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Measurement of Enriched Uranium and Uranium-Aluminum Fuel Materials with the AWCC

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SYMBOL DEFINITIONS

M = ^{235}mass (grams).

T = totals counting rate (s^{-1}).

T_0 = totals counting rate without sample (s^{-1}).

R = real coincidence counting rate (s^{-1}).

σ_R = standard deviation of R (s^{-1}).

σ_c = standard deviation of R or ΔT due to counting statistics only.

ΔT = totals counting rate above ^{241}AmLi source background (s^{1}).

S = component of T due to scattering by the sample (s^{-1}).

ΔT_c = ΔT corrected for scattering (s^{-1}).

F = component of T due to fission neutrons from NRX billets per gram of ^{235}U ($s^{-1}g^{-1}$).

m = ^{235}U mass per unit length of a fuel element (grams/centimeter).

σ_M = standard deviation of ^{235}U mass due to counting statistics only (grams).

σ_m = standard deviation of ^{235}U mass per unit length due to counting statistics only (grams/centimeter).

λ = decay constant for ^{241}Am.

MEASUREMENT OF ENRICHED URANIUM AND URANIUM-ALUMINUM FUEL MATERIALS WITH THE AWCC

by

M. S. Krick, H. O. Menlove, J. Zick, and P. Ikonomou

ABSTRACT

The active well coincidence counter (AWCC) was calibrated at the Chalk River Nuclear Laboratories (CRNL) for the assay of 93%-enriched fuel materials in three categories: (1) uranium-aluminum billets, (2) uranium-aluminum fuel elements, and (3) uranium metal pieces. The AWCC was a standard instrument supplied to the International Atomic Energy Agency under the International Safeguards Project Office Task A.51. Excellent agreement was obtained between the CRNL measurements and previous Los Alamos National Laboratory measurements on similar mockup fuel material. Calibration curves were obtained for each sample category.

I. INTRODUCTION

An International Atomic Energy Agency (IAEA) exercise was performed at the Chalk River Nuclear Laboratories (CRNL) of Atomic Energy of Canada, Ltd., to calibrate the active well coincidence counter (AWCC)[1] for the assay of highly enriched (93%) uranium fuel materials. Measurements were performed on three sample categories:

(1) Uranium-aluminum billets (21 wt% and 28 wt% uranium),

(2) Uranium metal pieces in cans, and

(3) Uranium-aluminum fuel pins (21 wt% and 28 wt% uranium).

The data acquired at CRNL were compared with data obtained at the Los Alamos National Laboratory, where mockup uranium and uranium-aluminum samples were prepared to obtain absolute response functions for the AWCC. From these results, calibration curves were established for each sample category.

II. DETECTOR

The assay instrument was a standard AWCC, which was supplied to the IAEA under the International Safeguards Project Office Task A.51. It is shown in Figs. 1 and 2 and is discussed in detail in Ref. 1. For the measurement of uranium metal pieces and uranium-aluminum billets, the samples are placed into the central cavity of the detector. Two ^{241}AmLi sources irradiate the samples with fast and epithermal neutrons that penetrate the samples and induce fissions. The fission neutrons are detected in the cylindrical assembly of polyethylene and ^{3}He proportional counters that surround the cavity.

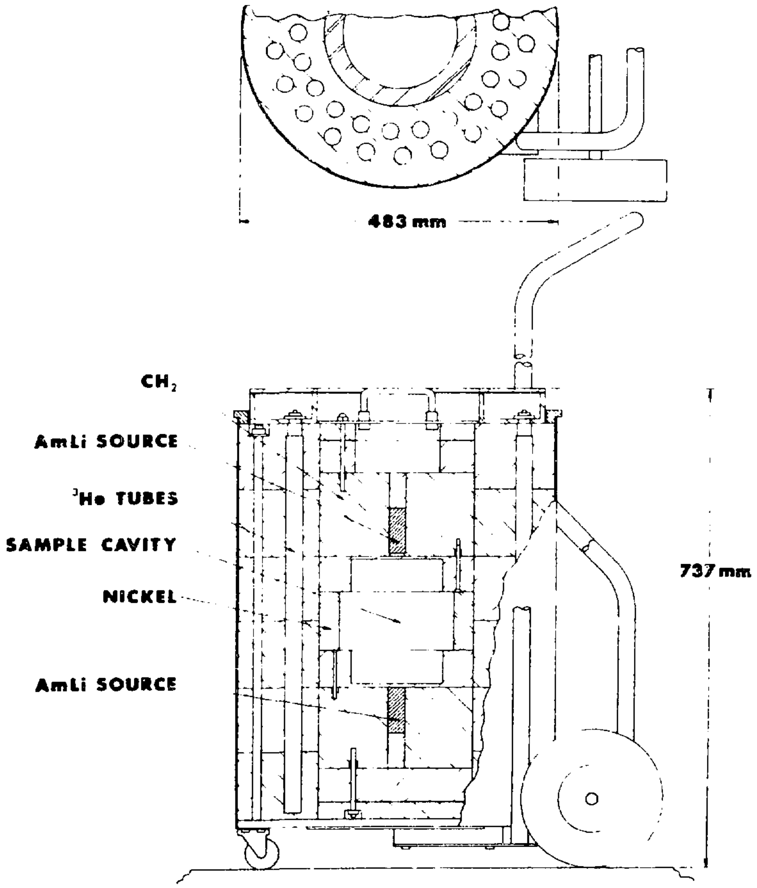

Fig. 1. Schem^tic diagram of the AWCC showing the normal configuration of the end plugs and AmLi neutron sources.

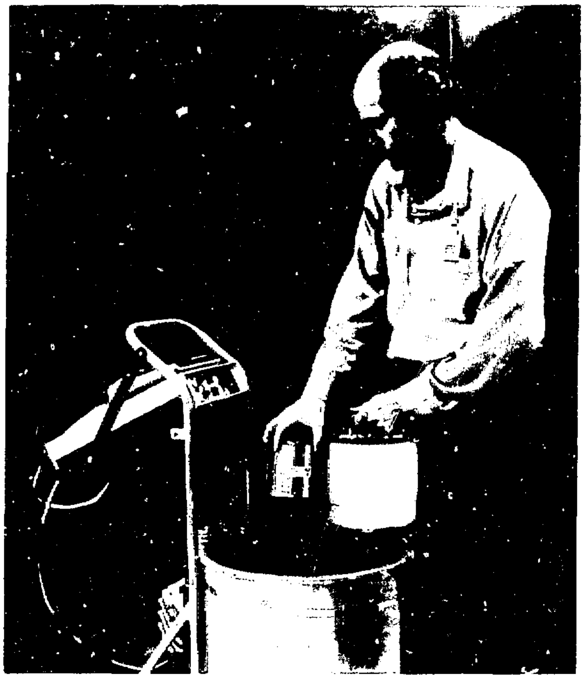

Fig. 2. Complete AWCC system, including detector, cart, and electronics for automated data collection and analysis.

Two methods of assay can be used with the same electronics system--coincidence analysis and totals analysis. Coincidence analysis depends on the measurement of the coincident fission neutrons with a coincidence circuit. The advantage to this method is that the neutrons that are detected from the ^{241}AmLi source and from room background do not contribute to the coincidence counts; the disadvantage is that the statistical error for coincidence counting is larger than for total neutron counting.

Totals analysis depends on the measurement of the total neutron count that is produced by background neutrons, ^{241}AmLi source neutrons, ^{241}AmLi neutrons scattered by the sample, and fission neutrons. The advantage to this method is an improved counting-statistics error relative to coincidence counting; the disadvantage is that the measurements are sensitive to changing backgrounds and varied scattering effects. This method is useful only for fixed sample geometries and stable backgrounds.

The detector can be converted to thermal-mode irradiation by removing the cadmium liners that surround the counting cavity. The fission rate is greatly increased in the thermal mode because of the increased ^{235}U fission cross section at thermal energies; the disadvantage, however, is the much poorer penetration of thermal neutrons into samples with medium-to-high ^{235}U densities. The thermal mode is used primarily for the measurement of small samples with low ^{235}U density (such as natural uranium oxide powder), which entails unacceptably poor counting-statistics errors when measured with fast-mode irradiation.

The AWCC can also be readily adapted for counting fuel pins. For this purpose the top and bottom end plugs are removed, and the detector is operated on its side. The fuel-pin adapter shown in Fig. 3 is installed in the AWCC so that the polyethylene cylinder is inside the AWCC body. The three Lucite rods support up to three fuel pins. The AmLi sources are removed from the end plugs and are inserted into a polyethylene tube (Fig. 4), which is inserted into the center of the polyethylene cylinder shown in Fig. 3. Because of the small diameter of the fuel pins, the AWCC fuel-pin adapter is designed to produce thermal irradiations; the fission rate is much higher in the thermal mode than in the fast mode, yet the sample penetration is adequate because of the small pin diameter.

III. URANIUM-ALUMINUM BILLETS

A. Sample Description

The billets are uranium-aluminum cylindrical castings as detailed in Table I. The uranium enrichment is always ∿93%. The two types of billets are (1) NRX, which are 28 wt% uranium, and (2) NRU, which are 21 wt% uranium.

Three billets of each type were fabricated at Los Alamos for study before the CRNL exercise. The first NRU mockup billet was a miscasting and has 17 wt% rather than 21 wt% uranium. The three mockup NRX billets have 97, 97, and 98 g of ^{235}U, and the three mockup NRU billets have 52, 67, and 68 g of ^{235}U.

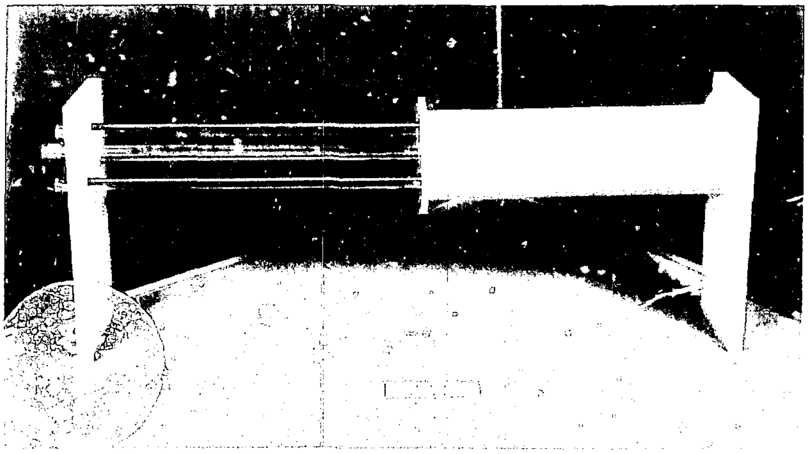

Fig. 3. Fuel-pin adapter for the AWCC showing the three fuel-pin guide tubes and the cylindrical, polyethylene, neutron-moderating assembly.

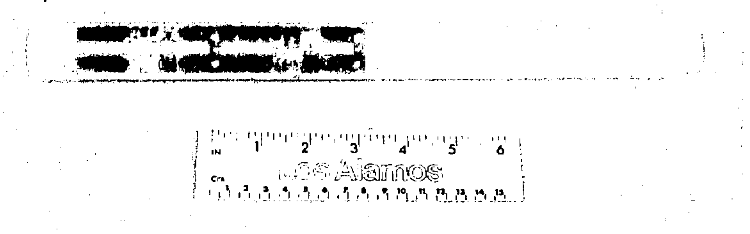

Fig. 4. The AmLi sources in the source holder for the AWCC fuel-pin adapter.

TABLE I

BILLET DATA
(Typical values)

	CRNL Billets		Los Alamos Mockup Billets	
	NRU	NRX	NRU	NRX
Diameter (cm)	3.6	3.6	3.6	3.6
Height (cm)	10.3	10.3	10.3	10.3
Mass (g)	359	395	345	371
Uranium mass (g)	75	111	72	104
^{235}U mass (g)	70	103	67	97
Enrichment (%)	93	93	93	93

B. Measurements: Fast Mode; Coincidence Analysis

The AWCC was used in its normal mode with cadmium in place. A circular billet holder was centered on the bottom of the sample cavity. This holder has indentations for six billets placed symmetrically in a circular pattern about the center; the height of the holder places the center of the billets at the center of the cavity. When three billets were counted, they were placed in alternate indentations.

Data on the Los Alamos billets are summarized in Table II. Note that the coincidence rate per gram of ^{235}U is about 10% higher for the NRU billets compared with the NRX billets. This is due to the higher absorption of the AmLi neutrons in the billet with higher ^{235}U density.

TABLE II

LOS ALAMOS MOCKUP BILLET MEASUREMENTS
(Fast mode)

Billet Type	No. of Billets	M (g)	R (s^{-1})	σ_R (s^{-1})	R/M ($s^{-1}g^{-1}$)
NRU	3	187	27.79	0.50	0.1486
NRX	3	292	39.36	0.34	0.1348

The corresponding data for the CRNL billets are given in Table III. Note that the coincidence rate for six billets is not quite twice the rate for three billets. This is caused by additional shielding of the AmLi neutrons by the addition of three billets.

The Los Alamos and CRNL measurements are compared in Table IV, where the ratios of the coincidence rates per gram of ^{235}U are given for groups of three NRU and NRX billets. Relative to the CRNL measurements, Los Alamos measurements have a greater response of 2.8 ± 1.9% for NRU billets and 1.7 ± 1.0% for NRX billets. Although these ratios are statistically consistent with zero excess, the excess is probably real because (1) one Los Alamos NRU mockup billet is only 17 wt% uranium, and (2) the Los Alamos billets are slightly smaller than the CRNL billets.

TABLE III

CRNL BILLET COINCIDENCE MEASUREMENTS
(Fast mode)

Billet Type	No. of Billets	M (g)	R (s^{-1})	σ_R (s^{-1})	R/M ($s^{-1}g^{-1}$)
NRU	3	210.8	30.48	0.16	0.1446
NRX	3	306.3	40.63	0.17	0.1326
NRU	6	421.0	58.25	0.45	0.1384
NRX	6	614.6	77.37	0.47	0.1259

TABLE IV

COMPARISON OF LOS ALAMOS AND CRNL BILLET MEASUREMENTS
(Fast mode; coincidence analysis)

Billet Type	No. of Billets	Ratio[a]
NRU	3	1.028 ± 0.019[b]
NRX	3	1.017 ± 0.010[b]

[a]Ratio of R/M for Los Alamos billets to R/M for CRNL billets.
[b]Standard deviation of ratio.

Calibration curves based on the CRNL data were derived for three- and six-billet assay configurations. A saturating response function was chosen of the form

$$R = A(1 - e^{-BM}) \quad ,$$

where A and B are calibration constants. The data in Table III determine the following calibration functions.

Three-billet calibration curve:

$$R = 89.60(1 - e^{-0.001973\ M}) \quad .$$

Six-billet calibration curve (shown as the lower curve in Fig. 5):

$$R = 160.0(1 - e^{-0.001075\ M}) \quad .$$

C. Measurements: Fast Mode; Totals Analysis

The AWCC electronics package measures the total counts and coincidence counts simultaneously, so both coincidence analysis and totals analysis can be performed for each measurement. The quantity of interest for totals analysis is the totals rate above that due to room background, the AmLi sources, and scattering of AmLi neutrons by the sample.

The contribution of sample scattering to the totals rate is usually unknown and must be evaluated for each material type and geometry. The scattering effect was estimated for billets by assuming that the scattering is the same for NRU and NRX billets.

Let T be the totals rate with a sample, T_0 the totals rate without a sample, S the contribution of scattering to the totals rate T, F the fission contribution to T per gram of ^{235}U for NRX billets, and

$$\rho = \frac{\left(\frac{R}{M}\right)_{NRU}}{\left(\frac{R}{M}\right)_{NRX}} \quad .$$

Then, approximately,

$$T_0 + S + M_{NRX} F = T_{NRX} \quad ,$$

and

$$T_0 + S + M_{NRU} \rho F = T_{NRU} \quad .$$

Solving these two equations for S and F for three- and six-billet data gives

$$S(\text{3-billet}) = 130 \ (s^{-1}) \quad ,$$

and

$$S(6\text{-billet}) = 237\ (s^{-1}) \quad .$$

Totals data for the CRNL billets are given in Table V. T is the measured totals rate, ΔT is the totals rate above the AmLi source rate [$\Delta T = T - T_0 = T - 3181\ (s^{-1})$], S is the scattering contribution, ΔT_c is ΔT corrected for scattering ($\Delta T_c = \Delta T - S$), and $\Delta T_c/M$ is the corrected net totals rate per gram of ^{235}U.

From the data in Table V, the following calibration functions were calculated.

Three-billet calibration curve:

$$\Delta T_c = 530.5(1 - e^{-0.001966\ M}) \quad .$$

Six-billet calibration curve:

$$\Delta T_c = 905.8(1 - e^{-0.001027\ M}) \quad .$$

TABLE V

CRNL BILLET TOTALS MEASUREMENTS

Billet Type	No. of Billets	M (g)	T (s^{-1})	ΔT (s^{-1})	S (s^{-1})	ΔT_c (s^{-1})	$\frac{\Delta T_c}{M}$ ($s^{-1}g^{-1}$)
None	0	0	3181	0	0	0	--
NRU	3	210.8	3491	310	130	180	0.854
NRX	3	306.3	3551	370	130	240	0.784
NRU	6	421.0	3736	555	237	318	0.755
NRX	6	614.6	3842	661	237	424	0.690

D. Measurements: Thermal Mode; Coincidence Analysis

Thermal-mode measurements of Los Alamos and CRNL billets are summarized in Table VI. Note that the coincidence rate per gram of ^{235}U is about 33% higher for six NRU billets than for six NRX billets, and that the coincidence rate for six NRX billets is only about 45% higher than the coincidence rate for three NRX billets. These numbers illustrate the low penetrability of the thermal neutrons in the billets.

The Los Alamos and CRNL measurements are compared in Table VII. The Los Alamos response for NRU billets is 2.8 ± 0.9% higher than the CRNL response; this is probably due to the one Los Alamos billet that has 17 wt% uranium rather than 21 wt%. The Los Alamos response for NRX billets is 1.9 ± 0.9% lower than the CRNL response, although a slightly higher response was expected.

TABLE VI

LOS ALAMOS AND CRNL THERMAL-MODE BILLET DATA

Laboratory	Billet Type	No. of Billets	M (g)	R (s^{-1})	σ_R (s^{-1})	R/M ($s^{-1}g^{-1}$)
Los Alamos	NRU	3	187	683	4.6	3.65
CRNL	NRU	3	211	748	4.8	3.55
Los Alamos	NRX	3	292	772	4.1	2.64
CRNL	NRX	3	308	830	6.0	2.69
CRNL	NRU	6	422	1096	5.4	2.60
CRNL	NRX	6	615	1200	4.7	1.95

The six-billet thermal calibration curve for CRNL billets (shown as the upper curve in Fig. 5) is

$$R = 1270(1 - e^{-0.004709\ M}) \quad .$$

TABLE VII

COMPARISON OF LOS ALAMOS AND CRNL BILLET MEASUREMENTS
(Thermal mode; coincidence analysis)

Billet Type	No. of Billets	Ratio[a]
NRU	3	1.028 ± 0.009[b]
NRX	3	0.981 ± 0.009[b]

[a]Ratio of R/M for Los Alamos billets to R/M for CRNL billets.
[b]Standard deviation of ratio.

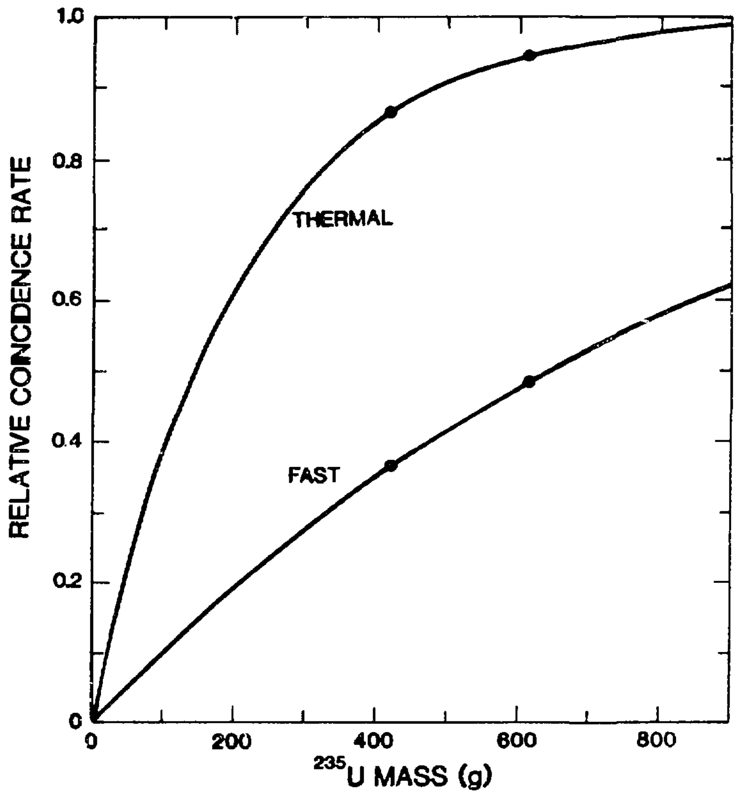

Fig. 5. Calibration curves for coincidence analysis of six-billet sets in fast and thermal modes. The coincidence rate is normalized to unity at saturation for each curve. The experimental points for NRU and NRX billets are also shown.

E. Errors

The choice among the various counting modes is made on the basis of overall error. For example, Table VIII shows the errors due to counting statistics only for six NRX billets and 1000-s measurements. The errors vary with the measurement time t as $1/\sqrt{t}$, so the errors for other counting times are readily determined. The error σ_C is the standard deviation of R or ΔT, and the error σ_M is the standard deviation of ^{235}U mass.

Fast coincidence measurements are usually preferred because (1) this method is independent of source and room background, and (2) the fast neutrons penetrate the samples well. However, σ_C is several times larger than for the other modes for a fixed counting time.

Thermal coincidence counting gives a small σ_C, but because the coincidence response is close to saturation at NRX masses (see Fig. 5), the corresponding mass error is about the same as for fast coincidence counting.

Fast totals counting has small σ_C and σ_M, but it is very sensitive to room background, source scattering, and instrument stability. For example, a 0.1% efficiency change between the background measurement and the assay measurement corresponds to a 1.3% mass error.

TABLE VIII

NRX, SIX-BILLET COUNTING-STATISTICS ERROR SUMMARY
(1000-s measurements)

Analysis (R or ΔT)	Mode	σ_C[a] (%)	$\sigma_M(\%) / \sigma_C(\%)$	σ_M[b] (%)
R	Fast	1.8	1.4	2.5
ΔT	Fast	0.6	1.4	0.8
R	Thermal	0.4	5.9	2.4
ΔT	Thermal	0.1	5.9	0.6

[a]Standard deviation of counting rate in per cent due to counting statistics in a 1000-s measurement.
[b]Standard deviation of ^{235}U mass in per cent due to counting statistics in a 1000-s measurement.

Thermal totals counting has a very small σ_c, but it combines the scattering problems of totals counting with the high-absorption problems of thermal-mode measurements.

Rough estimates for systematic errors (1σ) are 1% for fast coincidence mode, 1.5% for fast totals mode, 2% for thermal coincidence mode, and 2.5% for thermal totals mode.

IV. URANIUM PIECES*

A. Sample Description

The uranium pieces at CRNL are randomly sized metal lumps packaged in small cans. All of the uranium is 93% enriched. The pieces vary from small bles to chunks with volumes >10 cm^3. The sample cans contain from ~600 g to ~4.6 kg ^{235}U.

Uranium metal samples prepared at Los Alamos for general experimental work were used to study the response of the AWCC to metal samples. The Los Alamos samples are 93% uranium metal disks 1 cm thick by 6 or 7 cm in diameter. These disks were stacked to form large samples.

B. Measurements

Measurements were made with the AWCC in its normal fast-mode configuration. The samples were centered in the counting cavity with a lab jack. Thermal mode cannot be used with metal pieces because of the poor thermal-neutron penetrability. Only coincidence analysis was performed; totals analysis is not suitable for metal pieces because of the varying effect of sample scattering.

Measurements on the Los Alamos metal disks are summarized in Table IX. The coincidence rate per gram of ^{235}U is larger for small and large samples than for intermediate-size samples. This is because (1) the source neutrons penetrate small samples better than intermediate and large samples, and (2) neutron multiplication in the large samples overrides the lower response expected from poor sample penetration.

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*The general application of the AWCC to the assay of highly enriched uranium metal has been discussed in detail in Ref. 2.

TABLE IX

LOS ALAMOS METAL DISK MEASUREMENTS

^{235}U Mass (g)	R (s^{-1})	R/M ($s^{-1}g^{-1}$)
491.2	42.51	0.0865
982.9	79.74	0.0811
1475	117.9	0.0799
2456	202.1	0.0823
3440	294.1	0.0855

Measurements on the CRNL metal pieces are summarized in Table X. The smallest coincidence rate per gram of ^{235}U is also found for intermediate-size samples (for the same reasons).

The average R/M for the Los Alamos samples is 0.0831 and for the CRNL samples is 0.0796. The 4.4% higher average response of the Los Alamos samples is probably due to (1) higher neutron multiplication in a stack of metal disks relative to a random assembly of pieces of the same mass and (2) better penetrability of a single, thin disk relative to several chunks of the same mass.

TABLE X

CRNL METAL PIECE MEASUREMENTS

^{235}U Mass (g)	$R \pm \sigma_R$ (s^{-1})	R/M ($s^{-1}g^{-1}$)
562	43.5 ± 0.6	0.0774
605	46.4 ± 0.6	0.0767
1719	131.0 ± 1.3	0.0762
2798	224.3 ± 1.4	0.0802
4652	406.8 ± 1.4	0.0874

Figure 6 shows the coincidence rate vs mass for the Los Alamos and CRNL samples. The solid curve is a least-squares fit to the CRNL data only; the calibration curve is

$$R = 0.07694M - 9.073 \times 10^{-7} M^2 + 6.820 \times 10^{-10} M^3 \quad .$$

A cubic equation was chosen to accommodate both the absorption and multiplication characteristics of the calibration curve.

An additional measurement was made on a tightly packed, triangular assembly of three CRNL cans of metal pieces with a total ^{235}U mass of 1762 g. The measured coincidence rate is plotted as a square data point in Fig. 6. Assay of this sample arrangement with the calibration curve above yields a ^{235}U mass of 1778 ± 14 g, which is 0.91 ± 0.79% above the actual mass. Good accuracy can

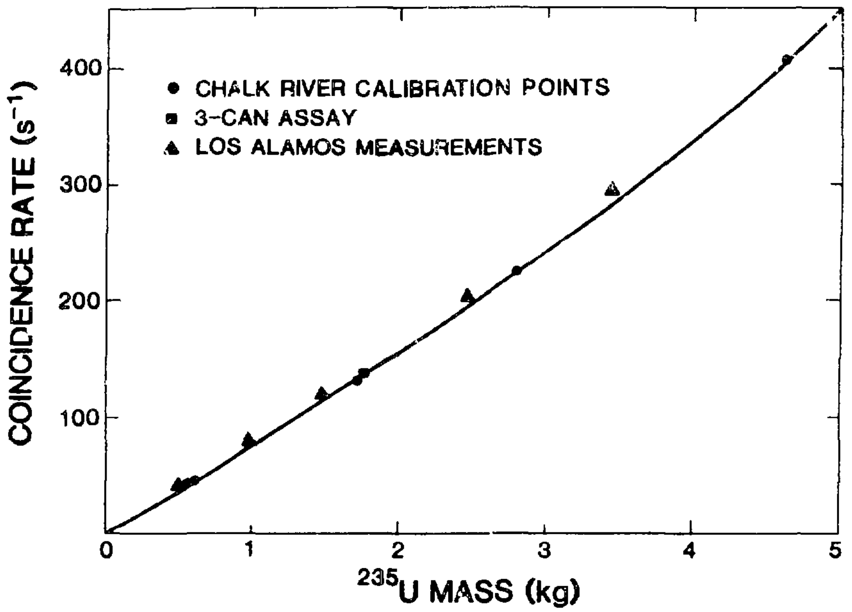

Fig. 6. Calibration curve for metal pieces derived by least-squares fitting to CRNL data for single cans (circles). Also shown is the experimental point for the measurement of a three-can set (square) and the metal disk data from Los Alamos (triangles).

therefore be obtained by measuring three cans at a time, provided that their masses are $\lesssim$600 g each; for larger masses, multiplication effects could complicate the assay.

C. Errors

The dominant error in the measurement of the high-mass CRNL uranium metal samples is due to the varying absorption and multiplication effects that arise from the random sizes of the pieces. A preliminary estimate for the standard deviation of R for CRNL samples as a result of varying sizes of the pieces is 2%.

For small-mass samples the counting-statistics error can also contribute appreciably to the total errors. Table XI shows the counting-statistics errors for CRNL samples measured for 1000 s. Above ~1.5 kg of ^{235}U, the counting-statistics error becomes small compared with the estimated sample-geometry error.

V. URANIUM-ALUMINUM FUEL CORES AND ELEMENTS

A. Sample Description

At CRNL the term "fuel cores" refers to the unclad uranium-aluminum fuel; the term "fuel elements" refers to the aluminum-clad cores. NRX elements have a core diameter of 0.635 cm and a cladding thickness of 0.076 cm; NRU elements

TABLE XI

CRNL METAL PIECES: COUNTING-STATISTICS ERRORS
(1000-s measurements)

^{235}U Mass (g)	σ_c (%)
562	2.9
605	2.7
1719	1.1
2798	0.7
4652	0.4

have a core diameter of 0.549 cm and a cladding thickness of 0.076 cm. The elements have an active length of about 270 cm.

Mockup fuel elements 60 cm long were fabricated at Los Alamos with NRX-type material and core diameters of 0.510 and 0.889 cm.

B. Measurements

The AWCC was converted to the fuel-pin configuration for these thermal-mode measurements. At CRNL the cores and elements were always measured three at a time; at Los Alamos only one mockup element of each diameter was available, and these were measured in the lower irradiation tube. The lower irradiation tube should be used for the measurement of single rods because in this tube the reflection of neutrons from the floor compensates for the absence of crosstalk among rods that are measured in sets of three.

Data on NRX measurements are presented in Table XII. Because a thermal-neutron irradiation is used, the detector response per gram of ^{235}U is dependent on the diameter and ^{235}U density of the fuel core. Figure 7 shows the coincidence rate per unit loading (g ^{235}U/cm) vs the loading (constant

TABLE XII

NRX-TYPE FUEL ELEMENT MEASUREMENT DATA

	Los Alamos[a]		CRNL[b]
Diameter (cm)	0.510	0.889	0.635
Grams ^{235}U/cm [c]	0.187	0.569	0.290
R per element	41.77	86.55	54.97
T	3842	4302	4858
T_0	3484	3594	3429
ΔT per element	358	708	476
R/(g ^{235}U/cm)	223	152	190
ΔT/(g ^{235}U/cm)	1914	1244	1641

[a] One element measured at a time.
[b] Three elements measured at a time.
[c] One element.

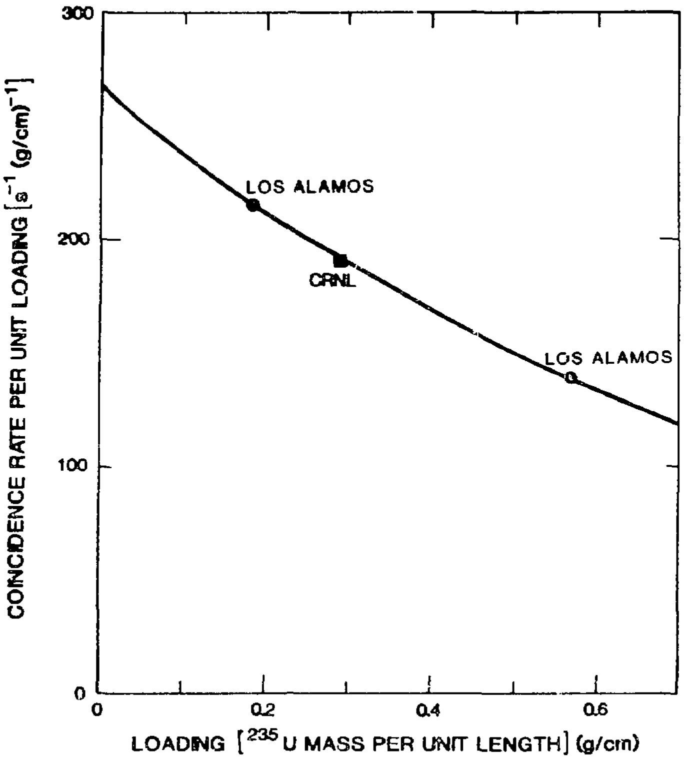

Fig. 7. Coincidence rate per unit loading vs loading for NRX-type fuel cores. The ^{235}U density is constant; the various loadings are obtained by varying the core diameter. The curve fitted to the Los Alamos points has the form Ae^{-Bm}.

^{235}U density, varying diameter); the rates are normalized to the AmLi rate T_0 for the CRNL rod. The two Los Alamos data points were fitted to the assumed form $R = A\ e^{-Bm}$, where A and B are constants and m is the loading; the result is the solid curve shown in Fig. 7. Based on this curve, the CRNL measurements differ from the Los Alamos measurements by -0.7%. A similar calculation based on totals rather than coincidence rates gives a difference of -1.5%. Thus, absolute ^{235}U mass measurements in CRNL NRX elements based on a calibration at Los Alamos are accurate to $\sim$1%.

For the construction of a calibration curve for fuel element assay, it is the detector response vs loading for a fixed diameter rather than the detector response vs diameter for a fixed ^{235}U density that is of interest. At Los Alamos, constant-diameter pressurized water reactor (PWR) fuel rods with 0.2, 0.7, and 3.2% enrichments were used to determine the constant B in the equation

$$R = A(1 - e^{-Bm}) \quad ,$$

where m is the loading in (g ^{235}U/cm). This constant was then used as an approximate shape parameter for NRU and NRX calibration curves.

From the data in Table XII, the following calibration curves for NRX cores or elements were calculated:

$$R = 252.2(1 - e^{-3.658\ m}) \quad ,$$

and

$$\Delta T = 2186(1 - e^{-3.658\ m}) \quad .$$

The coincidence and net totals rates are for the measurement of three cores or elements at a time. Note that the loading m is for a single rod. Figure 8 shows R and ΔT vs loading for NRX elements or cores.

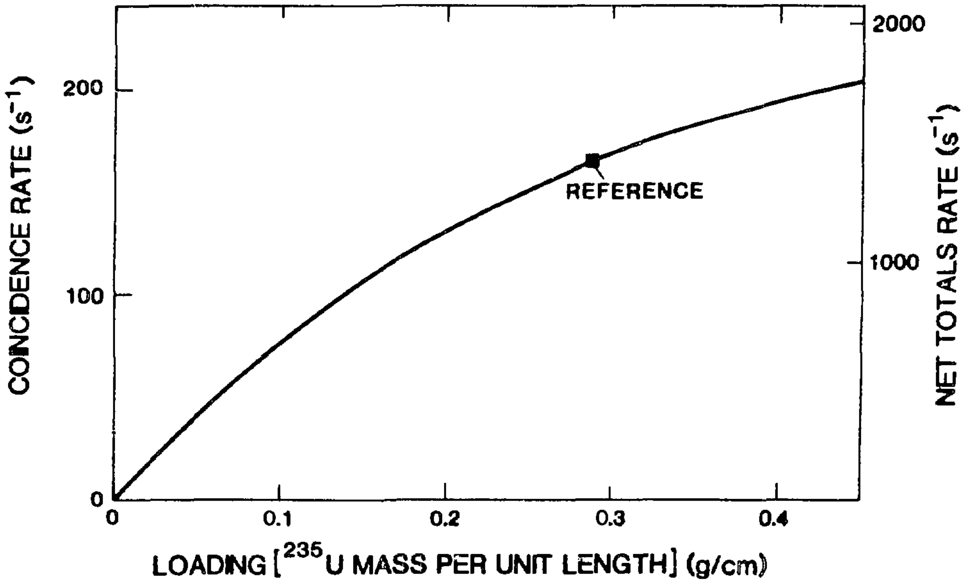

Fig. 8. Calibration curves for NRX fuel cores or elements. The coincidence rate and net totals rate are for three rods measured at a time. The loading is the loading for an individual core.

Table XIII shows data for NRU cores obtained at CRNL by measuring three cores at a time. From these data, the following calibration curves were obtained:

$$R = 252.8(1 - e^{-3.658\ m}) ,$$

and

$$\Delta T = 2274(1 - e^{-3.658\ m}) .$$

Again, the coincidence and totals rates are for the measurement of three rods at a time. The calibration curves above can be used only in the vicinity of the reference points because the shape is only an approximation obtained from PWR rod measurements.

TABLE XIII

CRNL NRU FUEL CORE MEASUREMENT DATA[a]

Diameter (cm)	0.549
Grams ^{235}U/cm [b]	0.151
R per element	35.77
T	4394
T_0	3429
ΔT per element	322
R/(g ^{235}U/cm)	237
ΔT/(g ^{235}U/cm)	2132

[a]Three elements measured at a time.
[b]One element.

C. Errors

Table XIV lists standard deviations σ_c for core and element measurements due to counting statistics only. The corresponding mass errors σ_m are also given. Both NRU and NRX rods can be measured to a standard deviation of 2% in 1000 s using coincidence analysis. Totals analysis produces a mass error of 0.4% for the same measurement time and may be the preferable assay method.

VI. NORMALIZATION

To account for any changes in the detector efficiency, data from future measurements of the uranium-aluminum fuel materials with the AWCC should be normalized using the AmLi sources. The normalization constant k is

$$k = \frac{\text{net source totals rate (at calibration)}}{\text{net source totals rate (new measurement)}} e^{-\lambda t} \quad ,$$

where the net source totals rate is the totals rate above room background produced by the AmLi sources with no sample in the detector, $\lambda = 1.6 \times 10^{-3}\ y^{-1}$ is the decay constant for ^{241}Am (half-life = 433 y), and t is the time in years between calibration and the new measurement.

TABLE XIV

FUEL ELEMENTS: COUNTING-STATISTICS ERRORS
(1000-s measurements on three elements)

Material Type	Analysis Method (R or ΔT)	σ_c (%)	$\frac{\sigma_m(\%)}{\sigma_c(\%)}$	σ_m (%)
NRU	R	1.5	1.3	2.0
NRX	R	1.1	1.8	2.0
NRU	ΔT	0.3	1.3	0.4
NRX	ΔT	0.2	1.8	0.4

Coincidence measurements are multiplied by $k^2 e^{\lambda t}$, and totals measurements are multiplied by $ke^{\lambda t}$ to normalize them to the calibration measurements.

The net source totals rates at the time of calibration (1981) were 3027 s^{-1} for billets, 3064 s^{-1} for uranium pieces, and 3326 s^{-1} for fuel elements and cores.

VII. SUMMARY

Table XV lists sample categories, practical measurement times, and mass errors for billets, metal pieces, and fuel elements. Estimated systematic errors are <1% for fuel elements, ∿1% for billets, and ∿2% for metal pieces.

TABLE XV

SUMMARY OF PRACTICAL MEASUREMENTS

Sample	Measurement Mode	Practical[a] Measurement Time (s)	σ_M[b] (%)
3 NRU billets	coincidence	3 x 1000	2.9
6 NRU billets	coincidence	3 x 1000	1.7
3 NRX billets	coincidence	3 x 1000	2.6
6 NRX billets	coincidence	3 x 1000	1.4
<1.5 kg metal[c]	coincidence	3 x 1000	1.6
>1.5 kg metal[d]	coincidence	3 x 300	0.7
3 NRU or NRX fuel elements	coincidence	3 x 500	1.6
3 NRU or NRX fuel elements	totals	3 x 500	0.3

[a] 3 x 1000 means three measurements of 1000 s each.

[b] Error due to counting statistics only.

[c] σ_M calculation was done for 600 g ^{235}U.

[d] σ_M calculation was done for 2800 g ^{235}U.

For fuel element measurements, totals analysis is expected to produce a lower mass error than coincidence analysis; this should be verified by performing both totals and coincidence analysis under realistic measurement conditions over a period of time. For billets, totals analysis will probably produce a larger mass error than coincidence analysis; this should be investigated by performing both totals and coincidence analysis under realistic measurement conditions over a period of time.

In addition to the measurements discussed in Secs. III-V, the AWCC can be used in its normal fast mode for the assay of dross. For such measurements, a fairly large group of dross pieces should be assayed together to reduce the percentage mass error. The AWCC could also be a useful device for quality control in fuel element manufacture.

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