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**SUBCRITICAL NOISE ANALYSIS
MEASUREMENTS WITH FRESH
AND SPENT RESEARCH
REACTOR FUEL ELEMENTS (U)**

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February 1999

**Prepared by the
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
managed by
Lockheed Martin Energy Research Corp.
for the
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WITH FRESH AND SPENT RESEARCH REACTOR FUEL ELEMENTS**

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ABSTRACT

The verification of the subcriticality is of utmost importance for the safe transportation and storage of nuclear reactor fuels. Transportation containers and storage facilities are designed such that nuclear fuels remain in a subcritical state. Such designs often involve excess conservatism because of the lack of relevant experimental data to verify the accuracy of Monte Carlo codes used in nuclear criticality safety analyses.

A joint experimental research program between Oak Ridge National Laboratory, Westinghouse Safety Management Solutions, Inc., and the University of Missouri was initiated to obtain measured quantities that could be directly related to the subcriticality of simple arrays of Missouri University Research Reactor (MURR) fuel elements. A series of measurements were performed to assess the reactivity of materials such as BORAL, stainless steel, aluminum, and lead that are typically used in the construction of shipping casks. These materials were positioned between the fuel elements. In addition, a limited number of measurements were performed with configurations of fresh and spent (irradiated) fuel elements to ascertain the reactivity of the spent fuel elements. In these experiments, fresh fuel elements were replaced by spent fuel elements such that the subcritical reactivity change could be measured.

The results of these measurements were used by Westinghouse Safety Management Solutions to determine the subcriticality of MURR fuel elements isolated by absorbing materials. The measurements were interpreted using the MCNP-DSP Monte Carlo code to obtain the subcritical neutron multiplication factor, k_{eff} , and the bias in k_{eff} that are used in criticality safety analyses.

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1. INTRODUCTION

Subcritical source-driven noise-analysis measurements^{1,2} were performed with a variety of configurations of research reactor fuel elements at the Missouri University Research Reactor (MURR) in July 1998. These measurements were performed to assess the subcriticality of research reactor fuel elements separated by neutron absorbing materials and to determine the reactivity of spent (irradiated) fuel elements. This collaborative program between Oak Ridge National Laboratory, Westinghouse Safety Management Solutions, Inc., and the University of Missouri was undertaken to obtain benchmark subcritical measurements that address the excess conservatism associated with the transportation and storage of research reactor fuel elements at the Savannah River Technology Center.

The subcritical noise-analysis method involved measurement of the time-dependent responses of a ^{252}Cf source in an ionization chamber and of neutron detectors that were placed in or near the fissile system. The time-dependent detector responses were Fourier-transformed. The Fourier-transformed data were then complex multiplied to obtain a variety of auto and cross spectra. The complex multiplication of a signal with itself was termed an auto spectrum while the complex multiplication of two different signals was termed a cross spectrum. The detector auto spectra, the source-detector cross spectra, and the detector-detector cross spectra were obtained simultaneously in this measurement. The source-detector cross spectra were the frequency domain equivalent of the randomly pulsed neutron measurement³ while the detector auto spectra were the equivalent of the single detector Rossi- α measurement and the detector-detector cross spectra were the equivalent of the two-detector Rossi- α measurement.⁴ A certain ratio of these spectra has been shown to be independent of detection efficiency for many applications. This ratio has also been shown to be independent of the source strength in the absence of an inherent spontaneous fission source in the fissile material. This spectral ratio was directly related to the subcritical reactivity of the fissile system.

This report provides a description of the measurement system in Chapter 2. A description of the test assembly and fuel elements is provided in Chapter 3. The results of the fresh and spent fuel measurements are presented in Chapters 4 and 5 respectively. The conclusions and recommendations for future work are presented in Chapter 6. The Appendices provide additional data from the experiments.

2. MEASUREMENT SYSTEM

The measurement system has three main components: a ^{252}Cf -source ionization chamber, neutron detectors, and electronics with a Fourier analyzer. A brief description of these components is provided in this section of the report.

2.1 ^{252}Cf SOURCE

The ^{252}Cf source was contained in an ionization chamber. The ionization chamber gas was a 90% Ar, 10% N mixture at 1 atmosphere pressure. The ^{252}Cf source had an outer diameter of 2.54 cm and was approximately 2.54-cm long. The ^{252}Cf mass of the source was approximately 0.11 μg and approximately 99% of the spontaneous fission events were counted. The fraction of spontaneous fission events was determined from a pulse height curve of the ^{252}Cf -source count rate as a function of the discriminator threshold setting. The discriminator only produced an output pulse if the input pulse exceeded the specified voltage amplitude. A plot of the count rate as a function of the discriminator threshold voltage is shown in Fig. 2.1. ^{252}Cf decayed by alpha particle emission and by spontaneous fission. The alpha decay rate was approximately 32 times the spontaneous fission rate. The ionization chamber pulses produced by the alpha particles were much lower in amplitude than those produced by the fission fragments. The heavier fission fragments lost more energy in the chamber gas. The alpha decay of the ^{252}Cf source was observed for low threshold settings as noted in the 35-mV region of the curve. As the threshold was increased, the alpha particle events in the chamber were discriminated against and only pulses from the fission fragments were observed over the relatively flat portion of the pulse height curve. Further increase of the threshold eliminated some of the fission fragment pulses and caused the count rate to decrease. The discriminator threshold was set near the center of this curve so that approximately 99% of the spontaneous fission events were counted. At various times during the measurements, the ^{252}Cf pulse-height curve was measured. Approximately 99% of the spontaneous fission events were measured except for the spent fuel measurements in which only 98.5% of the spontaneous fission events were measured. A small correction was applied to the measured spectral ratio values to account for the fact that not all fission events were counted. Neutron counting measurements using a source traceable to the National Institute of Standards were performed to determine the fraction of ^{252}Cf fission events that were counted. The results of these measurements were as presented in Appendix E.

2.2 NEUTRON DETECTORS

Two pairs of Reuter Stokes ^3He neutron detectors were used in these measurements. Both detector sets had the same physical dimensions and only the gas type and pressure differed between the two types of detectors. The detectors had a nominal 2.54-cm OD and were approximately 51.7-cm long. The nominal active length was approximately 40.6 cm. The detector chamber was comprised of aluminum 1100 with a 0.0813-cm wall

thickness. The detectors used in the fresh fuel measurements had a ^3He and CO_2 gas mixture with 4 atmospheres of ^3He . The detectors used in the spent fuel measurements were comprised of ^3He and CF_4 with 1 atmosphere of ^3He .

Fig. 2.1. ^{252}Cf pulse-height curve as a function of the discriminator threshold.

2.3 ELECTRONIC SYSTEM

The electronic system consisted of components that were used to convert the detector signals to an analog signal that could be digitized by the Fourier analyzer. The ^{252}Cf source was connected to a high-gain fast amplifier (AMP) with a high voltage (HV) input for the ionization chamber and a low voltage (DC) input to power the amplifier. The output was input to an ORTEC 935 constant fraction discriminator (CFD). The CFD was used to discriminate fission fragment pulses from alpha particle pulses. The output of the CFD was input to a RC filter to shape the NIM pulse from the CFD. The signal was then input to the Fourier analyzer where the signal was digitized. The signals from the ^3He detectors were sent to an ORNL developed preamplifier and then to an ORTEC 671 linear amplifier (AMP). A high voltage power supply was used to power the chamber. The ORTEC 671 linear amplifier time constant was set at $0.25 \mu\text{s}$. A modified preamplifier and fast timing linear amplifier were used in the spent fuel measurements. The modified preamplifier allowed the chambers to operate at higher count rates that

were expected for the spent fuel measurements. The linear amplifier output was sent to an ORTEC 550A single-channel analyzer (SCA). The SCA was used to reject unwanted pulses or pulses due to gamma ray pileup. The SCA output was directed to a TTL-to-NIM converter and then to the RC filter prior to being sent to the Fourier analyzer. A sketch of the electronic configuration is provided in Fig. 2.2. For the fresh fuel measurements, the SCA settings were such that all neutron capture events were counted. The SCA settings were varied in the spent fuel measurements to discriminate out the gamma ray pileup events.

The settings for the amplifiers and single channel analyzers were maintained for most of the measurements. The detector-system dead time was 500 ns for both the fresh and spent fuel measurements. The ^{252}Cf -source electronics dead time was approximately 30 ns for the fresh fuel measurements and approximately 70 ns for the spent fuel measurements. The dead time was determined by performing measurements of the signal auto correlation function for each detection channel using the nuclear material identification system processor. The threshold setting for the ^{252}Cf source varied depending on the amplifier that was used in the measurements but was always set such that approximately 99% of the fission fragments were counted. The voltage, gain, and threshold settings for the detectors used in the fresh fuel measurements are provided in Table 2.1.

Table 2.1. ^3He-detector electronics settings for fresh fuel measurements					
Detector number	Voltage (V)	Linear amplifier		Single channel analyzer	
		Coarse gain	Fine gain	Lower level (V)	Upper level (V)
98D01023 (N) ^a	1300	20	8.50	1	10
98D01024 (S)	1300	20	7.50	1	10
98D01026 (E)	1300	20	7.84	1	10
98D01028 (W)	1300	50	7.50	1	10

^a Direction in parenthesis designate the physical location of the detector in the assembly.

2.4 FOURIER PROCESSOR

ZONIC Corporation developed the Fourier processor. The processor had eight input channels that were sampled synchronously and a throughput disk that was used to store the time series of the detector response. A digital signal processor was used to digitize the input signals. The digitized signals were then Fourier transformed prior to being complex multiplied to compute the auto and cross spectra. A 300 MHz Macintosh computer was used to acquire and process the data from the processor using software developed by ZONIC Corporation. The software was programmable and was set such that all auto and cross spectra between the five channels could be calculated. The bandwidth, the number of data points, and the number of data blocks were all specified in the software. The spectral ratio values were computed from the auto and cross spectra.

Fig. 2.2. Sketch of equipment configuration.

The source and detector channels were such that the source was input into the first channel on the analyzer. The north detector was input into channel two of the analyzer and the south detector was input into channel three of the analyzer. The east and west detectors were input into analyzer channels four and five, respectively. These arrangements were used for all of the fresh fuel measurement configurations. The analyzer inputs were changed for the spent fuel measurements because not all detectors were used. The analyzer measured the auto spectra for each channel, G_{ii} , and the cross spectra between channels, G_{ij} . Six different spectral ratio values were obtained from the auto and cross spectra. The spectral ratio was defined as

$$R_{ij}(\omega) = \frac{G_{1i}^*(\omega)G_{1j}(\omega)}{G_{11}(\omega)G_{ij}(\omega)}, \quad (2.1)$$

where $G_{1i}(\omega)$ was the source-detector cross spectrum between the source and channel i , $G_{1j}(\omega)$ was the source-detector cross spectrum between the source and channel j , $G_{11}(\omega)$ was the source auto spectrum, $G_{ij}(\omega)$ was the cross spectrum between channels i and j , and the $*$ denoted the complex conjugation. The six spectral ratios were designated as $R_{23}(\omega)$, $R_{24}(\omega)$, $R_{25}(\omega)$, $R_{34}(\omega)$, $R_{35}(\omega)$, and $R_{45}(\omega)$. The spectral ratios were averaged over the low frequency region where the ratio was essentially constant.

The spectral ratio has been shown to be proportional to the system reactivity without dependence on the effective delayed neutron fraction:

$$R \sim C \frac{\Delta k}{k}. \quad (2.2)$$

This expression only held if point kinetics was applicable and the system was not very subcritical. By measuring the change in the spectral ratio, an estimate of the change in the system reactivity was obtained using the relation give in Eq. 2.2.

3. MEASUREMENT ASSEMBLY CONFIGURATION

Both fresh and spent fuel measurements were performed with the same experimental assembly. A variety of fresh fuel measurements were performed with various absorbing plates placed between the fuel elements.

3.1 EXPERIMENTAL ASSEMBLY

The experimental assembly was designed such that four MURR fuel assemblies in vertical positions could be spaced at varying distances from each other. The device sat on top of a freestanding 0.635-cm-thick, aluminum table that was either on the bottom of the fresh water tank or the reactor weir pool. The tank was a 7-ft. high, 6-ft.-inside diameter high-density polyethylene structure with a wall thickness of 1.11 cm. The assembly was positioned in the center of the tank such that the fuel elements were completely reflected by approximately 2 ft. of water. The experimental assembly is shown in Fig. 3.1.

The fuel assemblies were placed within a thin-walled aluminum sleeves that are evident in the photograph to protect the fuel elements. The sleeves were mounted on slide plates that allowed the fuel elements to be moved from the symmetric center in 1-mm increments. A nominal 2.54-cm-OD schedule-10 aluminum (type 1100) pipe was also positioned on the slide such that the detectors could be placed adjacent to the fuel elements. A 2.54-cm-thick lead collar was placed around the detector dry well for the spent nuclear fuel measurements. Each detector dry well could be positioned at five different locations on the aluminum slide plate such that the fuel-to-detector centerline distances could be varied from 7.5 cm to 13.5 cm in 1.5-cm increments. An additional schedule-10 aluminum pipe was placed on the end of the slide to stabilize the detector dry well. The slide plate construction is shown in the photograph in Fig. 3.2.

Each fuel element could be moved independently of each other until the elements came into contact with a dry well located in the center of the assembly. The central dry well was used for the ^{252}Cf source. The dry wells are also evident in Fig. 3.1. The slide mechanisms consisted of an aluminum plate that had an aluminum receiver for one fuel assembly and one detector dry well. The slide plate was controlled by a threaded screw drive that could be operated remotely above the tank using the manual controls that are evident in Fig. 3.1. The drive was calibrated such that one complete turn on the handle corresponded to a 1-mm slide movement. Mechanical counters were used to measure the fuel assembly position in steps of 0.1 mm. The spacing between fuel elements could be changed independently to evaluate the interaction between elements.

Fig. 3.1. Photograph from top of experimental assembly in fresh water tank.

Fig. 3.2. Photograph of the assembly slide plates.

The H-shaped cruciform that was evident in Fig. 3.1 was used to locate the plates in the assembly. The cruciform had springs such that the absorbing plates were always closest to the fuel elements. The cruciform was designed such that a maximum 0.635-cm-thick plate could be positioned between the fuel elements. A close view of the H-shaped cruciform is provided in Fig. 3.3. The outer edges of the plates in the East and West position were 7.770 cm from the center of the assembly. The outer edges of the plates in the North and South position were 2.959 cm from the center of the assembly. These plates simulated the use of such materials in spent fuel shipping casks.

Fig. 3.3. Photograph of the H-shaped cruciform.

The fuel assemblies could be rotated on the aluminum post that was used to maintain the fuel elements in the vertical position. The fuel element support post is shown in the photograph in Fig. 3.4. In these measurements the fuel elements could be rotated on the aluminum support post. Typically, the elements in the North and South positions were located such that the small side of the fuel element was nearest the source dry well. This orientation of the fuel element was designated as orientation A. If the large side of the fuel element was located nearest the source dry well, the fuel element was in orientation B. A majority of the measurements were performed with the North and South elements in orientation A and with the East and West elements in orientation B because this configuration had the highest k_{eff} . Measurements were also performed with all elements in orientation A and with all elements in orientation B. The fuel elements located in the standard configuration are shown in the photograph in Fig. 3.5. The numbers 2 and 3 evident on the detector supports corresponded to the South and East positions respectively.

Fig. 3.4. Photograph of fuel element support post.

Fig. 3.5. Photograph of fuel elements in standard orientation.

The vertical position of the ^{252}Cf source was variable using a clamping rod that was located on the top of the central dry well. The source ionization chamber was on the end of a 5-ft. long cable that was connected to the high gain fast amplifier that was mounted on the clamping rod. The source position was measurable to 0.318 cm. The detectors used in the measurements were centered about the active region of the fuel elements. Small aluminum (type 1100) pipes were placed in the bottom of the detector dry wells to maintain the detectors at the centerline of the fuel elements while lead plugs were used in place of the aluminum plugs for the spent fuel measurements. A complete description of the experimental assembly was given in the design document developed by MURR.⁵

3.2 ABSORBING PLATES

Absorbing plates were positioned between the fuel elements using the H-shaped cruciform shown in Figs. 3.1 and 3.3. As previously stated, tension springs were used in the cruciform to push the plates toward the fuel elements. The plates were positioned vertically in the assembly and extended beyond the full length of the fuel elements as shown in the photograph in Fig. 3.6. As shown in Fig. 3.6, the fuel element shrouds were positioned to be in contact with the plates.

Fig. 3.6. Photograph of plate measurements.

Aluminum 1100, stainless steel 304, lead, and borated-aluminum (BORAL) plates were used in these measurements. The dimensions of the plates are provided in Table 3.1 and were specified in English units as provided by the manufacturers. The plates had varying thickness and varying width. The narrow plates were used in the north and south positions while the wider plates were used in the east and west positions. Various combinations of plates were used to create a total plate thickness of approximately 0.635-cm. The dimensions and compositions of the plates were obtained from ref. 6.

Table 3.1. Absorbing plate dimensions				
Plate type	Quantity	Thickness (in)	Width (in)	Length (in)
304 Stainless Steel	3	0.120	11.875	48.0
	3	0.060	4.875	48.0
Aluminum 1100	3	0.125	11.875	48.0
	3	0.063	4.875	48.0
Lead	2	0.257	4.875	48.0
	2	0.378	11.875	48.0
BORAL	2	0.075	4.875	48.0
	2	0.075	11.875	48.0

The Aluminum Company of America® (ALCOA) provided aluminum plates that were used in these experiments. The 0.0630-in. thick plates had slightly different isotopic compositions than the 0.1250-in.-thick plates due to different manufacturing processes. The isotopic compositions for the aluminum plates are provided in Table 3.2. North American Stainless® (NAS) corporation manufactured the 4.875-in.-wide, 0.06-in.-thick 304SS plates, whereas Lukens® Corporation (LC) manufactured the 0.120-in.-thick, 11.875-in.-wide plates. The material isotopic composition data for each plate is presented in Table 3.3. Nuclear Lead Corporation manufactured the lead plates and the lead shields that were used in the measurements. The chemical composition of the lead material is provided in Table 3.4. AAR Advanced Structures manufactured the BORAL® plates that had a nominal 0.075-in. thickness with a 0.055-in-thick aluminum-1100 clad. The reported manufacturing tolerances were ± 0.005 -in. thickness, ± 0.062 -in. width, and ± 0.100 -in. length. The core material consisted of B_4C and aluminum with a nominal chemical composition defined in Table 3.5. The nominal ^{10}B loading of each plate was assumed to be $0.02 \text{ g } ^{10}B/\text{cm}^2$ with an assumed alloy density of 2.489 g/cm^3 .

Table 3.2. Aluminum plate composition		
Element	0.063-in. plates (wt. %)	0.125-in. plates (wt. %)
Aluminum	99.15	99.24
Copper	0.15	0.14
Iron	0.64	0.54
Silicon	0.06	0.08

Table 3.3. Stainless steel 304 plate composition		
Element	NAS steel (wt. %)	LC steel (wt. %)
Iron	70.841	70.724
Carbon	0.041	0.07
Cobalt	0.168	0.17
Chromium	18.233	18.11
Copper	0.298	0.40
Manganese	1.495	1.51
Molybdenum	0.301	0.39
Nickel	8.140	8.03
Nitrogen	0.055	0.07
Phosphorous	0.027	0.029
Sulfur	0.002	0.007
Silicon	0.382	0.49
Tin	0.017	0.0

Table 3.4. Lead plate and shield composition		
Element	Minimum impurities (wt. %)	Maximum impurities (wt. %)
Lead	99.958	99.89
Silver	0.002	0.020
Copper	0.040	0.080
Zinc	0.000	0.001
Iron	0.000	0.002
Bismuth	0.000	0.005
Arsenic, Antimony and Tin	0.000	0.002

Table 3.5. BORAL plate composition	
Element	Wt %
Aluminum	69.0
Boron	24.0
Carbon	6.0
Iron	0.5
Silicon	0.1
Titanium	0.1
Copper	0.1
Zinc	0.1

3.3 MURR FUEL ELEMENTS

The MURR fuel elements that were used in these experiments were comprised of highly enriched uranium (93.15 wt%). Each fuel element contained twenty-four curved uranium aluminum plates that were clad in aluminum. The uranium-aluminum (UAl_3) core region had a nominal 0.02-in. thickness. The core region was clad in 0.015-in. thick aluminum making a total nominal thickness of 0.05 in. The fuel plates were stacked together inside two side plates that maintained a fixed spacing (0.08 in) between the fuel plates that serve as cooling channels during reactor operation. The side plates were 0.15-in. thick aluminum. A sketch of the fuel plate arrangement is provided in Fig. 3.7⁷.

Fig. 3.7. Sketch of MURR fuel assembly construction.

The 24 fuel plates and the aluminum side plates were connected together with an upper and lower end fitting. A sketch of an end fitting is shown in Fig. 3.8. The end fittings were made with a 0.72-in-diameter locating-pin hole that was at the geometric center of the assembly. For these measurements, a locating pin with the same dimensions as those used in the reactor was used on the fuel assembly slide plate.

The material data for the fuel elements was provided by Babcock & Wilcox and is given in Table 3.6. The total uranium mass, UAl_3 mass, and the aluminum mass for each assembly is provided in Table 3.6. The tolerance for the water gap thickness was ± 0.008 in. The tolerance for the uranium enrichment was ± 0.0005 wt% and the tolerance for the uranium mass was ± 0.1 g. The composition of each plate is provided in Tables in Appendix A.

Table 3.6. Fuel assembly compositions					
Assembly	Uranium (g)	^{235}U (g)	UAl_3 (g)	Al (g)	Enrichment (wt%)
MO-517 (N)	830.48	773.60	1180.59	851.59	93.15
MO-518 (S)	830.36	773.48	1180.59	851.72	93.15
MO-519 (E)	830.39	773.52	1180.56	852.12	93.15
MO-520 (W)	830.62	773.73	1177.14	859.98	93.15

Fig. 3.8. MURR fuel element end fitting.

3.4 EXPERIMENTAL ASSEMBLY DIMENSIONAL CALIBRATION

Before and after the fresh fuel measurements were completed a series of dimensional measurements were performed on the experimental assembly. Calibration measurements were necessary to establish the spacing between the fuel elements and the center of the source dry well and to set the mechanical counters. The center-to-fuel spacing was defined as the distance between the center of the source dry well and the center of the locating pin. This summary of the assembly calibration was obtained from ref. 6.

Setting the mechanical counters on a specific value and using a caliper to measure the distance between the center of a dummy fuel assembly and the source dry well calibration measurements were performed. Using machined aluminum spacers to measure the distance between the fuel element locating pin and the source dry well provided additional calibration measurements. These aluminum spacers had widths of 2.00, 4.00, 6.00, 8.00, 10.00, and 12.00 cm. The mechanical counter positions were recorded for each of these spacers. The calipers and aluminum spacers used for calibrations are shown in Fig. 3.9.

The fuel-to-detector spacing was fixed and was determined by the aluminum slide plate on which the fuel assemblies and detector dry wells were mounted. The distances between the fuel element and the detector centerline in centimeters were 7.5, 9.0, 10.5, 12.0, and 13.5. The aluminum slide plate is shown in the photograph in Fig. 3.10. Four bolts were used to mount the detector dry well to the aluminum slide plate. Data for the calibration measurements are supplied in Appendix B.

The uncertainties in the measurement configuration were considered to use these measurements for subcritical benchmarks. The general manufacturing tolerances of the assemblies were ± 0.005 in. whereas the tolerance for the slide mechanism was ± 0.1 mm. The uncertainty in the detector position was small and was estimated to be ± 0.005 in.

Fig. 3.9. Calibration measurement tools.

Fig. 3.10. Aluminum slide plate.

4. FRESH FUEL MEASUREMENTS

A variety of measurements were performed with the fresh fuel elements in the fresh water tank. These measurements included inverse multiplication measurements, source scans, detector variation measurements, repeatability measurements, fuel element separation measurements, fuel orientation measurements, and plate measurements. Additional measurements were performed as reported in the Appendices.

4.1 INVERSE MULTIPLICATION MEASUREMENTS

Inverse multiplication measurements were performed to determine the closest position that the fuel elements could be placed and to satisfy NRC requirements. The source was placed in the center dry well and the four 4-atmosphere ^3He detectors were placed in their dry wells. A set of reference measurements with all aluminum fuel elements in the North and South positions were used for the inverse multiplication measurements because the detectors moved with the fuel elements as the fuel elements were brought closer together and because of the water that was displaced by the fuel elements. Detector counts at various center-to-fuel separations were acquired to obtain the needed references. The detector count rates were obtained as the fuel elements were brought closer together and were divided by the reference count rates at each position to obtain the properly normalized multiplication. The average multiplication was defined as the average multiplication of the four values obtained at each fuel element position. The fuel element position was defined as the sum of the four different position readings. The reference count rates for all four detectors as a function of the sum of the position indicators are contained in Table 4.1. The count rates for all four detectors as a function of the sum of the positions for measurements with four fuel elements are presented in Table 4.2. The inverse multiplication curve obtained from this data is presented in Fig. 4.1. The four fuel elements can be brought completely in contact with each other because the inverse multiplication curve did not extrapolate to 0.1 ($k_{\text{eff}} < 0.90$).

Table 4.1. Reference count rates as a function of fuel element position				
Sum of fuel element position	North detector count rate (counts/sec)	South detector count rate (counts/sec)	East detector count rate (counts/sec)	West detector count rate (counts/sec)
2239	840	836	807	752
1839	1040	1048	1010	939
1439	1304	1311	1285	1169
1239	1487	1479	1436	1341
1039	1644	1657	1577	1474
939	1852	1840	1586	1472
739	2073	2071	1781	1661
599	2207	2142	1977	1854
559	2206	2147	2063	1926
519	2212	2164	2143	2030

Table 4.2. Count rates as a function of fuel element position with four fuel elements				
Sum of fuel element position	North detector count rate (counts/sec)	South detector count rate (counts/sec)	East detector count rate (counts/sec)	West detector count rate (counts/sec)
2239	4003	4018	3212	3071
1839	5596	5601	4551	4365
1439	8148	8098	6688	6482
1239	10021	9960	8243	8011
1039	12291	12209	10144	9901
939	14010	13863	11062	10816
739	16759	16558	13258	13017
599	18067	17759	14698	14458
559	18220	17908	15086	14843
519	18320	17981	15428	15235

Fig. 4.1. Inverse multiplication curve for four atmosphere ^3He detectors as a function of fuel element position.

4.2 SOURCE AXIAL SCAN

A series of measurements were performed to determine the sensitivity of the measurement to the axial source position and to determine the near optimum location for the source. The measurements were performed with the assembly configuration as described in Table 4.3.

Table 4.3. Assembly configuration for source axial scan				
Parameter	North	East	South	West
Fuel Orientation ^a	A	B	A	B
Center-to-Fuel Spacing (cm) ^b	6.745	8.109	6.712	8.299
Detector-to-Fuel Spacing (cm) ^c	10.5	10.5	10.5	10.5

^a Orientation A corresponds to the small side of the fuel element closest to the center and orientation B corresponds to the large side of the fuel element closest to the center.

^b Spacing between fuel centerline and source dry well centerline.

^c Spacing between detector centerline and fuel element centerline.

Both count rate and noise analysis measurements were obtained as the source position was varied from 30 cm below the fuel centerline to 30 cm above the fuel centerline that covered the active region of the fuel element. After the measurements were completed, it was discovered that detector 3 (south position) was raised slightly due to tension in the detector cables. The count rates and spectral ratio values detectors that exclude detector 3 were used to determine the optimum source location. The optimum location of the source was very near the center of the fuel element. The detector count rates as a function of source position are provided in Table 4.4. The count rate for detector 3 was asymmetric because this detector was raised slightly from the fuel element centerline.

Table 4.4. Detector count rate for varying source location					
Source position (cm)	Number ^a	North counts/sec	East counts/sec	South counts/sec	West counts/sec
30	20	7090	6007	9147	5860
15	19	12494	10530	13886	10310
10	18	14376	12117	14937	11867
4	16 and 17	15361	13163	15104	12939
0	14 and 15	15913	13385	14513	13132
-10	21	14476	12170	11538	12036
-15	22	12747	10710	9482	10637
-30	23	5106	4307	3316	4332

^a Measurement file number.

The data in Table 4.4 was best illustrated by plotting the count rate as a function of source position as shown in Fig. 4.2. The detector count rates were symmetric about the fuel centerline except for detector 3. The count rates indicated that the optimum location of the source was at the center of the fuel element because the neutron count rate was the highest with the source at the center of the active region of the fuel elements. After the source scan was complete, detector 3 was centered axially.

Fig. 4.2. Detector count rates as a function of source axial position.

The spectral ratio values obtained from these measurements are presented in Table 4.5 and represented the low frequency average. The uncertainties in the spectral ratio values were computed as the standard deviation of the means. The spectral ratio values that were obtained using detector 3 (south position) were asymmetric because detector 3 was raised slightly above the centerline. Therefore, the optimum source location was determined by using spectral ratio values that did not involve detector 3, namely spectral ratio values 24, 25, and 45. These ratio values indicated that the optimum location of the source was near the fuel centerline. This was to be expected because the measurement configuration was essentially symmetric and indicated that the aluminum table did not have a significant affect on neutron reflection. The low frequency averages of the spectral ratio values 24 and 45 were as plotted as a function of source axial position in Fig. 4.3. These spectral ratio values peaked at the fuel centerline.

Table 4.5. Spectral ratio values for varying source axial position

Source position ^a (cm)	No.	Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
		R ^b	σ^c	R	σ	R	σ	R	σ	R	σ	R	σ
30	20	0.195	0.002	0.147	0.001	0.145	0.002	0.182	0.002	0.181	0.002	0.153	0.002
15	19	0.287	0.002	0.241	0.003	0.242	0.003	0.271	0.003	0.269	0.003	0.249	0.003
10	18	0.302	0.002	0.276	0.003	0.270	0.002	0.297	0.003	0.291	0.003	0.286	0.002
4	16	0.312	0.002	0.290	0.002	0.291	0.002	0.302	0.002	0.295	0.004	0.299	0.003
	17	0.314	0.002	0.292	0.002	0.290	0.002	0.297	0.002	0.297	0.002	0.305	0.003
0	14	0.312	0.002	0.300	0.002	0.300	0.003	0.299	0.003	0.297	0.003	0.309	0.002
	15	0.308	0.003	0.302	0.002	0.295	0.003	0.303	0.003	0.294	0.002	0.314	0.004
-10	21	0.268	0.002	0.279	0.002	0.276	0.002	0.257	0.003	0.253	0.002	0.292	0.003
-15	22	0.237	0.002	0.255	0.003	0.251	0.002	0.225	0.003	0.223	0.002	0.265	0.002
-30	23	0.092	0.001	0.112	0.002	0.113	0.001	0.086	0.001	0.087	0.001	0.115	0.002

^a Source position above and below centerline.

^b Low frequency average of spectral ratio.

^c Standard deviation of the mean of the low frequency spectral ratio average.

Fig. 4.3. Spectral ratio values 24 and 45 as a function of source axial position.

4.3 FUEL-TO-DETECTOR SEPARATION

A series of measurements were performed to determine the best location of the detectors with respect to the fuel element centerline. The best location was determined such that the detectors had a relatively small affect on the system reactivity while maintaining high detector count rates. The fuel-element configuration for these measurements is provided in Table 4.6. The fuel spacing was selected to correspond to the spacing that would be used for the plate measurements. The fuel was in orientation ABAB.

Table 4.6. Assembly configuration for detector spacing optimization				
Parameter	North	East	South	West
Fuel Orientation ^a	A	B	A	B
Center-to-Fuel Spacing (cm) ^b	8.114	12.665	8.127	12.941

^a Orientation A corresponds to the small side of the fuel element closest to the center and orientation B corresponds to the large side of the fuel element closest to the center.

^b Spacing between fuel centerline and source dry well centerline.

Both count rate data and noise analysis data were used to determine the best location for the detectors. The detector count rates were the highest with the detectors closest to the fuel elements because of the reduced distance between the fissile material and the neutron detector. The count rate data as a function of the detector position is given in Table 4.7. The count rates decreased slightly as the detector was moved from 7.5 cm spacing to the 9 cm spacing and then reduced more significantly as the detector was moved further away from the fuel. The data presented in Table 4.8 are plotted in Fig. 4.4.

Table 4.7. Detector count rates as a function of detector position				
Detector position (cm)	North counts/sec	East counts/sec	South counts/sec	West counts/sec
7.5	8419	4967	8519	4954
9.0	7868	4603	7864	4587
10.5	6653	3886	6636	3859
12.0	5341	3058	5212	3047
13.5	4056	2320	3965	2325

The spectral ratio values as a function of detector spacing were measured and are presented in Table 4.8. The spectral ratio values decreased as the detector was moved away from the fuel element indicating that the reactivity was increasing. The 4-atmosphere ³He detector behaved as a control rod close to the fuel element. The 9.0-cm spacing was chosen as the best location because the detector had less impact on the reactivity than the 7.5-cm spacing, and the detector count rate for the 9.0-cm spacing was significantly higher than that for the 10.5, 12.0, or 13.5-cm spacing.

Fig. 4.4. Detector count rate as a function of detector-fuel element separation.

Table 4.8. Spectral ratio values for varying detector position

Detector position (cm)	No.	Ratio 23		Ratio 24 ^c		Ratio 25 ^c		Ratio 34 ^c		Ratio 35 ^c		Ratio 45	
		R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
7.5	36	0.550	0.006	0.460	0.005	0.452	0.005	0.457	0.005	0.449	0.006	0.539	0.012
9.0	34	0.556	0.009	0.460	0.004	0.449	0.008	0.462	0.005	0.452	0.008	0.514	0.020
	35	0.548	0.008	0.440	0.007	0.437	0.010	0.444	0.004	0.457	0.010	0.505	0.006
10.5	32	0.518	0.011	0.442	0.006	0.440	0.010	0.446	0.006	0.438	0.005	0.517	0.010
	33	0.530	0.006	0.436	0.008	0.448	0.007	0.445	0.007	0.440	0.006	0.492	0.012
12.0	37	0.536	0.009	0.437	0.007	0.436	0.011	0.425	0.007	0.443	0.009	0.501	0.015
	38	0.523	0.007	0.442	0.010	0.428	0.007	0.453	0.008	0.425	0.008	0.499	0.010
13.5	39	0.521	0.004	0.433	0.002	0.425	0.003	0.443	0.004	0.426	0.002	0.507	0.007

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

^c Ratio values 24, 25, 34, and 35 should be approximately the same.

4.4 MEASUREMENT REPRODUCIBILITY

The reproducibility of the measurements was evaluated by repeating two particular measurement configurations at various times during the two weeks of measurements. The precision to which a measurement could be reproduced was important to use the results for benchmarking Monte Carlo calculations. The precision could have been best evaluated by repeating the same measurement numerous times. However, because of the short duration of this measurement program, only a small set of repeat measurements was performed.

Reference measurements were performed with the fuel elements separated to the position for the plate measurements without any plates being present. The orientation and configuration of the fuel assemblies for these measurements is given in Table 4.9. These measurements established the base values for the spectral ratio to which a measurement with plates were compared and were repeated at various times during the measurements over a one week period. The results of these measurements were indicative of the ability to reposition the fuel elements and repeat the measurements. The spectral ratio values obtained from these measurements are summarized in Table 4.10. The individual measurement values were obtained by averaging the frequency dependent spectral ratio values over the low frequency range in which the spectral ratio was essentially flat. The standard deviations of the individual measurement values were the standard deviations of the means of the low frequency averages. The spectral ratio values for these measurements were averaged together using the inverse of the sample variance as a weight function. The resulting average is also presented in Table 4.10 along with the sample set standard deviation. The standard deviation of the sample set did not differ significantly from the standard deviation of the mean of the individual spectral ratio values thereby indicating that the variation between measurements was not significant. The standard deviation of the sample set was on the order of one to two percent of the low frequency average of the spectral ratio values. The standard deviation of the sample set was to be used when comparing measured and calculated spectral ratio values. The average frequency-dependent spectral signatures for these reference measurements are provided in Appendix H.

Table 4.9. Assembly configuration for plate-spacing reference measurements				
Parameter	North	East	South	West
Fuel Orientation ^a	A	B	A	B
Center-to-Fuel Spacing (cm) ^b	8.114	12.665	8.127	12.941

^a Orientation A corresponds to the small end of the fuel element closest to the center and orientation B corresponds to the large end of the fuel element closest to the center.

^b Spacing between fuel centerline and source dry well centerline.

Table 4.10. Reference spectral ratio values with the fuel elements separated to position corresponding to the plate separation

No.	Ratio 23		Ratio 24 ^d		Ratio 25 ^d		Ratio 34 ^d		Ratio 35 ^d		Ratio 45	
	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
34	0.556	0.009	0.460	0.004	0.449	0.008	0.462	0.005	0.452	0.008	0.514	0.020
35	0.548	0.008	0.440	0.007	0.437	0.010	0.444	0.004	0.457	0.010	0.505	0.006
40	0.556	0.009	0.450	0.006	0.448	0.005	0.472	0.005	0.440	0.007	0.520	0.010
85	0.570	0.005	0.461	0.005	0.447	0.006	0.458	0.006	0.462	0.007	0.524	0.006
94	0.550	0.009	0.460	0.007	0.440	0.006	0.459	0.006	0.455	0.006	0.500	0.011
114	0.552	0.009	0.442	0.005	0.457	0.008	0.450	0.005	0.458	0.007	0.532	0.012
115	0.550	0.004	0.446	0.009	0.458	0.006	0.469	0.007	0.455	0.004	0.506	0.010
126	0.539	0.006	0.462	0.009	0.447	0.005	0.454	0.008	0.467	0.007	0.531	0.012
127	0.556	0.007	0.467	0.006	0.446	0.006	0.445	0.007	0.439	0.006	0.509	0.009
130	0.560	0.008	0.446	0.006	0.463	0.014	0.454	0.004	0.447	0.003	0.514	0.008
137	0.565	0.006	0.447	0.007	0.440	0.006	0.446	0.008	0.432	0.005	0.510	0.008
143	0.547	0.006	0.471	0.005	0.444	0.006	0.444	0.003	0.450	0.004	0.516	0.008
152	0.557	0.003	0.457	0.002	0.453	0.002	0.456	0.002	0.460	0.002	0.524	0.005
165	0.546	0.006	0.483	0.011	0.457	0.009	0.483	0.011	0.463	0.008	0.527	0.015
171	0.549	0.008	0.451	0.007	0.456	0.007	0.446	0.007	0.461	0.006	0.521	0.018
Mean	0.554	0.008 ^c	0.457	0.012	0.451	0.007	0.454	0.012	0.455	0.011	0.517	0.010

^a Low frequency average of spectral ratio.^b Standard deviation of the mean of the low frequency spectral ratio average.^c Standard deviation of the sample set.^d Ratio values 24, 25, 34, and 35 should be approximately the same.

The data in Table 4.10 were best illustrated by plotting the spectral ratio value as a function of measurement number. These results are presented in Figs. 4.5 through 4.10. For most measurements, the individual measurement values were within one standard deviation of the average value of the sample set. The individual measured values with their uncertainties were all within two standard deviations of the average value and sample set standard deviation. The variation of the individual measurement values about the sample mean did not exhibit any particular trend as a function of time. However, additional measurements would have been necessary to determine the distribution of the individual measurement values about the sample mean because the sample set consisted of only 15 values.

A second set of nine reference measurements were performed with the fuel elements closer together. The fuel elements were in the same orientation as the previous measurements but were spaced much closer together. The assembly configuration for the close-spaced reference measurements is given in Table 4.11. Again these measurements indicated the ability to reproduce the measurements. The spectral ratio values obtained from these measurements are summarized in Table 4.12. The individual measurement values were obtained by averaging the frequency dependent spectral ratio values over the low frequency range in which the spectral ratio was essentially flat. The standard deviations of the individual measurement values were the standard deviations of the means of the low frequency averages. The spectral ratio values for these measurements were averaged together using the inverse of the sample variance as a weight function. The resulting average is also presented in Table 4.12 along with the sample set standard deviation. The standard deviation of the sample set was between one to two percent of the low-frequency spectral ratio value.

Table 4.11. Assembly configuration for close-spaced reference measurements				
Parameter	North	East	South	West
Fuel Orientation ^a	A	B	A	B
Center-to-Fuel Spacing (cm) ^b	7.931	9.519	7.918	9.615

^a Orientation A corresponds to the small end of the fuel element closest to the center and orientation B corresponds to the large end of the fuel element closest to the center.

^b Spacing between fuel centerline and source dry well centerline.

These results of the close-spaced reference measurements are presented in Figs. 4.11 through 4.16. For most measurements, the individual measurement values were within one standard deviation of the average value of the sample set. The individual measured values with their uncertainties were all within two standard deviations of the average value and sample set standard deviation. The variation of the individual measurement values about the sample mean did not exhibit any particular trend as a function of time. However, additional measurements would have been necessary to determine the distribution of the individual measurement values about the sample mean because the sample set consisted of only 9 values.

Fig. 4.5. Spectral ratio 23 value for reference measurements at plate spacing.

Fig. 4.6. Spectral ratio 24 value for reference measurements at plate spacing.

Fig. 4.7. Spectral ratio 25 value for reference measurements at plate spacing.

Fig. 4.8. Spectral ratio 34 value for reference measurements at plate spacing.

Fig. 4.9. Spectral ratio 35 value for reference measurements at plate spacing.

Fig. 4.10. Spectral ratio 45 value for reference measurements at plate spacing.

Table 4.12. Spectral ratio values for close-spaced reference measurements

No.	Ratio 23		Ratio 24 ^d		Ratio 25 ^d		Ratio 34 ^d		Ratio 35 ^d		Ratio 45	
	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
41	0.387	0.003	0.352	0.003	0.352	0.003	0.342	0.002	0.349	0.006	0.373	0.003
46	0.385	0.003	0.347	0.003	0.345	0.005	0.360	0.003	0.342	0.003	0.376	0.004
47	0.389	0.002	0.351	0.002	0.346	0.002	0.355	0.002	0.349	0.002	0.377	0.003
54	0.380	0.003	0.346	0.003	0.349	0.004	0.350	0.003	0.337	0.003	0.385	0.007
59	0.382	0.004	0.353	0.003	0.350	0.005	0.356	0.004	0.348	0.003	0.385	0.004
65	0.379	0.003	0.357	0.003	0.353	0.002	0.364	0.004	0.352	0.003	0.380	0.002
66	0.388	0.004	0.354	0.003	0.353	0.004	0.362	0.003	0.353	0.003	0.377	0.003
141	0.388	0.003	0.359	0.004	0.354	0.003	0.360	0.002	0.351	0.002	0.389	0.005
142	0.393	0.003	0.354	0.004	0.357	0.003	0.352	0.002	0.357	0.002	0.380	0.004
Mean	0.387	0.005 ^c	0.352	0.004	0.351	0.004	0.355	0.007	0.349	0.006	0.379	0.005

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

^c Standard deviation of the sample set.

^d Ratio values 24, 25, 34, and 35 should be approximately the same.

Fig. 4.11. Spectral ratio 23 value for close-spaced reference measurements.

Fig. 4.12. Spectral ratio 24 value for close-spaced reference measurements.

Fig. 4.13. Spectral ratio 25 value for close-spaced reference measurements.

Fig. 4.14. Spectral ratio 34 value for close-spaced reference measurements.

Fig. 4.15. Spectral ratio 35 value for close-spaced reference measurements.

Fig. 4.16. Spectral ratio 45 value for close-spaced reference measurements.

4.5 FUEL ELEMENT SEPARATION MEASUREMENTS

A series of measurements were performed in which the spacing between the fuel elements was varied. In some measurements, only one element was moved while in others all four elements were moved simultaneously.

4.5.1 Movement of All Fuel Elements

Two sets of measurements were performed in which all four elements were moved simultaneously with the difference between the sets being the starting position. The fuel elements were in the standard ABAB orientation for both sets of measurements. The first set of measurements was performed beginning at the close-spaced configuration presented in the reproducibility measurement section. The fuel elements were then moved in 1-cm increments. The assembly configuration for these measurements is provided in Table 4.13.

Table 4.13. Fuel separation measurements beginning at close-spaced reference position					
Average ^a distance change (cm)	Run no.	Distance from center of assembly (cm)			
		North (A) ^b	East (B) ^b	South (A) ^b	West (B) ^b
0	41	7.931	9.519	7.918	9.615
0	46	7.931	9.519	7.918	9.615
1.03	42	8.903	10.524	8.911	10.766
1.03	43	8.903	10.524	8.911	10.766
2.03	44	9.903	11.515	9.901	11.776
3.03	45	10.903	12.505	10.898	12.782

^a Average distance change for all four elements.

^b Orientation of fuel element in the assembly.

The spectral ratio values for the fuel traverse measurements are presented in Table 4.14. As expected, the spectral ratio values increased as the fuel elements were separated indicating that the system reactivity was decreasing. The interactions between the fuel elements decreased as the elements were moved apart. The spectral ratio values for detector combinations that were 180° apart changed most significantly because the interaction between these fuel elements decreased the most. A plot of the spectral ratio values as a function of the average change in the distance from the original reference point is shown in Fig. 4.17. Spectral ratio values 23 and 45 changed the most while the other spectral ratio values essentially all changed the same amount. The spectral ratio values 24, 25, 34, and 35 were all in close agreement as expected because of the essential symmetric configuration of the fuel elements.

The spectral ratio values 23 and 45 changed 21% for a 1-cm move of the fuel elements while the spectral ratio values 24, 25, 34, and 35 changed an average of 16%. Further movement of the fuel elements from the center of the assembly produced larger changes in the spectral ratio values. The spectral ratio values 23 and 45 changed 45% and 50% respectively from the values for the starting position for the additional 1-cm move of the fuel elements whereas the spectral ratio values 24, 25, 34, and 35 only changed ~29%. The final 1-cm movement of the fuel elements produced a 70% change in spectral ratio values 23 and 45 relative to the values for the starting position. This change was almost a factor of two larger than the change in spectral ratio values 24, 25, 34, and 35 that only changed 40%. These results demonstrated that spectral ratio values for detectors that were 180° apart were more indicative of the overall interaction between fuel elements. Elements that were located 180° apart had more water between the elements than adjacent detectors because the distance change was the greatest for these detectors.

Table 4.14. Spectral ratio values for fuel element traverse from close-spaced reference position												
No.	Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
41	0.387	0.003	0.352	0.003	0.352	0.003	0.342	0.002	0.349	0.006	0.373	0.003
46	0.385	0.003	0.347	0.003	0.345	0.005	0.360	0.003	0.342	0.003	0.376	0.004
42	0.471	0.003	0.405	0.004	0.402	0.005	0.411	0.004	0.404	0.004	0.456	0.006
43	0.466	0.006	0.407	0.007	0.404	0.005	0.411	0.005	0.405	0.005	0.458	0.007
44	0.561	0.004	0.454	0.004	0.438	0.003	0.466	0.002	0.449	0.004	0.566	0.005
45	0.659	0.005	0.491	0.003	0.493	0.002	0.502	0.004	0.486	0.003	0.650	0.006

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

Fig. 4.17. Spectral ratio values for fuel element traverse measurements from close-spaced reference position.

The second set of traverse measurements was performed with the fuel beginning at the in-contact position. The fuel elements were moved in ~0.5-cm and ~1.0-cm increments from the in-contact position. The configuration of the fuel elements for these measurements is given in Table 4.15. In some instances, the measurements were essentially statistical repeats for a given configuration. For example, run numbers 162a and 162b were statistical repeats for the same configuration without changing the experimental assembly. Therefore, the spectral signatures for these measurements were combined together and the spectral ratio values were the average of both measurements.

Table 4.15. Fuel traverse measurements beginning at in-contact position					
Average ^a distance change (cm)	No.	Distance from center of assembly (cm)			
		North (A) ^b	East (B) ^b	South (A) ^b	West (B) ^b
0.000	160	6.745	8.109	6.712	8.299
0.000	161	6.745	8.109	6.712	8.299
0.511	162a	7.239	8.634	7.215	8.822
0.511	162b	7.239	8.634	7.215	8.822
0.511	162 ^c	7.239	8.634	7.215	8.822
0.993	163a	7.835	9.125	7.717	9.263
0.993	163b	7.835	9.125	7.717	9.263
0.993	163 ^c	7.835	9.125	7.717	9.263
1.999	164a	8.703	10.122	8.713	10.324
1.999	164b	8.703	10.122	8.713	10.324
1.999	164 ^c	8.703	10.122	8.713	10.324

^a Average distance change for all four elements.

^b Orientation of fuel element in the assembly.

^c Results for this run number were obtained from the average of the two previous measurements.

The spectral ratio values for the fuel traverse measurements beginning at the in-contact position are provided in Table 4.16. The ratio values increased as the fuel elements were separated indicating that the system reactivity was decreasing. The interactions between the fuel elements decreased as the elements were moved apart. The spectral ratio values for detector combinations that were 180° apart changed most significantly because the interaction between these fuel elements decreased the most. A plot of the spectral ratio values as a function of the average change in the distance from the original reference point is given in Fig. 4.17. Spectral ratio values 23 and 45 changed the most while the other spectral ratio values essentially changed the same amount. Again, the spectral ratio values 24, 25, 34, and 35 were similar because of the nearly symmetric configuration of the fuel elements.

The spectral ratio values 23 and 45 changed 6%, 13%, and 42% from the values for the in-contact reference position for the three movements of the fuel elements. The spectral ratio values 24, 25, 34, and 35 changed on average 4.5%, 9%, and 30% from the values

for the in-contact reference position for the three movements of the fuel elements. As shown for the previous fuel movements, the spectral ratio values 23 and 45 changed slightly more than the spectral ratio values 24, 25, 34, and 35. These results further emphasize that the spectral ratio values for detectors 180° apart were more indicative of the overall system reactivity and were more sensitive to changes in the assembly configuration. These changes in the spectral ratio values were smaller than those values for the close-spaced reference position because the fuel elements were closer together and the interactions between fuel elements remained high.

Table 4.16. Spectral ratio values for fuel element traverse from in-contact position												
No.	Ratio 23		Ratio 24 ^c		Ratio 25 ^c		Ratio 34 ^c		Ratio 35 ^c		Ratio 45	
	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
160	0.321	0.002	0.307	0.002	0.302	0.002	0.307	0.002	0.303	0.002	0.309	0.002
161	0.318	0.002	0.309	0.002	0.307	0.002	0.305	0.002	0.304	0.002	0.314	0.001
162a	0.338	0.003	0.323	0.002	0.317	0.002	0.317	0.002	0.317	0.002	0.323	0.002
162b	0.342	0.002	0.322	0.002	0.319	0.002	0.319	0.002	0.318	0.002	0.330	0.001
162 ^c	0.339	0.002	0.322	0.001	0.319	0.001	0.318	0.002	0.318	0.002	0.329	0.002
163a	0.360	0.002	0.330	0.002	0.326	0.004	0.333	0.003	0.333	0.003	0.349	0.003
163b	0.364	0.002	0.334	0.003	0.332	0.003	0.342	0.002	0.340	0.003	0.355	0.002
163 ^c	0.362	0.002	0.331	0.002	0.329	0.002	0.338	0.001	0.338	0.002	0.353	0.002
164a	0.460	0.005	0.405	0.004	0.407	0.006	0.397	0.004	0.391	0.005	0.436	0.005
164b	0.448	0.004	0.390	0.004	0.395	0.004	0.391	0.004	0.400	0.003	0.446	0.006
164 ^c	0.455	0.004	0.397	0.003	0.395	0.003	0.394	0.003	0.396	0.002	0.442	0.004

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

^c Ratio values 24, 25, 34, and 35 should be approximately the same.

Fig. 4.18. Spectral ratio values for fuel element traverse measurements from in-contact position.

4.5.2 Movement of North Fuel Element

Measurements were also performed in which only a single fuel element in the A orientation was moved to study the affects of spacing of the fuel elements. The north fuel element was moved in ~1.0-cm increments from the close-spaced reference position. The configuration of the fuel elements for these measurements is given in Table 4.17. The north fuel element was moved three different times as shown in Table 4.17.

Table 4.17. Traverse of north fuel element beginning at close-spaced reference position					
Distance change (cm)	No.	Distance from center of assembly (cm)			
		North (A) ^a	East (B) ^a	South (A) ^a	West (B) ^a
0	46	7.931	9.519	7.918	9.615
0	47	7.931	9.519	7.918	9.615
0	54	7.931	9.519	7.918	9.615
0.972	48	8.903	9.519	7.918	9.615
0.972	49	8.903	9.519	7.918	9.615
1.972	50	9.903	9.519	7.918	9.615
1.972	51	9.903	9.519	7.918	9.615
3.972	52	11.903	9.519	7.918	9.615
3.972	53	11.903	9.519	7.918	9.615

^a Orientation of fuel element in the assembly.

The spectral ratio values for these measurements are provided in Table 4.18. As shown previously, the spectral ratio values increased as the fuel element was moved away from the reference position. The spectral ratio 23 value increased 7% with a 0.972-cm move of the north fuel element away from the center of the assembly. The spectral ratio value 45 changed ~5% for the same movement of the north fuel element and the spectral ratio values 24, 25, 34, and 35 changed an average of ~3.5%. Movement of the north fuel element another 1-cm produced 11% and 12% changes in spectral ratio values 23 and 45 from those for the close-spaced reference position. The spectral ratio values 24, 25, 34, and 35 changed an average of ~8.7% from the reference values. The spectral ratio values decreased further with an additional 2-cm movement of the north fuel element. Again, the largest change was evident in spectral ratio values 23 and 45 that changed 22% and 26% respectively from the reference values. The spectral ratio values 24, 25, 34, and 35 changed an average of ~17.5% from the reference values. These results demonstrated the approximate reactivity worth of the north element. The essentially symmetric changes in spectral ratio values 23 and 45 demonstrated that the interaction between fuel elements was highly dependent on the assembly configuration. Fuel elements in the north and south positions had more fissile material closer to the assembly center because of the orientation of these elements.

These measurements were to be used to determine the reactivity worth for an element in orientation A as a function of position using the MCNP-DSP Monte Carlo code.

Table 4.18. Spectral ratio values for north fuel element traverse from close-spaced reference position

No.	Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
46	0.385	0.003	0.347	0.003	0.345	0.005	0.360	0.003	0.342	0.003	0.376	0.004
47	0.389	0.002	0.351	0.002	0.346	0.002	0.355	0.002	0.349	0.002	0.377	0.003
54	0.380	0.003	0.346	0.003	0.349	0.004	0.350	0.003	0.337	0.003	0.385	0.007
48	0.414	0.005	0.367	0.004	0.355	0.003	0.377	0.003	0.363	0.003	0.400	0.004
49	0.415	0.005	0.367	0.003	0.355	0.004	0.364	0.004	0.356	0.004	0.395	0.004
50	0.427	0.005	0.379	0.005	0.378	0.003	0.389	0.003	0.378	0.005	0.411	0.002
51	0.428	0.004	0.388	0.006	0.377	0.005	0.386	0.004	0.376	0.004	0.437	0.007
52	0.471	0.004	0.408	0.005	0.401	0.006	0.415	0.004	0.401	0.004	0.480	0.006
53	0.472	0.007	0.420	0.005	0.422	0.006	0.417	0.004	0.410	0.005	0.470	0.007

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

4.5.3 Movement of East Fuel Element

Measurements were also performed in which only a single fuel element in the B orientation was moved to allow the reactivity worth of this fuel element as a function of position to be determined. The fuel element was moved in ~2.0-cm increments from the close-spaced reference position. The configuration of the fuel elements for these measurements is given in Table 4.19. The spectral ratio values for these measurements are provided in Table 4.20. As shown previously, the spectral ratio values increased as the fuel element was moved away from the reference position. These measurements were to be used to determine the reactivity worth as a function of position for an element in the B orientation. The change in the spectral ratio values for moving the east fuel element was essentially the same as the change in spectral ratio values for moving the north fuel element.

Table 4.19. Traverse of east fuel element beginning at close-spaced reference position					
Distance change (cm)	No.	Distance from center of assembly (cm)			
		North (A) ^a	East (B) ^a	South (A) ^a	West (B) ^a
0.000	54	7.931	9.519	7.918	9.615
0.000	59	7.931	9.519	7.918	9.615
1.996	55	7.931	11.515	7.918	9.615
1.996	56	7.931	11.515	7.918	9.615
3.990	57	7.931	13.509	7.918	9.615
3.990	58	7.931	13.509	7.918	9.615

^a Orientation of fuel element in the assembly.

As with the movement of the north fuel element, the spectral ratio values increased as the east fuel element was moved away from the center of the assembly. The spectral ratio values 23 and 45 changed ~12% and ~23% from the reference values as the fuel element was moved away from the center of the assembly. The spectral ratio values 24, 25, 34, and 35 changed on average 8% and 16% from the reference values as the fuel elements were moved away from the center of the assembly. These changes in the spectral ratio values were smaller than the changes observed for similar movements of a fuel element in the north position because the north and south fuel elements were closer to the center of the system than fuel elements in the east and west positions. The elements in the north and south positions had a greater impact on the overall system reactivity.

Table 4.20. Spectral ratio values for east fuel element traverse from close-spaced reference position

No.	Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
54	0.380	0.003	0.346	0.003	0.349	0.004	0.350	0.003	0.337	0.003	0.385	0.007
59	0.382	0.004	0.353	0.003	0.350	0.005	0.356	0.004	0.348	0.003	0.385	0.004
55	0.435	0.005	0.379	0.004	0.378	0.004	0.380	0.004	0.381	0.005	0.423	0.006
56	0.429	0.005	0.382	0.004	0.374	0.003	0.382	0.004	0.379	0.005	0.423	0.006
57	0.468	0.006	0.421	0.005	0.405	0.005	0.422	0.007	0.397	0.004	0.470	0.008
58	0.481	0.006	0.425	0.006	0.410	0.005	0.427	0.004	0.393	0.005	0.470	0.010

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

4.6 FUEL ORIENTATION MEASUREMENTS

Measurements were performed that can be used to investigate the changes associated with the orientation of the fuel elements in the assembly. The center-to-fuel spacing was selected to have the fuel elements close to each other. The configurations for these measurements are given in Table 4.21. The difference in the size of the inner and outer dimensions of the fuel elements limited the closeness to which the fuel elements could be placed in the BBBB configuration; therefore, this configuration cannot be directly compared to the ABAB or AAAA configurations.

Table 4.21. Assembly configuration for different fuel orientation measurements				
Fuel orientation ^a (NESW)	Center-to-fuel spacing (cm) ^b			
	North	East	South	West
ABAB	7.931	9.519	7.918	9.615
AAAA	7.931	9.519	7.918	9.615
BBBB	10.103	9.519	10.099	9.615

^a Orientation A corresponds to the small end of the fuel element closest to the center and orientation B corresponds to the large end of the fuel element closest to the center.

^b Spacing between fuel centerline and source dry well centerline.

The spectral ratio values for these measurement configurations are provided in Table 4.22. The ABAB configuration was the standard close-spaced reference position, and the values that were reported in Table 4.22 for this configuration were the average values of all measurements in this configuration. The ABAB configuration had lower spectral ratio values than the AAAA configuration by 8% for ratios with the detectors 180° apart because the fissile material was closer together in with the ABAB configuration. The BBBB spectral ratio values were higher than the ABAB spectral ratio values because of the separation between the fuel elements was greater. The most reactive configuration for this measurement assembly was the ABAB configuration.

Table 4.22. Spectral ratio values for different fuel element orientations

Orientation	Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
ABAB	0.387	0.005	0.352	0.004	0.351	0.004	0.355	0.007	0.349	0.006	0.379	0.005
AAAA (60) ^c	0.422	0.003	0.371	0.004	0.372	0.005	0.373	0.005	0.368	0.004	0.396	0.004
AAAA (61) ^c	0.416	0.004	0.377	0.003	0.368	0.003	0.378	0.004	0.378	0.005	0.424	0.004
BBBB (62) ^c	0.444	0.004	0.400	0.007	0.399	0.005	0.398	0.006	0.400	0.004	0.454	0.007
BBBB (63) ^c	0.440	0.004	0.399	0.004	0.397	0.004	0.395	0.005	0.403	0.003	0.457	0.005

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency average of the spectral ratio.

^c Measurement run number.

4.7 ALUMINUM PLATE MEASUREMENTS

This section presents the results of measurements in which aluminum plates were positioned between the fuel elements. The aluminum plates were either $\sim 1/16$ - or $\sim 1/8$ - inch thick. The plates all had the same lengths (48 inches) but had different widths. The plates positioned in the North and South position had the same width ($4 \frac{7}{8}$ inches), and those positioned in the East and West positions had the same width ($11 \frac{7}{8}$ inches). The plate guides were designed such that a maximum of four plates could be located in one guide. The plates $\sim 1/16$ - and $\sim 1/8$ -inch plates were used together to construct the $\sim 3/16$ - and $\sim 1/4$ -inch total thickness. The spectral ratio values obtained from these measurements are presented in Table 4.23 as a function of the number of $1/16$ -inch thick plates or equivalent that were used in the measurements. The individual measurement values were obtained by averaging the frequency dependent spectral ratio values over the low frequency range in which the spectral ratio was essentially constant for all reported spectral ratio values unless otherwise noted. The standard deviations of the individual measurement values are the standard deviations of the means of the low frequency averages for all spectral ratio values unless otherwise noted. Some of the individual measurements were simply statistical repeats in which a second set of data was obtained prior to changing the experimental assembly. These statistical repeat measurements were combined together and are also presented in Table 4.23.

The spectral ratio data presented in Table 4.23 are plotted as a function of the aluminum plate mass in Figs. 4.19 to 4.24. The mass was determined using the density and dimensions of the plates. The individual spectral ratio values and the sums of statistical measurements are plotted as a function of the aluminum mass. The dashed lines indicate the one standard deviation spread of the reference measurements, i.e. the standard deviation of the sample set for the fifteen reference measurements. As evident in Figs. 4.19 through 4.24, most of the data values were within one standard deviation of the reference measurements and all of the measurements were within two standard deviations of the reference measurements. The aluminum plates did not significantly affect the measured spectral ratio values, and thus did not change the subcriticality.

Table 4.23. Measured spectral ratio values with varying number of 1/16-inch thick aluminum plates between the fuel elements																
No.	Number of plates				Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	N	E	S	W	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
70	1	-	1	-	0.559	0.010	0.470	0.005	0.448	0.006	0.474	0.007	0.439	0.004	0.523	0.008
71	1	-	1	-	0.547	0.006	0.462	0.006	0.432	0.005	0.456	0.006	0.444	0.007	0.499	0.010
Sum ^c	1	-	1	-	0.555	0.008	0.456	0.005	0.439	0.003	0.462	0.005	0.447	0.005	0.513	0.006
72	2 ^d	-	2	-	0.564	0.004	0.480	0.007	0.458	0.007	0.462	0.006	0.451	0.005	0.536	0.011
73	2	-	2	-	0.550	0.007	0.455	0.007	0.444	0.005	0.455	0.008	0.446	0.006	0.520	0.015
Sum	2	-	2	-	0.551	0.005	0.471	0.005	0.446	0.003	0.454	0.004	0.446	0.006	0.520	0.015
74	3 ^e	-	3	-	0.533	0.006	0.444	0.008	0.448	0.006	0.448	0.006	0.456	0.004	0.511	0.005
75	3	-	3	-	0.550	0.006	0.466	0.007	0.444	0.006	0.453	0.006	0.451	0.007	0.525	0.010
Sum	3	-	3	-	0.542	0.005	0.453	0.005	0.448	0.004	0.457	0.004	0.451	0.004	0.519	0.006
76	3	1	3	1	0.543	0.008	0.452	0.005	0.451	0.007	0.454	0.006	0.433	0.006	0.511	0.007
77	3	1	3	1	0.556	0.006	0.464	0.007	0.445	0.006	0.463	0.006	0.448	0.007	0.525	0.010
Sum	3	1	3	1	0.561	0.008	0.453	0.005	0.450	0.003	0.457	0.004	0.445	0.004	0.516	0.009
78	2	1	2	1	0.535	0.008	0.447	0.006	0.445	0.006	0.453	0.005	0.436	0.007	0.502	0.010
79	1	1	1	1	0.553	0.006	0.473	0.006	0.452	0.006	0.460	0.006	0.465	0.007	0.504	0.007
80	1	2	1	2	0.535	0.008	0.446	0.005	0.435	0.006	0.471	0.006	0.442	0.005	0.515	0.011
81	2	2	2	2	0.550	0.006	0.443	0.004	0.461	0.007	0.456	0.006	0.451	0.007	0.528	0.010
82	3	2	3	2	0.549	0.007	0.451	0.005	0.437	0.006	0.455	0.007	0.456	0.008	0.524	0.009
83	3	3	3	3	0.556	0.008	0.470	0.008	0.441	0.005	0.472	0.005	0.448	0.003	0.505	0.009
84	4 ^f	4	4	4	0.555	0.009	0.453	0.006	0.462	0.005	0.450	0.006	0.454	0.005	0.517	0.013

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

^c Represents the summing of the spectral signatures of the two previous measurements.

^d Actual plate thickness is $\sim 1/8$ inch for measurements using two plates.

^e One $\sim 1/16$ -inch and one $\sim 1/8$ -inch thick plate are used to produce $\sim 3/16$ -inch thick plate.

^f Two $\sim 1/8$ -inch thick plates or one $\sim 1/8$ -inch thick plate with two $\sim 1/16$ -inch thick plates are used to construct $\sim 1/4$ -inch thick plate.

Fig. 4.19. Spectral ratio 23 values as a function of aluminum plate mass.

Fig. 4.20. Spectral ratio 24 values as a function of aluminum plate mass.

Fig. 4.21. Spectral ratio 25 values as a function of aluminum plate mass.

Fig. 4.22. Spectral ratio 34 values as a function of aluminum plate mass.

Fig. 4.23. Spectral ratio 35 values as a function of aluminum plate mass.

Fig. 4.24. Spectral ratio 45 values as a function of aluminum plate mass.

4.8 LEAD PLATE MEASUREMENTS

This section presents the results of measurements in which lead plates were positioned between the fuel elements. The average spectral ratio values at low frequency obtained from these measurements are presented in Table 4.24 as a function of the number of plates. The statistical repeat measurements were combined together and are also presented in Table 4.24.

The sums of statistical measurements are plotted as a function of the lead mass in Figs. 4.25 through 4.30. The sums of the individual measurements were more statistically significant than individual measurements because the sums had twice as many data blocks. The dashed lines indicated the one standard deviation spread of the fifteen reference measurements. The results of the lead plate measurements were not significantly different from the reference measurements at the plate spacing. The spectral ratio values obtained from detectors 2 and 3 decreased slightly as a function of lead mass while the other spectral ratio values did not exhibit any clear pattern for changes in the lead mass. Except for the spectral ratio 23, a majority of the spectral ratio values were within two standard deviations of the reference plate measurements. The spectral ratio 23 values ranged from 3% to 7% less than the value for the reference measurements at the plate spacing. This was more than a factor of two greater than the uncertainty in the repeatability of the reference measurements. Although most of the spectral ratio values did not exhibit any particular trend with lead mass some of the spectral ratio values were consistent with each other. Consider the measurements with lead plates in the north and south positions (measurements 108 and 109). The spectral ratio values 24, 25, 34, and 35 were all the same because the plate configuration was symmetric. Likewise, the results of measurements with lead plates in the east and west positions (measurements 100 and 101) demonstrated consistent results. The spectral ratio values 24, 25, 34, and 35 were all the same because again this was a symmetric configuration. One of the more interesting observations concerning this data was that the spectral ratio values were slightly lower than those for the reference plate measurements. This could indicate that the reactivity increased when adding lead plates. However, because most of the spectral ratio values were within two standard deviations of the reference measurements with no plates, the affects of the lead were considered small.

Table 4.24. Measured spectral ratio values with varying number of lead plates between the fuel elements

No.	Number of plates				Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	N	E	S	W	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
96	1	1	1	1	0.519	0.006	0.444	0.005	0.444	0.009	0.443	0.007	0.435	0.004	0.484	0.005
97	1	1	1	1	0.516	0.008	0.420	0.005	0.425	0.006	0.438	0.004	0.424	0.007	0.496	0.009
Sum ^c	1	1	1	1	0.516	0.004	0.432	0.004	0.434	0.005	0.438	0.003	0.425	0.003	0.487	0.007
98		1	1	1	0.525	0.007	0.422	0.007	0.418	0.006	0.442	0.006	0.419	0.004	0.470	0.007
99		1	1	1	0.530	0.007	0.435	0.005	0.435	0.006	0.446	0.008	0.443	0.005	0.506	0.007
Sum		1	1	1	0.522	0.007	0.435	0.005	0.435	0.006	0.446	0.008	0.443	0.005	0.506	0.007
100		1		1	0.517	0.006	0.457	0.006	0.439	0.005	0.458	0.008	0.440	0.004	0.493	0.015
101		1		1	0.536	0.005	0.462	0.005	0.443	0.006	0.434	0.007	0.450	0.007	0.502	0.008
Sum		1		1	0.530	0.003	0.449	0.005	0.441	0.005	0.449	0.004	0.441	0.003	0.495	0.010
102		1			0.540	0.006	0.442	0.005	0.439	0.008	0.444	0.009	0.435	0.007	0.483	0.013
103		1			0.542	0.006	0.448	0.006	0.440	0.006	0.463	0.008	0.448	0.004	0.522	0.009
Sum		1			0.535	0.005	0.440	0.006	0.440	0.006	0.462	0.007	0.448	0.004	0.517	0.010
104	1	1			0.544	0.007	0.446	0.004	0.435	0.005	0.455	0.006	0.429	0.006	0.538	0.017
105	1	1			0.529	0.006	0.455	0.010	0.434	0.007	0.443	0.005	0.452	0.007	0.507	0.011
Sum	1	1			0.535	0.003	0.442	0.003	0.429	0.004	0.446	0.004	0.442	0.004	0.522	0.010
106	1	1	1		0.521	0.008	0.444	0.006	0.437	0.005	0.454	0.008	0.446	0.006	0.506	0.014
107	1	1	1		0.528	0.005	0.448	0.005	0.434	0.005	0.445	0.006	0.452	0.006	0.497	0.012
Sum	1	1	1		0.526	0.006	0.447	0.003	0.431	0.004	0.446	0.005	0.448	0.003	0.487	0.011
108	1		1		0.534	0.004	0.448	0.006	0.444	0.005	0.450	0.007	0.442	0.005	0.483	0.010
109	1		1		0.534	0.006	0.441	0.008	0.452	0.005	0.458	0.011	0.446	0.005	0.510	0.009
Sum	1		1		0.541	0.004	0.445	0.005	0.445	0.004	0.443	0.004	0.445	0.003	0.491	0.007
110	1				0.536	0.004	0.435	0.007	0.447	0.007	0.436	0.008	0.436	0.003	0.509	0.013
111	1				0.547	0.013	0.438	0.006	0.442	0.005	0.444	0.007	0.441	0.007	0.537	0.006
Sum	1				0.538	0.007	0.436	0.007	0.443	0.004	0.434	0.004	0.440	0.004	0.533	0.007

^a Low frequency average of spectral ratio.^b Standard deviation of the mean of the low frequency spectral ratio average.^c Represents the summing of the spectral signatures of the two previous measurements.

Fig. 4.25. Spectral ratio 23 values as a function of lead plate mass.

Fig. 4.26. Spectral ratio 24 values as a function of lead plate mass.

Fig. 4.27. Spectral ratio 25 values as a function of lead plate mass.

Fig. 4.28. Spectral ratio 34 values as a function of lead plate mass.

Fig. 4.29. Spectral ratio 35 values as a function of lead plate mass.

Fig. 4.30. Spectral ratio 45 values as a function of lead plate mass.

4.9. STAINLESS STEEL PLATE MEASUREMENTS

This section presents the results of measurements in which stainless steel plates were positioned between the fuel elements. The stainless steel plates were either 0.06- or 0.12-inch thick. The plates all had the same lengths (48 inches) but had different widths. The plates positioned in the north and south position had the same width (4 7/8 inches), and those positioned in the east and west positions had the same width (11 7/8 inches). The plate guides were designed such that a maximum of four plates could be located in one guide. The plates were used together to construct the $\sim 3/16$ - and $\sim 1/4$ -inch total thickness. The spectral ratio values obtained from these measurements are presented as a function of the number of 0.06-inch thick plates or equivalent that were used in the measurements in Table 4.25. Some of the individual measurements were simply statistical repeats in which additional sets of data were obtained prior to changing the experimental assembly. These statistical repeat measurements were combined together and are also presented in Table 4.25.

The data in Table 4.25 are presented as a function of the steel plate mass in Figs. 4.31 to 4.36. The sums of statistical measurements are plotted as a function of the steel mass. Repeat measurements not performed sequentially were not summed together because of the potential for very slight differences in the system configuration. These measurements are evident when two or more values were plotted for a given mass. The dashed lines indicate the one standard deviation spread of the fifteen reference measurements. As can be seen from the figures, the steel plates significantly changed the measured spectral ratio values. Measurement results with a single plate in the north and south positions were essentially the same as those obtained from the reference measurements except for spectral ratio value 23. A single small plate in the north and south positions did not affect the interaction between adjacent elements and did not affect the interaction between elements located in the east and west positions. However, as the number of plates (mass) was increased the spectral ratio values increased significantly indicating that k_{eff} was decreasing. This may have occurred because of a combination of water displacement near the fuel elements and because of the neutron absorption in the stainless steel. The sums of the spectral signatures were more statistically converged than the individual measurements. The results for these measurements showed very good repeatability when comparing the sums of two measurements.

Many measurements were performed with symmetric plate configurations. Consider the sum of measurements 112 and 113 with one steel plate in the north and south positions. This configuration was symmetric with respect to the north and south fuel elements. Therefore, the spectral ratios 24, 25, 34, and 35 were in close agreement as can be seen from the data presented in Table 4.23. Likewise, the spectral ratios 24, 25, 34 and 35 were in close agreement for sum of measurements 116 and 117 and for the sum measurements 118 and 119. These measurements had symmetric plate configurations. The spectral ratios 24, 25, 34, and 35 for the sum of measurements 116 and 117 did not differ from those for the sum of measurements 118 and 119 and indicated that the additional plate had a small affect on the interaction between adjacent fuel elements.

Table 4.25. Measured spectral ratio values with varying number of stainless steel plates between the fuel elements

No.	Number of plates				Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	N	E	S	W	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
90	4	4	4	4	0.685	0.003	0.549	0.003	0.527	0.002	0.549	0.003	0.551	0.003	0.631	0.005
91	3	3	3	3	0.654	0.004	0.533	0.003	0.526	0.003	0.529	0.003	0.527	0.003	0.636	0.005
112	1		1		0.564	0.007	0.456	0.006	0.449	0.006	0.450	0.005	0.461	0.006	0.528	0.012
113	1		1		0.569	0.007	0.461	0.007	0.456	0.004	0.454	0.005	0.456	0.004	0.535	0.018
Sum ^c	1		1		0.570	0.004	0.458	0.003	0.451	0.003	0.453	0.005	0.457	0.004	0.505	0.010
116	2		2		0.615	0.009	0.482	0.005	0.488	0.008	0.486	0.006	0.474	0.006	0.527	0.012
117	2		2		0.604	0.006	0.465	0.005	0.476	0.007	0.489	0.008	0.511	0.007	0.554	0.010
Sum ^c	2		2		0.608	0.005	0.482	0.003	0.484	0.006	0.484	0.005	0.485	0.005	0.541	0.010
118	3		3		0.615	0.007	0.466	0.006	0.473	0.006	0.475	0.006	0.494	0.008	0.546	0.008
119	3		3		0.618	0.011	0.477	0.010	0.487	0.007	0.481	0.008	0.494	0.008	0.598	0.010
Sum ^c	3		3		0.617	0.006	0.481	0.007	0.479	0.005	0.478	0.005	0.484	0.007	0.565	0.006
120	3	1	3	1	0.631	0.004	0.503	0.004	0.508	0.004	0.513	0.004	0.509	0.004	0.607	0.006
121	3	1	3	1	0.630	0.005	0.510	0.005	0.505	0.005	0.505	0.005	0.496	0.006	0.579	0.012
Sum ^c	3	1	3	1	0.629	0.004	0.504	0.003	0.502	0.004	0.511	0.003	0.504	0.004	0.605	0.005
122	2	1	2	1	0.628	0.005	0.502	0.005	0.497	0.004	0.504	0.005	0.507	0.005	0.559	0.009
123	2	1	2	1	0.635	0.003	0.487	0.005	0.487	0.005	0.511	0.005	0.515	0.005	0.588	0.009
Sum ^c	2	1	2	1	0.628	0.003	0.496	0.003	0.488	0.003	0.508	0.003	0.506	0.003	0.568	0.007
124	2	2	2	2	0.631	0.003	0.512	0.002	0.512	0.002	0.511	0.002	0.510	0.002	0.585	0.003
131	1	1	1	1	0.608	0.004	0.491	0.004	0.488	0.004	0.500	0.003	0.491	0.003	0.559	0.005
133	1	3	1	3	0.630	0.004	0.510	0.003	0.507	0.002	0.522	0.003	0.509	0.002	0.615	0.007
134	1	3	1	3	0.631	0.003	0.511	0.003	0.506	0.003	0.523	0.002	0.503	0.002	0.605	0.008
145a	4	4	4	4	0.674	0.005	0.556	0.004	0.526	0.004	0.546	0.004	0.552	0.004	0.640	0.013
145b	4	4	4	4	0.661	0.007	0.551	0.003	0.531	0.003	0.541	0.005	0.537	0.005	0.577	0.005
Sum ^c	4	4	4	4	0.673	0.004	0.554	0.003	0.532	0.003	0.548	0.003	0.543	0.003	0.615	0.007

^a Low frequency average of spectral ratio.^b Standard deviation of the mean of the low frequency spectral ratio average.^c Represents the sum of the spectral signatures of the two previous measurements.

Table 4.25. (continued)

No.	Number of plates				Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	N	E	S	W	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
153a		2		2	0.606	0.005	0.490	0.004	0.498	0.004	0.501	0.003	0.490	0.003	0.563	0.005
153b		2		2	0.614	0.004	0.487	0.004	0.488	0.003	0.502	0.004	0.495	0.004	0.575	0.005
Sum		2		2	0.603	0.003	0.487	0.003	0.491	0.003	0.501	0.003	0.492	0.003	0.569	0.003
155	1	2	1	2	0.610	0.005	0.501	0.004	0.506	0.004	0.507	0.003	0.510	0.003	0.608	0.009
156	1	2	1	2	0.617	0.002	0.498	0.003	0.499	0.005	0.505	0.003	0.513	0.004	0.585	0.007
Sum ^c	1	2	1	2	0.612	0.003	0.501	0.003	0.500	0.004	0.505	0.002	0.511	0.002	0.596	0.006
157	3	2	3	2	0.640	0.005	0.508	0.004	0.510	0.004	0.516	0.003	0.520	0.005	0.601	0.008
158	3	2	3	2	0.639	0.005	0.515	0.004	0.502	0.006	0.520	0.006	0.534	0.005	0.613	0.006
159a	2	3	2	3	0.646	0.005	0.524	0.004	0.514	0.006	0.525	0.004	0.528	0.004	0.638	0.007
159b	2	3	2	3	0.666	0.004	0.528	0.002	0.514	0.003	0.535	0.003	0.534	0.006	0.603	0.007
159c	2	3	2	3	0.662	0.004	0.529	0.004	0.522	0.004	0.527	0.003	0.536	0.003	0.601	0.005
Sum ^d	2	3	2	3	0.658	0.002	0.528	0.002	0.517	0.002	0.528	0.002	0.534	0.003	0.614	0.005
166a	2	4	2	4	0.656	0.006	0.543	0.006	0.524	0.005	0.523	0.002	0.521	0.004	0.633	0.006
166b	2	4	2	4	0.664	0.004	0.541	0.004	0.519	0.004	0.538	0.004	0.517	0.004	0.640	0.007
166c	2	4	2	4	0.676	0.004	0.539	0.004	0.532	0.005	0.530	0.005	0.536	0.005	0.590	0.006
166d	2	4	2	4	0.645	0.007	0.543	0.004	0.527	0.004	0.551	0.005	0.540	0.004	0.624	0.019
Sum ^e	2	4	2	4	0.662	0.002	0.542	0.002	0.529	0.002	0.536	0.002	0.525	0.003	0.623	0.007

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

^c Represents the sum of the spectral signatures of the two previous measurements.

^d Represents the sum of the spectral signatures of the three previous measurements.

^e Represents the sum of the spectral signatures of the four previous measurements.

Table 4.25. (continued)

No.	Number of plates				Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	N	E	S	W	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
167a	4	4			0.606	0.004	0.518	0.003	0.485	0.002	0.514	0.003	0.488	0.003	0.581	0.005
167b	4	4			0.613	0.002	0.519	0.003	0.482	0.003	0.515	0.003	0.480	0.002	0.579	0.005
167c	4	4			0.621	0.003	0.512	0.003	0.486	0.002	0.520	0.003	0.488	0.003	0.585	0.003
167d	4	4			0.610	0.003	0.519	0.002	0.485	0.002	0.519	0.002	0.487	0.002	0.589	0.004
167e	4	4			0.617	0.003	0.516	0.003	0.486	0.002	0.514	0.002	0.483	0.002	0.602	0.006
167f	4	4			0.621	0.003	0.515	0.004	0.482	0.003	0.518	0.003	0.485	0.002	0.587	0.004
167g	4	4			0.620	0.003	0.515	0.002	0.489	0.003	0.514	0.003	0.486	0.002	0.571	0.003
167i	4	4			0.617	0.003	0.510	0.003	0.489	0.003	0.510	0.003	0.479	0.002	0.566	0.006
Sum ^c	4	4			0.618	0.002	0.516	0.001	0.487	0.001	0.513	0.001	0.485	0.001	0.584	0.002
168a	1	4			0.606	0.004	0.519	0.004	0.477	0.003	0.514	0.005	0.474	0.002	0.581	0.008
168b	1	4			0.601	0.004	0.512	0.004	0.473	0.002	0.505	0.003	0.481	0.004	0.548	0.008
Sum ^d	1	4			0.600	0.003	0.517	0.003	0.471	0.002	0.507	0.002	0.478	0.003	0.570	0.005
169a		4			0.587	0.003	0.494	0.002	0.459	0.003	0.495	0.003	0.474	0.004	0.551	0.008
169b		4			0.587	0.003	0.500	0.004	0.466	0.003	0.494	0.004	0.477	0.003	0.552	0.007
Sum ^d		4			0.588	0.002	0.498	0.002	0.465	0.003	0.491	0.003	0.474	0.002	0.552	0.003
170a	2	2			0.582	0.003	0.506	0.003	0.475	0.003	0.493	0.003	0.478	0.002	0.553	0.005
170b	2	2			0.581	0.007	0.492	0.004	0.463	0.004	0.493	0.003	0.470	0.004	0.538	0.007
Sum ^d	2	2			0.581	0.004	0.499	0.002	0.469	0.002	0.493	0.002	0.479	0.002	0.544	0.004

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

^c Represents the sum of the spectral signatures of the eight previous measurements.

^d Represents the sum of the spectral signatures of the two previous measurements.

Fig. 4.31. Spectral ratio 23 values as a function of stainless steel plate mass.

Fig. 4.32. Spectral ratio 24 values as a function of stainless steel plate mass.

Fig. 4.33. Spectral ratio 25 values as a function of stainless steel plate mass.

Fig. 4.34. Spectral ratio 34 values as a function of stainless steel plate mass.

Fig. 4.35. Spectral ratio 35 values as a function of stainless steel plate mass.

Fig. 4.36. Spectral ratio 45 values as a function of stainless steel plate mass.

Spectral ratio 23 was most affected by addition of plates in the north and south positions with no plates in the east and west positions. Spectral ratio 23 changed from 0.57 to 0.62 for one to three plates in the north and south positions. Spectral ratio 45 changed from 0.51 to 0.57 for one to three plates in the north and south positions. The change in these spectral ratios occurred because the fuel elements in the north and south positions became more isolated from those in the east and west positions.

The magnitude of the change that was created when plates were added depends on the total number of plates in the system. Consider measurements in which one plate was in the east and west positions. The spectral ratio values 24, 25, 34, and 35 statistically did not change when one, two, or three plates were placed in the north and south positions. The spectral value ratios 24, 25, 34, and 35 varied only a few percent. The changes in spectral ratio 23 were quite small compared to the changes in spectral ratio 45. Spectral ratio 23 changed from 0.61 to 0.63 for the addition of one to three plates in the north and south positions while the spectral ratio 45 changed from 0.56 to 0.61. Plates in the east and west positions had a greater effect on the spectral ratio values, and this was to be expected because of the size of these plates. The same behavior was evident for measurements with two plates in the east and west positions with varying numbers of plates in the north and south positions.

Measurements were performed in which plates were placed in asymmetric positions in the system. These included measurements with four plates in the east position and varying number of plates in the north position (measurements 167, 168, and 169). The spectral ratio values involving detector 2 (north position) increased as the number of plates in the north position increased. Spectral ratio 23 values were 0.588 ± 0.002 , 0.600 ± 0.003 , and 0.618 ± 0.002 for 0, 1, and 4 plates in the north position, respectively. The change in spectral ratio 45 was less significant because plates were only added to the north position. The spectral ratio values 24, 25, 34, and 35 are non-symmetric because the plates were not symmetric. In general, the spectral ratio values increased the most as the number of plates in the system increased. As expected, the plates in the east and west positions had the greatest affect on the spectral ratios because of the size of these plates. Symmetric configurations of plates produced consistent results for symmetric combinations of detectors and the results of the asymmetric configurations also produced consistent results. Symmetric configurations of 1, 2, 3, and 4 plates in all positions changed the spectral ratio 23 values 10%, 14%, 18%, and 24%, respectively with respect to the reference measurements without plates. These results indicate the change in the system reactivity because the spectral ratio is proportional to reactivity.

4.10 BORAL PLATE MEASUREMENTS

This section presents the results of measurements in which BORAL plates were positioned between the fuel elements. The BORAL plates were 0.075-inch thick. The plates all had the same lengths (48 inches) but had different widths. The plates positioned in the north and south position had the same width (4 7/8 inches), and those positioned in the east and west positions had the same width (11 7/8 inches). The spectral ratio values obtained from these measurements are presented as a function of the number of plates in Table 4.26. Some of the individual measurements were simply statistical repeats in which a second set of data was obtained prior to changing the experimental assembly. These statistical repeat measurements were combined together and are also presented in Table 4.26.

The data presented in Table 4.26 are plotted as a function of the BORAL plate mass in Figs. 4.37 to 4.42. The sums of statistical measurements were plotted as a function of the BORAL mass. The dashed lines indicate the one standard deviation spread of the reference measurements. As expected, the spectral ratio values changed significantly with the addition of the BORAL plates. These plates were strong absorbers that limited the interaction between fuel elements and reduced the overall reactivity of the system. When analyzing the results of the measurements it was important to not only consider the total mass of the absorber but also its location.

The position of the BORAL plates affected the six spectral ratio values differently. Symmetric placement of the BORAL plates produced spectral ratio values that were symmetric. Symmetric measurements with one BORAL plate in both the east and west positions produced symmetric spectral ratio values for combinations involving detectors 4 and 5. The spectral ratio values 24, 25, 34, and 35 were statistically the same and range from 0.578 to 0.585. These values were well within the repeatability of the measurements and were considered the same. Likewise, symmetric measurements with one BORAL plate in both the north and south positions produced symmetric spectral ratio values for ratio combinations involving detectors 2 and 3. Additionally, measurements with one BORAL plate in all positions produce symmetric results. The spectral ratio values 24, 25, 34, and 35 are within two percent of each other. The BORAL plates drastically changed the coupling between the fuel elements.

The results of measurements with plates positioned asymmetrically in the system produced expected results. Consider the sum of measurements 151a through 151d in which the BORAL plate was placed in the west position. Recalling that detectors 3, 4, and 5 are in the south, east, and west positions respectively, notice that the spectral ratio 34 was not changed as significantly as the spectral ratio 35. The BORAL plate greatly affected ratio 35 because it limits the interactions between the south and west elements but only slightly affected the interaction between the south and east elements. The spectral ratio 34 value for this measurement was greater than the spectral ratio 34 for the reference measurement because of the coupling between all of the elements. The results for spectral ratio 24 were consistent with that for spectral ratio 34, and likewise, the spectral ratio 25 was essentially the same as spectral ratio 35 for this measurement with a

single BORAL plate in the west position. The measurements with one BORAL plate in the north position produced expected results. The spectral ratios 24 and 25 were within one percent of each other and the spectral ratios 34 and 35 were also within one percent of each other.

The BORAL plate measurements demonstrated how effective boron was in isolating the fuel elements from each other. The addition of a small BORAL plate drastically changed the spectral ratio values because the interaction between elements was dramatically affected. The impact of the BORAL plates depended on the number of plates and on the location of the plates. The addition of a large plate was more important than the addition of a small plate because of the additional amount of boron in the large plates. The change in the spectral ratio and hence the change in the reactivity ranged from 11% to 48%. The 11% change occurred for a single BORAL plate in the north position, and the 48% change occurred when all four BORAL plates were placed in the assembly.

Table 4.26. Measured spectral ratio values with varying number of BORAL plates between the fuel elements

No.	Number of plates				Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	N	E	S	W	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
125	1	1	1	1	0.822	0.007	0.637	0.005	0.635	0.005	0.657	0.005	0.635	0.007	0.782	0.011
135	1	1	1	1	0.822	0.004	0.627	0.003	0.633	0.004	0.646	0.006	0.638	0.004	0.758	0.007
136a	1				0.621	0.005	0.512	0.004	0.502	0.003	0.487	0.002	0.476	0.003	0.584	0.006
136b	1				0.617	0.004	0.519	0.004	0.505	0.004	0.494	0.004	0.480	0.004	0.574	0.010
Sum ^c	1				0.619	0.004	0.512	0.003	0.503	0.002	0.488	0.002	0.478	0.003	0.576	0.006
146a	1	1		1	0.755	0.004	0.623	0.004	0.620	0.005	0.592	0.003	0.603	0.004	0.702	0.024
146b	1	1		1	0.765	0.007	0.616	0.008	0.614	0.009	0.577	0.007	0.598	0.005	0.765	0.019
146c	1	1		1	0.762	0.005	0.620	0.006	0.626	0.004	0.599	0.004	0.601	0.004	0.714	0.007
146d	1	1		1	0.761	0.007	0.610	0.007	0.616	0.006	0.607	0.006	0.600	0.005	0.743	0.010
Sum ^d	1	1		1	0.762	0.001	0.609	0.006	0.613	0.004	0.595	0.002	0.597	0.003	0.739	0.007
147	1		1		0.702	0.005	0.530	0.004	0.522	0.003	0.545	0.005	0.537	0.003	0.657	0.009
148	1		1	1	0.753	0.006	0.546	0.005	0.590	0.013	0.560	0.006	0.634	0.010	0.690	0.018
149a	1		1	1	0.746	0.007	0.540	0.003	0.616	0.006	0.555	0.004	0.633	0.005	0.730	0.022
149b	1		1	1	0.770	0.009	0.556	0.004	0.576	0.004	0.548	0.004	0.631	0.006	0.692	0.011
149c	1		1	1	0.735	0.007	0.549	0.005	0.607	0.008	0.554	0.004	0.661	0.010	0.651	0.014
149d	1		1	1	0.757	0.007	0.548	0.006	0.581	0.011	0.545	0.002	0.594	0.006	0.707	0.016
Sum ^d	1		1	1	0.752	0.005	0.544	0.004	0.607	0.004	0.555	0.003	0.633	0.005	0.696	0.009
150a	1			1	0.714	0.005	0.538	0.006	0.581	0.005	0.498	0.006	0.577	0.005	0.709	0.014
150b	1			1	0.707	0.005	0.536	0.005	0.597	0.007	0.505	0.003	0.575	0.005	0.641	0.009
150c	1			1	0.703	0.008	0.536	0.004	0.611	0.005	0.500	0.006	0.583	0.004	0.652	0.012
150d	1			1	0.689	0.014	0.526	0.005	0.605	0.008	0.496	0.003	0.565	0.006	0.631	0.011
Sum ^d	1			1	0.707	0.003	0.530	0.003	0.597	0.003	0.497	0.002	0.576	0.003	0.661	0.006

^a Low frequency average of spectral ratio.^b Standard deviation of the mean of the low frequency spectral ratio average.^c Represents the summing of the spectral signatures of the two previous measurements.^d Represents the summing of the spectral signatures of the four previous measurements.

Table 4.26. (continued)

No.	Number of plates				Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	N	E	S	W	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
151a				1	0.625	0.004	0.493	0.004	0.540	0.006	0.477	0.003	0.545	0.005	0.608	0.007
151b				1	0.617	0.005	0.478	0.003	0.542	0.008	0.486	0.005	0.545	0.005	0.606	0.009
151c				1	0.624	0.003	0.480	0.005	0.527	0.006	0.474	0.003	0.561	0.006	0.589	0.007
151d				1	0.610	0.005	0.492	0.002	0.543	0.005	0.477	0.004	0.546	0.004	0.591	0.009
Sum ^c				1	0.631	0.003	0.484	0.001	0.540	0.003	0.480	0.002	0.547	0.003	0.598	0.004
154a		1		1	0.716	0.007	0.575	0.005	0.583	0.006	0.582	0.004	0.592	0.006	0.685	0.007
154b		1		1	0.706	0.004	0.579	0.004	0.573	0.005	0.580	0.006	0.579	0.005	0.667	0.011
154c		1		1	0.715	0.004	0.579	0.005	0.570	0.006	0.583	0.004	0.595	0.004	0.670	0.009
154d		1		1	0.720	0.004	0.571	0.005	0.578	0.004	0.583	0.004	0.588	0.004	0.668	0.008
154e		1		1	0.713	0.005	0.565	0.006	0.580	0.004	0.579	0.003	0.582	0.003	0.671	0.012
154f		1		1	0.692	0.006	0.576	0.006	0.580	0.006	0.579	0.004	0.600	0.005	0.692	0.015
154g		1		1	0.701	0.004	0.591	0.005	0.570	0.006	0.581	0.004	0.591	0.005	0.683	0.009
154h		1		1	0.702	0.005	0.583	0.005	0.574	0.004	0.593	0.005	0.581	0.004	0.670	0.009
Sum ^d		1		1	0.714	0.003	0.582	0.002	0.578	0.002	0.585	0.002	0.585	0.002	0.678	0.004

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

^c Represents the sum of the spectral signatures of the four previous measurements.

^d Represents the sum of the spectral signatures of the eight previous measurements.

Fig. 4.37. Spectral ratio 23 values as a function of BORAL plate mass.

Fig. 4.38. Spectral ratio 24 values as a function of BORAL plate mass.

Fig. 4.39. Spectral ratio 25 values as a function of BORAL plate mass.

Fig. 4.40. Spectral ratio 34 values as a function of BORAL plate mass.

Fig. 4.41. Spectral ratio 35 values as a function of BORAL plate mass.

Fig. 4.42. Spectral ratio 45 values as a function of BORAL plate mass.

5. SPENT FUEL MEASUREMENTS

Limited exploratory spent fuel measurements were performed in the MURR weir pool that was adjacent to the reactor pool. The experimental assembly was modified by replacing the 7-ft dry-wells with 18-ft dry-wells and lead plugs were used in place of the aluminum plugs in the bottom of the dry wells for additional shielding. As previously stated, 2.54-cm-thick lead shields were placed around the detectors on the exterior of the dry wells. The lead shields were encased in aluminum and were 24-in. long. In these measurements, the 1-atm- ^3He detectors in the east and west positions were input as channels 2 and 3 into the frequency analyzer. The detector in the south position was input as channel 4 into the frequency analyzer. Although the dry well was present, a detector was not placed in the north position because of the high gamma radiation field at this location. The orientation and configuration of the fuel elements for these measurements is given in Table 5.1 and a photograph of the assembly is given in Fig. 5.1.

Table 5.1. Assembly configuration for spent fuel measurements

Parameter	North	East	South	West
Fuel Orientation ^a	A	B	A	B
Center-to-Fuel Spacing (cm) ^b	6.745	8.109	6.712	8.299
Detector-to-Fuel Spacing (cm) ^c	10.5	10.5	10.5	10.5

^a Orientation A corresponds to the small end of the fuel element closest to the center and orientation B corresponds to the large end of the fuel element closest to the center.

^b Spacing between fuel centerline and source dry well centerline.

^c Spacing between fuel element centerline and detector dry well centerline.

Measurements were performed with four fresh fuel elements, one spent and three fresh fuel elements, and two fresh and two spent fuel elements. The fuel element assembly identifiers for these measurements are provided in Table 5.2. Spent fuel elements MO-461 and MO-463 had an estimated burnup of 143 MWD with approximately 6 months of cooling time.

Table 5.2. Fuel element identifiers for spent fuel measurements

Fuel element location	Four fresh	Three fresh and one spent	Two fresh and two spent
North	MO-517	MO-461	MO-461
East	MO-519	MO-519	MO-519
South	MO-518	MO-518	MO-463
West	MO-520	MO-520	MO-520

Fig. 5.1. Spent fuel measurement configuration.

The assembly was lowered into the weir pool using a crane whose hook and steel cables were between the detector dry wells. The hook remained in place during these measurements and put tension on the dry wells. The dry wells may not have remained perpendicular although a rope was used to try to keep the detectors perpendicular. Furthermore, there was no way to estimate the effects of raising and lowering the test assembly into the weir pool. Variations to the assembly geometry were to be investigated when analyzing these measurements. Furthermore, the effects of slight rotations in the fuel elements were to be investigated in the analyses. No measurement device was used to ensure that the elements did not rotate during the placement of the fuel elements in the test assembly; visual inspections were adequate to ensure that the elements were not rotated about their center. The assembly in the weir pool is shown in Fig. 5.2.

Fig. 5.2. Assembly in reactor weir pool.

The detector in the south position remained in its position for all measurements, but its high voltage was turned off for the two spent fuel element measurements. The high gamma ray background would have saturated the response of this detector. The results of the measurements are provided in Table 5.3. As can be seen from the data provided in Table 5.3, the spectral ratio values increased as more spent fuel elements were used in the measurements and indicated that the reactivity was decreasing. The spectral ratio values presented in Table 5.3 were corrected because only 98.5% of the spontaneous fission events of the source were counted for the spent fuel measurements. The temperature varied approximately 4°F over the period of these measurements. Fresh fuel measurements were performed with two different detector threshold settings. Measurement number 192 corresponded to a high threshold setting that was used for the spent fuel measurements whereas number 193 had a 1 volt threshold that was the same as measurements performed in the fresh water tank. The spectral ratio values for the fresh fuel measurements did not depend on the detector threshold values because the spectral ratio is essentially independent of detection efficiency. The measurements with a single spent fuel element were repeated at different times. The results for the two measurements with a single spent fuel element were in good agreement with each other although the temperature varied 4°F from one measurement to another. This indicated that the small change in temperature did not drastically affect the results of the measurements. However, these measurement files were not averaged together because the fuel elements were removed between the measurements and changes in the spectral ratio values due to temperature could be masked by changes in the apparatus. The spectral ratio value 23 changed approximately 5% as a result of replacing one fresh element in the north position

with one spent fuel element. The spectral ratio values 24 and 34 were essentially the same as evident from the results in Table 5.3. The average of spectral ratio values 24 and 34 changed approximately 5% as a result of replacing one fresh fuel element in the north position with a spent fuel element. The results of the two measurements with two spent and two fresh elements were combined together because these measurements represented statistical repeats for the same fuel element configuration. Only a single spectral ratio value was obtained because the detector in the south position was turned off due to the high gamma ray background at the detector. The spectral ratio value 23 changed approximately 11% when two fresh fuel elements in the north and south positions were replaced with spent fuel elements.

Table 5.3. Measured spectral ratio values for spent fuel measurements

Configuration	Number	Temperature (°F)	Ratio 23		Ratio 24		Ratio 34	
			R ^a	σ^b	R ^a	σ^b	R ^a	σ^b
4 fresh	192	106.5	0.298	0.003	0.289	0.002	0.290	0.003
4 fresh	193	106.8	0.301	0.003	0.286	0.003	0.288	0.003
3 fresh, 1 spent	189	103.3 - 104.1	0.313	0.003	0.307	0.002	0.299	0.003
3 fresh, 1 spent	194	107.1 - 107.5	0.315	0.003	0.304	0.002	0.304	0.002
2 fresh, 2 spent	190	104.4 - 105.5	0.331	0.006				
2 fresh, 2 spent	191	105.5 - 106.2	0.322	0.006				
Average of 2 fresh and 2 spent ^c	Avg.	-	0.331	0.004				

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

^c Represents the summing of the spectral signatures of the two previous measurements.

Count rate data was also obtained during these measurements. These count rates are presented in Table 5.4. The count rates for detectors in the east and west positions decreased with the addition of the spent fuel elements because fewer fission events were occurring in the fuel elements as a result of the reduced uranium content in the spent fuel elements and because of the reduced detection efficiency. Lowering the threshold for the fresh fuel measurements further increased the detector count rates for the fresh fuel measurements.

Table 5.4. Detector count rate values for spent fuel measurements					
Configuration	No.	Temperature (°F)	South (counts/sec)	East (counts/sec)	West (counts/sec)
4 fresh	192	106.5	4085	2996	2429
4 fresh	193	106.8	6726	7503	7377
3 fresh, 1 spent	189	103.3 - 104.1	4025	2949	2384
3 fresh, 1 spent	194	107.1 - 107.5	3052	2884	2403
2 fresh, 2 spent	190	104.4 - 105.5		1456	841
2 fresh, 2 spent	191	105.5 - 106.2		1462	845

Additional count rate measurements were performed with one spent fuel element and three fresh fuel elements with the ^{252}Cf source removed. The average detector count rates were 256, 167 and 128 counts per second for detectors in the south, east, and west positions respectively. The counts were approximately 5% of the count rate with the source present. The detector thresholds were set such that mostly neutron events contributed to the detector response; therefore, some of these counts without the source present must be attributed to an inherent source in the spent fuel element and some fraction of gamma ray counts. The count rate measurements without the ^{252}Cf source were repeated for measurements with two spent fuel elements. The average detector count rates were 198 and 98 counts per second for the east and west detectors, respectively. This was approximately 12% of the count rate with the source present. Again, these counts can be attributed to an inherent source in the spent fuel elements and counting some gamma rays. As expected the percentage doubled when two spent fuel elements were used instead of one spent fuel element.

Additional spent fuel measurements were to be performed in which the affects of the elements are heightened. These measurements were only preliminary and were performed as an addition to the fresh fuel measurements.

6. SUMMARY AND CONCLUSIONS

Subcritical noise analysis measurements were successfully performed with a variety of configurations of research reactor fuel elements at the Missouri University Research Reactor (MURR) in July 1998. These measurements were performed to assess the subcriticality of research reactor fuel elements separated by neutron absorbing materials and to determine the reactivity worth of spent (irradiated) fuel elements. This collaborative program between Oak Ridge National Laboratory, Westinghouse Safety Management Solutions, Inc., and the University of Missouri was undertaken to obtain benchmark subcritical measurements that address the excess conservatism associated with the transportation and storage of research reactor fuel elements at the Savannah River Technology Center.

Measurements were performed to determine the optimum source axial location, the optimum detector location, and the repeatability of the measurements. The results demonstrated that the optimum source location was near the axial center of the active region of the fuel elements and that the optimum detector location was a 9.0-cm separation between the fuel centerline and the detector centerline. Two sets of reference measurements were performed to investigate the repeatability of the measurements. The results of the measurements demonstrated that the uncertainty in the measured spectral ratio values was approximately 1% to 2%. This uncertainty represented the sample set standard deviation obtained from the two reference sets. The standard deviation of the sample set did not differ significantly from the standard deviation of the mean of the individual spectral ratio values thereby indicating that the variation between measurements was not significant. The standard deviation of the sample set should be used when comparing measured and calculated spectral ratio values.

The results also demonstrated that the selected configuration of the fuel elements had the highest reactivity. Fuel element traverse measurements were performed in which all fuel elements or a single fuel element was moved from a reference position. The results indicated that the reactivity of the system decreased as the fuel elements were moved apart and that the detectors located 180° apart were the most sensitive to changes in system reactivity. The fuel elements in the north and south positions had a greater reactivity worth than fuel elements in the east and west positions as demonstrated by the fuel traverse measurements in which only one fuel element was moved.

Measurements were performed with a variety of plates positioned between the fuel element to simulate isolation of fuel elements from each other. In general, symmetric arrangements of plates produced expected results in that symmetric spectral ratio values were essentially the same. Asymmetric arrangements of plates produced spectral ratio values as expected. The magnitude of the change that was created when plates were added depended on the total number of plates in the system. The aluminum plates did not significantly affect the measured spectral ratio values. Most of the data values fell within one standard deviation of the reference measurements and all of the measurements fell within two standard deviations of the reference measurements for these measurements.

The majority of the lead plate measurements demonstrated that lead had little effect on the system reactivity. The spectral ratio values obtained from detectors 2 and 3 decreased slightly as a function of lead mass while the other spectral ratio values did not exhibit any clear pattern for changes in the lead mass. Except for the spectral ratio 23, a majority of the spectral ratio values were within two standard deviations of the reference plate measurements. The spectral ratio 23 values differed from 2% to 6% from the reference measurements. This difference is greater than the uncertainty in the reproducibility of the measurements. However, the remaining spectral ratio values were consistent with each other and were within two standard deviations of the reference measurements and hence demonstrated that lead has little effect on the system reactivity.

The stainless steel plates had a significant impact on the reactivity of the system and performed well in isolating the fuel elements from each other. Measurement results with a single plate in the north and south position were statistically the same as those obtained from the reference measurements. However, as the number of plates (mass) was increased the spectral ratio values increased significantly indicating that k_{eff} was decreasing. This may have occurred because of a combination of water displacement near the fuel elements and because of the neutron absorption in the stainless steel. As expected, the plates in the east and west positions had the greatest effect on the spectral ratios because of the size of these plates. Symmetric configurations of plates produced predictable results for symmetric combinations of detectors and the results of the asymmetric configurations also produced expected results. The change in the spectral ratio values and hence the approximate change in reactivity from the reference measurements varied from 2% to 24%.

The BORAL plates produced the largest changes in the spectral ratio values and in the reactivity of the system. The BORAL plate measurements demonstrated how effective boron was in isolating the fuel elements from each other. The addition of a small BORAL plate drastically changed the spectral ratio values because the interaction between elements was dramatically affected. The impact of the BORAL plates depended on the number of plates and on the location of the plates. The addition of a large plate was more important than the addition of a small plate because of the size of the large plates. The change in the spectral ratio values and hence the approximate change in reactivity from the reference measurements ranged from 11% to 48%.

The spent fuel measurements were only preliminary measurements. The results indicated that a measurable change could be determined when one or two fresh fuel elements were replaced by spent fuel elements. The spectral ratio value for detectors 180° apart changed 5% when one fresh fuel element was replaced with a spent fuel element and changed 11% when two fresh fuel elements were replaced with spent fuel elements. The detector count rates also decreased when the fresh-fuel elements were replaced with spent fuel elements. Count rate measurements performed without the ^{252}Cf source present indicated that an inherent source was present in the spent fuel assemblies and some gamma ray events were probably counted. This inherent source cannot be estimated based on the

detector count rates without the ^{252}Cf source, because some gamma ray events were probably counted.

The results of these fresh fuel measurements can be used as a subcritical benchmark for Monte Carlo transport codes. Measurements with and without plates provide data that can be used to benchmark Monte Carlo codes. The results of the spent fuel measurements cannot be used as benchmark data unless destructive analyses of the fuel elements are performed and the contribution of the inherent source to the spectral ratio values can be determined. However, the reactivity of the spent fuel configurations can still be estimated even without detailed knowledge of the fission product content. Additional spent fuel measurements are needed in which large perturbations to the system can be made by replacing all fresh elements with spent fuel elements.

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APPENDIX A

FRESH FUEL CONTENT DATA

Babcox and Wilcox in Tables A.1 through A.4 provided the fuel content data for the four fresh assemblies.

Table A.1. Fuel contents for MO-517							
Plate	Volume	Total U	UAl ₃ weight	Al in matrix	U-235	U-238	Al
	cm ³	g/plate		excluding bound	g/plate	g/plate	g/plate
1	13.51	20.62	28.95	21.09	19.20	1.42	29.42
2	14.31	21.84	31.08	22.00	20.35	1.50	31.23
3	15.12	23.06	32.81	23.21	21.48	1.58	32.96
4	15.92	24.27	34.53	24.83	22.61	1.66	35.09
5	16.73	25.50	36.26	26.12	23.76	1.75	36.87
6	17.53	26.70	37.98	27.60	24.87	1.83	38.88
7	18.33	27.90	39.70	28.82	25.99	1.92	40.63
8	19.13	29.13	41.43	29.50	27.14	1.99	41.80
9	19.94	30.34	43.15	31.46	28.27	2.08	44.27
10	20.74	31.59	44.90	32.56	29.43	2.16	45.87
11	21.55	32.77	46.62	33.85	30.53	2.24	47.70
12	22.35	33.99	48.33	35.35	31.67	2.34	49.68
13	23.15	35.18	50.08	36.49	32.77	2.41	51.39
14	23.95	36.42	51.81	37.72	33.93	2.49	53.12
15	24.76	37.66	53.53	38.29	35.08	2.58	54.16
16	25.56	38.87	55.26	40.31	36.21	2.66	56.70
17	26.36	40.10	56.99	40.80	37.36	2.75	57.69
18	27.17	41.27	58.69	42.30	38.44	2.82	59.72
19	27.97	42.50	60.43	43.31	39.59	2.91	61.24
20	28.77	43.71	62.17	44.56	40.72	2.99	63.03
21	29.58	44.94	63.87	46.08	41.86	3.08	65.01
22	30.38	46.14	65.60	47.34	42.98	3.16	66.80
23	31.18	47.37	67.35	48.41	44.12	3.25	68.39
24	31.99	48.58	69.07	49.59	45.25	3.33	70.08
Total	545.99	830.48	1180.59	851.59	773.60	56.88	1201.70

Table A.2. Fuel contents for MO-518							
Plate	Volume	Total U	UA13 weight	Al in matrix	U-235	U-238	Al
	cm ³	g/plate		excluding bound	g/plate	g/plate	g/plate
1	13.51	20.64	28.95	21.09	19.22	1.42	29.39
2	14.31	21.84	31.08	22.00	20.34	1.50	31.24
3	15.12	23.06	32.80	23.35	21.48	1.58	33.09
4	15.92	24.27	34.53	24.83	22.61	1.66	35.09
5	16.73	25.50	36.26	26.12	23.75	1.75	36.88
6	17.53	26.69	37.98	27.60	24.87	1.82	38.89
7	18.33	27.88	39.70	28.82	25.97	1.91	40.64
8	19.14	29.13	41.44	29.50	27.13	1.99	41.81
9	19.94	30.35	43.15	31.46	28.27	2.08	44.26
10	20.74	31.57	44.90	32.56	29.41	2.16	45.89
11	21.55	32.76	46.62	33.85	30.52	2.24	47.71
12	22.34	33.99	48.33	35.35	31.67	2.33	49.69
13	23.15	35.21	50.08	36.49	32.79	2.42	51.36
14	23.95	36.41	51.80	37.72	33.91	2.49	53.11
15	24.76	37.66	53.53	38.29	35.08	2.58	54.16
16	25.56	38.86	55.26	40.31	36.20	2.66	56.70
17	26.36	40.08	56.98	40.80	37.33	2.74	57.70
18	27.17	41.27	58.69	42.30	38.44	2.82	59.72
19	27.97	42.52	60.45	43.31	39.61	2.91	61.24
20	28.77	43.710	62.17	44.56	40.71	2.99	63.02
21	29.58	44.95	63.80	46.07	41.87	3.08	64.99
22	30.38	46.14	65.60	47.34	42.98	3.16	66.80
23	31.18	47.39	67.35	48.41	44.13	3.25	68.37
24	31.99	48.49	69.07	49.59	45.17	3.32	70.17
Total	545.99	830.36	1180.59	851.72	773.48	56.88	1201.95

Table A.3. Fuel contents for MO-519							
Plate	Volume	Total U	UAl3 weight	Al in matrix	U-235	U-238	Al
	cm ³	g/plate		excluding bound	g/plate	g/plate	g/plate
1	13.51	20.63	28.95	21.09	19.21	1.42	29.41
2	14.31	21.85	31.09	22.00	20.35	1.50	31.24
3	15.12	23.04	32.80	23.35	21.46	1.58	33.11
4	15.92	24.27	34.52	24.97	22.61	1.66	35.22
5	16.73	25.50	36.26	26.12	23.76	1.75	36.88
6	17.53	26.70	37.98	27.60	24.88	1.83	38.88
7	18.33	27.92	39.70	28.82	26.01	1.91	40.60
8	19.14	29.12	41.44	29.50	27.12	1.99	41.82
9	19.94	30.33	43.15	31.46	28.25	2.08	44.29
10	20.74	31.58	44.90	32.56	29.41	2.16	45.88
11	21.55	32.75	46.62	33.85	30.51	2.24	47.72
12	22.34	33.99	48.33	35.35	31.66	2.33	49.69
13	23.15	35.21	50.08	36.49	32.80	2.42	51.36
14	23.95	36.42	51.80	37.72	33.92	2.49	53.10
15	24.76	37.66	53.53	38.29	35.08	2.58	54.16
16	25.56	38.88	55.26	40.31	36.22	2.66	56.69
17	26.36	40.07	56.98	40.80	37.33	2.74	57.71
18	27.17	41.27	58.69	42.30	38.44	2.82	59.72
19	27.97	42.49	60.44	43.31	39.58	2.91	61.26
20	28.77	43.74	62.15	44.82	40.75	2.99	63.22
21	29.58	44.94	63.87	46.08	41.87	3.08	65.01
22	30.38	46.15	65.60	47.33	42.99	3.16	66.78
23	31.18	47.30	67.35	48.41	44.05	3.25	68.46
24	31.99	48.57	69.07	49.59	45.25	3.33	70.09
Total	545.99	830.39	1180.56	852.12	773.52	56.88	1202.29

Table A.4. Fuel contents for MO-520							
Plate	Volume	Total U	UAl3 weight	Al in matrix	U-235	U-238	Al
	cm ³	g/plate		excluding bound	g/plate	g/plate	g/plate
1	13.51	20.63	28.95	21.09	19.21	1.42	29.41
2	14.31	21.84	31.07	22.09	20.35	1.50	31.32
3	15.12	23.07	32.80	23.35	21.49	1.58	33.08
4	15.92	24.28	34.52	24.97	22.62	1.66	35.21
5	16.73	25.51	36.25	26.27	23.76	1.75	37.01
6	17.53	26.72	37.98	27.60	24.89	1.83	38.86
7	18.33	27.91	39.70	28.82	26.00	1.91	40.61
8	19.14	29.14	41.43	29.67	27.15	1.99	41.96
9	19.94	30.35	43.15	31.46	28.27	2.08	44.26
10	20.74	31.59	44.60	33.16	29.42	2.16	46.17
11	21.55	32.77	46.62	33.85	30.52	2.24	47.70
12	22.35	33.99	48.03	35.80	31.67	2.33	49.84
13	23.15	35.23	49.74	37.09	32.82	2.41	51.60
14	23.95	36.43	51.46	38.41	33.94	2.49	53.44
15	24.76	37.66	53.11	39.51	35.08	2.58	54.96
16	25.56	38.90	54.89	41.05	36.24	2.66	57.04
17	26.36	40.08	56.60	41.56	37.33	2.74	58.08
18	27.17	41.25	58.69	42.30	38.43	2.82	59.74
19	27.97	42.53	60.04	44.12	39.62	2.91	61.63
20	28.77	43.74	62.15	44.82	40.75	2.99	63.23
21	29.58	44.95	63.87	46.08	41.88	3.08	65.00
22	30.38	46.11	65.60	47.34	42.96	3.16	66.83
23	31.18	47.35	67.35	48.41	44.10	3.25	68.41
24	31.99	48.59	68.54	51.16	45.26	3.33	71.11
Total	545.99	830.62	1177.14	859.98	773.73	56.89	1206.50

APPENDIX B

ASSEMBLY CALIBRATION DATA

A series of measurements were performed to calibrate the slide counters with the actual separation between the fuel centerline and the source dry well that was located in the center of the assembly. The data for these measurements were as given in Table B.1.

Table B.1. Slide calibration data							
North		South		East		West	
Counter reading	Center-to-center spacing (cm)	Counter reading	Center-to-center spacing (cm)	Counter reading	Center-to-center spacing (cm)	Counter reading	Center-to-center spacing (cm)
58	6.623	55	6.712	39	6.584	30	6.584
60	6.745	175	7.918	194	8.109	210	8.299
180	7.931	195	8.127	239	8.584	233	8.584
200	8.114	242	8.584	334	9.519	350	9.615
252	8.623	444	10.584	440	10.584	432	10.584
452	10.623	642	12.584	642	12.584	630	12.584
652	12.623	843	14.584	841	14.584	832	14.584
854	14.623						

APPENDIX C

SYSTEM CONFIGURATION FOR ALL MEASUREMENTS

The source, detector, and fuel assembly configurations for the measurements were as provided in Table C.1. The detector position was given in terms of the center of the detector dry well to the center of the fuel element spacing. The source position was provided in terms of the distance from the centerline of the active region of the fuel. In measurements 172 through 187, the source was placed in the north dry well whose centerline was 9.0-cm from the fuel element centerline.

Table C.1. Source, detector, and fuel element configuration															
Run no.	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position (cm)	Source position (cm)
	N	E	S	W	N	E	S	W	Type	N	E	S	W		
1	A				10.903				-	-	-	-	-	10.5	0
2	A				10.903				-	-	-	-	-	10.5	0
2r	A				10.903				-	-	-	-	-	10.5	0
3	A		A		10.903				-	-	-	-	-	10.5	0
4	A		A		10.903				-	-	-	-	-	10.5	0
4r	A		A		10.903				-	-	-	-	-	10.5	0
5	A		A		10.903				-	-	-	-	-	10.5	0
6	A	B	A		10.903	12.505			-	-	-	-	-	10.5	0
7	A	B	A		10.903	12.505			-	-	-	-	-	10.5	0
8	A	B	A		10.903	12.505			-	-	-	-	-	10.5	0
9	A	B	A	B	10.903	12.505			-	-	-	-	-	10.5	0
10	A	B	A	B	9.903	11.515			-	-	-	-	-	10.5	0
11	A	B	A	B	8.903	10.524			-	-	-	-	-	10.5	0
12	A	B	A	B	6.745	8.278	6.762	8.299	-	-	-	-	-	10.5	0
13	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0
14	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0
15	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0
16	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	4
17	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	4
18	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	10
19	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	15
20	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	30
21	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	-10
22	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	-15

Table C.1. (continued)

Run no.	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position (cm)	Source position (cm)
	N	E	S	W	N	E	S	W	Type	N	E	S	W		
23	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	-30
24	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0
25	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	10.5	0
26	A	B	A	B	10.903	12.505	10.898	12.782	-	-	-	-	-	10.5	0
27	A	B	A	B	10.903	12.505	10.898	12.782	-	-	-	-	-	10.5	0
28	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	10.5	0
29	A	A	A	A	8.603	8.732	8.614	8.910	-	-	-	-	-	10.5	0
30	A	A	A	A	8.603	8.732	8.614	8.910	-	-	-	-	-	10.5	0
31	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	10.5	0
32	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	10.5	0
33	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	10.5	0
34	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
35	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
36	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	7.5	0
37	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	12	0
38	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	12	0
39	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	13.5	0
40	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
41	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
42	A	B	A	B	8.903	10.524	8.911	10.766	-	-	-	-	-	9	0
43	A	B	A	B	8.903	10.524	8.911	10.766	-	-	-	-	-	9	0
44	A	B	A	B	9.903	11.515	9.901	11.776	-	-	-	-	-	9	0
45	A	B	A	B	10.903	12.505	10.898	12.782	-	-	-	-	-	9	0
46	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0

Table C.1. (continued)

Run no.	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position (cm)	Source position (cm)
	N	E	S	W	N	E	S	W	Type	N	E	S	W	(cm)	(cm)
47	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
48	A	B	A	B	8.903	9.519	7.918	9.615	-	-	-	-	-	9	0
49	A	B	A	B	8.903	9.519	7.918	9.615	-	-	-	-	-	9	0
50	A	B	A	B	9.903	9.519	7.918	9.615	-	-	-	-	-	9	0
51	A	B	A	B	9.903	9.519	7.918	9.615	-	-	-	-	-	9	0
52	A	B	A	B	11.903	9.519	7.918	9.615	-	-	-	-	-	9	0
53	A	B	A	B	11.903	9.519	7.918	9.615	-	-	-	-	-	9	0
54	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
55	A	B	A	B	7.931	11.515	7.918	9.615	-	-	-	-	-	9	0
56	A	B	A	B	7.931	11.515	7.918	9.615	-	-	-	-	-	9	0
57	A	B	A	B	7.931	13.509	7.918	9.615	-	-	-	-	-	9	0
58	A	B	A	B	7.931	13.509	7.918	9.615	-	-	-	-	-	9	0
59	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
60	A	A	A	A	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
61	A	A	A	A	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
62	B	B	B	B	10.103	9.519	10.099	9.615	-	-	-	-	-	9	0
63	B	B	B	B	10.103	9.519	10.099	9.615	-	-	-	-	-	9	0
64	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
65	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
66	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
67	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
68	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
69	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
70	A	B	A	B	8.114	12.665	8.127	12.941	Al	1	-	1	-	9	0

Table C.1. (continued)

Run no.	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position (cm)	Source position (cm)
	N	E	S	W	N	E	S	W	Type	N	E	S	W		
71	A	B	A	B	8.114	12.665	8.127	12.941	Al	1	-	1	-	9	0
72	A	B	A	B	8.114	12.665	8.127	12.941	Al	2	-	2	-	9	0
73	A	B	A	B	8.114	12.665	8.127	12.941	Al	2	-	2	-	9	0
74	A	B	A	B	8.114	12.665	8.127	12.941	Al	3	-	3	-	9	0
75	A	B	A	B	8.114	12.665	8.127	12.941	Al	3	-	3	-	9	0
76	A	B	A	B	8.114	12.665	8.127	12.941	Al	3	1	3	1	9	0
77	A	B	A	B	8.114	12.665	8.127	12.941	Al	3	1	3	1	9	0
78	A	B	A	B	8.114	12.665	8.127	12.941	Al	2	1	2	1	9	0
79	A	B	A	B	8.114	12.665	8.127	12.941	Al	1	1	1	1	9	0
80	A	B	A	B	8.114	12.665	8.127	12.941	Al	1	2	1	2	9	0
81	A	B	A	B	8.114	12.665	8.127	12.941	Al	2	2	2	2	9	0
82	A	B	A	B	8.114	12.665	8.127	12.941	Al	3	2	3	2	9	0
83	A	B	A	B	8.114	12.665	8.127	12.941	Al	3	3	3	3	9	0
84	A	B	A	B	8.114	12.665	8.127	12.941	Al	4	4	4	4	9	0
85	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
86	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
87	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
88	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
89	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
90	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	4	4	9	0
91	A	B	A	B	8.114	12.665	8.127	12.941	SS	3	3	3	3	9	0
92	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	1	1	1	9	0
93	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	1	1	1	9	0
94	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0

Table C.1. (continued)

Run no.	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position (cm)	Source position (cm)
	N	E	S	W	N	E	S	W	Type	N	E	S	W		
95	A	B	A	B	8.114	12.665	8.127	12.941	Lead	-	-	-	1	9	0
96	A	B	A	B	8.114	12.665	8.127	12.941	Lead	1	1	1	1	9	0
97	A	B	A	B	8.114	12.665	8.127	12.941	Lead	1	1	1	1	9	0
98	A	B	A	B	8.114	12.665	8.127	12.941	Lead	-	1	1	1	9	0
99	A	B	A	B	8.114	12.665	8.127	12.941	Lead	-	1	1	1	9	0
100	A	B	A	B	8.114	12.665	8.127	12.941	Lead	-	1	-	1	9	0
101	A	B	A	B	8.114	12.665	8.127	12.941	Lead	-	1	-	1	9	0
102	A	B	A	B	8.114	12.665	8.127	12.941	Lead	-	1	-	-	9	0
103	A	B	A	B	8.114	12.665	8.127	12.941	Lead	-	1	-	-	9	0
104	A	B	A	B	8.114	12.665	8.127	12.941	Lead	1	1	-	-	9	0
105	A	B	A	B	8.114	12.665	8.127	12.941	Lead	1	1	-	-	9	0
106	A	B	A	B	8.114	12.665	8.127	12.941	Lead	1	1	1	-	9	0
107	A	B	A	B	8.114	12.665	8.127	12.941	Lead	1	1	1	-	9	0
108	A	B	A	B	8.114	12.665	8.127	12.941	Lead	1	-	1	-	9	0
109	A	B	A	B	8.114	12.665	8.127	12.941	Lead	1	-	1	-	9	0
110	A	B	A	B	8.114	12.665	8.127	12.941	Lead	1	-	-	-	9	0
111	A	B	A	B	8.114	12.665	8.127	12.941	Lead	1	-	-	-	9	0
112	A	B	A	B	8.114	12.665	8.127	12.941	SS	1	-	1	-	9	0
113	A	B	A	B	8.114	12.665	8.127	12.941	SS	1	-	1	-	9	0
114	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
115	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
116	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	-	2	-	9	0
117	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	-	2	-	9	0
118	A	B	A	B	8.114	12.665	8.127	12.941	SS	3	-	3	-	9	0

Table C.1. (continued)

Table C.1. (continued)															
	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position	Source position
Run no.	N	E	S	W	N	E	S	W	Type	N	E	S	W	(cm)	(cm)
119	A	B	A	B	8.114	12.665	8.127	12.941	SS	3	-	3	-	9	0
120	A	B	A	B	8.114	12.665	8.127	12.941	SS	3	1	3	1	9	0
121	A	B	A	B	8.114	12.665	8.127	12.941	SS	3	1	3	1	9	0
122	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	1	2	1	9	0
123	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	1	2	1	9	0
124	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	2	2	2	9	0
125	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	1	1	1	9	0
126	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
127	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
128	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
129	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
130	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
131	A	B	A	B	8.114	12.665	8.127	12.941	SS	1	1	1	1	9	0
132	A	B	A	B	8.114	12.665	8.127	12.941	SS	1	1	1	1	9	0
133	A	B	A	B	8.114	12.665	8.127	12.941	SS	1	3	1	3	9	0
134	A	B	A	B	8.114	12.665	8.127	12.941	SS	1	3	1	3	9	0
135	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	1	1	1	9	0
136a	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	-	-	9	0
136b	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	-	-	9	0
137	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
138	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
139a	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
139b	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
139c	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0

Table C.1. (continued)

Run no.	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position (cm)	Source position (cm)
	N	E	S	W	N	E	S	W	Type	N	E	S	W		
139d	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
139e	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
140	A	B	A	B	7.931	9.519	7.918	9.615	-	-	-	-	-	9	0
141	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
142	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
143	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
144a	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	4	4	9	0
144b	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	4	4	9	0
144c	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	4	4	9	0
145a	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	4	4	9	0
145b	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	4	4	9	0
146a	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	1	-	1	9	0
146b	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	1	-	1	9	0
146c	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	1	-	1	9	0
146d	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	1	-	1	9	0
147	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	1	-	9	0
148	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	1	1	9	0
149a	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	1	1	9	0
149b	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	1	1	9	0
149c	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	1	1	9	0
149d	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	1	1	9	0
150a	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	-	1	9	0
150b	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	-	1	9	0
150c	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	-	1	9	0

Table C.1. (continued)

Run no.	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position (cm)	Source position (cm)
	N	E	S	W	N	E	S	W	Type	N	E	S	W		
150d	A	B	A	B	8.114	12.665	8.127	12.941	Boral	1	-	-	1	9	0
151a	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	-	-	1	9	0
151b	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	-	-	1	9	0
151c	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	-	-	1	9	0
151d	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	-	-	1	9	0
152	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
153a	A	B	A	B	8.114	12.665	8.127	12.941	SS	-	2	-	2	9	0
153b	A	B	A	B	8.114	12.665	8.127	12.941	SS	-	2	-	2	9	0
154a	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	1	-	1	9	0
154b	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	1	-	1	9	0
154c	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	1	-	1	9	0
154d	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	1	-	1	9	0
154e	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	1	-	1	9	0
154f	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	1	-	1	9	0
154g	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	1	-	1	9	0
154h	A	B	A	B	8.114	12.665	8.127	12.941	Boral	-	1	-	1	9	0
155	A	B	A	B	8.114	12.665	8.127	12.941	SS	1	2	1	2	9	0
156	A	B	A	B	8.114	12.665	8.127	12.941	SS	1	2	1	2	9	0
157	A	B	A	B	8.114	12.665	8.127	12.941	SS	3	2	3	2	9	0
158	A	B	A	B	8.114	12.665	8.127	12.941	SS	3	2	3	2	9	0
159a	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	3	2	3	9	0
159b	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	3	2	3	9	0
159c	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	3	2	3	9	0
160	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	9	0

Table C.1. (continued)

Run no.	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position (cm)	Source position (cm)
	N	E	S	W	N	E	S	W	Type	N	E	S	W		
161	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	9	0
162a	A	B	A	B	7.239	8.634	7.215	8.822	-	-	-	-	-	9	0
162b	A	B	A	B	7.239	8.634	7.215	8.822	-	-	-	-	-	9	0
163a	A	B	A	B	7.733	9.125	7.717	9.263	-	-	-	-	-	9	0
163b	A	B	A	B	7.733	9.125	7.717	9.263	-	-	-	-	-	9	0
164a	A	B	A	B	8.703	10.122	8.713	10.324	-	-	-	-	-	9	0
164b	A	B	A	B	8.703	10.122	8.713	10.324	-	-	-	-	-	9	0
165	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
166a	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	4	2	4	9	0
166b	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	4	2	4	9	0
166c	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	4	2	4	9	0
166d	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	4	2	4	9	0
167a	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	-	-	9	0
167b	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	-	-	9	0
167c	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	-	-	9	0
167d	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	-	-	9	0
167e	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	-	-	9	0
167g	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	-	-	9	0
167i	A	B	A	B	8.114	12.665	8.127	12.941	SS	4	4	-	-	9	0
168a	A	B	A	B	8.114	12.665	8.127	12.941	SS	1	4	-	-	9	0
168b	A	B	A	B	8.114	12.665	8.127	12.941	SS	1	4	-	-	9	0
169a	A	B	A	B	8.114	12.665	8.127	12.941	SS	-	4	-	-	9	0
169b	A	B	A	B	8.114	12.665	8.127	12.941	SS	-	4	-	-	9	0
170a	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	2	-	-	9	0

Table C.1. (continued)

Run no.	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position (cm)	Source position (cm)
	N	E	S	W	N	E	S	W	Type	N	E	S	W		
170b	A	B	A	B	8.114	12.665	8.127	12.941	SS	2	2	-	-	9	0
171	A	B	A	B	8.114	12.665	8.127	12.941	-	-	-	-	-	9	0
172a	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
172b	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
172c	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
172d	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
173a	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
173b	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
174a	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
174b	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
174c	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
175a	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
175b	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
176	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
177	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
178a	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
178b	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
179	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
180	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
181	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
183	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
185	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
186	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)
187	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0 (N)

Table C.1. (continued)															
Run no.	Fuel orientation				Center-to-fuel spacing				Absorbing plates					Det. position (cm)	Source position (cm)
	N	E	S	W	N	E	S	W	Type	N	E	S	W		
189	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0
190	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0
191	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0
192	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0
193	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0
194	A	B	A	B	6.745	8.109	6.712	8.299	-	-	-	-	-	10.5	0

APPENDIX D

FOURIER ANALYSIS SYSTEMS SETTINGS

The settings for the RC units, sampling rates, block size, and number of data blocks acquired for each run were as specified in Table D.1.

Table D.1. Electronic systems configuration									
Run no.	RC frequency (kHz)					RC gain	Block size	Band width (kHz)	Blocks (k)
	1	2	3	4	5				
1	50	50	50	50	50	1.75	1024	10	10
2	50	50	50	50	50	1.75	512	10	30
2r	50	50	50	50	50	1.75	512	10	30
3	50	50	50	50	50	1.75	1024	10	10
4	50	50	50	50	50	1.75	512	10	30
4r	50	50	50	50	50	1.75	512	10	30
5	20	20	20	20	20	1.75	1024	5	30
6	50	50	50	50	50	1.75	1024	10	10
7	50	50	50	50	50	1.75	512	10	30
8	20	20	20	20	20	1.75	1024	5	10
9	50	50	50	50	50	1.75	1024	10	10
10	50	50	50	50	50	1.75	1024	10	10
11	50	50	50	50	50	1.75	1024	10	10
12	50	50	50	50	50	1.75	1024	10	10
13	50	50	50	50	50	1.75	1024	10	10
14	20	20	20	20	20	1.75	512	5	10
15	20	20	20	20	20	1.75	512	5	10
16	20	20	20	20	20	1.75	512	5	10
17	20	20	20	20	20	1.75	512	5	10
18	20	20	20	20	20	1.75	512	5	10
19	20	20	20	20	20	1.75	512	5	10
20	20	20	20	20	20	1.75	512	5	10
21	20	20	20	20	20	1.75	512	5	10
22	20	20	20	20	20	1.75	512	5	10
23	20	20	20	20	20	1.75	512	5	10
24	20	20	20	20	20	1.75	512	5	10
25	20	20	20	20	50	1.75	512	5	10
26	20	20	20	20	50	1.75	512	5	10
27	20	20	20	20	50	1.75	512	5	10
28	20	20	20	20	50	1.75	512	5	10
29	20	20	20	20	50	1.75	512	5	10

Table D.1. (continued)									
Run no.	RC frequency (kHz)					RC gain	Block size	Band width (kHz)	Blocks (k)
	1	2	3	4	5				
30	20	20	20	20	50	1.75	512	5	10
31	20	20	20	20	50	1.75	512	5	10
32	20	20	20	20	50	1.75	512	5	10
33	20	20	20	20	50	1.75	512	5	10
34	20	20	20	20	20	1.75	512	5	10
35	20	20	20	20	20	1.75	512	5	10
36	20	20	20	20	20	1.75	512	5	10
37	20	20	20	20	20	1.75	512	5	10
38	20	20	20	20	20	1.75	512	5	10
39	20	20	20	20	20	1.75	512	5	100
40	20	20	20	20	20	1.75	512	5	10
41	20	20	20	20	20	1.75	512	5	10
42	20	20	20	20	20	1.75	512	5	10
43	20	20	20	20	20	1.75	512	5	10
44	20	20	20	20	20	1.75	512	5	10
45	20	20	20	20	20	1.75	512	5	10
46	20	20	20	20	20	1.75	512	5	10
47	20	20	20	20	20	1.75	1024	2	5
48	20	20	20	20	20	1.75	512	5	10
49	20	20	20	20	20	1.75	512	5	10
50	20	20	20	20	20	1.75	512	5	10
51	20	20	20	20	20	1.75	512	5	10
52	20	20	20	20	20	1.75	512	5	10
53	20	20	20	20	20	1.75	512	5	10
54	20	20	20	20	20	1.75	512	5	10
55	20	20	20	20	20	1.75	512	5	10
56	20	20	20	20	20	1.75	512	5	10
57	20	20	20	20	20	1.75	512	5	10
58	20	20	20	20	20	1.75	512	5	10
59	20	20	20	20	20	1.75	512	5	10
60	20	20	20	20	20	1.75	512	5	10
61	20	20	20	20	20	1.75	512	5	10
62	20	20	20	20	20	1.75	512	5	10
63	20	20	20	20	20	1.75	512	5	10
64	20	20	20	20	20	1.75	512	5	350
65	20	20	20	20	20	1.75	512	5	10
66	20	20	20	20	20	1.75	512	5	10
67	20	20	20	20	20	1.75	512	5	10
68	20	20	20	20	20	1.75	512	5	10

Table D.1. (continued)									
Run no.	RC frequency (kHz)					RC gain	Block size	Band width (kHz)	Blocks (k)
	1	2	3	4	5				
69	20	20	20	20	20	1.75	512	5	10
70	20	20	20	20	20	1.75	512	5	10
71	20	20	20	20	20	1.75	512	5	10
72	20	20	20	20	20	1.75	512	5	10
73	20	20	20	20	20	1.75	512	5	10
74	20	20	20	20	20	1.75	512	5	10
75	20	20	20	20	20	1.75	512	5	10
76	20	20	20	20	20	1.75	512	5	10
77	20	20	20	20	20	1.75	512	5	10
78	20	20	20	20	20	1.75	512	5	10
79	20	20	20	20	20	1.75	512	5	10
80	20	20	20	20	20	1.75	512	5	10
81	20	20	20	20	20	1.75	512	5	10
82	20	20	20	20	20	1.75	512	5	10
83	20	20	20	20	20	1.75	512	5	10
84	20	20	20	20	20	1.75	512	5	10
85	20	20	20	20	20	1.75	512	5	10
86	20	20	20	20	20	1.75	512	5	10
87	20	20	20	20	20	1.75	512	5	10
88	20	20	20	20	20	1.75	512	5	10
89	20	20	20	20	20	1.75	512	5	10
90	20	20	20	20	20	1.75	512	5	100
91	20	20	20	20	20	1.75	512	5	75
92	20	20	20	20	20	1.75	512	5	10
93	20	20	20	20	20	1.75	512	5	10
94	20	20	20	20	20	1.75	512	5	10
95	20	20	20	20	20	1.75	512	5	10
96	20	20	20	20	20	1.75	512	5	10
97	20	20	20	20	20	1.75	512	5	10
98	20	20	20	20	20	1.75	512	5	10
99	20	20	20	20	20	1.75	512	5	10
100	20	20	20	20	20	1.75	512	5	10
101	20	20	20	20	20	1.75	512	5	10
102	20	20	20	20	20	1.75	512	5	10
103	20	20	20	20	20	1.75	512	5	10
104	20	20	20	20	20	1.75	512	5	10
105	20	20	20	20	20	1.75	512	5	10
106	20	20	20	20	20	1.75	512	5	10
107	20	20	20	20	20	1.75	512	5	10

Table D.1. (continued)									
Run no.	RC frequency (kHz)					RC gain	Block size	Band width (kHz)	Blocks (k)
	1	2	3	4	5				
108	20	20	20	20	20	1.75	512	5	10
109	20	20	20	20	20	1.75	512	5	10
110	20	20	20	20	20	1.75	512	5	10
111	20	20	20	20	20	1.75	512	5	10
112	20	20	20	20	20	1.75	512	5	10
113	20	20	20	20	20	1.75	512	5	10
114	20	20	20	20	20	1.75	512	5	10
115	20	20	20	20	20	1.75	512	5	10
116	20	20	20	20	20	1.75	512	5	10
117	20	20	20	20	20	1.75	512	5	10
118	20	20	20	20	20	1.75	512	5	10
119	20	20	20	20	20	1.75	512	5	10
120	20	20	20	20	20	1.75	512	5	50
121	20	20	20	20	20	1.75	512	5	50
122	20	20	20	20	20	1.75	512	5	50
123	20	20	20	20	20	1.75	512	5	50
124	20	20	20	20	20	1.75	512	5	150
125	20	20	20	20	20	1.75	512	5	1000
126	20	20	20	20	20	1.75	512	5	10
127	20	20	20	20	20	1.75	512	5	10
128	20	20	20	20	20	1.75	512	5	10
129	20	20	20	20	20	1.75	512	5	10
130	20	20	20	20	20	1.75	512	5	10
131	20	20	20	20	20	1.75	512	5	50
132	20	20	20	20	20	1.75	512	5	50
133	20	20	20	20	20	1.75	512	5	100
134	20	20	20	20	20	1.75	512	5	100
135	50	50	50	50	50	1.75	1024	10	1000
136a	50	50	50	50	50	1.75	1024	10	50
136b	50	50	50	50	50	1.75	1024	10	50
137	20	20	20	20	20	1.75	512	5	10
138	20	20	20	20	20	1.75	512	5	10
139a	20	20	20	20	20	1.75	512	5	2
139b	20	20	20	20	20	1.75	512	5	2
139c	20	20	20	20	20	1.75	512	5	2
139d	20	20	20	20	20	1.75	512	5	2
139e	20	20	20	20	20	1.75	512	5	2
140	20	20	20	20	20	1.75	512	5	10
141	20	20	20	20	20	1.75	512	5	10

Table D.1. (continued)									
Run no.	RC frequency (kHz)					RC gain	Block size	Band width (kHz)	Blocks (k)
	1	2	3	4	5				
142	20	20	20	20	20	1.75	512	5	10
143	20	20	20	20	20	1.75	512	5	5
144a	20	20	20	20	20	1.75	1024	10	50
144b	20	20	20	20	20	1.75	1024	10	50
144c	20	20	20	20	20	1.75	1024	10	50
145a	20	20	20	20	20	1.75	1024	10	50
145b	20	20	20	20	20	1.75	1024	10	50
146a	20	20	20	20	20	1.75	1024	10	100
146b	20	20	20	20	20	1.75	1024	10	100
146c	20	20	20	20	20	1.75	1024	10	100
146d	20	20	20	20	20	1.75	1024	10	100
147	20	20	20	20	20	1.75	1024	10	100
148	20	20	20	20	20	1.75	1024	10	50
149a	20	20	20	20	20	1.75	1024	10	50
149b	20	20	20	20	20	1.75	1024	10	50
149c	20	20	20	20	20	1.75	1024	10	50
149d	20	20	20	20	20	1.75	1024	10	50
150a	20	20	20	20	20	1.75	1024	10	50
150b	20	20	20	20	20	1.75	1024	10	50
150c	20	20	20	20	20	1.75	1024	10	50
150d	20	20	20	20	20	1.75	1024	10	50
151a	20	20	20	20	20	1.75	1024	10	50
151b	20	20	20	20	20	1.75	1024	10	50
151c	20	20	20	20	20	1.75	1024	10	50
151d	20	20	20	20	20	1.75	1024	10	50
152	20	20	20	20	20	1.75	512	5	350
153a	20	20	20	20	20	1.75	512	5	50
153b	20	20	20	20	20	1.75	1024	10	50
154a	20	20	20	20	20	1.75	1024	10	95
154b	20	20	20	20	20	1.75	1024	10	95
154c	20	20	20	20	20	1.75	1024	10	95
154d	20	20	20	20	20	1.75	1024	10	95
154e	20	20	20	20	20	1.75	1024	10	95
154f	20	20	20	20	20	1.75	1024	10	95
154g	20	20	20	20	20	1.75	1024	10	95
154h	20	20	20	20	20	1.75	1024	10	95
155	20	20	20	20	20	1.75	512	5	50
156	20	20	20	20	20	1.75	512	5	50
157	20	20	20	20	20	1.75	512	5	50

Table D.1. (continued)									
Run no.	RC frequency (kHz)					RC gain	Block size	Band width (kHz)	Blocks (k)
	1	2	3	4	5				
158	20	20	20	20	20	1.75	512	5	50
159a	20	20	20	20	20	1.75	512	5	50
159b	20	20	20	20	20	1.75	512	5	50
159c	20	20	20	20	20	1.75	512	5	50
160	20	20	20	20	20	1.75	512	5	10
161	20	20	20	20	20	1.75	512	5	10
162a	20	20	20	20	20	1.75	512	5	10
162b	20	20	20	20	20	1.75	512	5	10
163a	20	20	20	20	20	1.75	512	5	10
163b	20	20	20	20	20	1.75	512	5	10
164a	20	20	20	20	20	1.75	512	5	10
164b	20	20	20	20	20	1.75	512	5	10
165	20	20	20	20	20	1.75	512	5	10
166a	20	20	20	20	20	1.75	512	5	45
166b	20	20	20	20	20	1.75	512	5	45
166c	20	20	20	20	20	1.75	512	5	45
166d	20	20	20	20	20	1.75	512	5	45
167a	20	20	20	20	20	1.75	512	5	100
167b	20	20	20	20	20	1.75	512	5	100
167c	20	20	20	20	20	1.75	512	5	100
167d	20	20	20	20	20	1.75	512	5	100
167e	20	20	20	20	20	1.75	512	5	100
167g	20	20	20	20	20	1.75	512	5	100
167i	20	20	20	20	20	1.75	512	5	100
168a	20	20	20	20	20	1.75	512	5	50
168b	20	20	20	20	20	1.75	512	5	50
169a	20	20	20	20	20	1.75	512	5	50
169b	20	20	20	20	20	1.75	512	5	50
170a	20	20	20	20	20	1.75	512	5	50
170b	20	20	20	20	20	1.75	512	5	50
171	20	20	20	20	20	1.75	512	5	10
172a	20	20	20	20	20	1.75	1024	5	100
172b	20	20	20	20	20	1.75	1024	5	100
172c	20	20	20	20	20	1.75	1024	5	100
172d	20	20	20	20	20	1.75	1024	5	100
173a	20	20	20	20	20	1.75	1024	5	50
173b	20	20	20	20	20	1.75	1024	5	25
174a	20	20	20	20	20	1.75	1024	5	15
174b	20	20	20	20	20	1.75	1024	5	15

Table D.1. (continued)									
Run no.	RC frequency (kHz)					RC gain	Block size	Band width. (kHz)	Blocks (k)
	1	2	3	4	5				
174c	20	20	20	20	20	1.75	1024	5	15
175a	20	20	20	20	20	1.75	512	4	50
175b	20	20	20	20	20	1.75	512	4	50
176	20	20	20	20	20	1.75	512	4	100
177	20	20	20	20	20	1.75	512	4	50
178a	20	20	20	20	20	1.75	512	4	20
178b	20	20	20	20	20	1.75	512	4	20
179	20	20	20	20	20	1.75	512	4	100
180	20	20	20	20	20	1.75	2048	5	?
181	20	20	20	20	20	1.75	2048	5	10
183	20	20	20	20	20	1.75	2048	5	10
185	20	20	20	20	20	1.75	2048	5	40
186	20	20	20	20	20	1.75	2048	5	40
187	20	20	20	20	20	1.75	2048	5	40
188	20	20	20	20	20	1.75	2048	5	3.37
189	20	20	20	20	20	1.75	2048	5	40
190	20	20	20	20	20	1.75	2048	5	40
191	20	20	20	20	20	1.75	2048	5	40
192	20	20	20	20	20	1.75	2048	5	20
193	20	20	20	20	20	1.75	2048	5	5
194	20	20	20	20	20	1.75	2048	5	40

APPENDIX E

SOURCE AND DETECTOR COUNT RATES

The source and detector count rates for each measurement were as provided in Table E.1.

Table E.1. Source and detector count rates						
Run no.	Source 1	2	3	4	5	Fraction of source events counted
1	65221	2396	570	532	519	0.986
2	65221	2396	570	532	519	0.986
2r	65221	2396	570	532	519	0.986
3	65214	2513	2295	638	630	0.986
4	65214	2513	2295	638	630	0.986
4r	65214	2513	2295	638	630	0.986
5	65238	2514	2303	638	630	0.987
6	65218	2938	2708	2564	676	0.986
7	65218	2938	2708	2564	676	0.986
8	65238	2938	2705	2566	676	0.987
9	65238	3457	3174	2748	2710	0.987
10	65214	4872	4479	3930	3840	0.986
11	65238	7173	6589	5850	5729	0.987
12	65170	15881	14517	13215	13119	0.986
13	65290	15917	14523	13393	13144	0.987
14	65213	15913	14517	13385	13132	0.986
15	65213	15913	14517	13385	13132	0.986
16	65405	15631	15104	13163	12939	0.989
17	65405	15631	15104	13163	12939	0.989
18	65425	14376	14937	12117	11867	0.989
19	65408	12494	13886	10530	10310	0.989
20	65414	7090	9147	6007	5860	0.989
21	65422	14476	11538	12170	12036	0.989
22	65550	12747	9482	10710	10637	0.991
23	65421	5106	3316	4307	4332	0.989
24	65503	15916	15719	13396	13225	0.991
25	65592	10697	10645	8786	8628	0.993
26	65593	3476	3436	2764	2722	0.993
27	65540	3455	3428	2745	2687	0.992
28	65607	10729	10642	8788	8658	0.993
29	65541	9263	9351	9344	9137	0.992

Table E.1. Source and detector count rates (continued)						
Run no.	Source 1	2	3	4	5	Fraction of source events counted
30	65558	9271	9346	9349	9151	0.992
31	65510	6646	6628	3883	3847	0.991
32	65533	6654	6640	3881	3855	0.992
33	65564	6653	6636	3886	3859	0.992
34	65563	7868	7864	4603	4587	0.992
35	65563	7868	7864	4603	4587	0.992
36	65532	8419	8519	4967	4954	0.992
37	65568	5341	5212	3058	3047	0.992
38	65568	5341	5212	3058	3047	0.992
39	65541	4056	3965	2320	2325	0.992
40	65519	7917	7867	4622	4627	0.992
41	65561	12724	12647	10578	10475	0.992
42	65521	8496	8438	6981	6907	0.992
43	65521	8496	8438	6981	6907	0.992
44	65549	5786	5781	4713	4649	0.992
45	65152	4117	4127	3314	3251	0.986
46	65622	12739	12638	10571	10459	0.993
47	65541	12742	12648	10567	10455	0.992
48	65506	10580	11758	9725	9605	0.991
49	65557	10578	11759	9720	9600	0.992
50	65519	8679	11015	8945	8841	0.992
51	65546	8675	11018	8961	8838	0.992
52	65525	5690	9950	7801	7691	0.992
53	65521	5700	9961	7811	7696	0.992
54	65506	12678	12633	10559	10437	0.991
55	65496	10862	10861	7092	9227	0.991
56	65496	10862	10861	7092	9227	0.991
57	65160	9577	9612	4594	8440	0.986
58	65160	9577	9612	4594	8440	0.986
59	65145	12688	12631	10563	10446	0.986
60	65153	11438	11653	10117	9989	0.986
61	65153	11438	11653	10117	9989	0.986
62	65149	7342	7295	7966	7775	0.986
63	65149	7342	7295	7966	7775	0.986
64	65142			10478	10339	0.986
65	65133	12658	12518	10480	10355	0.986
66	65133	12658	12518	10480	10355	0.986
67	65133	12658	12518	10480	10355	0.986
68	65133	12658	12518	10480	10355	0.986

Table E.1. Source and detector count rates (continued)						
Run no.	Source 1	2	3	4	5	Fraction of source events counted
69	65135	7786	7699	4527	4514	0.986
70	65136	7891	7789	4579	4569	0.986
71	65136	7891	7789	4579	4569	0.986
72	65114	7983	7907	4648	4652	0.986
73	65114	7983	7907	4648	4652	0.986
74	65127	8061	7992	4710	4677	0.986
75	65127	8061	7992	4710	4677	0.986
76	65107	8122	8061	4708	4735	0.986
77	65107	8122	8061	4708	4735	0.986
78	65122	8054	7979	4640	4693	0.986
79	65120	7988	7920	4610	4645	0.986
80	65118	8053	8007	4684	4733	0.986
81	65116	8142	8086	4746	4771	0.986
82	65582	8214	8173	4801	4828	0.993
83	65127	8292	8235	4861	4898	0.986
84	65200	8413	8405	4995	5004	0.987
85	65188	7864	7802	4496	4552	0.987
86	65136	7853	7782	4501	4545	0.986
87	65136	7853	7782	4501	4545	0.986
88	65136	7853	7782	4501	4545	0.986
89	65136	7853	7782	4501	4545	0.986
90	65118	5661	5602	3169	3147	0.986
91	65116	5844	5783	3277	3264	0.986
92	65103	3897	3720	2232	1886	0.986
93	65100	3918	3738	1871	1873	0.986
94	65100	7922	7801	4526	4566	0.987
95	65100	7734	7368	4422	1530	0.987
96	65118	9165	8959	5390	5456	0.987
97	65118	9165	8959	5390	5456	0.987
98	65450	8843	8742	5193	5243	0.992
99	65450	8843	8742	5193	5243	0.992
100	65129	8606	8440	5015	5072	0.987
101	65129	8606	8440	5015	5072	0.987
102	65088	8154	7993	4878	4582	0.986
103	65088	8154	7993	4878	4582	0.986
104	65092	8433	8191	5046	4737	0.986
105	65092	8433	8191	5046	4737	0.986
106	65083	8663	8513	5249	4912	0.986
107	65083	8663	8513	5249	4912	0.986

Table E.1. Source and detector count rates (continued)						
Run no.	Source 1	2	3	4	5	Fraction of source events counted
108	65515	8319	8147	4614	4812	0.993
109	65515	8319	8147	4614	4812	0.993
110	65088	8113	7858	4456	4662	0.986
111	65088	8113	7858	4456	4662	0.986
112	65090	7237	7117	3963	4210	0.986
113	65090	7237	7117	3963	4210	0.986
114	65081	7815	7683	4305	4512	0.986
115	65093	7781	7607	4280	4485	0.986
116	65092	6982	6849	3893	3962	0.986
117	65092	6983	6842	3894	3961	0.986
118	65101	6807	6667	3773	3867	0.987
119	65101	6807	6667	3773	3867	0.987
120	65089	6355	6235	3421	3551	0.986
121	65078	6498	6372	3482	3639	0.986
122	65078	6499	6372	3482	3640	0.986
123	65084	6494	5377	3478	3636	0.986
124	65077	6239	6116	3295	3451	0.986
125	65066	3705	3626	1760	1835	0.986
126	65055	7837	7704	4315	4513	0.987
127	65055	7837	7704	4315	4513	0.987
128	65052	12617	12383	9851	10317	0.987
129	65081	12436	12095	9656	10133	0.987
130	65055	7886	7750	4342	4557	0.987
131	65245	6711	6633	3638	3766	0.990
132	65245	6711	6633	3638	3766	0.990
133	65190	6225	6139	3239	3418	0.989
134	65101	6221	6135	3237	3418	0.987
135	65083	3779	3590	1816	1897	0.987
136a	65061	5687	6533	3391	3527	0.987
136b	65061	5687	6533	3391	3527	0.987
137	65049	7866	7729	4317	4536	0.987
138	65049	12681	12418	9853	10346	0.987
139a	65055	12550	12174	9676	10246	0.987
139b	65055	12550	12174	9676	10246	0.987
139c	65055	12550	12174	9676	10246	0.987
139d	65055	12550	12174	9676	10246	0.987
139e	65055	12550	12174	9676	10246	0.987
140	65118	12580	12255	9782	10160	0.988
141	65075	12512	12271	10178	10139	0.988

Table E.1. Source and detector count rates (continued)						
Run no.	Source 1	2	3	4	5	Fraction of source events counted
142	65075	12291	12024	10166	9832	0.988
143	65105	7676	7500	4475	4258	0.988
144a	65078	5680	5513	3114	3054	0.988
144b	65078	5680	5513	3114	3054	0.988
144c	65078	5680	5513	3114	3054	0.988
145a	65002	5633	5493	3098	3056	0.987
145b	65106	5699	5552	3080	3085	0.988
146a	65097	3806	3844	2046	1938	0.988
146b	65097	3806	3844	2046	1938	0.988
146c	65097	3806	3844	2046	1938	0.988
146d	65097	3806	3844	2046	1938	0.988
147	65104	4962	4901	2825	2864	0.989
148	65110	4238	4163	2677	1877	0.989
149a	65085	4235	4167	2675	1874	0.988
149b	65085	4235	4167	2675	1874	0.988
149c	65085	4235	4167	2675	1874	0.988
149d	65085	4235	4167	2675	1874	0.988
150a	65072	3397	4270	3255	2089	0.988
150b	65072	3397	4270	3255	2089	0.988
150c	65072	3397	4270	3255	2089	0.988
150d	65072	3397	4270	3255	2089	0.988
151a	65067	6109	6070	4021	2425	0.988
151b	65067	6109	6070	4021	2425	0.989
151c	65067	6109	6070	4021	2425	0.988
151d	65067	6109	6070	4021	2425	0.989
152	65068	7636	7551	4462	4269	0.988
153a	65070	6607	6579	3798	3592	0.988
153b	65070	6607	6579	3798	3592	0.988
154a	65054	4871	4837	2287	2205	0.988
154b	65054	4871	4837	2287	2205	0.988
154c	65054	4871	4837	2287	2205	0.988
154d	65054	4871	4837	2287	2205	0.988
154e	65054	4871	4837	2287	2205	0.988
154f	65054	4871	4837	2287	2205	0.988
154g	65054	4871	4837	2287	2205	0.988
154h	65054	4871	4837	2287	2205	0.988
155	65066	6295	6248	3517	3384	0.989
156	65036	6296	6249	3515	3382	0.988
157	65046	5984	5925	3355	3217	0.989

Table E.1. Source and detector count rates (continued)						
Run no.	Source 1	2	3	4	5	Fraction of source events counted
158	65046	5984	5926	3356	3215	0.989
159a	65040	5921	5861	3298	3132	0.989
159b	65040	5921	5861	3298	3132	0.989
159c	65040	5921	5861	3298	3132	0.989
160	65029	18321	18004	15479	15216	0.988
161	65027	18331	18016	15458	15211	0.988
162a	65040	16553	16265	13958	13786	0.988
162b	65040	16553	16265	13958	13786	0.989
163a	65049	13945	13731	11713	11580	0.989
163b	65049	13945	13731	11713	11580	0.989
164a	65019	9306	9176	7298	7608	0.988
164b	65019	9306	9176	7298	7608	0.988
165	65021	7627	7644	4457	4383	0.988
166a	64877	5797	5673	3200	3131	0.986
166b	64877	5797	5673	3200	3131	0.986
166c	64877	5797	5673	3200	3131	0.986
166d	64877	5797	5673	3200	3131	0.986
167a	65013	6254	6586	3412	3856	0.988
167b	65013	6254	6586	3412	3856	0.988
167c	65013	6254	6586	3412	3856	0.988
167d	65013	6254	6586	3412	3856	0.988
167e	65013	6254	6586	3412	3856	0.988
167g	65013	6254	6586	3412	3856	0.988
167i	65013	6254	6586	3412	3856	0.988
168a	65005	6608	6728	3517	4009	0.989
168b	65005	6608	6728	3517	4009	0.989
169a	64979	6911	6871	3610	4151	0.988
169b	64979	6911	6871	3610	4151	0.988
170a	65008	6688	6970	3695	4025	0.989
170b	65008	6688	6970	3695	4025	0.989
171	65006	7683	7697	4510	4388	0.989
172a	64955	7067	7087	9405		0.988
172b	64955	7067	7087	9405		0.988
172c	64955	7067	7087	9405		0.988
172d	64955	7067	7087	9405		0.988
173a	64924	2613	2844	2856		0.988
173b	64924	2613	2844	2856		0.988
174a	64920	5183	5667	5715		0.988
174b	64920	5183	5667	5715		0.988

Table E.1. Source and detector count rates (continued)						
Run no.	Source 1	2	3	4	5	Fraction of source events counted
174c	64920	5183	5667	5715		0.988
175a	64933	677	727	718		0.988
175b	64933	677	727	718		0.988
176	64942	678	726	716		0.988
177	64948	680	727	738		0.989
178a	64935	2661	2851	2864		0.988
178b	65933	2658	2851	2865		0.988
179	64750	2620	2853	2864		0.986
180		32	26			
181	64503	2957	3009			0.985
183	64492	2953	3004			0.984
185	64467	947	990			0.984
186	64495	916	959			0.984
187	64466	926	986			0.984
188	64179	2959	4054	2396		0.985
189	64177	2949	4025	2384		0.985
190	64154	1456		841		0.984
191	64155	1462		845		0.984
192	64192	2996	4085	2429		0.985
193	64182	7503	6726	7377		0.985
194	64167	2884	3052	2403		0.984

APPENDIX F

EVALUATION OF BUBBLES IN ASSEMBLY

The formation of bubbles in the experimental was a concern because no actions were taken to ensure that bubble formation would be minimized. The affects of voids in the assembly were analyzed by forcing air at various flow rates up through the bottom of the fuel element in the south position. The fuel elements were designed such that water was between the individual fuel plates. The results of the forced-air flow measurements are provided in Table F.1. All of the spectral ratio values were within one standard deviation of the case with no forced-air flow. The values for the no forced-air flow were the average values for the plate-spacing reference measurement. As can be seen from these results, formation of bubbles in the test assembly was not a measurable affect because the fuel elements were over-moderated.

Table F.1. Spectral ratio values for different forced air flow rates

Flow rate (liter/min)	Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
0	0.554	0.008	0.457	0.012	0.451	0.007	0.454	0.012	0.455	0.011	0.517	0.010
0.1	0.556	0.005	0.453	0.007	0.447	0.006	0.471	0.005	0.465	0.009	0.509	0.011
0.5	0.562	0.007	0.460	0.006	0.451	0.002	0.461	0.009	0.449	0.010	0.532	0.011

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

APPENDIX G

FUEL TILTING MEASUREMENTS

The affects of tilting the fuel elements was investigated because the spacing of the fuel elements significantly affected the results of the measurements. Measurements were performed in which the top fuel elements were pulled inward approximately $1/16$ to $1/8$ in. and pulled outward approximately $3/16$ to $1/4$ in. Ropes were tied to the top of the fuel elements to apply tension to the element. The results of the measurements are provided in Table G.1. These measurements were performed with the assembly in the close-spaced reference configuration. The spectral ratio values changed an average of 6% for both the inward and outward tilts of the fuel elements. This change was considered significant because it was greater than the uncertainty in the measurements

Table G.1. Spectral ratio values for tilting of fuel elements												
Tilt (in)	Ratio 23		Ratio 24		Ratio 25		Ratio 34		Ratio 35		Ratio 45	
	R ^a	σ^b	R	σ	R	σ	R	σ	R	σ	R	σ
0	0.383	0.005	0.348	0.004	0.347	0.003	0.351	0.006	0.345	0.005	0.374	0.005
0.635	0.398	0.003	0.372	0.004	0.363	0.003	0.367	0.003	0.370	0.002	0.401	0.004
-0.3175	0.361	0.003	0.342	0.004	0.338	0.003	0.332	0.003	0.329	0.003	0.350	0.004

^a Low frequency average of spectral ratio.

^b Standard deviation of the mean of the low frequency spectral ratio average.

APPENDIX H

SPECTRAL SIGNATURES FOR FRESH FUEL REFERENCE MEASUREMENTS AT PLATE SPACING

This appendix contains average spectral signatures for the reference measurements with the fuel elements separated at the position for the plate measurements. These signatures show the frequency dependence of these quantities. The average at each frequency point and the standard deviation of the mean at each frequency point were calculated for the fifteen reference measurements. The average spectral ratio values are shown in Fig. H.1 to H.6. The average spectral ratio values were essentially constant over the low-frequency range. Except for the spectral ratio signatures, the spectral functions were normalized by dividing by the source auto spectrum. The average source auto spectrum is shown in Fig. H.7. The average detector auto spectra for one of the detectors is shown in Fig. H.8. The detector auto spectra decreased as a function of frequency and could be fitted to determine the prompt neutron decay constant. An average source-detector cross spectra was estimated from the fifteen measurements. The real and imaginary parts of the source-detector cross spectra are shown in Figs. H.9 and H.10. The source-detector cross spectrum consisted of both a real and an imaginary component. These spectra could also be fitted to obtain the prompt neutron decay constant using a calibration spectrum. A detector-detector cross spectrum was also obtained for the fifteen reference measurements. The real and imaginary components of the detector-detector cross spectra are shown in Figs. H.11 and H.12. The imaginary component of the detector-detector cross spectrum was essentially zero.

Fig. H.1. Frequency-dependent average spectral ratio 23 for reference measurements at plate spacing.

Fig. H.2. Frequency-dependent average spectral ratio 24 for reference measurements at plate spacing.

Fig. H.3. Frequency-dependent average spectral ratio 25 for reference measurements at plate spacing.

Fig. H.4. Frequency-dependent average spectral ratio 34 for reference measurements at plate spacing.

Fig. H.5. Frequency-dependent average spectral ratio 35 for reference measurements at plate spacing.

Fig. H.6. Frequency-dependent average spectral ratio 45 for reference measurements at plate spacing.

Fig. H.7. Frequency-dependent average source auto spectrum for reference measurements at plate spacing.

Fig. H.8. Frequency-dependent average detector auto spectrum for reference measurements at plate spacing.

Fig. H.9. Frequency-dependent real source-detector cross spectrum for reference measurements at plate spacing.

Fig. H.10. Frequency-dependent imaginary source-detector cross spectrum for reference measurements at plate spacing.

Fig. H.11. Frequency-dependent real detector-detector cross spectrum for reference measurements at plate spacing.

Fig. H.12. Frequency-dependent imaginary detector-detector cross spectrum for reference measurements at plate spacing.

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