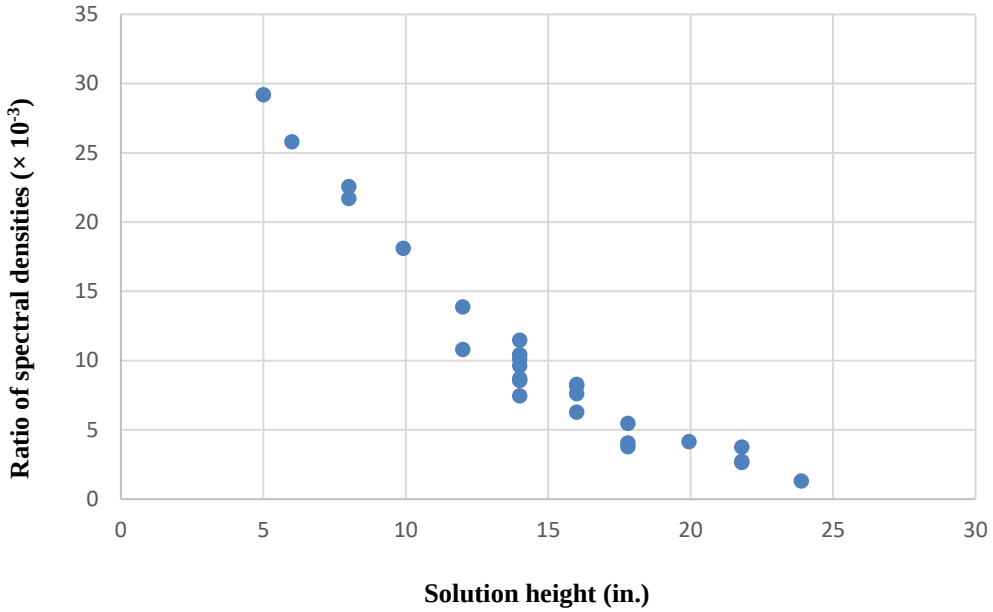

Figure 3.1. Ratio of spectral densities as a function of solution height with a central source in the axial pipe and detectors vertically centered on the outside of the tank 120° apart.

Various data can be extrapolated as a function of solution height to estimate the height of the solution at delayed criticality. Extrapolations of the ratios of spectral densities as a function of solution height were 64.1 cm with the Cf source on the radial surface, 65.2 cm with the Cf source in the axial center of the axial pipe and extrapolation of the ratio of spectral density, 65.5 cm for inverse count rate extrapolation with the central source, and 64.3 cm for inverse count rate extrapolation with the source on the radial surface.

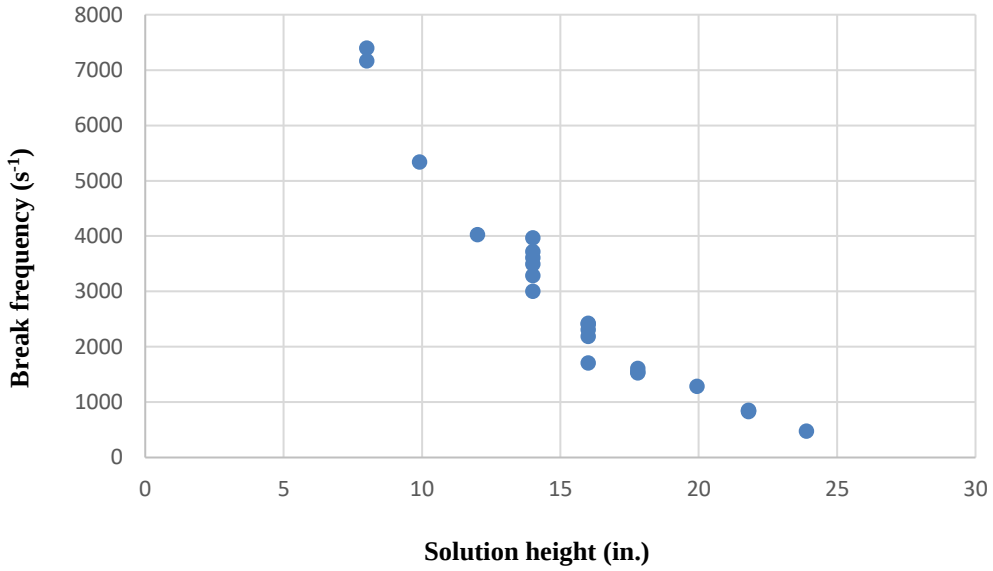

Figure 3.2. Break frequency as a function of solution height with a central source in the axial pipe and detectors vertically centered.

Prior to the measurements, calculations were performed for the measurement with the source adjacent to the radial surface of the tank for a solution concentration of 450 g/L rather than the actual concentration of 468 g/L. When repeated with the proper solution concentrations and experimental solution heights for both configurations of the tank (with and without the central source tube), these calculations can be used to interpret the ratio of spectral densities and the break frequencies to infer the neutron multiplication factors. However, the results of these previous calculations are presented in an Appendix E.

3.2.2 Correction to Ratio of Spectral Densities for Uncounted Californium Fissions

The parallel plate ionization chambers used for these measurements do not count all the Cf fissions. The uncounted Cf fissions for these chambers were determined using higher-order correlations developed by Mattingly in his dissertation [8] in 1995. These uncounted fissions contribute to cross power spectral densities in the denominator of the ratio of spectral densities but not in the numerator. All measurement before Mattingly's work requires this correction to the ratio before determining the neutron multiplication factor. A measurement is performed with the Cf source of low intensity to ensure that no pulses from alpha decay are counted with the source and two detectors (1 and 2) spaced in air about 50 cm from the source and 180° from the source. This location ensures that cross talk between from the same particle from the source is negligible. The cross power spectral density between both detectors, G_{12}, contains contributions from all Cf fissions while the higher-order spectral density, G_{S12}, contains only contributions from Cf fissions that have been detected. The ratio G_{S12}/G_{12} is the fraction of Cf fission counted. This value was measured to be 0.96, and the denominator of the ratio of spectral densities needs to be multiplied by 0.96. The online ratios of spectral densities must be multiplied by 1.04 before determination of the subcritical neutron multiplication factor. After this correction for undetected Cf fissions, the values of $(1-k_{eff})/k_{eff}$ could increase by about 4%, resulting in the neutron multiplication factor from the interpretation being reduced.

3.2.3 Needed Additional Analysis of the Ratio of Spectral Densities

For other than the direct benchmark calculation of the ratio of spectral densities [9], these ratios will have to be interpreted using the point kinetics models to obtain the subcritical neutron multiplication factor, k_{eff}**.** Two models exist for this interpretation: the Pare/Mihalczo [10] and Akcasu/Stolle [11] interpretation, the former in which detection of the first event in a coincidence between the two detectors does not affect the next count, and the Akcasu/Stolle model where it does. Ever since this was originally pointed out by Difilippo in 1986 [12] the author's analysis of the ratio of spectral density data has been done by both methods and has consistently shown that the Akcasu/Stolle model gives incorrect neutron multiplication factors at values below $k_{eff} = 0.80$. It is expected that this will also be the case for these data but in any case should be done to verify. These inferred neutron multiplication factors can be compared with the calculations in the benchmark analysis.

3.3 NEUTRON COUNT RATES

The ratio of count rate with and without the Cf source is needed in the analysis of the ratio of spectral densities to obtain the subcritical neutron multiplication factor. It can be obtained by measurement of the count rate in external detectors with and without the Cf source in the location for the measurement of the ratio of spectral densities. With the source inserted, the count rate is related to the total fission rate induced by Cf and the inherent source fission from the ^{240}Pu. With the Cf source removed, the count rate is related to the inherent source fission. This ratio can be expressed as $(F_c\ I_c\ \nu_c + F_i\ I_i\ \nu_i) / (F_i\ I_i\ \nu_i)$, where F_c is the Cf fission rate, I_c is the importance of Cf neutrons for causing fission, and ν_c is the number of neutrons per Cf fission with similar quantities defined for fission induced by the inherent source neutron from ^{240}Pu. The results of these measurements are given in Tables 3.3 and 3.4. Additional count rates are given in Appendix C. These count rates can also be used to determine the subcritical neutron

multiplication actor down to k_{eff} = 0.90 using the modified source neutron multiplication analysis method [13], which accounts for changes in detection efficiency and source effectiveness as the solution height is decreased.

Table 3.3. Counts in 80 s with and without the Cf source present for measurements with the source on the radial surface.

Run number	Solution height (in.)	Cf source	Cf source height (in.)	Detector 1 count rate (counts per 80 s)	Detector 2 count rate (counts per 80 s)
AEa	17.8	16 in	9.0	<44,013> <45,324>	<45,324>
	17.8	16 out		10,832	11,448
AFb	14.5	16 in	7.25	24,142	25,557
	14.5	16 out		5,692	6,158
BCa	14.4	16 in	9.0	23,667	25,316
	14.4	16 out		5,600	6,000
BCa	13.05	16 in	6.5	<18,646>	<20,044>
		16 out		4,371	4,688
CAa	13.05	16 in	6.5	18,597	20,037
		16 out		4,371	4,688
CAa	15.87	16 in	8	31,200	32,300
		16 out		7,449	7,933
CBa	15.87	16 in	6.5	27,273	29,043
		16 out		7,449	7,939
CDa	11.2	16 in	6.5	<13,514>	<15,356>
		16 out		3,149	3,594
DDA	10.0	16 in	5	<10,821>	<12,751>
		16 out		<2,619>	<2,988>
FAa	8.0	16 in	4	<8,539>	<10,529>
		16 out		<2,034>	<2,395

Table 3.4. Counts in 80 s for measurements with the central Zircaloy source tube with the source CF 17 and 16 with detectors outside.

Run number	Solution height (in.)	Cf source	Cf source height (in.)	Detector 1 count rate (counts per 80 s)	Detector 2 count rate (counts per 80 s)	Detector 3 count rate (counts per 80 s)
GCa	17.9	17 in	9.0	<75,926>	<75,643>	
		out		9,536	9,837	
	17.9	16 in	9.0	<171,261>	<170,565>	
HEa	14	17 in top	14.0	16,787	17,239	19,075
		out		<4,803>	<4,971>	<5,227>
	14	17 in c	7.0	36,481	35,973	43,181
HEa	16	17 in top	16	15,910	15,910	18,078
		out		6,824	7,030	7,684
	14	17 in c	8	53,817	52,386	63,502
HGa	12	17 in	6.0	25,889	26,113	30,796
		out		3,546	3,767	3,827
HHa	8	17 in	4	12,829	13,812	13,890
		out		2,099	2,413	2,033
IBa	16	17 in top	16	21,108	21,891	23,267
		out		6,631	7,093	7,570
IBa	16	17 in r	8	14,951	16,217	
IBa	14	17 in r	7	10,719	11,843	
		out		4,651	5,108	5,265
	14	17 in c	7	<35,572>	<36,799>	<42,523>
IBa	10	17 in top	10	10,548	11,592	11,045
		out		2,584	3,007	2,603
IHa	12	17 in top	12	13,125	14,537	14,018
		out		3,482	3,367	3,531
JBa	14	17 in c	7	<36,008>	<35,903>	41,873
		out		4,579	5,758	5,211
Background	0	No solution	NA	1,231	1,389	1,161
JBa	6	17 in c	3	<9,543>	<10,176>	<10,003>
		out		1,752	2,067	1,718
Background	0	No solution	NA	1,248	1,392	1,170
JHa	13.95	17 in c	7	<34,984>	<34,984>	<42,010
		out		4,579	5,158	5,211
	13.95	16 in c	7	78,330	81,319	94,053
Background	0	No solution	NA	1,239	1,391	1,155
JHa	12	17 radial	6	7,895	9,164	
		out		3,442	3,926	3,538
KAa	8	17 in c	4	12,979	13,726	13,809
		out		2,108	2,438	2,007
	17.9	17 c top	17.9	<28,441>	<29,203>	<33,111>

Run number	Solution height (in.)	Cf source	Cf source height (in.)	Detector 1 count rate (counts per 80 s)	Detector 2 count rate (counts per 80 s)	Detector 3 count rate (counts per 80 s)
		out		9,619	10,110	11,093
		17 radial	17.9	21,499	2,2619	31,739
LAa	10	17 c	5	17,177	18,089	18,509
		out		2,593	2,867	2,569
LAa	6	17 c	3	6,317	6,889	6,422
		out		1,725	2,015	1,618
LBa	5	17 c	2.5	7,806	8,526	8,218
		out		1,615	1,852	1,553

These count rates can be used for benchmarks if the location of the Pacific Northwest National Laboratory detector and their configuration can be defined accurately from the critical facility logbooks and the operations manual for the facility. The count rates may be affected by the proximity of the facility solution storage tanks, which were 39 in. from the rectangular reflector tank that surrounded the cylindrical tank. For lower solution heights, a contribution exists from the storage tanks that contributed to the count rate, and this could not be separated experimentally. The amount of fissile solution in the storage tanks is a function of how much solution is in the cylindrical experimental tank. In Table 3.4, there are some background count rates with all of the solution in the storage tank and the cylindrical experimental vessel empty. Perhaps the best way to get the ratio of fission rates is from calculating the fission rates with and without the source.

3.4 RATIO OF TOTAL FISSION TO THOSE INDUCED BY CALIFORNIUM

This ratio is needed in the analysis of the ratio of spectral densities to obtain the subcritical neutron multiplication factor. It can be obtained by measuring the count rate in external detectors with and without the Cf source in the location to measure the ratio of spectral densities. With the source inserted, the count rate is related to the total fission rate induced by Cf and inherent source fission from the ^{240}Pu, and with the Cf source removed, the count rate is related to the inherent source fission. This ratio can be expressed as $(F_c\ I_c\ \nu_c + F_i\ I_i\ \nu_i)/(F_i\ I_i\ \nu_i)$, where F_c is the Cf fission rate, I_c is the importance of Cf neutrons for causing fission, and ν_c is the number of neutrons per Cf fission with similar quantities defined for fission induced by the inherent source neutron from ^{240}Pu. The results of these measurements are given in Tables 3.3 and 3.4.

4. SUMMARY OF ADDITIONAL PROCESSING OF EXPERIMENTAL

The parameters needed to interpret the ratio of spectral densities need to be recalculated for the cylindrical tank both with and without the central Zircaloy source pipe. The original data need to be reexamined to better determine the ratio of spectral densities. To examine the original CSDNA data, additional work has to be done on the data (which was acquired on a VAX computer) with present computers to convert into a modern format for analysis. These ratios can be calculated directly, as described in Reference 8. Then, the ratio of spectral densities can be interpreted to obtain the subcritical neutron multiplication factors. Uncertainty analysis needs to be performed to determine the experimental uncertainty in the experimental multiplication factors, which can then be compared with calculations.

The auto and cross power spectral densities need to be refitted simultaneously to better determine the break frequency from which the prompt neutron decay constant can be obtained. These values can be compared with calculation by Monte Carlo or S_n transport theory methods. The neutron lifetime and delayed neutron fractions need to be calculated as a function of solution height for the measurements with and without the central Zircaloy source pipe. Break frequency noise analysis can then be used to determine the subcritical neutron multiplication factor, which is usually accurately down to $k_{eff} = 0.80$.

5. CONCLUSIONS

Near critical and subcritical Cf source-driven noise analysis (CFDNA) measurements have been performed for a mixed U (188.4 g/L) Pu (280.4 g/L) nitrate solution in a cylindrical tank. The experiment tank was of stainless steel with a height of 56.72 cm, a diameter of 35.38 cm, an outside diameter of 35.54 cm, and a height of 56.72 cm. The thickness of the bottom of the stainless-steel tank was 0.9525 cm. The reentrant tube into the solution for the Cf source was Zircaloy with a density of 6.57 g/cm^3. The inside diameter of the reentrant tube was 2.7788 cm; the outside diameter was 3.1496 cm, and the bottom thickness was 0.635 cm. The bottom of the solution tank was 6.25 in. above the bottom of the large empty reflector tank that surrounded the cylindrical solution tank. The neutron multiplication factor determined from the inverse kinetics rod drop near delayed critical for the tank without the central source pipe was $k_{eff} = 0.9916$ with a solution height of 53.18 cm. The neutron multiplication factor determined from the inverse kinetics rod drop near delayed critical for the tank without the central source pipe was $k_{eff} = 0.9920$ with a solution height of 60.70 cm.

This report summarizes the experimental data and points out additional experimental evaluation of the data to convert it into a form where information for the measurements performed can be used at a later date. Researchers could perform the required uncertainty and calculational analyses and documentation to use these data for an International Criticality Safety Benchmark Program (ICSBEP) or Nuclear Energy Agency benchmark. The data from these measurements are available from the Oak Ridge National Laboratory Records Management Services Department, and the logbook is available from ICSBEP at Idaho National Laboratory.

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APPENDIX A. SKETCH OF THE MONTE CARLO MODEL OF THE CALIFORNIUM IONIZATION CHAMBERS

A sketch of the Monte Carlo N-Particle (MCNP) model of these ionization chambers is given in Figure A.1. An MCNP model can obtained from the International Nuclear Criticality Safety Benchmark Program/ Nuclear Energy Agency benchmark report SUB-HEU-SOL-THERM-002.

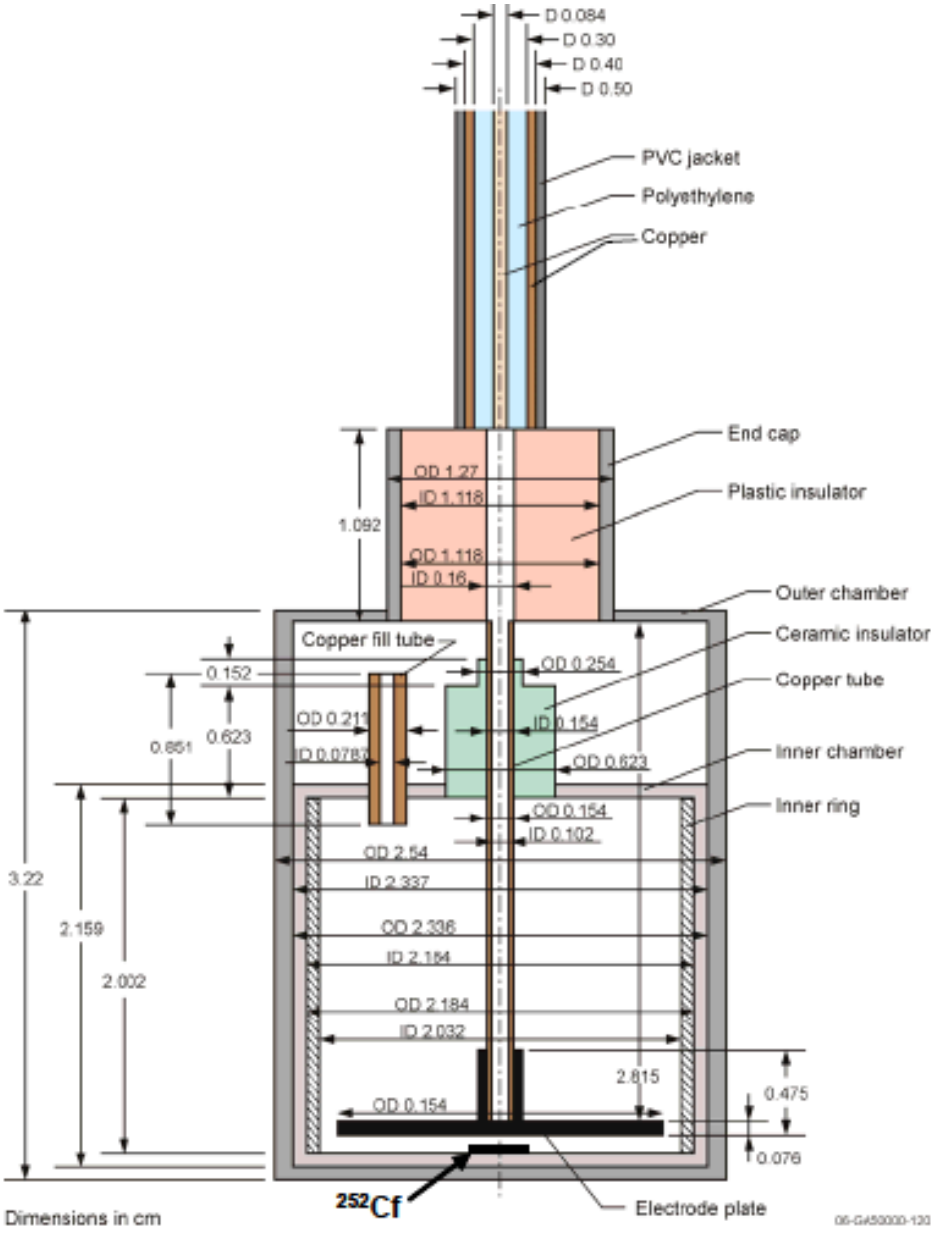

Figure A.1. Sketch of the MCNP model of the Cf ionization chambers.

APPENDIX B. INVERSE KINETIC ROD DROP MEASUREMENTS CLOSE TO DELAYED CRITICAL

In these measurements, the solution in both cylindrical tanks was raised to a height for which the systems were above delayed criticality with the safety (moderator) blade adjacent to the tank surface. The fission rate was increased until it was sufficiently high that the sources present contributed negligibly to the fission rate. Then the solution height was lowered until the systems were at delayed criticality, and the fission rate was maintained at a constant rate until the delayed neutrons had come to equilibrium (over 10 min). The systems remained at this constant level for some time while the count rate was recorded before the safety (moderator) blade was removed quickly. The count rate continued to be recorded as the fission rate decreased to a constant low level. After the initial prompt, neutron decrease, the shape of the decay was determined by the properties of the delayed neutrons, source intensities, and reactivity. These data were acquired on a Technical Measurements Corporation multichannel time analyzer with 1,028 0.2 s time intervals. These data are presented in Figures B.1 and B.2. These data should be reevaluated for the benchmark with the present data for the delayed neutrons. The uncertainties in the delayed neutron parameters can be used to determine the uncertainties in the reactivities after the safety blade was removed. In these tables, the first column on the left is the time interval, entry 1 is time zero, and the last entry of the first line is that for time = 1.40 s. The entry in the second column is for time 1.60 s, and the last entry on the second line is for time 3.00 s, and so on. Time increases to the right and down. Missing values will have to be interpolated for the final reactivity determination from the inverse kinetic rod drop data.

Table B.1. Count rate as a function of time every 0.2 s before and after the safety blade removal for the inverse kinetic rod drop measurement for the tank with the central Zircaloy source insertion pipe and a solution height of 60.68 cm. (Page 213 of ORNL logbook H00227; column 1 is the multichannel analyzer channel number).

RTDEFGYOUY91233455677899876123

0	1	12045	11737	11817	11784	11849	11743	11787
8	11846	11675	12106	11847	11527	11795	11860	11494
16	11965	11936	11836	11915	11925	11722	11666	11781
24	11887	11730	11981	11730	11811	11880	11706	11658
32	11896	11938	11932	11956	11780	11768	12031	11812
40	11694	11640	12020	11899	11965	11661	11894	11667
48	12037	11793	11974	11849	11641	11799	11873	11871
56	11719	11889	11898	11944	12027	11718	11777	12034
64	11703	11983	11743	12047	11854	11893	11788	12017
72	11807	11801	11952	11793	11779	11810	11874	11950
80	11853	11799	11879	11859	11893	11855	12002	11723
88	11856	11929	11606	11584	9047	5888	5617	5605
96	5490	5445	5434	5400	5394	5162	5164	5347
104	5174	4977	5079	4952	4988	4923	5051	4938
112	4999	4824	4887	4886	4849	4703	4822	4800
120	4592	4759	4682	4804	4785	4619	4715	4626
128	4634	4645	4681	4701	4691	4619	4662	4618
136	4449	4664	4549	4561	4576	4545	4484	4471
144	4364	4547	4386	4479	4430	4398	4428	4393
152	4319	4313	4326	4455	4305	4427	4388	4359
160	4387	4314	4219	4285	4219	4341	4213	4302
168	4310	4265	4360	4367	4280	4367	4253	4238
176	4152	4321	4162	4178	4190	4256	4288	4249
184	4080	4058	4166	4133	4329	4243	4179	4160
192	4280	4116	4055	4204	4259	4144	4199	4214
200	4043	4000	4111	4121	4136	4057	4100	4295
208	4044	4114	3993	4016	4062	4019	4046	4141
216	4211	4043	4117	4058	4001	4037	4005	4033
224	4038	4121	4082	4055	3981	3964	4119	4123
232	4136	3978	4002	4066	4059	3945	4021	3942
240	3958	3990	3874	3847	3999	3983	4063	4049
248	3780	3980	4061	4022	3967	3946	4129	3964
256	3851	3960	3906	4006	3969	3856	4001	4009
264	4080	3972	4045	3857	3877	4029	3891	4037
272	3906	3880	3896	3860	4008	3904	3954	3943
280	3891	3866	3982	3874	3947	3984	3816	3835
288	3894	3935	3885	3875	3994	3851	3836	3834
296	3827	3837	3815	3943	3873	3945	3780	3856
304	3836	3915	3844	3803	3824	3887	3860	3916
312	3887	3804	3869	3871	3853	3689	3736	3811
320	3830	3863	3875	3724	3902	3854	3799	3819
328	3887	3831	3799	3896	3899	3794	3797	3890
336	3772	3790	3802	3847	3726	3925	3770	3746
344	3851	3711	3844	3810	3851	3775	3810	3841
352	3778	3915	3755	3810	3758	3891	3859	3847
360	3782	3807	3725	3670	3773	3660	3780	3726

368	3841	3694	3772	3625	3748	3826	3730	3834
376	3698	3719	3739	3763	3625	3753	3681	3742
384	3813	3783	3670	3651	3747	3659	3731	3752
392	3616	3649	3796	3857	3812	3647	3743	3660
400	3748	3790	3854	3764	3714	3673	3655	3782
408	3670	3745	3614	3696	3704	3628	3727	3723
416	3601	3799	3736	3749	3742	3619	3801	3749
424	3582	3648	3629	3740	3726	3785	3764	3663
432	3706	3614	3694	3677	3575	3802	3678	3655
440	3698	3626	3749	3734	3731	3686	3609	3712
448	3748	3711	3720	3745	3623	3665	3733	3698
456	3696	3763	3629	3631	3617	3639	3608	3750
464	3770	3537	3704	3711	3695	3617	3617	3719
472	3688	3766	3687	3641	3658	3764	3631	3662
480	3736	3659	3719	3624	3708	3694	3644	3709
488	3750	3707	3626	3549	3641	3683	3601	3656
496	3658	3692	3637	3767	3641	3679	3641	3668
504	3618	3706	3531	3750	3605	3659	3653	3607
512	3797	3718	3758	3683	3586	3621	3562	3490
520	3647	3648	3592	3693	3666	3557	3676	3606
528	3556	3605	3591	3544	3671	3662	3567	3646
536	3520	3653	3663	3566	3603	3616	3646	3703
544	3575	3491	3563	3500	3676	3650	3626	3743
552	3671	3598	3571	3658	3739	3532	3543	3689
560	3603	3663	3480	3631	3562	3539	3540	3601
568	3495	3585	3638	3603	3613	3669	3739	3649
576	3543	3646	3589	3533	3642	3555	3619	3589
584	3574	3649	3634	3635	3528	3576	3633	3688
592	3702	3595	3590	3573	3634	3489	3586	3576
600	3681	3616	3551	3639	3656	3587	3572	3625
608	3534	3569	3549	3540	3588	3432	3540	3566
616	3445	3663	3547	3673	3649	3535	3595	3593
624	3655	3731	3566	3558	3611	3548	3624	3577
632	3586	3675	3660	3728	3615	3633	3622	3573
640	3592	3681	3525	3514	3659	3594	3675	3572
648	3561	3607	3592	3560	3460	3666	3617	3653
656	3502	3617	3609	3537	3587	3503	3637	3500
664	3624	3557	3631	3583	3616	3609	3596	3516
672	3586	3551	3581	3532	3677	3480	3602	3517
680	3580	3508	3607	3585	3477	3608	3555	3535
688	3457	3615	3601	3673	3585	3597	3581	3496
696	3508	3613	3630	3719	3610	3585	3509	3492
704	3554	3475	3635	3595	3522	3649	3572	3576
712	3593	3480	3506	3671	3600	3726	3619	3495

720	3606	3529	3651	3546	3532	3512	3518	3571
728	3599	3567	3588	3508	3528	3517	3672	3539
736	3552	3562	3601	3501	3544	3532	3698	3520
744	3475	3591	3499	3589	3453	3625	3573	3578
752	3500	3568	3545	3542	3524	3505	3582	3595
760	3683	3651	3599	3643	3529	3408	3616	3587
768	3461	3477	3534	3617	3635	3473	3494	3511
776	3514	3602	3571	3537	3599	3530	3558	3577
784	3591	3480	3602	3481	3578	3447	3528	3641
792	3535	3563	3506	3568	3523	3544	3463	3539
800	3547	3621	3618	3526	3524	3626	3558	3492
808	3520	3610	3629	3444	3479	3578	3521	3492
816	3497	3524	3522	3523	3541	3650	3553	3532
824	3544	3614	3595	3587	3514	3566	3571	3558
832	3483	3565	3498	3536	3502	3540	3610	3529
840	3553	3582	3580	3540	3563	3526	3571	3470
848	3609	3570	3608	3628	3576	3480	3618	3545
856	3493	3567	3645	3522	3618	3529	3540	3525
864	3514	3611	3492	3623	3517	3515	3496	3540
872	3608	3513	3557	3568	3542	3449	3619	3627
880	3609	3510	3604	3453	3564	3484	3540	3598
888	3612	3482	3468	3471	3420	3545	3629	3610
896	3561	3492	3632	3600	3582	3518	3426	3537
904	3448	3573	3553	3523	3453	3562	3583	3532
912	3625	3539	3553	3540	3419	3568	3577	3527
920	3549	3549	3477	3514	3580	3549	3511	3441
928	3523	3554	3509	3454	3498	3602	3626	3551
936	3460	3509	3620	3550	3583	3434	3441	3622
944	3456	3488	3533	3580	3551	3391	3554	3491
952	3400	3464	3467	3424	3601	3462	3485	3556
960	3507	3386	3496	3473	3442	3622	3529	3365
968	3623	3524	3485	3595	3583	3507	3545	3609
976	3529	3505	3487	3471	3493	3537	3489	3506
984	3481	3570	3502	3550	3575	3526	3539	3472
992	3589	3625	3516	3477	3417	3484	3549	3467
1000	3522	3534	3521	3533	3477	3483	3545	3505
1008	3581	3552	3537	3376	3573	3597	3565	3557
1016	3414	3520	3513	3539	3563	3546	3514	3522

Table B.2. Count rate as a function of time every 0.2 s before and after the safety blade removal for the IKRD measurement for the tank without the central Zircaloy source insertion pipe and a solution height of 53.18 cm. (Page 113 of ORNL logbook H00227; column 1 is the multichannel analyzer channel number).

7/21/1961

0	1	8658	8711	8789	8586	8838	8864	8690
9	8575	8933	8644	8933	8648	8745	8744	8857
16	8751	8749	8698	8747	8835	8599	8678	8520
24	8845	8975	8850	8514	8511	8798	8855	8759
32	8588	8759	8643	8711	8839	8757	8766	8524
40	8632	8848	8616	8742	8749	8766	8765	8739
8	8756	8502	8784	8832	8580	8460	8801	8841
56	8584	8695	8847	7117	3765	3493	3428	3469
64	3343	3314	3278	3278	3242	3205	3130	3018
72	3036	3064	3016	2968	3016	2951	2905	2962
80	2851	2866	2755	2920	2828	2827	2771	2687
88	2732	2872	2675	2801	2753	2734	2658	2705
96	2613	2747	2530	2575	2622	2564	2637	2598
104	2607	2537	2501	2491	2473	2502	2669	2473
112	2500	2529	2506	2439	2552	2566	2438	2510
120	2477	2464	2426	2480	2398	2454	2407	2416
128	2466	2419	2329	2440	2431	2334	2338	2287
136	2386	2325	2308	2346	2317	2399	2439	2387
144	2349	2359	2353	2400	2411	2292	2370	2354
152	2291	2311	2243	2295	2351	2296	2306	2286
160	2228	2259	2294	2262	2357	2312	2189	2222
168	2260	2252	2238	2238	2251	2279	2219	2204
176	2268	2213	2265	2216	2194	2257	2210	2194
184	2200	2148	2310	2097	2274	2151	2218	2126
192	2231	2128	2219	2233	2176	2136	2185	2214
200	2162	2094	2224	2171	2172	2121	2149	2159
208	2126	2084	2172	2166	2130	2222	2107	2110
216	2101	2090	2213	2136	2054	2148	2103	2130
224	2140	2153	2127	2068	2038	2086	2037	2134
232	2038	2134	2096	2108	2093	2095	2100	2161
240	2076	2168	2111	2086	2112	2079	2123	2116
248	2057	2057	2133	2092	2059	2089	2004	2020
256	2050	2106	2042	2017	2061	2095	2120	2100
264	2038	2050	2043	2018	2026	1983	2060	2037
272	2022	2030	2038	2011	1972	2010	2008	2056
280	1987	2017	1993	2119	2079	2031	2049	2049
288	2016	2050	1952	2063	2035	2001	1982	2050
296	2009	1974	1968	1975	2013	2022	2090	2009
304	2024	1986	2013	1971	1987	1892	1987	1949
312	1977	1916	2034	1962	1979	2024	1970	1997
320	1983	1945	1928	1980	1920	1888	1952	1916
328	1964	1990	1980	2034	1926	1991	1872	1971
336	1975	1980	1935	1983	1945	1964	2037	1967

344	1992	1962	1889	1983	2003	2048	1925	1900
352	1914	2006	1992	1908	1938	1964	1928	1936
360	1978	1848	1869	1951	1886	1934	1837	1999
368	1889	1952	2002	1992	1902	1942	2004	1979
376	1962	1971	1910	1826	1879	1968	1968	2046
384	1890	1902	1910	1967	1925	1977	1881	1859
392	1919	1951	1857	1901	1970	1979	1938	1868
400	1953	1922	1926	1895	1928	1825	1931	1974
408	1940	1951	1918	1847	1864	1812	1932	1891
416	1871	1930	1874	1841	1910	2027	1906	1915
424	1849	1941	1935	1888	1942	1901	1970	1869
432	1894	1881	1827	1990	1897	1952	1943	1854
440	1894	1913	1854	1960	1959	1906	1856	1847
448	1873	1917	1919	1876	1835	1864	1848	1879
456	1928	1835	1859	1878	1841	1941	1952	1883
464	1952	1847	1830	1858	1925	1879	1822	1881
472	1919	1853	1852	1812	1875	1917	1844	1877
480	1996	1893	1872	1862	1890	1823	1840	1911
488	1886	1903	1862	1844	1872	1835	1869	1795
496	1812	1830	1781	1943	1855	1805	1842	1877
504	1806	1870	1842	1817	1883	1931	1860	1833
512	1849	1948	1866	1913	1787	1814	1833	1869
520	1832	1853	1874	1812	1855	1863	1941	1854
528	1974	1893	1859	1869	1897	1834	1962	1830
536	1819	1888	1858	1825	1864	1854	1919	1878
544	1893	1839	1782	1799	1947	1834	1837	1850
552	1852	1874	1812	1879	1881	1891	1815	1849
560	1822	1805	1872	1870	1860	1838	1810	1804
568	1876	1831	1843	1817	1786	1900	1904	1830
576	1873	1796	1827	1815	1882	1842	1875	1901
584	1748	1827	1868	1751	1814	1897	1736	1811
592	1854	1935	1855	1866	1886	1846	1802	1858
600	1873	1889	1854	1862	1837	1850	1815	1867
608	1874	1831	1791	1837	1780	1868	1818	1853
616	1857	1795	1873	1805	1845	1900	1805	1844
624	1930	1753	1840	1800	1811	1877	1757	1819
632	1763	1910	1818	1817	1840	1923	1788	1829
640	1896	1805	1765	1850	1852	1797	1769	1814
648	1795	1868	1847	1746	1803	1782	1804	1839
656	1895	1798	1792	1798	1781	1732	1763	1800
664	1744	1846	1828	1839	1862	1767	1856	1849
672	1760	1845	1722	1853	1903	1757	1793	1817
680	1835	1847	1827	1818	1754	1729	1776	1871

688	1792	1802	1760	1824	1873	1817	1884	1818
696	1831	1793	1776	1799	1837	1786	1786	1850
704	1924	1760	1768	1843	1790	1784	1821	1805
712	1788	1828	1741	1844	1712	1854	1829	1758
720	1801	1859	1780	1795	1804	1803	1737	1775
728	1741	1842	1879	1827	1788	1879	1800	1745
736	1760	1775	1816	1709	1835	1834	1780	1851
744	1865	1783	1814	1854	1701	1882	1834	1828
752	1831	1757	1827	1725	1870	1862	1745	1768
760	1787	1809	1881	1872	1793	1784	1769	1808
768	1895	1809	1764	1791	1843	1784	1861	1814
776	1771	1850	1850	1802	1842	1806	1810	1807
784	1758	1826	1724	1768	1811	1778	1867	1790
792	1836	1829	1750	1739	1741	1866	1773	1830
800	1897	1825	1847	1789	1784	1777	1779	1814
808	1730	1853	1902	1772	1695	1805	1765	1821
816	1838	1773	1751	1834	1772	1773	1766	1761
824	1796	1819	1795	1811	1851	1833	1838	1744
832	1761	1825	1783	1785	1811	1784	1746	1783
840	1788	1783	1766	1793	1872	1738	1854	1786
848	1771	1839	1827	1766	1727	1841	1890	1814
856	1829	1760	1814	1848	1721	1723	1736	1778
864	1771	1693	1798	1730	1813	1758	1801	1780
872	1774	1739	1830	1814	1865	1773	1808	1736
880	1763	1790	1748	1822	1745	1747	1863	1744
888	1817	1809	1831	1703	1752	1841	1808	1719
896	1768	1813	1812	1828	1700	1738	1757	1806
904	1777	1710	1768	1726	1784	1830	1859	1798
912	1751	1880	1724	1828	1730	1857	1709	1754
920	1800	1801	1813	1815	1787	1806	1740	1663
928	1834	1831	1839	1726	1801	1808	1811	1826
936	1842	1793	1768	1794	1848	1753	1718	1799
944	1791	1782	1772	1785	1802	1753	1718	1852
952	1783	1839	1699	1809	1841	1857	1806	1759
960	1761	1766	1865	1815	1890	1771	1780	1762
968	1816	1758	1676	1820	1773	1733	1758	1821
976	1759	1685	1781	1830	1881	1807	1835	1750
984	1756	1819	1782	1811	1784	1753	1765	1772
992	1708	1761	1745	1867	1831	1741	1811	1804
1000	1707	1754	1734	1848	1813	1842	1741	1785
1008	1786	1769	1740	1894	1757	1815	1791	1742
1016	1815	1717	1769	1734	1735		1740	1797

APPENDIX C. ADDITIONAL NEUTRON COUNTING INFORMATION

This appendix lists additional count rate information with the Cf source inserted and removed and with no source and no solution in the cylindrical tank.

Table C.1. Detector count rate as a function of fuel solution height for various ^{252}Cf source locations.

Fuel solution height (in.)	Central zircalloy pipe	Source	Location	Date	Count rate from proportional counters (counts per s)				
					#1[a]	#2[a]	#3[a]	#4[b]	#5[a]
20.9	out	16	R	7-21	2056	2123	2657	9013	
19.4	out	16	R	7-21	947	974	1342	4234	
17.5	out	16	R	7-21	550	567			
		none	--	7-21	135	142			
14.5	out	16	R	7-21	302	319			
		none	--	7-21	71	77			
17.5	out	16	R	7-22	571	597			37054
15.9	out	16	R	7-22	386	407			24149
14.5	out	16	R	7-22	296	316			17581
		none	--	7-22	70	75			4365
13.05	out	16	R	7-22	233	251			
		none	--	7-22	54.1	59.3			
		16	R	7-23	232	250			14328
		none	--	7-23	54.6	58.6			3546
15.9	out	16	R	7-23	390	404			25353
		none	--	7-23	93	99			
		16	R 3/4	7-23	341	363			21623
		none	--	7-23	93	99			
		16	R 1/4	7-23	351	373			22210
11.2	out	16	R	7-23	169	192			9374
		none	--	7-23	39.4	44.9			
20.53	out	16	R	7-24	1530	1589	2058	6754	77621
20.25	out	16	R	7-24	1281	1328	1759		
10	out	16	R	7-24	135	159			
		none	--	7-24	32.7	37.6			
8	out	16	R	7-26	107	132			3853
		none	--	7-26	25.4	29.9			
7.06	out	16	R	7-26					2970

Fuel solution height (in.)	Central zircalloy pipe	Source	Location	Date	Count rate from proportional counters (counts per s)				
					#1[a]	#2[a]	#3[a]	#4[b]	#5[c]
0	out	none[d]	--	7-27	15.4	17.4	14.5		
17.9	in	17	C	7-27	949	946	1136		60657
		none	--	7-27	119	123	138		
		16	C	7-27	2141	2123	2548		91705
10	in	17	C	7-27					17827
		none	--	7-27	33	37	36		
16	in	17	C	7-28	673	655	794	3240	45202
		none	--	7-28	85	88	96	480	
		17	T	7-28				1032	12648
14	in	17	C	7-28	456	450	540	2173	33649
		none	--	7-28	60	62.1	65.7	381	
		17	T	7-28	210	215	238		13873
12	in	17	C	7-28	324	326	385	1546	
		none	--	7-28	44.3	47.1	47.8	298	
8	in	17	C	7-29	160	173	174		
		none	--	7-29	26.2	30.2	25.4		
16	in	17	T	7-29	263	274	290	1310	11828
		none	--	7-29	83	89	95	490	5333
		17	R	7-29	187	204			15919
14	in	17	R	7-29	134	148			8171
		none	--	7-29	58.1	63.9	65.8		
		17	C	7-29	453	460	529		33032
12	in	17	T	7-29	164	182	175		24715
		none	--	7-29	43.5	48.3	44.1		2633
10	in	17	T	7-29	132	145	139	702	7211
		none	--	7-29	32.3	37.6	32.5	280	1582
6	in	17	C	7-29	118	127	125	696	6239
		none	--	7-29	21.9	25.8	21.5	228	639
14	in	17	C	7-30	450	449	523	2054	32607
		none	--	7-30	57.2	64.5	65.1	386	3757
		17	C	7-30	439	457	523		32000
		16	C	7-30	979	1016	1176		64565
		17	C	7-30	436	457	527		

Fuel solution height (in.)	Central zircalloy pipe	Source	Location	Date	Count rate from proportional counters (counts per s)				
					#1[a]	#2[a]	#3[a]	#4[b]	#5[c]
12	in	17	R	7-30	99	115		621	5606
		none	--	7-30	43.0	49.1	44.2	306	2530
8	in	17	C	7-31	162	172	173	505	5029
		none	--	7-31	26.4	30.5	25.0	201	978
0	in	none[d]	--	7-31	15.6	17.4	14.6	180	179
17.9	in	17	T	7-31	356	366	414		
		17	R	7-31	269	283	397	1255	16859
		none	--	7-31	120	126	139	605	7812
8	in	17	T	8-1	104	115	108	505	5029
		none	--	8-1	26.1	30.2	25.1	201	978
10	in	17	C	8-1	215	226	231	1160	15196
		none	--	8-1	32.4	37.1	32.1	277	1544
10	in	17	T	8-1				687	6909
6	in	17	T	8-1	79.6	86.1	80.3	497	2963
		none	--	8-1	21.6	25.2	20.2	229	607
5	in	17	C	8-2	97.6	107	103	607	4683
		none	--	8-2	20.2	23.1	19.4	221	485
4	in	17	C	8-2	84.1	90.5	89.4	557	3590
		none	--	8-2	18.4	21.5	17.5	213	380
0	in	none[d]	--	8-3	15.1	16.7	14.3	197	240
23.9	in	17	C	8-3	4386	4535	5086	17200	66841
		none	--	8-3					
21.8	in	17	C	8-3	2078	2132	2469	8727	66783
		17	T	8-3	689	719	799	3028	25417
		17	R	8-3	595	620	776	2643	
		none	--	8-3	285	297	330	1312	
19.93	in	17	C	8-3	1305	1323	1569		70512
		17	T	8-3	439	459	513	2010	25980
		17	R	8-3	377	399	524	1788	22544
		none	--	8-3	177	187	205	871	10970

APPENDIX D. BREAK FREQUENCY NOISE ANALYSIS AND PROMPT NEUTRON DECAY CONSTANT

This appendix defines the break frequency [D.1] and presents data from another measurement to show how the data is fitted [D.2] to determine the break frequency. The break frequency, sometimes called the cutoff frequency, is the frequency at which the response initiates its decrease (Figure D.1). This frequency is determined by fitting the cross or auto spectral densities to an amplitude and a break frequency. The data can be fitted to one break frequency because the point kinetics model is applicable, which is usually true for neutron multiplication factors above 0.80. At further subcritical, this model does not work because the data cannot be fitted in this manner to a single break frequency. This gives a quantitative estimate of when point kinetics interpretation cannot be used for this method.

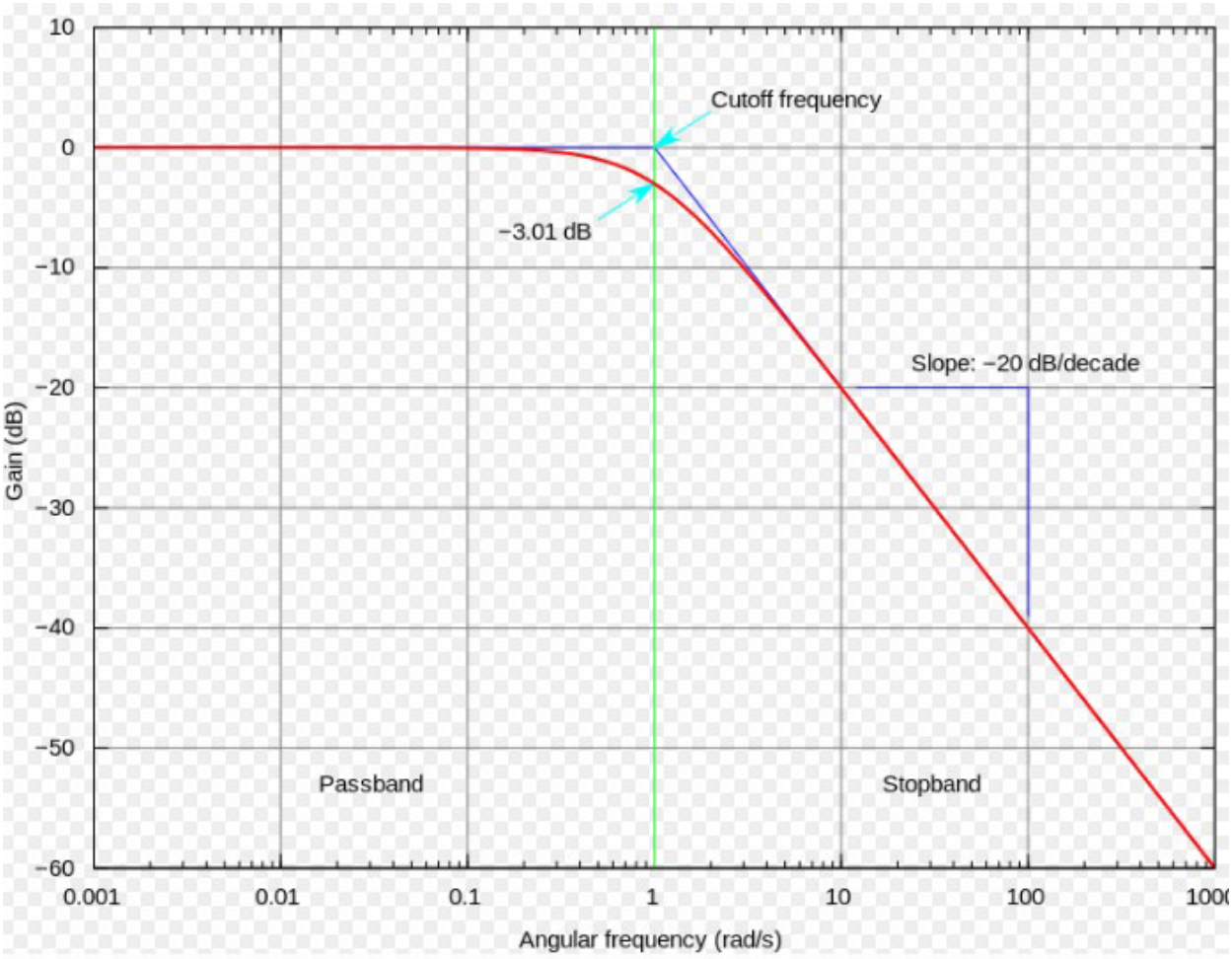

Figure D.1. Definition of the cutoff or break frequency. [Courtesy of Wikipedia, "Cutoff frequency"https//en.wikipedia.org>wild>cutofffrequency]

The prompt neutron decay constants were obtained by simultaneously fitting the auto power spectral densities of detectors 2 and 3, the real and imaginary parts of the cross power spectral densities between the detectors and the source, and the real and imaginary parts of the cross power spectral densities between the two detectors. In this simultaneously fitting, all eight functions of frequency were corrected for the frequency response of the measurement systems. The frequency response was determined in separate measurements with only the source and two detectors spaced in air. This fitting determined the

break frequency (f_b), which is related to the prompt neutron decay constant (α) by the relation $\alpha = 2\pi f_b$. The measured prompt neutron decay constants presented in Table B.1 increase in magnitude as the system becomes more subcritical. For some of the configurations, the prompt neutron decay constants were obtained from single mode fits of the measured spectra, while for other configurations two mode fits were performed for the measured spectra. Examination of the real and cross power spectral densities is plotted as the abscissa and the imaginary part is the ordinate, single mode decay, characterized by the resulting curve being in the fourth quadrant (i.e., real part > 0 and imaginary part < 0). Some results for one configuration of another experiment are given in Figures D.2 and D.3 [D.2]. A change of sign of either the real or the imaginary part of G_{12} signifies the presence of higher modes. The prompt neutron decay constants vary from 290 ± 9 inverse seconds at delayed critical to ~15,000 inverse seconds for a configuration of 289 fuel pins with 1,511 ppm boron. An example of some results of the fitting are given in Figures D.2 and D.3.

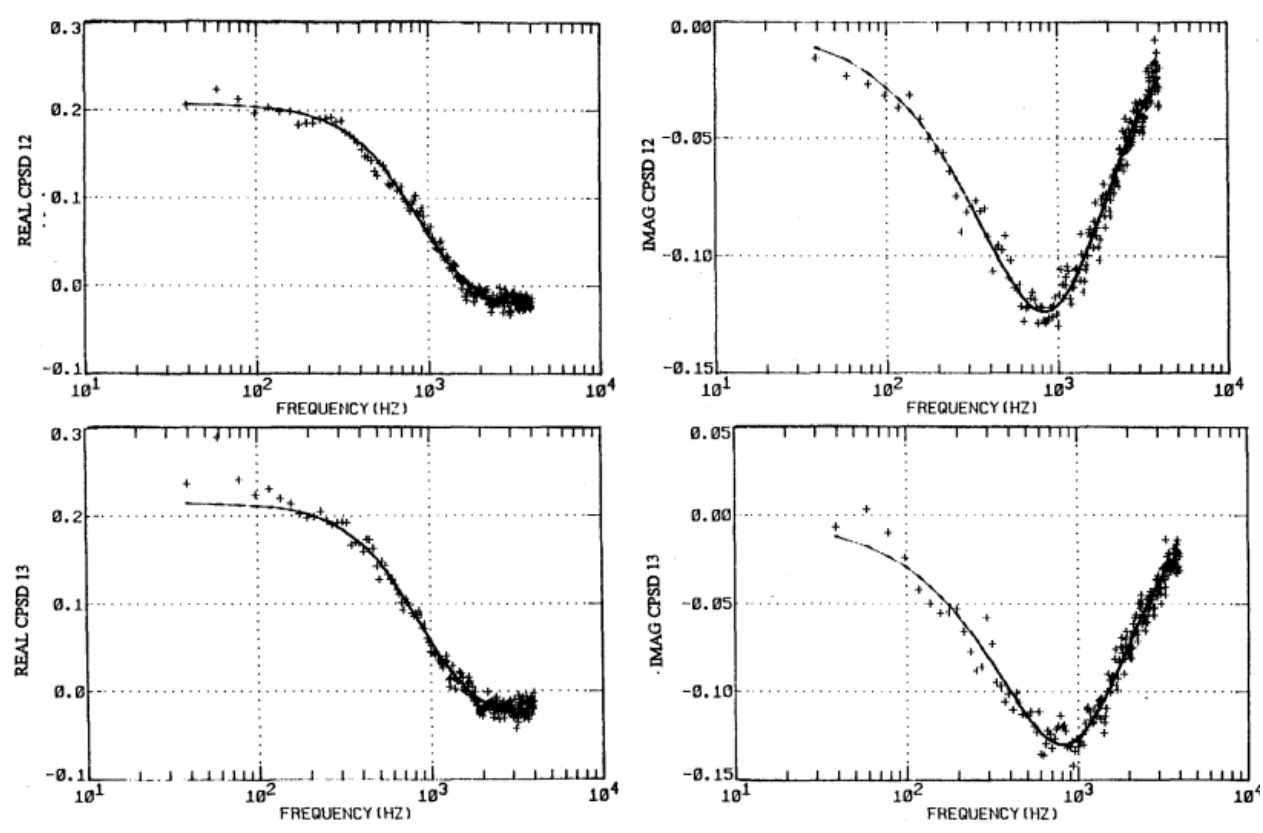

Figure D.2. Real and imaginary parts of the cross power spectral densities between the two detectors (2 and 3) and the californium source (1) for a fuel pin configuration of 4,962 fuel pins with a boron concentration of 2,386 ppm for detector 2 located at 30.4 cm SE–S–SW and detector 3 located at 30.4 cm NE–N–NW (the solid lines are the results of fitting all eight functions simultaneously).

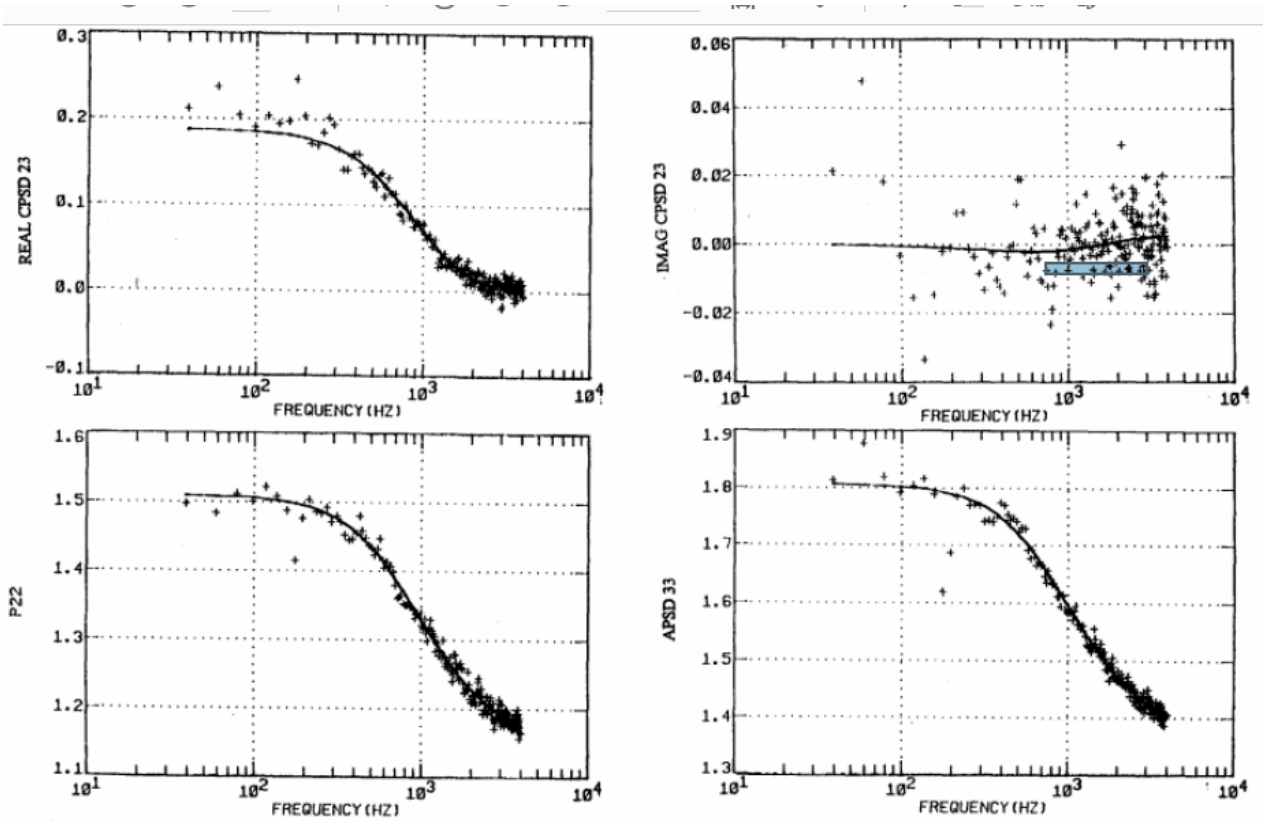

Figure D.3. Real and imaginary parts of the cross power spectral density between the two detectors (2 and 3). Auto power spectral densities for detectors 2 and 3 for a fuel pin configuration with a boron concentration of 2,386 ppm for detector 2 located at 30.4 cm SE–S–SW and detector 3 located at 30.4 cm NE–N–NW (the solid lines are the results of fitting all eight functions simultaneously).

REFERENCES

D.1. R. E. Uhrig, *Random Noise Techniques in Nuclear Reactor Systems*, The Ronald Press (January 1970).

D.2. John T. Mihalczo, "Critical and Subcritical Californium Source Driven Noise Analysis Measurements with PWR Fresh Fuel Pins", ORNL/TM-2021/1606 (Feb 2021)

APPENDIX E. PARAMETERS FOR INTERPRETATION OF RATIO OF SPECTRAL DENSITIES

These parameters for interpretation of the ratio of spectral densities were calculated for the measurements with the californium source on the outside of the tank before the measurements for a solution of 450 g/L, whereas the actual experiment solution concentration was 468 g/L. The concentrations were sufficiently close that they could be used to obtain the neutron multiplication factor from the ratio of spectral densities using point kinetic methods. The calculated parameters for the measurements with the californium on the outside of the tank without the central source pipe at the vertical center are given in Table E1. However, for eventual interpretation of the ratio of spectral densities the measurements with the californium source in the center of the tank should be used to infer the neutron multiplication factor. From other measurements a central source and symmetric location of detectors far from the source has been ideal for interpretation to obtain the neutron multiplication factor from the ratio of spectral densities.

Table E.1. Parameters for interpretation of the ratio of spectral densities with source on outside of the tank.

Solution height (cm)	Californium importance, I_c	I_c/I	I_i/I	Beta effective	Neutron lifetime (10^{-6} s)	k_{eff}[a]	Spatial effects (R) correction	Number of neutrons per fission (v)
50	1.1260	0.3705	0.7168	2.7909	4.1426	0.9941	1.1766	2.8796
40	1.3519	0.3682	0.7266	2.8283	4.1301	0.9606	1.1713	2.8801
30	1.6818	0.3679	0.7482	2,8946	4.1995	0.8994	1.1692	2.8800
20	2.1856	0.3724	0.7967	3.0413	4.0301	0.7717	1.1732	2.8806
10	2,8692	0.3884	0.9113	3.4480	3.7541	0.4575	1.1869	2.8876

[a] Calculated.

For the final benchmark analysis to determine the neutron multiplication factor from the ratio of spectral densities, these numbers should be recalculated for the experimental tank with and without the central Zircaloy source pipe. Changes in the neutron lifetime and delayed neutron fraction will have to be calculated for the break frequency noise analysis determination of the subcritical neutron multiplication factor.