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LA-UR--91-1568

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SUBMITTED TO: European Safeguards Research and Development Corporation (ESARDA)
Avignon, France
May 14-16, 1991
(FULL PAPER)

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ACTIVE WELL COINCIDENCE COUNTER MEASUREMENTS OF ENRICHED URANIUM FUEL ASSEMBLIES IN SCANNING AND STATIONARY MODES*

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Abstract

Enriched uranium fuel assemblies were measured with an Active Well Coincidence Counter (AWCC) at the Beloyarskaya Nuclear Power Plant. Special AWCC inserts, electronics, and software were used. Stationary and scanning measurements were performed to establish calibrations and performance specifications for the assay of ^{235}U and ^{235}U/cm for BN600 fuel.

1. Introduction

A measurement exercise was conducted at the BN600 reactor facility at the Beloyarskaya Nuclear Power Plant to evaluate the Active Well Coincidence Counter (AWCC) /1/ for the nuclear safeguards verification of enriched uranium fuel assemblies. The normal AWCC technique is to induce fissions in the fuel with neutrons from americium-lithium (AmLi) isotopic neutron sources and to count the coincident neutrons from the fissions with coincidence circuitry. Once a calibration is established, the coincidence count rate determines the ^{235}U content of the fuel. However, because the enriched region of the fuel assemblies is much longer than the irradiation region of the AWCC, a single, stationary measurement of the fuel determines the ^{235}U mass per unit length; the length of the enriched region (the active length) must be measured separately to determine the total ^{235}U mass of the fuel.

One method for measuring the active length of the fuel is to manually scan the fuel assembly with a collimated gamma-ray detector. The disadvantage of the method for nuclear safeguards is that the gamma-ray measurement only determines the active length of the surface of the fuel. The operational disadvantages are that the safeguards inspector must handle measurement equipment close to the fuel assembly along its active length and must have a means for marking and measuring the distance along the assembly.

Another method of measuring the active length is to scan the fuel assembly with the AWCC. In this method the fuel assembly is lowered by crane through the AWCC and the total neutron count rate is measured in short counting intervals. The advantages of the method are that the fuel assembly does not need a wrapper for protection and for marking, inspectors and hand-held equipment do not need to be close to the assembly, and the measurement and analysis are largely automatic. The disadvantage is that the crane speed must be known or measured.

Instead of using a stationary measurement plus a scan for the verification of fuel assemblies, a single scan can suffice if it is slow enough that the error from counting statistics is as low as required for the type of verification being done. The active length is then not needed for the verification of the total ^{235}U content. (The scan, nevertheless, automatically provides the length as part of the analysis.) As before, the crane speed must be known or measured.

In this exercise both stationary and scanning measurements were evaluated. A more detailed report on this exercise will soon be available /2/.

2. Material and Methods

Facility and Fuel

The BN600 facility /3/ is a 600 MWe fast breeder reactor near the city of Sverdlovsk, USSR. The enriched uranium fuel assemblies have enrichments of 17%, 21%, or 26%. The enriched assemblies used for this exercise have 100-cm active lengths with adjacent 30-cm depleted regions at each end. A simplified drawing of a fuel assembly is shown in Fig. 1.

The assemblies have an hexagonal cross section with 9.6 cm across the flats. The outer cladding is stainless steel 0.2 cm thick. The enriched assemblies contain 127 UO_2 fuel pins with an outer diameter of 6.9 mm; the fuel-pin cladding is stainless steel 0.4 mm thick. Figure 2 shows the cross section of an enriched fuel assembly.

The ^{235}U masses of the assemblies vary from approximately 4700 g to approximately 7200 g.

Detector

The detector is a standard AWCC modified for use at the BN600 facility. The normal end plugs, nickel reflector, and cadmium liner were removed and replaced with a custom insert for the BN600 fuel. A 15-cm diam irradiation channel at one side of the polyethylene insert is for the fuel assembly. A 4.2-cm diam hole in the polyethylene insert is for the AmLi sources; 1.0 cm of polyethylene separates the AmLi sources from the 15-cm diam irradiation channel. Figure 3 shows vertical and horizontal cross sections of the modified AWCC.

The 15-cm diam hole is lined with cadmium 0.4 mm thick to prevent thermal neutrons from escaping the polyethylene and inducing fissions in the fuel assembly; i.e., the AWCC is operated in the fast mode. Because the ^{235}U mass in the fuel assemblies is high, the thermal mode

*Los Alamos National Laboratory effort supported by the International Safeguards Project Office.

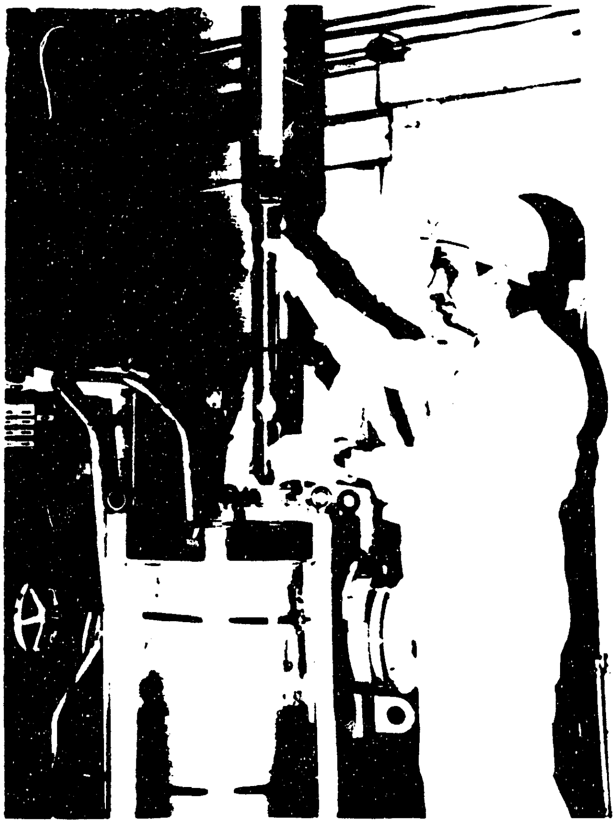

Fig. 4. BN600 fuel assembly being positioned for lowering into the AWCC.

measurements, the raw data from an SR4 circuit are almost the same as those from a JSR-11.

The SR4 was set to a predelay of 3 µs and a gate length of 64 µs.

A custom data collection and analysis program for IBM PCs was written to perform the stationary and scanning measurements. The SR4 coincidence module has no manual controls; it is operated from the computer via a 9600 baud RS-232-C serial port. Because the data transfer time is short, the raw data from the SR4 can be displayed on the computer display in near real time.

For stationary measurements, the counting rates, results, and errors are updated and displayed about once a second as the measurement proceeds; for scanning measurements, the total count rate is plotted on the computer display as the scan proceeds.

Experimental Fuel Handling

Two cranes were used for the scanning measurements; each crane had a fast and a slow speed. The small crane (5-tonne capacity) is the normal fuel-handling crane and has a downward slow speed of 3.6 cm/s. The large crane (30-tonne capacity) has a downward slow speed of 0.23 cm/s. The fast speeds of the cranes are about an order of magnitude faster than the slow speeds.

All scanning measurements were made using the slow crane speeds while the fuel was being lowered through the AWCC. For this exercise the AWCC was positioned over a fuel-transfer hole in the floor of the room. The 100-cm enriched region of an assembly passes through the center of the AWCC in about 30 s with the fast crane and in about 7 min with the slow crane.

Stationary Measurements

Two fuel assemblies of each enrichment were centered in the AWCC and measured in the stationary position. Most measurements were 1000 s long. A 1000 s measurement produces a coincidence-count-rate standard deviation from counting statistics of 2.0% for a 17%-enriched assembly and 1.5% for a 26%-enriched assembly.

The six calibration data points were fit by least squares using the Deming code /6/ and a calibration equation of the form

$$R = \frac{am}{1 + bm} ,$$

where R is the coincidence rate, m is the ^{235}U mass/cm, and the calibration constants are a and b. The calibration curve is plotted with the data points in Fig. 5.

Slow Scans

For the slow scanning measurements, the fuel assemblies were lowered through the AWCC with the slow crane at a speed of 0.23 cm/s. The SR4 coincidence circuit was cycled with a 3-s measurement time and the raw data were stored for each cycle. During the scan the totals count rate was plotted vs time on the computer display, so the progress of the scan could be observed. The totals count rate distribution for a slow scan of a 26%-enriched assembly is shown in Fig. 6; the totals rates are averaged over three cycles to smooth the distributions.

Eight slow scans were done with six different assemblies; all three enrichments were used.

The totals rate is not used directly to assay the ^{235}U mass of the fuel because the totals rate depends strongly on the scattering and absorption effects of the fuel on the AmLi source neutrons as well as on the ^{235}U induced fission rate. The totals rate scan, however, easily identifies the enriched region of the fuel and determines the active length; the coincidence counts obtained in the active region can then be used to assay the total ^{235}U mass of the fuel.

The enriched region of the fuel assembly is indicated in Fig. 6. The lower count rate above and below the enriched region is caused by neutron scattering and absorption in the depleted uranium, which does not contribute a significant number of induced fission neutrons. The complex distribution above the depleted region is caused by scattering and absorption effects from the end of the fuel assembly and the fuel-handling hardware.

Figure 7 shows the coincidence counts measured for the same scan; there are statistically significant coincidence counts only from the enriched region of the fuel assembly. The integral of the coincidence counts determines the total ^{235}U mass; an effective coincidence rate is calculated for the scan and the mass is obtained from the stationary calibration curve.

The shape of the curve of the totals rate vs time during the transitions between the enriched and depleted regions of the fuel is determined by the AWCC irradiation characteristics and the crane speed; the average absolute slope of the totals rate curve in the transition regions is used to calculate the crane speed. The width of the totals rate distribution, calculated as the distance between half-height positions in the transition regions, determines the active length.

Fast Scans

The short measurement time for fast scans (about 30 s for the active region) produces large measurement errors, but the fast scans can still be useful for verifying the active

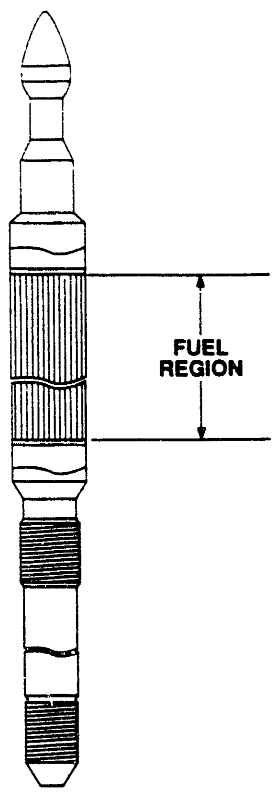

Fig. 1. Simplified drawing of a BN600 fuel assembly.

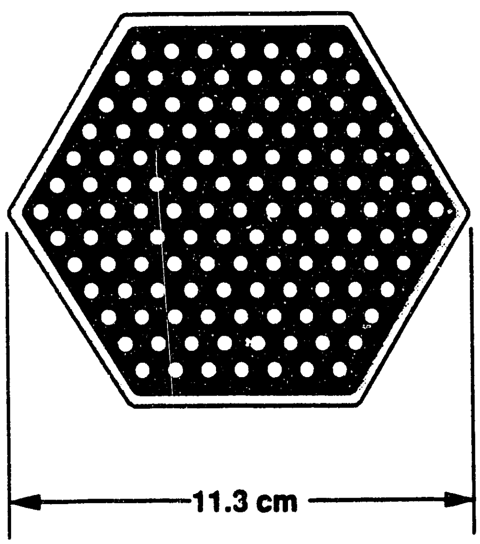

Fig. 2. Cross section of a BN600 fuel assembly with enriched uranium fuel.

is not satisfactory because of the poor thermal-neutron penetration into the fuel.

Cadmium is not used as a liner around most of the polyethylene insert so that the detection efficiency of the AWCC for induced-fission neutrons is high; however, a small rectangle of cadmium (about 10 cm wide by 20 cm long) is glued to the outside of the insert next to the AmLi sources to reduce the count rate from the AmLi sources.

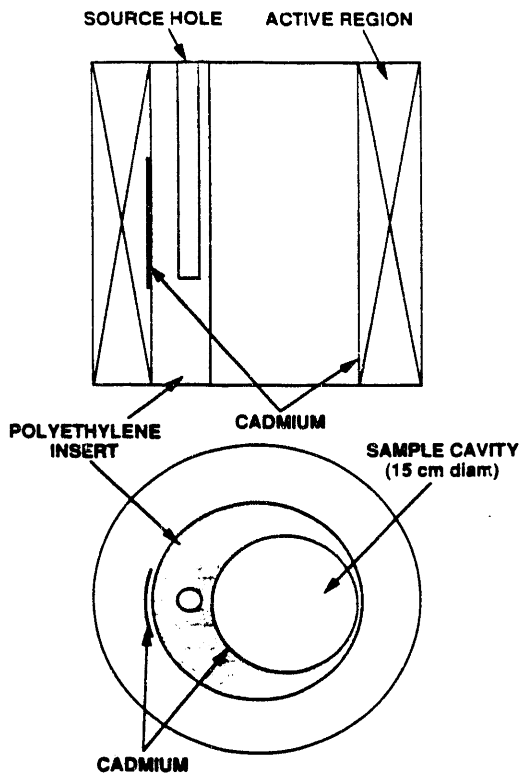

Fig. 3. Diagram of vertical and horizontal cross sections of the modified AWCC.

The AmLi neutrons do not produce real coincidence counts, but increase the error of the real coincidence counts by increasing the random neutron count rate.

A photograph of the modified AWCC in use at the BN600 facility is shown in Fig. 4; a fuel assembly is being positioned for a scanning measurement.

Two AmLi neutron sources are used to induce fissions in the fuel; each has a yield of about 50 000 neutrons per second. The two sources are placed in a custom, polyethylene source rod that slides into the source hole shown in Fig. 3.

<u>Electronics and Software</u>

The AWCC has AMPTEK /4/ preamplifiers in its junction box, so the AWCC requires +5 V to power the preamplifiers and +1680 V for the ^{3}He proportional counters; the output is standard TTL logic signals, consisting of neutron pulses 50 ns wide.

The standard JSR-11* coincidence counting circuit /5/ was not used for this exercise because short measurement and readout times were needed for the scanning measurements; the shortest measurement time is 1.0 s for the JSR-11 and the readout time is about 2 s.

Instead of the JSR-11, a new Los Alamos prototype NIM coincidence circuit, designated the SR4 (Shift Register; 4 MHz), was used because it has a minimum measurement time of 0.1 s and a readout time of 22 ms. The SR4 circuit will be described in a future publication, but the operating principle is the same as that for the JSR-11. At low count rates, such as obtained from AWCC

* Jomar Systems, Los Alamos, NM, USA, 87544

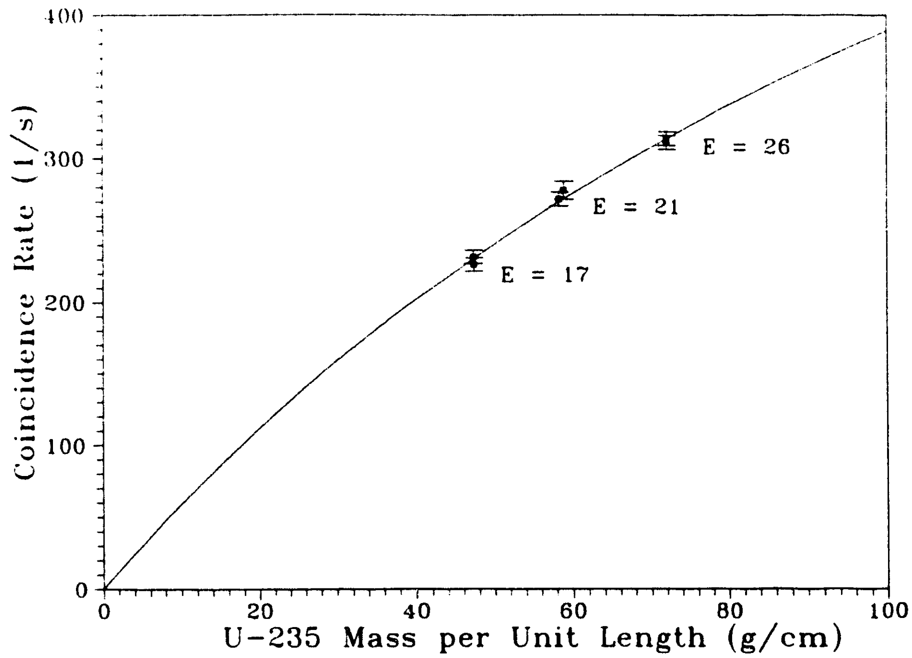

Fig. 5. Calibration curve for stationary assays of BN600 enriched uranium fuel assemblies.

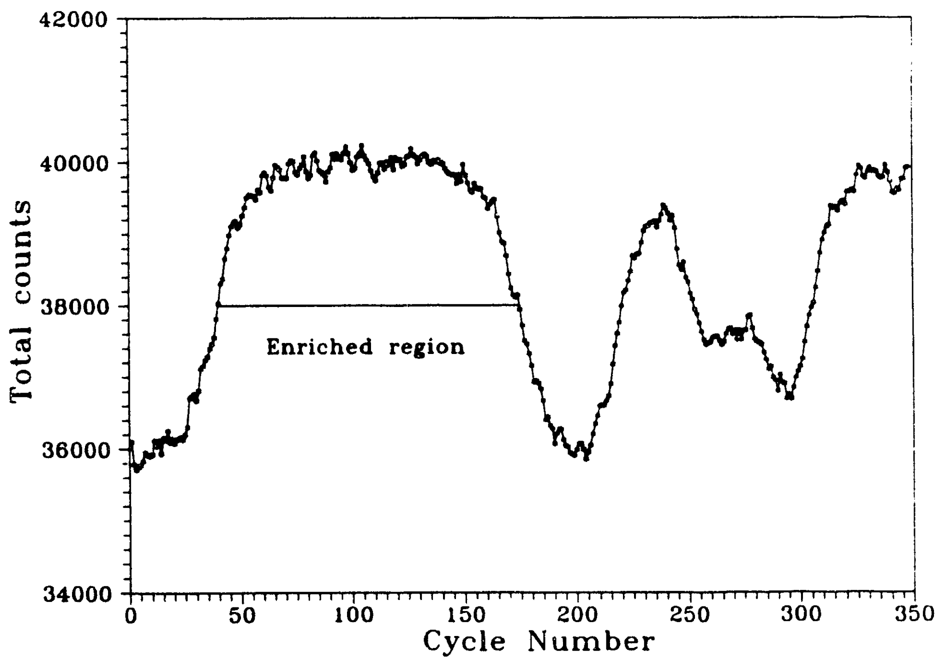

Fig. 6. Plot of the totals count rate for a slow scan of a 26%-enriched fuel assembly. The totals rate is plotted vs the cycle number; each cycle is a 3-s measurement.

lengths in connection with stationary measurements or for performing gross defect measurements. In general, the measurement and analysis of fast scans is the same as that for slow scans. The main differences are that the crane speed is 3.6 cm/s instead of 0.23 cm/s and the measurement time per cycle is 0.5 s instead of 3 s.

Seventeen fast scans were performed, ten of which were consecutive repetitions on a single 21%-enriched assembly.

The average active length initially measured from the 17 scans was 96.8 ± 1.2 cm, so the half-height to half-height analysis of the totals distribution underestimates the

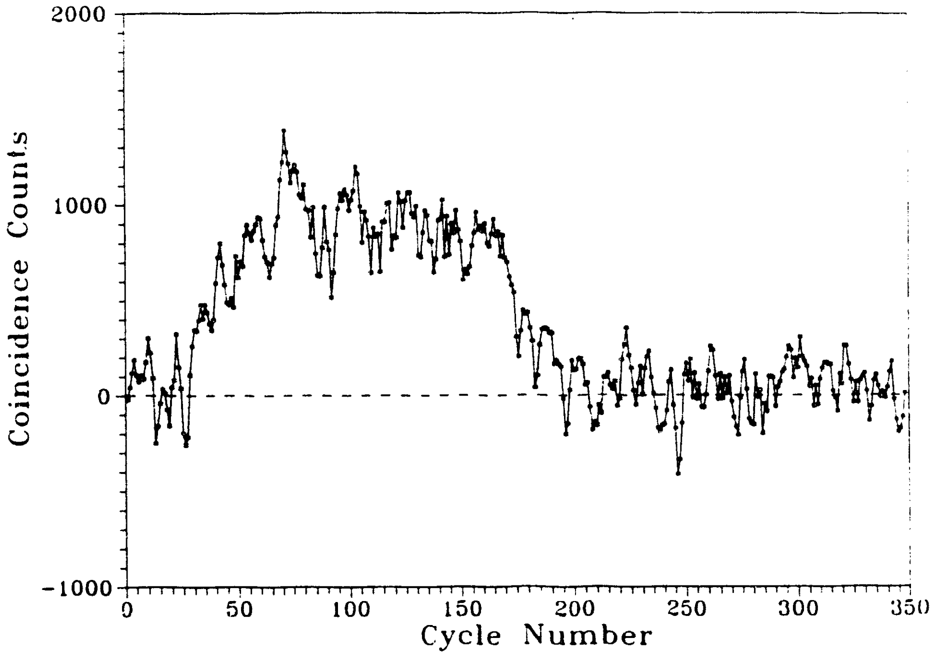

Fig. 7 Plot of the coincidence count rate vs the cycle number for the same scan as shown in Fig. 6 for the totals count rate.

active length by about 3% for fast scans. A correction factor of 1.033 was introduced to account for this bias.

3. Results

Stationary Measurements

Calibration constants were established for the stationary assay of enriched uranium BN600 assemblies. The standard deviation of the assay mass for a 1000-s measurement is 2.8% for a 17%-enriched assembly, 2.5% for a 21%-enriched assembly, and 2.4% for a 26%-enriched assembly.

Slow Scans

The mass, active length, and crane speed results for the eight slow scans are shown in Table I.

The standard deviations for the mass measurements are 3.9% for 26%-enriched fuel, 4.2% for 21%-enriched fuel and 4.6% for 17%-enriched fuel. The average absolute mass difference between the measured and accepted values is 3.9% and the average mass difference is -0.9%.

The average absolute active length difference between measured and accepted values is 1.1% and the average active length difference is 0.6%. The sample standard deviation of the active length measurements is 1.4%.

The eight slow scans were used to calibrate the crane speed measurements for slow scans, so the average crane speed in Table I is approximately the reference value of 0.23 cm/s. The sample standard deviation of the crane speed measurements is 6.4%.

Fast Scans

The standard deviation of the mass measurements is 22% for 26%-enriched fuel, 24% for 21%-enriched fuel and 26% for 17%-enriched fuel. The average absolute mass difference between measured and accepted values is 14.9% and the average mass difference is -0.4%. The sample standard deviation of the active length measurements is 5.1% and the sample standard deviation for the crane speed is 13%.

Summary

Table II summarizes the final results by giving the standard deviation in percent for the measurement of mass, active length, and crane speed for the three measurement types: stationary, slow scan, and fast scan. For stationary measurements, the mass refers to the ^{235}U mass per unit length of fuel, whereas for the scanning measurements the mass refers to the total ^{235}U mass in the assembly. The mass standard deviations are given for the three enrichments: 17%, 21%, and 26%.

If the crane speed is known, a partial defect measurement of the fuel assemblies for total ^{235}U mass can be done either by making a single slow scan for the total ^{235}U mass or by making a stationary measurement for the ^{235}U mass per unit length of fuel and a fast scan for the active length.

In either case the measurement of the crane speed from a single scan is not accurate enough for a partial defect measurement. If there is a possibility of crane speed variations, the crane speed can be checked with a stop watch during the scan.

More accurate measurements can be performed by combining a stationary measurement with a slow scan.

A single, fast scan can be used for a gross defect measurement.

Similar, but passive, scanning measurements could be used for the assay of MOX fuel assemblies. Because of the higher count rates, the precision of the measurements would be better than those for enriched uranium assemblies.

Table I. Slow Scan Results							
Sample	Enrichment (%)	Active Length (cm)	Crane Speed (cm/s)	Accepted ^{235}U Mass (g)	Measured ^{235}U Mass (g)	σ (Meas. ^{235}U Mass) (g)	Δm[a] (%)
1	26	100.3	0.216	7198	6997	276	−2.79
2	17	99.5	0.238	4733	4818	222	1.80
3	21	98.9	0.245	5832	5938	247	1.82
4	26	103.2	0.237	7197	6922	270	−3.82
5	21	101.0	0.223	5832	5655	236	−3.03
6	17	100.3	0.216	4733	5125	225	8.28
7	21	101.7	0.216	7176	6512	259	−9.25
8	21	99.6	0.254	7176	7183	284	0.10

a

$$\Delta m = \frac{\text{measured } ^{235}U \text{ - accepted } ^{235}U \text{ mass}}{\text{accepted } ^{235}U \text{ mass}} \times 100$$

Table II. Standard Deviation Summary			
Relative Standard Deviation (%)			
Quantity	Method		
	Stationary (1000 s)	Slow Scan (~600 s)	Fast Scan (~60 s)
Mass (E[a] = 17%)	2.8	4.6	26
Mass (E = 21%)	2.5	4.2	24
Mass (E = 26%)	2.4	3.9	22
Active length	---	1.4	5.1
Crane Speed	---	6.4	13

[a] E = Enrichment

4. References

/1/ H. 0. Menlove, "Description and Operation Manual for the Active Well Coincidence Counter," Los Alamos Scientific Laboratory report LA-7823-M (1979).

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/6/ P. M. Rinard and A. Goldman, "A Curve-Fitting Package for Personal Computers," Los Alamos National Laboratory report LA-11082-MS, Rev. 1 (1988).

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