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Measurement of Highly Enriched Uranium Metal Buttons with the High-Level Neutron Coincidence Counter Operating in the Active Mode

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MEASUREMENT OF HIGHLY ENRICHED URANIUM METAL BUTTONS WITH THE HIGH-LEVEL NEUTRON COINCIDENCE COUNTER OPERATING IN THE ACTIVE MODE

by

John E. Foley

ABSTRACT

The portable High-Level Neutron Coincidence Counter is used in the active mode with the addition of AmLi neutron sources to assay the ^{235}U content of highly enriched metal pieces or "buttons." I conclude that the portable instrument is a practical instrument for assaying uranium metal buttons with masses in the range of 1.5 to 4 kg.

I. INTRODUCTION

A measurement problem of particular concern to the International Atomic Energy Agency (IAEA) is the determination of the ^{235}U content of highly-enriched uranium (93 percent) pieces or "buttons". These buttons, which are typically about 6 cm diameter by 4 cm thick and have a mass of about 2 kg, are the feed materials to facilities that fabricate Materials Test Reactor (MTR) types of fuel assemblies.

Gamma-ray measurement instruments cannot be used for assay of these buttons because the 186-keV gamma rays from ^{235}U travel only a short distance (less than 2 mm) in uranium metal. Thus, only those gamma rays that originate near the surface will escape from the buttons, and consequently the interiors of these buttons cannot be "seen".

Neither fast nor thermal neutron coincidence counters, which are used to assay plutonium by detecting neutrons from the spontaneous fission of ^{241}Pu, are practical instruments for assaying ^{235}U directly because ^{235}U does not spontaneously fission at an appreciable rate.

A. Random Driver Type of Assay Instrument

Fissions can, however, be induced in the ^{235}U in the buttons by fast neutron interrogation from neutron sources (such as AmLi) and the neutrons produced from these fissions can be used as a "signature" for the assay of ^{235}U. Because both the neutrons from the interrogation sources and the neutrons from the induced fissions are fast neutrons and thus readily penetrate these highly-enriched buttons, the interiors of the buttons can be seen and an assay of their entire volumes, and not just their surfaces, is possible.

The assay instrument must be able to distinguish the neutrons from induced fission, which provide the assay signature, from those of the interrogation sources. Various techniques have been used to do this: 1) the pulsed neutron technique using delayed neutrons for assay, 2) energy discrimination technique using biased neutron detectors to distinguish fast fission neutrons from lower energy source neutrons, and 3) time-correlation techniques using neutron coincidence counting to distinguish time-correlated fission neutrons from uncorrelated (or random) source neutrons.

The assay approach discussed in this report is based on the third method: neutrons from (α,n) sources are used to induce fissions in the ^{235}U and the induced fissions are detected by neutron coincidence counting. An assay instrument that determines the ^{235}U content by inducing fissions using (α,n) neutron sources and detecting these fissions with the neutron coincidence counting technique is generally referred to as a "Random Driver" type of instrument.[1] The term "random" in the name refers to the (α,n) neutron interrogation source which emits neutrons randomly (i.e., one at a time), in contrast to the neutrons from induced fissions, which are time-correlated (i.e., produced more than one at a time). The coincidence counting technique is then used to distinguish the time-correlated induced fission neutrons from the randomly produced source neutrons.

The sources that are used to induce fissions in the ^{235}U are AmLi neutron sources. In addition to being random sources, which are required by the technique, these sources induce few fissions in ^{238}U because they produce neutrons with energies that are primarily subthreshold (less than 1 MeV) for fission in ^{238}U. Therefore, relatively few fissions occur in the ^{238}U contained in the buttons and thus the measured neutron coincidence rate is proportional to the induced fission rate in the ^{235}U (which fission with neutrons of all energies).

The original Random Driver[1-4] type of assay instruments were "fast" systems in that they detected the fast neutrons from induced fissions with plastic scintillation detectors, which are sensitive to gamma rays and fast neutrons (but not to thermal neutrons). These fast detectors were required because of the high neutron counting rates (10 000 to 100 000 counts/s) that were generated by the AmLi neutron sources (having yields of about 5×10^5 neutrons/s) located within the instruments. The plastic scintillation detectors were shielded with Pb (~ 5 cm thick) to reduce their sensitivity to gamma rays, and thus, the instruments were large and heavy (~ 1000 kg). The plastic scintillation detectors with their associated photomultiplier tubes were inherently unstable and frequent normalization of the response of the instrument to standards was required for accurate assays.

The Random Driver could be used to assay the 2-kg uranium metal buttons of interest to the IAEA, but because the instrument is so large, heavy, and unstable, it could not be used easily by the IAEA for field applications. A much smaller, lighter, and more stable instrument would be required.

B. Thermal Neutron Counters

Early attempts to use lighter and more stable thermal neutron counters, such as polyethylene moderated ^{3}He detectors, rather than fast plastic scintillation detectors for Random Driver types of instruments were not very successful because the coincidence counting electronics equipment that was used with these counters would not operate well (because of large deadtime losses) at high count rates. A Random Driver instrument based on a thermal neutron coincidence counter[5,6] that was built in the early 1970's would work only with small neutron sources (~ 10^3 neutrons/s); consequently, the sensitivity was low and the assay times were long. Even though the thermal neutron counter had the advantage of higher efficiency, greater stability, and lower weight, the fast scintillation detectors had to be used in the early Random Drivers in order to achieve reasonable sensitivities and short assay times.

In the past few years, however, the electronics equipment for neutron coincidence counting[7] with thermal neutron counters has improved greatly. A thermal neutron coincidence counter (Fig. 1) that was developed for the IAEA,[8] called the portable High-Level Neutron Coincidence Counter (HLNCC), for assay of plutonium can operate at count rates in excess of 100 000 counts/s with very small deadtime losses.

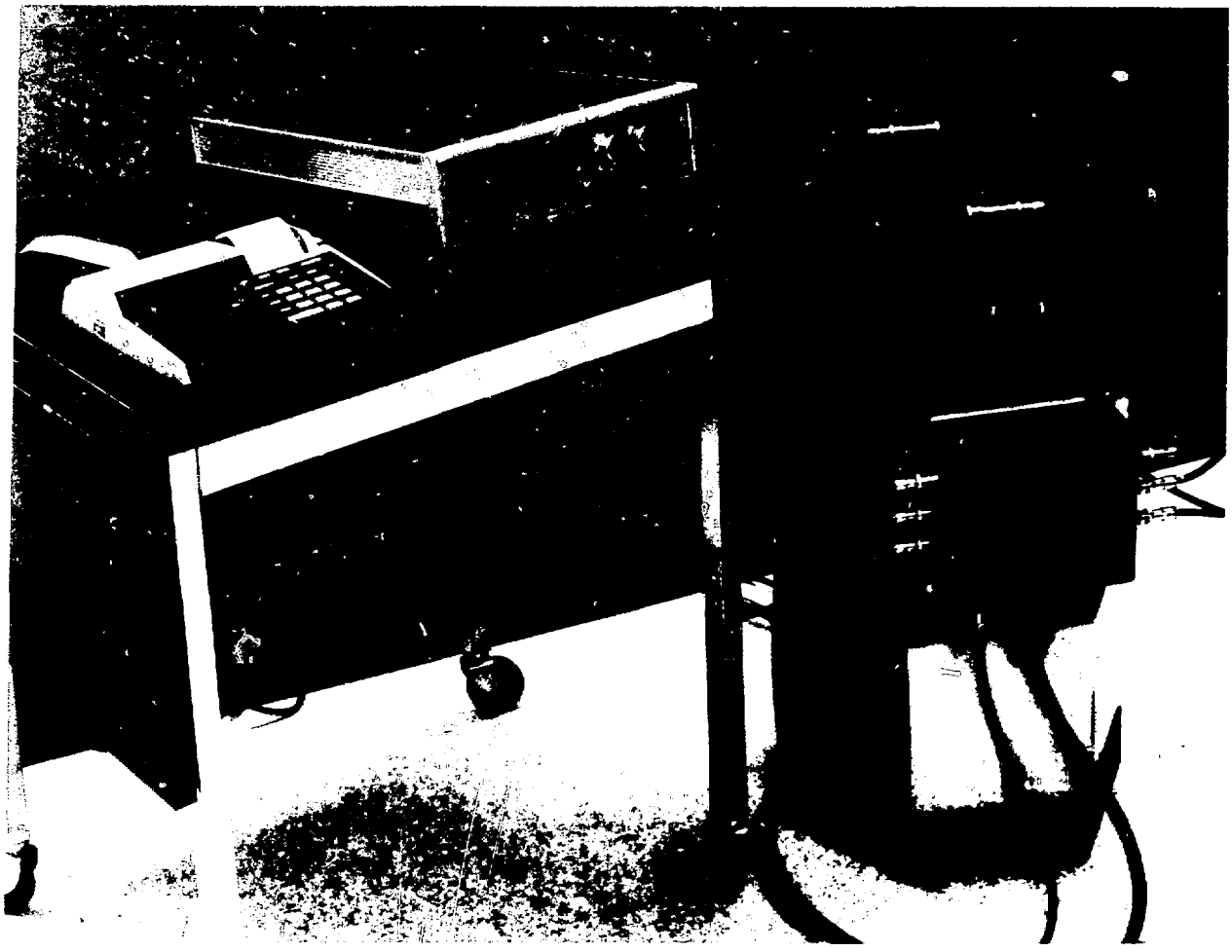

Fig. 1.
The High-Level Neutron Coincidence Counter (HLNCC) that is in routine use by the IAEA for assay of plutonium.

By using this new electronics equipment, it appeared that a Random Driver type of assay instrument could be built based on a thermal neutron coincidence counter that would have a reasonable sensitivity and short assay times. The instrument would be smaller, lighter, and more stable than the Random Drivers using fast plastic scintillation detectors. It would thus be more acceptable to the IAEA for field applications.

C. HLNCC Operating in Active Mode

This report summarizes my efforts to assay highly-enriched uranium metal buttons with a portable Random Driver type of instrument consisting of a

thermal neutron counter (polyethylene moderated ^{3}He detectors) and AmLi neutron sources (Fig. 2). The neutron counter and the coincidence counting electronics equipment used are those of the HLNCC (Fig. 1). The top and bottom reflector caps of this instrument were replaced with source assemblies that contain the AmLi neutron sources (see Fig. 3).

This version of the assay instrument is being pursued so that the IAEA can use its existing HLNCCs in the active mode to assay the uranium metal buttons, in addition to using them in the normal way (passive mode) to assay plutonium. This active version of the HLNCC is identical to the standard HLNCC (Fig. 1), except for the addition of the new source assemblies (Fig. 3).

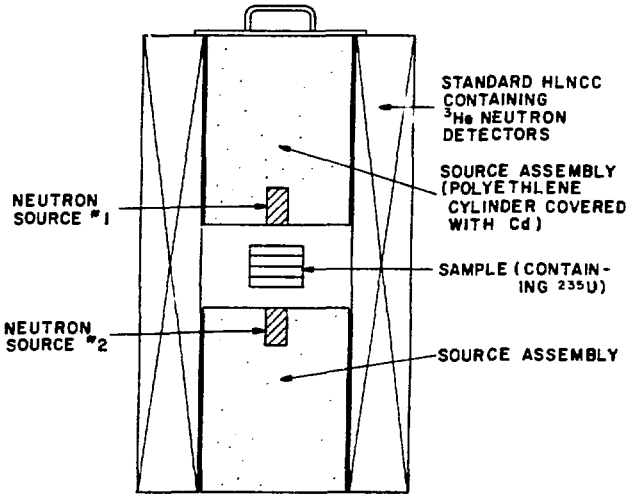

Fig. 2.
Configuration of the active version of the HLNCC.

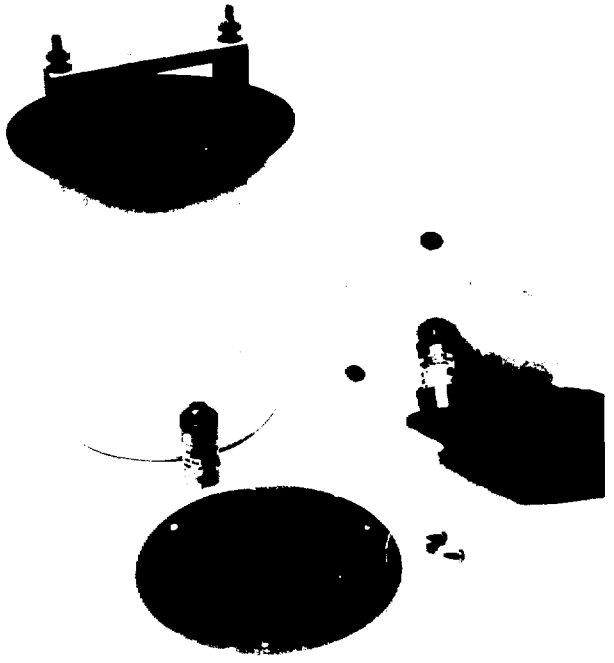

Fig. 3.
Top and bottom source assemblies and AmLi neutron sources

Because this active assay instrument is designed around an existing neutron counter, the HLNCC, so that it could be used to assay uranium as well as plutonium, I had limited flexibility in optimizing the performance of the instrument. It will be shown in this report that the usefulness of the instrument for metal buttons is for those having masses greater than about 500 g.

In Appendix A, I give a simplified theory of the operation of the active instrument and show that the performance is dependent on the ratio of the square of the detector efficiency (ε) to the gate width (t_g) of the coincidence logic unit (and thus to the die-away time of the neutron counter); i.e., to ε^2/t_g. Significant gains in the performance can be achieved if the efficiency of the neutron counter is increased from the present value of the HLNCC of about 10 percent to about 30 percent, which corresponds to an optimized neutron detector having two rings of ^{3}He detectors.

Such an optimized instrument has been built,[9] called the Active Well Coincidence Counter (AWCC), and its performance is about an order of magnitude higher than the version based on the HLNCC being discussed in this report. However, the development of this optimized AWCC will not diminish the usefulness of the active HLNCC for the assay of highly-enriched uranium metal buttons. The active HLNCC has several attractive features even if its performance is lower than that of the AWCC: it is portable, it gives reasonable counting times for highly-enriched buttons, and perhaps most importantly, the IAEA already has several HLNCCs, and with the addition of source assemblies and AmLi neutron sources, these instruments become capable of assaying uranium metal buttons.

II. THE ACTIVE HLNCC

As mentioned above, the active version of the HLNCC is identical to the standard HLNCC except for the replacement of the top and bottom reflector caps by new source assemblies (Fig. 3), which contain the AmLi neutron sources. These sources assemblies (17.5 cm diam. by 23 cm high) are constructed of polyethylene in order to provide some shielding of the ^{3}He detectors in the HLNCC from the neutron sources.* This shielding is desirable because it reduces the

*The importance of this shielding in improving the performance of the instrument was suggested by H. O. Menlove, LASL.

accidentally produced coincidence rate and thus increases the assay precision for a given assay time.

The two AmLi neutron sources have strengths of 1.1×10^4 neutrons/s each. As shown in Appendix A, larger source strengths are not required. These sources as manufactured* are double encapsulated in 304-type stainless steel and they have external measurements of 1.91 cm (0.75 inches) in diameter by 3.18 cm (1.25 inches) in length. Each source contains about 0.09 Ci (or 0.027 g) of ^{241}Am.

To reduce the gamma-ray dose rate from the ^{241}Am so that the sources can be handled more safely, I enclosed the sources inside tungsten containers (Fig. 4) having a minimum wall thickness of 0.25 cm (0.1 inches). The outside dimensions of the tungsten containers are 2.54 cm (1.0 inches) in diameter by 5.08 cm (2.0 inches) in length. The gamma-ray dose rate is less than 1 mR/h on the surface of the tungsten container. One end of each tungsten container is keyed (Fig. 5) with a pin so that a source will fit (1) into only the proper source assembly (Fig. 2) and (2) into only the proper orientation.

*Monsanto Research Corporation, Dayton, Ohio, USA, Model 24169BT container, IAEA Certificate of Competent Authority, Special Form Radioactive Material Encapsulation Certificate number USA/0186/S.

Fig. 4.
AmLi source inside tungsten shield.

Fig. 5.
AmLi neutron sources in tungsten containers with keyed pins.

The configuration and dimensions of the active HLNCC that was used for the measurements are shown in Fig. 6. The assay chamber is about 11 cm high. The ends of the source assemblies that face the assay chamber and the inside surface of the HLNCC are covered with Cd sheet. Thus, the entire assay chamber is lined with Cd. The Cd liner is required for two reasons: (1) for "hardening" the neutron flux so that good penetration of the sample is achieved and (2) for criticality safety.

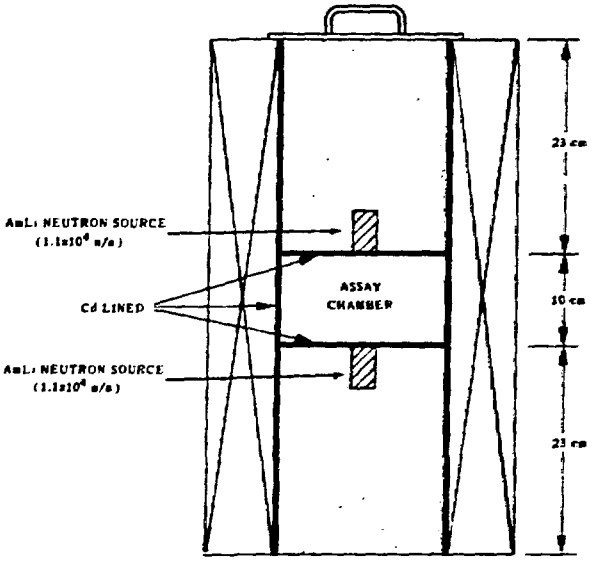

Fig. 6.
Configuration of the active HLNCC used during the measurements.

Because the samples to be assayed are placed into an assay chamber (Fig. 6) that is completely surrounded by polyethylene, which is a good neutron reflector, care must be taken concerning criticality safety. The samples exhibit higher levels of neutron multiplication when inside the chamber. Prior to using the active HLNCC for assay, a criticality safety analysis must be done to establish an upper limit to the mass that can be put safely into the assay chamber.

Before using the instrument for the assay of the uranium metal buttons that were used in this investigation, a mass of 4.3 kg of total uranium (i.e., ^{235}U + ^{238}U) was established as a safe limit. Administrative controls were also established so that double batching of the buttons could not occur.

This limit of 4.3 kg was satisfactory for this investigation because : 4.3 kg would be assayed in any measurement. If assays of larger masses were anticipated, a higher limit could possibly be developed by performing a criticality analysis.

III. URANIUM METAL BUTTONS

Buttons of different sizes are assembled by stacking various numbers of disks of highly-enriched (93 percent ^{235}U) uranium metal (Fig. 7). Disks with two different diameters (6.11 cm and 7.11 cm) are used so that the change in response as a function of the diameter of the buttons can be studied.

The characteristics of these highly-enriched metal disks are given in Table I. With the 6.00 cm diameter disks I can assemble buttons ranging in height from 0.5 cm (containing about 245 g ^{235}U) to 8.00 cm (containing about 3930 g ^{235}U) in steps of 0.5 cm; and with the 7.00 cm diameter disks I can assemble buttons from 1.00 cm high (containing about 725 g ^{235}U) to 4.00 cm high (containing about 2913 g ^{235}U) in steps of 1.00 cm. A 4.00 cm high button (6.00 cm diameter) containing 1967 g ^{235}U that was assembled from these disks is shown in Fig. 8.

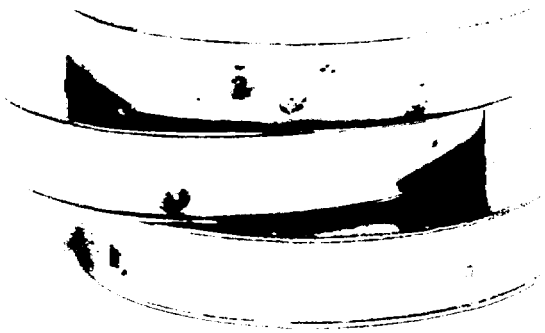

Fig. 7.
Examples of the highly-enriched uranium metal disks used to construct buttons.

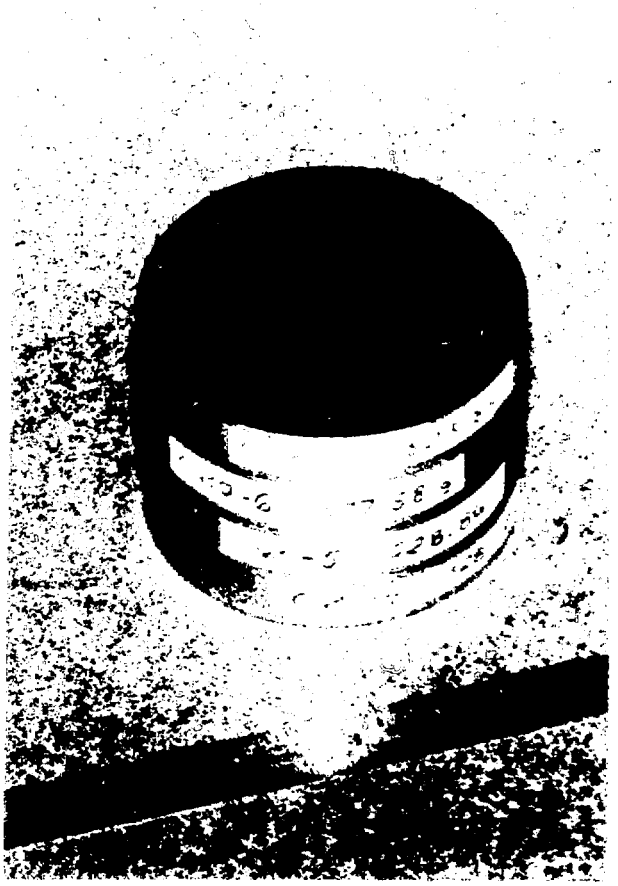

Fig. 8.
A 4.00-cm-high button assembled from four highly-enriched uranium metal disks.

TABLE I

U(93) METAL DISK SAMPLES*

I.D.	Enrichment (%)	Total Weight (g)	Total U (g)	U-235 (g)	Description
C20-8	93.17	270.86	264.33	246.28	0.50 cm thick x 6.00 cm dia.
C20-9	93.17	269.51	262.27	244.36	0.50 cm thick x 6.00 cm dia.
C20-1	93.17	536.48	527.73	491.69	1.00 cm thick x 6.00 cm dia.
C20-2	93.17	537.49	527.21	491.20	1.00 cm thick x 6.00 cm dia.
C20-3	93.17	537.61	528.30	492.22	1.00 cm thick x 6.00 cm dia.
C20-4	93.17	535.86	528.32	492.24	1.00 cm thick x 6.00 cm dia.
C20-5	93.17	538.75	528.86	492.74	1.00 cm thick x 6.00 cm dia.
C20-6	93.17	536.16	527.58	491.55	1.00 cm thick x 6.00 cm dia.
C20-7	93.17	531.72	523.84	488.06	1.00 cm thick x 6.00 cm dia.
C19-1	93.15	728.60	717.57	668.42	1.00 cm thick x 7.00 cm dia.
C19-2	93.15	727.59	716.07	667.02	1.00 cm thick x 7.00 cm dia.
C19-3	93.15	728.22	718.07	668.88	1.00 cm thick x 7.00 cm dia.
C19-4	93.15	728.79	718.33	669.12	1.00 cm thick x 7.00 cm dia.

*These samples have been plated with a thin Ni layer to prevent oxidation.

IV. MEASUREMENTS

I have completed the following investigations with the active version of the HLNCC:

1. Determined the response of the instrument as a function of the mass of the buttons.
2. Determined the response of the instrument as a function of the location of the button inside the assay chamber.
3. Determined the change in the response of the instrument to substitution of depleted uranium for highly-enriched uranium.

Appendix B gives the specific details related to the electronic settings and source configurations for the measurements.

A. Response as a Function of the Mass of the Button

The measured neutron coincidence count rates that were obtained for buttons having different masses are given in Table II and are plotted in Fig. 9. For these measurements the buttons were always centered--both vertically and horizontally--in the assay chamber. The upward curvature of the response curve seen in Fig. 9 is probably due to: (1) neutron multiplication in the button, and (2) nonlinear response with position (to be discussed in the next section of this report) in the assay chamber.

In Fig. 9, I observe that the response is insensitive to the diameter of the button for diameters in the range of 6 to 7 cm.

The standard deviation (1σ) of a measurement is almost entirely governed by the accidental coincidence rate produced by the AmLi neutron sources and it is essentially independent of the mass of the sample being assayed (see Appendix A). It is also nearly independent of the strengths of the AmLi neutron sources. For a 1000-s count time, the standard deviation of a measurement (as estimated from Poisson statistics) is ~50 g of ^{235}U. The precision of an assay in terms of percent standard deviation (standard deviation divided by the mass) for 1000-s assays as a function of the mass of the button is shown in Fig. 10.

TABLE II

MEASURED COINCIDENCE RATE
(Data plotted in Fig. 9)

Sample	^{235}U Mass (g)	Coincidence Rate* (cps)
6 cm dia samples		
C20-1	491.69	2.02 ± 0.14
C20-1,-2	982.89	3.38 ± 0.18
C20-1,-2,-3,-4	1967.35	7.55 ± 0.20
C20-1,-2,-3,-4,-5,-6	2951.64	12.00 ± 0.21
C20-1,-2,-3,-4,-5,-6 -7,-8,-9	3930.34	13.49 ± 0.33
7 cm dia samples		
C19-1	668.42	2.49 ± 0.10
C19-1,-2	1335.44	5.15 ± 0.13
C19-1,-2,-3	2004.32	7.94 ± 0.12
C19-1,-2,-3,-4	2673.44	10.84 ± 0.21

*Uncertainty given is one standard deviation (1σ) obtained from Poisson statistics.

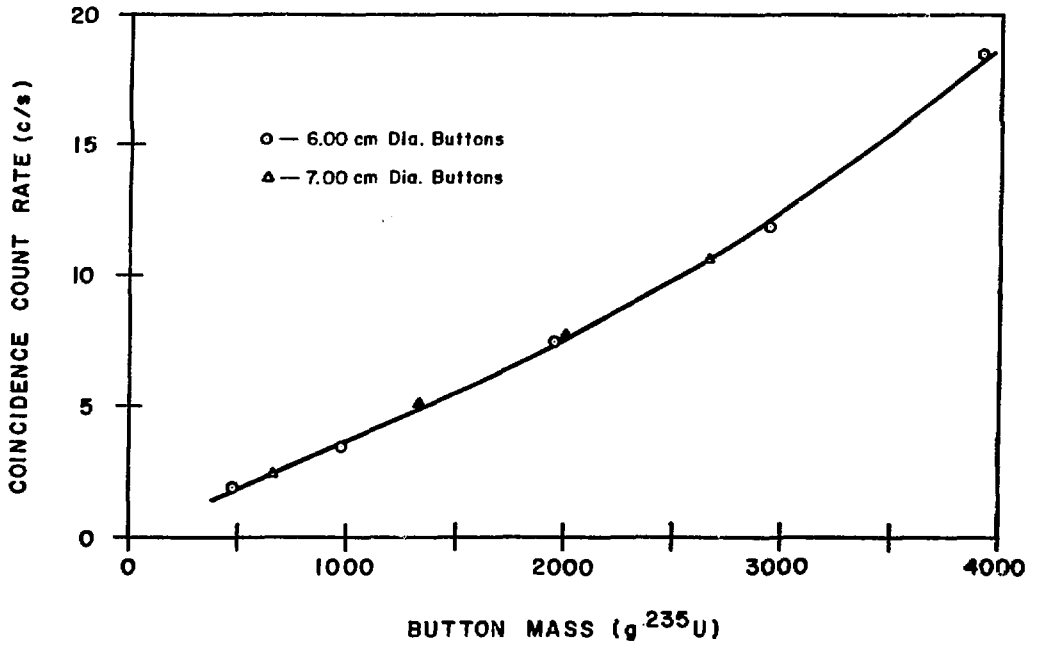

Fig. 9.
Response as a function of the mass of the highly-enriched metal buttons.

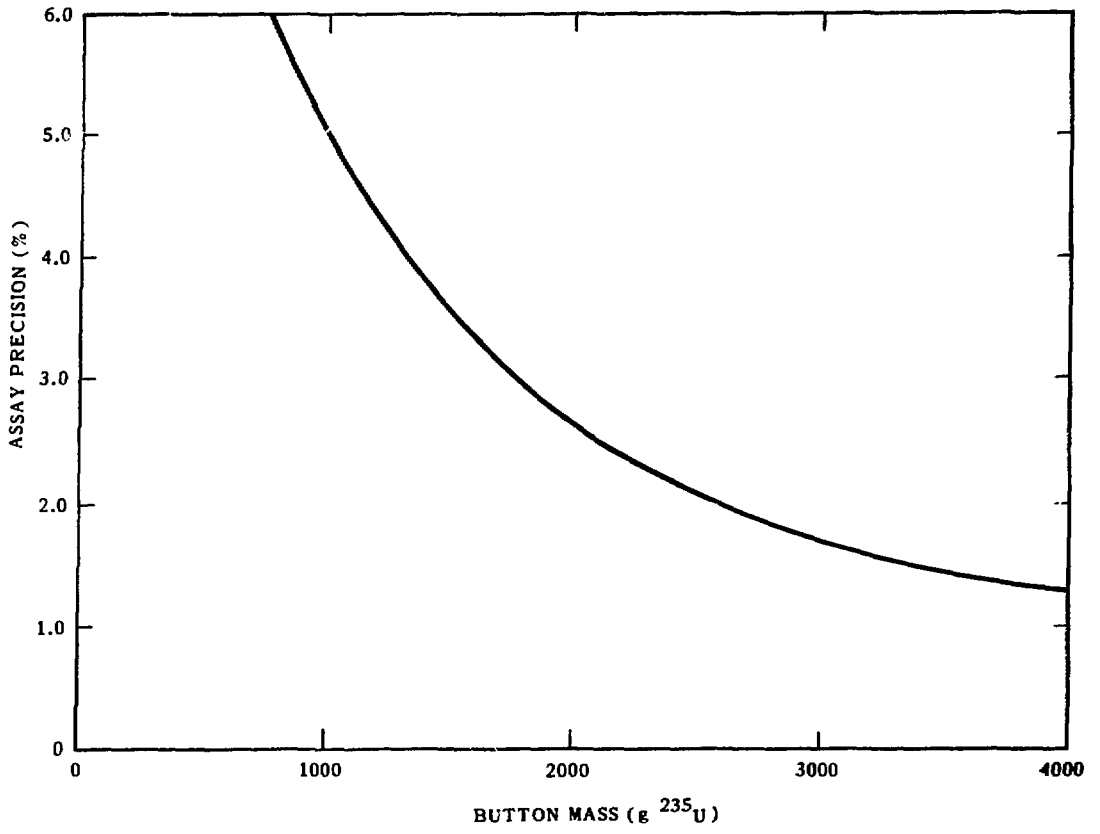

Fig. 10.
Estimated assay precision (1σ) as a function of button mass for a 1000-s assay.

B. Response as a Function of Location of Button Inside Chamber

A 6.00 cm dia by 4.00 cm high button containing 1967 g of ^{235}U was counted at various vertical positions within the 10 cm high assay chamber. The button was always centered radially in the chamber. The response as a function of the vertical position normalized to the response at the center of the chamber is shown in Fig. 11. The zero in Fig. 11 distance corresponds to the button being centered in the chamber while the 3 cm position corresponds to the button being displaced as close to the lower neutron source as possible, i.e., the button is sitting on the lower source assembly.

This position effect indicates that part of the upward curvature seen in Fig. 9 is due to the nonlinear response with position. The larger mass buttons are taller than the lower mass ones and thus more of their volumes are in the regions of the assay chamber with higher responses.

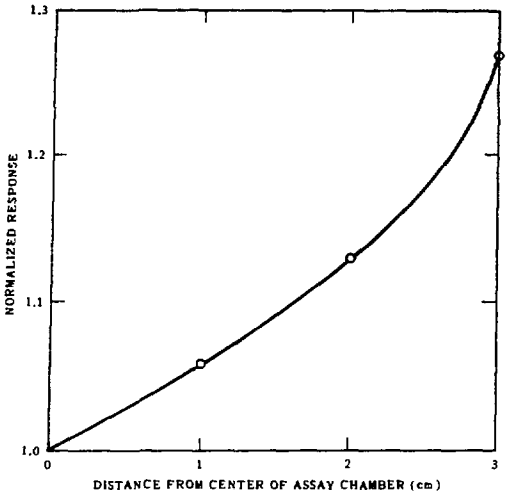

Fig. 11.
Normalized response of a 4.00-cm-high button as a function of vertical position inside the assay chamber. The zero distance corresponds to the button located at center of assay chamber.

C. Response to Substitution of Depleted Uranium

Measurements were made on two buttons to determine the change in response if a fraction of the highly-enriched metal is replaced with depleted (0.2 percent ^{235}U) uranium metal. A 4.00 cm high button (containing 2111 g of uranium or 1967 g of ^{235}U) and a 6.00 cm high button (containing 3168 g of uranium or 2952 g of ^{235}U) were assembled by stacking highly-enriched metal disks (each 1.00 cm thick by 6.00 cm dia). Fig. 12 illustrates the configuration of these buttons. The position of each disk in the button is identified by a number; position 1 corresponds to the top position of both buttons; position 4 to the bottom position of the 4.00 cm high button and position 6 to the bottom position of the 6.00 cm high button. During these measurements the highly-enriched uranium metal disks in various positions were replaced by disks of depleted uranium of the same size. Table III gives the normalized responses for various substitutions. These responses are also plotted in Figs. 13 and 14. I observe that the decrease in response is roughly linear with the amount of ^{235}U removed.

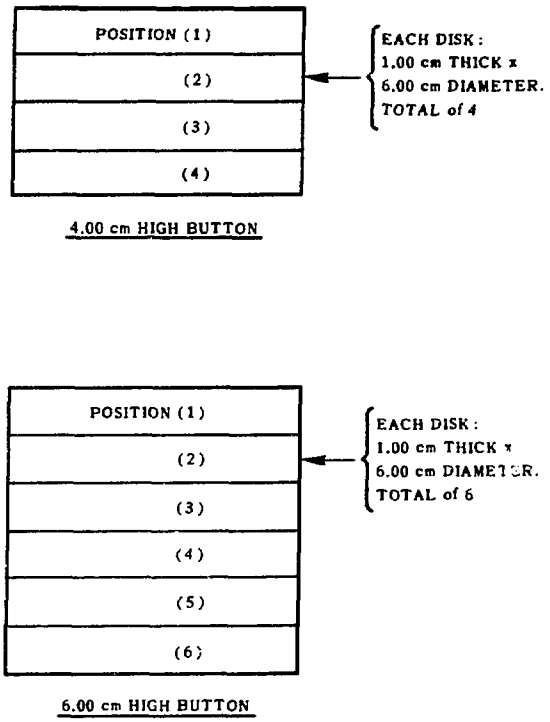

Fig. 12.
Button configuration and disk position indication for depleted uranium substitution.

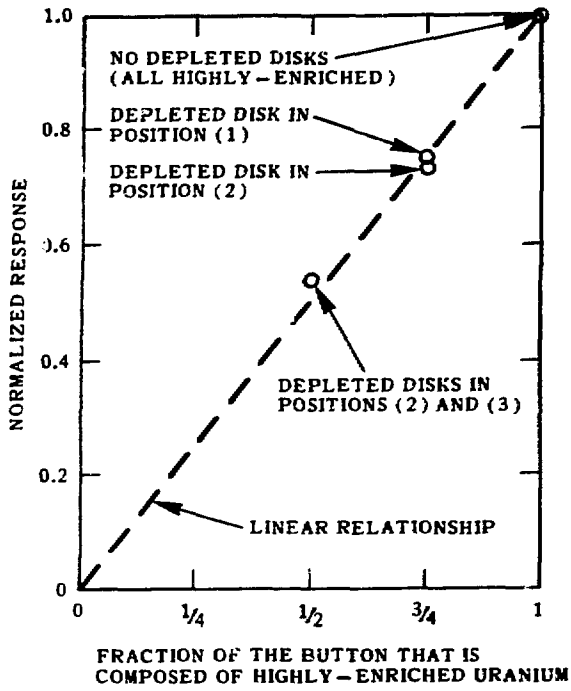

Fig. 13.
Normalized response for substitution of depleted uranium in a 4.00-cm-high button.

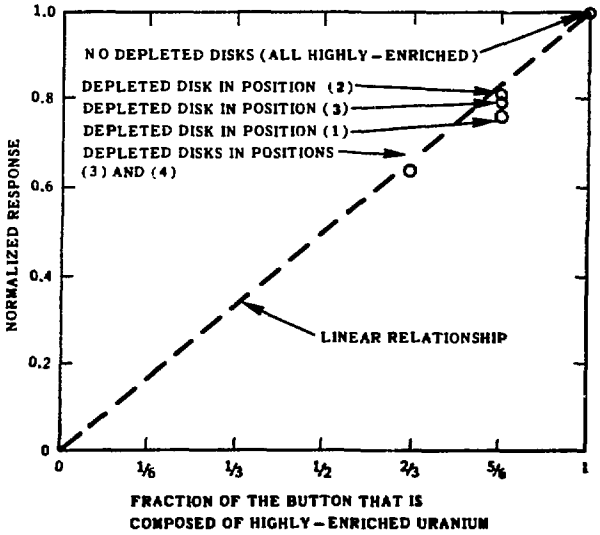

Fig. 14.
Normalized response for substitution of depleted uranium on a 6.00-cm-high button.

TABLE III

RESPONSE TO SUBSTITUTION OF DEPLETED URANIUM

4 cm High Button

Button Configuration	Normalized Response
No depleted disks	1.00
Depleted disk in position 1	0.74 ± 0.02
Depleted disk in position 2	0.73 ± 0.02
Depleted disk in positios 2 and 3	0.54 ± 0.02

6 cm High Button

Button Configuration	Normalized Response
No depleted disks	1.00
Depleted disk in position 1	0.77 ± 0.01
Depleted disk in position 2	0.79 ± 0.01
Depleted disk in position 3	0.78 ± 0.01
Depleted disk in positions 3 and 4	0.63 ± 0.01

V. SUMMARY

The results obtained from the investigations that are summarized in this report indicate that the active version of the HLNCC--which is identical to the HLNCC except that the top and bottom reflector caps have been replaced with source assemblies that contain AmLi neutron sources--is a practical instrument for assaying highly-enriched uranium metal buttons with masses in the range of 0.5-4 kg. Some specific conclusions that were obtained in the investigation are:

A. There is sufficient count rate to give reasonable counting statistics on highly-enriched uranium metal buttons in 1000 s (about 15 minutes). Using a 10 cm high assay chamber, I obtained ~2.5 percent counting precision on a 2 kg button in 1000 s.

B. The response curve (or calibration curve) obtained during these measurements (Fig. 9) is a smooth function--but not a linear function--of the ^{235}U mass of the button. The nonlinearity observed in Fig. 9 is probably due to (1) neutron multiplication in the button, and (2) location of the button within

the assay chamber. The nonlinearity is not large, however, and a determination of the mass of the button from a measured coincidence count rate using a calibration curve such as that of Fig. 9 should be straightforward.

C. The response of the instrument is independent of the diameter of the button, at least for buttons having diameters in the range of 6-7 cm.

D. The ^{235}U assay gives the correct result in the case where part of the highly-enriched uranium has been substituted by depleted uranium. Figs. 13 and 14 indicate that the change in response is roughly linear with the amount of mass substituted. I infer from this result that the instrument is adequately sampling the entire volume of the button and is not sampling just the surface.

ACKNOWLEDGMENTS

I would like to thank A. Ramalho of the IAEA, and H. O. Menlove and R. B. Walton of LASL for their expert help with this investigation.

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APPENDIX A

THEORY OF OPERATION OF THE AWCC

I. CALCULATIONS

The induced fission rate in the button is given approximately by

$$\dot{I} = KMS \quad , \tag{A-1}$$

where K - is a constant (fisson/n - g)
M - mass of U-235 in sample (g)
S - neutron source strength (n/s).

The observed coincidence rate from these induced fissions is given approximately by

$$\dot{C} = B\epsilon^2\dot{I}$$
$$= B\epsilon^2 KMS \quad , \tag{A-2}$$

where B - is a constant related to the multiplicity ($\bar{\nu}$) of the fissioning isotope
ϵ - is the efficiency of the neutron detector for detecting fission neutrons.

The accidental coincidence rate produced by the random source is

$$\dot{A} = \epsilon'^2 S^2 t_g \quad , \tag{A-3}$$

where t_g - gate width of the coincidence unit
ϵ' - is the efficiency of the detector for detecting source neutrons.

The geometry of the detector is such that the efficiency for detecting fission neutrons (ϵ) is higher than the efficiency for detecting source neutrons (ϵ'). For example, the solid angle for detecting fission neutrons is nearly 4π, whereas that for the source neutrons is more nearly 2π. I will let $\epsilon' = \alpha\epsilon$, where α is a constant equal to the ratio of the solid angles of the detector for source and fission neutrons ($\alpha \sim 1/2$). Then

$$A = \alpha^2 \epsilon^2 S^2 t_g \quad . \tag{A-4}$$

The count rate in the real and accidental scaler, $(\overline{R + A})$, is then

$$(\overline{R + A}) = B\epsilon^2 KMS + \alpha^2 \epsilon^2 S^2 t_g \quad , \tag{A-5}$$

and the count rate in the accidental scaler A is

$$A = \alpha^2 \epsilon^2 S^2 t_g \quad . \tag{A-6}$$

The assay precision, p, defined as the standard deviation of the number of coincidence counts to the number of coincidence counts is approximately (assuming Poisson statistics)

$$p = \frac{\sqrt{(B\epsilon^2 KMS + 2\alpha^2 \epsilon^2 S^2 t_g)\ T}}{B\epsilon^2 KMST} \quad ,$$

where T is the assay time. The time required to obtain a desired assay precision is

$$T = \frac{1}{\epsilon^2 p^2 (BKM)^2 S} (BKM + 2\alpha^2 S t_g) \quad . \tag{A-7}$$

For large values of S (i.e. when $2\alpha^2 St_g >> BKM$) this equation reduces to

$$T = \frac{2\alpha^2 t_g}{P^2 \epsilon^2 B^2 K^2 M^2} , \qquad (A-8)$$

which is independent of S.

II. NUMERICAL VALUES

Estimates for all of the parameters can be easily obtained. For example, the following values are good estimates for a system based on the HLNCC:

$\epsilon = 0.10$
$t_g = 32 \times 10^{-6}$ s
$\alpha = 1/2$
$B = 2.$

An estimate of the value of K can be obtained from Eq. 2 by using the measured values of the coincidence rate found in Table II. The estimate of K obtained is

$K \sim 1 \times 10^{-5}$ fissions/n-g.

III. ESTIMATE OF REQUIRED NEUTRON SOURCE STRENGTH

Eq. A-8 is satisfied when

$$S >> \frac{BKM}{2\alpha^2 t_g} .$$

Using the numerical values estimated above, I find that for a button having a mass of ~2000 g ^{235}U that

$S >> 2500$ n/s .

Thus, the neutron source strength does not need to be larger than about 10^4 n/s. A larger source strength will not reduce the assay time - diminishing returns have been reached with this source strength.

IV. CONCLUSIONS DRAWN FROM THESE CALCULATIONS

Two important conclusions can be drawn from these calculations:

1. The time required to assay a sample is nearly independent of the strength of the neutron source when the strength is above ~10^4 n/s.
2. It is important that the ratio of the square of the detector efficiency (ε) to the gate width (t_g) be as large as possible, i.e., ε^2/t_g should be maximized. The neutron detector should thus have a high efficiency and a short neutron die-away time.

APPENDIX B
EQUIPMENT SETTINGS

I. HLNCC SPECIFICS

A. Detector: IAEA Unit 1

B. Electronics: HLNCC electronics package, serial number 002

C. High voltage = 1500 volts

D. Discriminator setting = 1.5 volts

E. Gate width = 32 μs

II. RANDOM NEUTRON SOURCES

A. Top source MCR AmLi no. 76, 1.1 x 10^4 n/s

B. Bottom source MCR AmLi no. 78, 1.1 x 10^4 n/s

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