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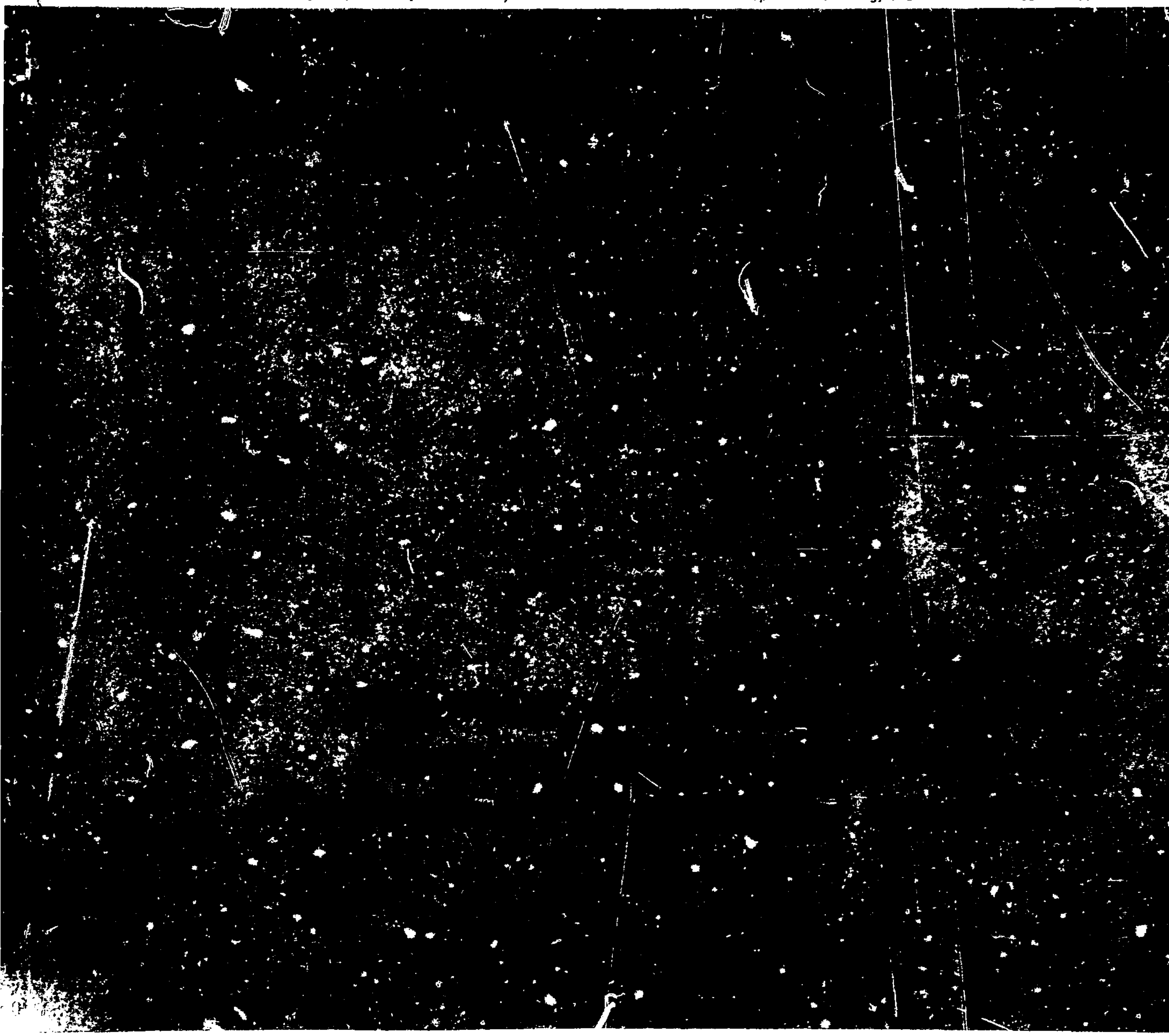

Los Alamos
Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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Description and Performance Characteristics for the Neutron Coincidence Collar for the Verification of Reactor Fuel Assemblies

Howard O. Menlove

Los Alamos

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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DESCRIPTION AND PERFORMANCE CHARACTERISTICS FOR THE NEUTRON COINCIDENCE COLLAR FOR THE VERIFICATION OF REACTOR FUEL ASSEMBLIES

by

Howard O. Menlove

ABSTRACT

An active neutron interrogation method has been developed for the measurement of ^{235}U content in fresh fuel assemblies. The neutron Coincidence Collar uses neutron interrogation with an AmLi neutron source and coincidence counting the induced fission reaction neutrons from the ^{235}U. This manual describes the system components, operation, and performance characteristics. Applications of the Coincidence Collar to PWR and BWR types of reactor fuel assemblies are described.

I. INTRODUCTION

The neutron Coincidence Collar was developed to verify the ^{235}U content in reactor fuel assemblies. This instrument uses an AmLi neutron source to interrogate the entire cross section of the fuel assembly. The AmLi neutrons are low enough in energy so that the primary fission rate in the ^{238}U is negligible.

The ^{235}U enrichment of the exterior fuel rods can be measured using passive gamma-ray techniques; however, because of absorption problems the interior rods cannot be measured with this approach. An autoradiograph, with x-ray film placed between the fuel pins, has been used by the International Atomic Energy Agency (IAEA) and Brumback[1] at Argonne National Laboratory (ANL) to give semiquantitative verification of the enrichment of the interior fuel pins. However, this approach is both time consuming and intrusive.

Several years ago, we developed an active neutron technique[2] (the neutron Collar) to verify ^{235}U content by neutron interrogation and fast neutron counting using ^4He detectors. This approach has limited sensitivity in the interior regions of pressurized water reactor (PWR) fuel assemblies because of thermal-neutron penetrability problems and geometric considerations. Recent advances with the Active Well Coincidence Counter[3] have made it possible to apply this same technical approach to the verification of full light water reactor (LWR) fuel assemblies. The method involves neutron interrogation with an AmLi neutron source and coincidence counting the induced fission reaction neutrons from the ^{235}U. The coincidence counting separates the fission neutrons, which originate from ^{235}U, from the random neutrons used in the interrogation. This "Coincidence Collar" approach has the following advantages over the previously developed neutron "Collar".

1. The AmLi neutron source strength requirement is a factor of 10 smaller, reducing transportation and handling problems. The prior Collar uses a 5×10^5 n/s source and the Coincidence Collar uses a 5×10^4 n/s source.
2. The sensitivity to the removal of interior fuel pins in an assembly is at least a factor of two better with the Coincidence Collar because of fast neutron multiplication and coincidence counting enhancement and the source detector geometry.
3. In addition to verifying the ^{235}U in the active interrogation mode, the Coincidence Collar can verify the ^{238}U in the passive mode and give a rough confirmation of ^{234}U content.
4. The Coincidence Collar uses the same electronics as the high-level neutron coincidence counter (HLNCC), so the IAEA has an inventory of the units and is familiar with its use and maintenance.

The Coincidence Collar has significant advantages over presently available techniques for the verification of fresh fuel assemblies. This manual describes the system components, operation, and performance characteristics. Applications of the Coincidence Collar to PWR, boiling water reactor (BWR), and other type fuel assembly configurations are described.

II. SYSTEM DESCRIPTION

A. Detector Body

A schematic diagram of the Coincidence Collar is shown in Fig. 1. The fuel assembly is surrounded by three detector banks and the AmLi source moderator

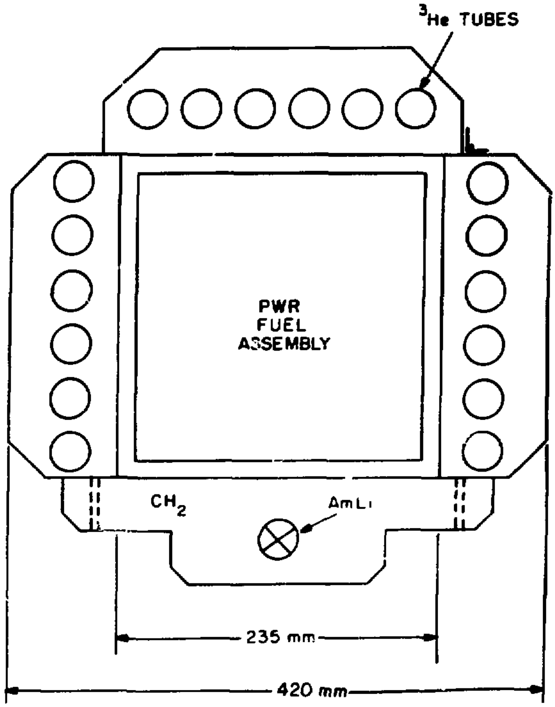

Fig. 1
Schematic diagram of Coincidence Collar showing the AmLi neutron source and the ^{3}He detector banks. The top detector bank neutron source pivots open to accommodate PWR, BWR, or HWR fuel assemblies.

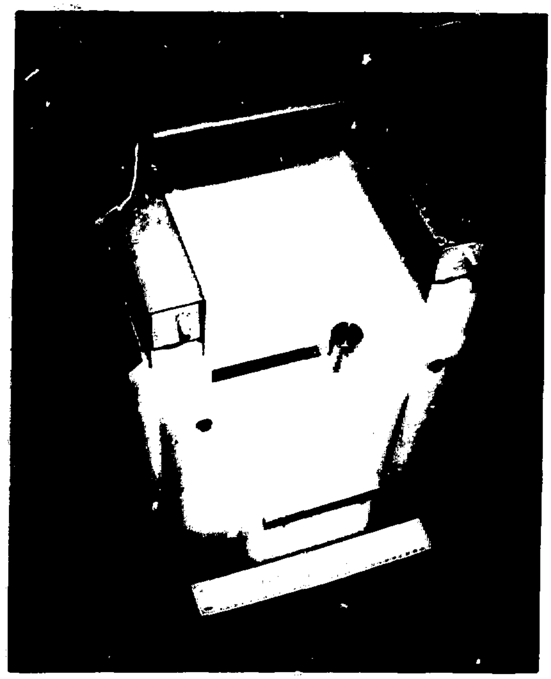

Fig. 2
Top view of Coincidence Collar showing the three CH_2 detector banks and the AmLi neutron interrogation source.

(see Appendix A). The ^{3}He detectors are embedded in high-density polyethylene. The detector unit is about 0.43 m long and the back detector section pivots on a hinge to facilitate placing the system around fuel assemblies. Figure 2 is a top view of the Coincidence Collar with the back door (^{3}He detector bank) closed in the normal configuration for counting PWR fuel assemblies. Figure 3 shows the back door open for the movement to or from a vertical fuel assembly. The three detector banks, the He tubes and junction boxes, and the neutron source moderator weigh a total of ~24 kg. This unit and its associated electronics are normally supported by a cart that is described in Sec. III-E.

The original design of the Coincidence Collar had two AmLi sources, one on the front and one on the back of the assembly, to obtain better penetrability into the central region of the fuel assembly. However, the experiments demonstrated that the sensitivity to rod removal in the central and back regions was as good or better when the back AmLi source was replaced by the ^{3}He detector bank shown in Fig. 1.

No cadmium liners are used with the Coincidence Collar for normal operation because the interrogation uses thermal neutrons. In-plant tests have demonstrated that it is unnecessary to shield the unit from external neutrons. In a typical fuel fabrication plant, the neutron background is primarily from spontaneous fission of ^{238}U in the large UO_2 inventory and these neutrons have energies above the cadmium cutoff (0.3 eV). Measurements using a prototype Coincidence Collar at a large fabrication plant for reactor fuel confirmed this conclusion.

Fig. 3
Top view of Coincidence Collar with rear door open for placing unit around sample.

For application to BWR fuel assemblies or other small elements, the side detector banks on the Coincidence Collar adjust inward to a second set of bolt holes to obtain better coupling between the detectors and the sample. The smaller BWR configuration is shown in Fig. 4. Each Coincidence Collar can be adjusted for PWR or BWR geometry. Only two positions are used because each detector-source geometry requires a separate calibration and it is desirable to reduce the calibration effort. Thus, small variations between the different type of assemblies are accommodated within these two settings.

B. Neutron Source

The Coincidence Collar uses an AmLi neutron source purchased from Monsanto Research Corporation, Dayton, Ohio. Table I lists the characteristics of the source and Fig. 5 is a photograph of one of the sources. Figure 6 is a schematic diagram of the tungsten shield, fabricated at Los Alamos, that is placed around the AmLi source to reduce the gamma-ray dose. The source gives a dose of 0.1 mR/h in air at a distance of 30 cm and less than 0.3 mR/h at the surface of the assay system. Each source is attached to a CH_2 rod as shown in Fig. 7 to facilitate handling and removal from the Coincidence Collar for the passive portion of the assay.

The AmLi sources have a long half-life (432 yr) so the original source will last for the life of the assay system. The AmLi source has a neutron yield of approximately 4.5×10^5 n/s, which is an order of magnitude less than the source used in the original Collar supplied to the IAEA. This should simplify some aspects of handling and transportation. The present Coincidence Collar was designed with a CH_2 sleeve in the source hole so that it will accommodate the larger sources that the IAEA now has for the original Collar, as well as the smaller source of the present size. The statistical performance of the unit is approximately the same for both source intensities, and either size can be used with the system. However, the calibration curve must be renormalized if the source intensity is changed.

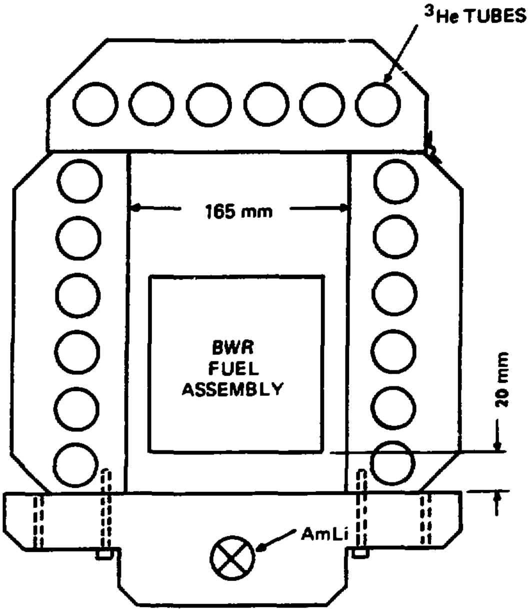

Fig. 4
Schematic diagram of Coincidence Collar with sides moved in to correspond to the BWR configuration.

Fig. 5
Photograph of AmLi neutron source inside its tungsten container (or pipe).

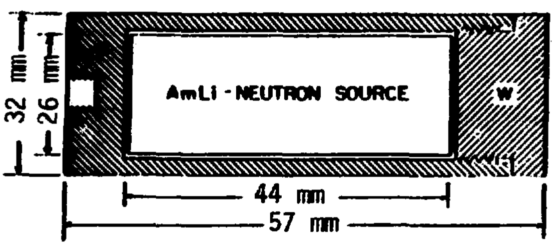

Fig. 6
Schematic diagram of tungsten holder for the AmLi neutron sources.

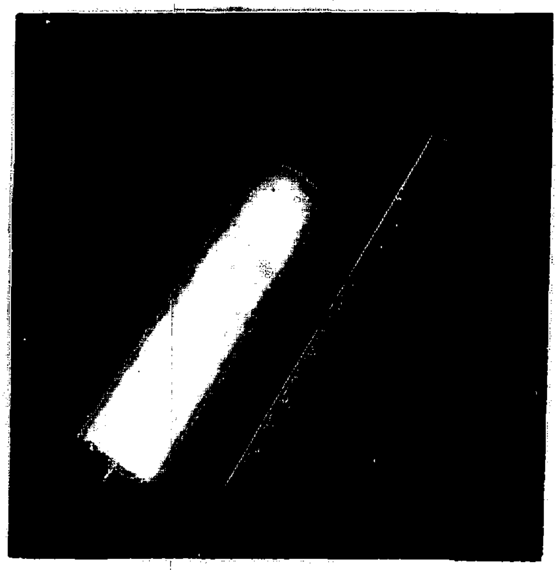

Fig. 7
AmLi neutron source and CH_2 handling rod for use in the Coincidence Collar.

TABLE I

$^{241}AmO_2$-Li NEUTRON SOURCE CHARACTERISTICS

Coincidence Collar	Source Number	Am't of ^{241}Am	Li	Emission Rate
1	MRC-AmLi-91	0.63 Ci or 0.185 g	2.3 g	4.55×10^4 n/s
2	MRC-AmLi-92	0.63 Ci or 0.183 g	2.3 g	4.48×10^4 n/s
3	MRC-AmLi-93	0.66 Ci or 0.193 g	2.3 g	4.67×10^4 n/s

Technical Information

Chemical Form:	AmO_2
Isotope:	Am-241
Source Container Description:	MRC Model 2724-BT
Shipping Container:	10 gal drum, 6M-1026 USDOT Spec. 6m, Type B
Purchase Order Number: (Monsanto Research Corporation)	5LBO-0253R-1

The AmLi sources were fabricated by the Monsanto Research Corporation, Dayton Laboratory, Dayton, Ohio, and are designated Model 2724-BT. The AmO_2 is contained in two 304 stainless steel cylinders with welded top plugs. The inner cylinder has an o.d. of 17.8 mm and the outer cylinder has an o.d. of 25.4 mm. The overall length is 34.8 mm. This doubly contained source is then placed in the unsealed tungsten container shown in Fig. 6. The sealed steel container (Model 2724-BT) has the IAEA Certificate of Competent Authority US/0043/S.

C. Neutron Detector Tubes

The Coincidence Collar has three identical banks of ^{3}He tubes. Each bank contains six tubes (Reuter-Stokes model RS-P4-2813-107-W) that are 2.54 cm in diameter and 33 cm long (active length). The detectors are matched to operate at the same high voltage (~1500 V) with a resolution of better than 9 percent. These detectors have been fabricated to match the ^{3}He tubes used in the IAEA's HLNCC units and they should operate satisfactorily at the same hv and discriminator settings used with the HLNCC electronics.

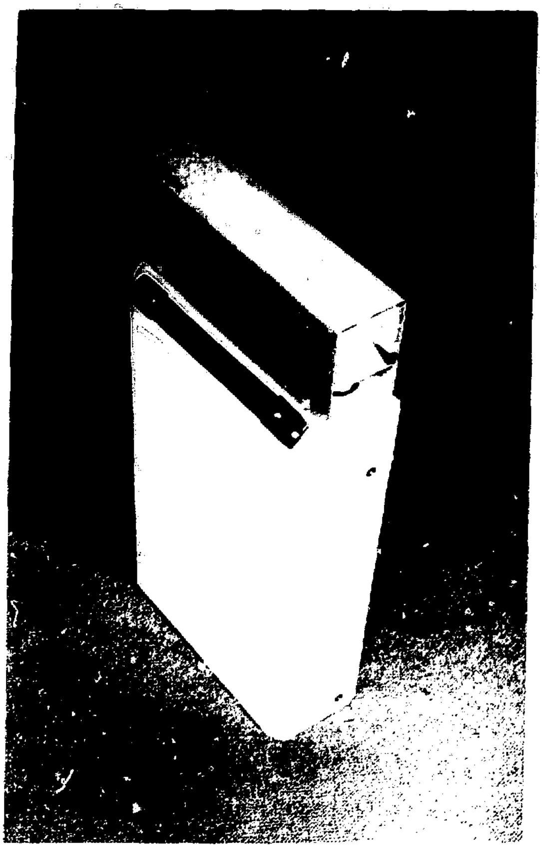

Fig. 8
Side detector bank removed from Coincidence Collar.

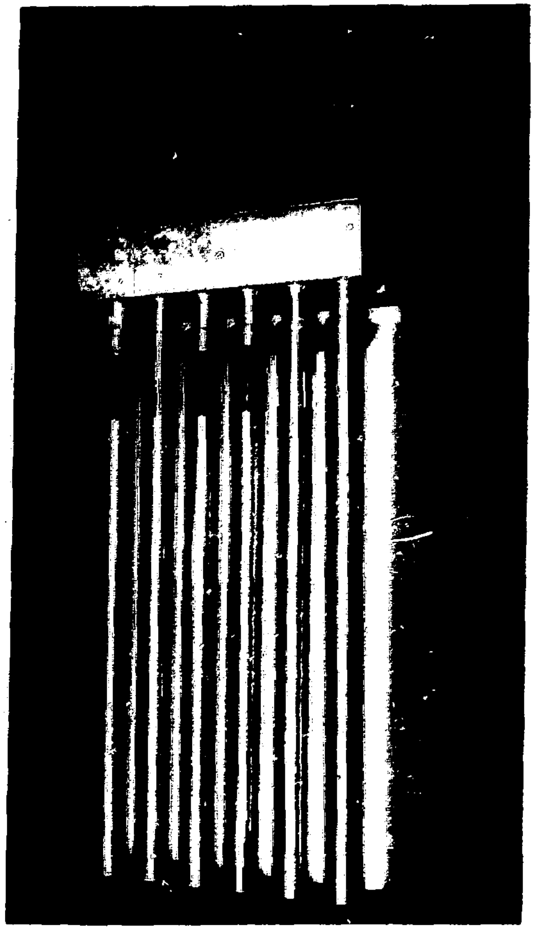

Fig. 9
Side detector bank with ^3He tubes removed from CH_2 moderator.

Figure 8 shows one detector bank and Fig. 9 shows the bank with the ^3He tubes removed. The individual detectors are interchangeable and the three detector banks are also interchangeable among the different Coincidence Collar units.

The hv junction box shown in Fig. 10 contains a desiccant to reduce the moisture content in the box to prevent hv breakdown. The lid of the junction box is sealed to the body with a silicon rubber sealer. The detectors are wired to give six tubes on each of the three lines that feed to the preamplifier box. The lid of the junction box is "stepped" to reduce electronic noise leakage into the box.

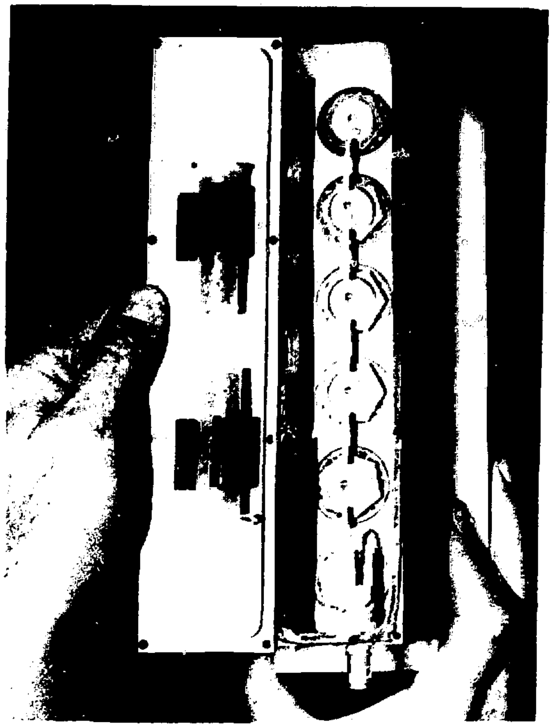

Fig. 10
View of inside of hv junction box for ^{3}He detector bank.

D. Electronics

The electronics for the present unit are the same as that used for the HLNCC.[4] The preamp box contains the hv input for the ^{3}He detectors and separate preamps for six lines of electronics. This Coincidence Collar uses only three lines and thus there are three spare lines. The primary purpose of this is to give an interchangeability of parts with the HLNCC. The signal leads from the preamp box are connected to the main electronics package shown in Fig. 11. This unit contains the hv and low voltage power supplies, six amplifier-discriminator lines, a microprocessor, and the shift register[5] coincidence logic.

The electronics unit is directly interfaced to the HP-97 programmable calculator shown in Fig. 11. A microprocessor in the unit reads out the run time, total counts, real coincidence plus accidental counts, and accidental counts to the HP-97. The HP-97 is then used to reduce the data using the software package selected by the operator. Details concerning the design, fabrication, and operation of the electronics system are published elsewhere.[4,5]

E. Detector Cart and Portability

A front view of the Coincidence Collar cart is shown in Fig. 12. This cart has been designed to accommodate the detector and the electronics package. The detector is attached to the cart as shown in Fig. 13, and it stays attached for the measurement and the transfer from one assembly position to the next. During shipment, the electronic package and HP-97 are lifted off the cart and are placed in a case provided for shipment and storage. For movement within a building, the electronics can remain attached to the detector and cart. The cart is made of aluminum and weighs about 8 kg.

To give the capability of verifying more than one vertical position on the fuel assembly, the cart has adjustable legs. This gives the possibility of the following distances between the floor and the bottom of the Coincidence Collar: 0, 43, 76, and 109 cm. For some applications, it might be necessary to completely remove the Coincidence Collar from the cart. An example of this would be a horizontal fuel assembly or a scanning measurement with the assembly being lowered through a hole in the floor by means of an overhead crane. The Coincidence Collar can be operated independent of the support cart.

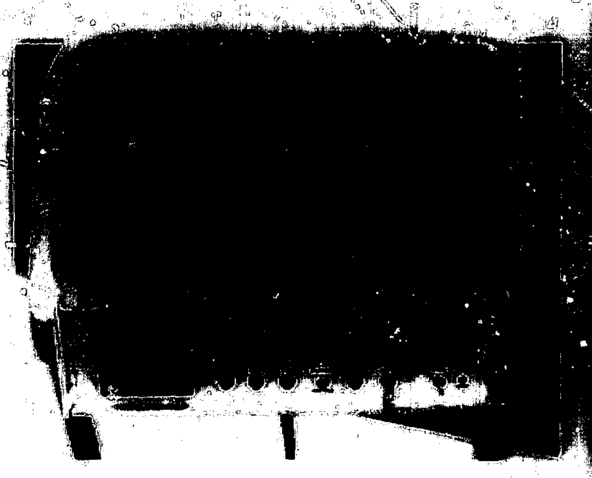

Fig. 11
Photograph of the coincidence electronics (IRT Model HEC-100) and the HP-97 programmable calculator used with the Coincidence Collar.

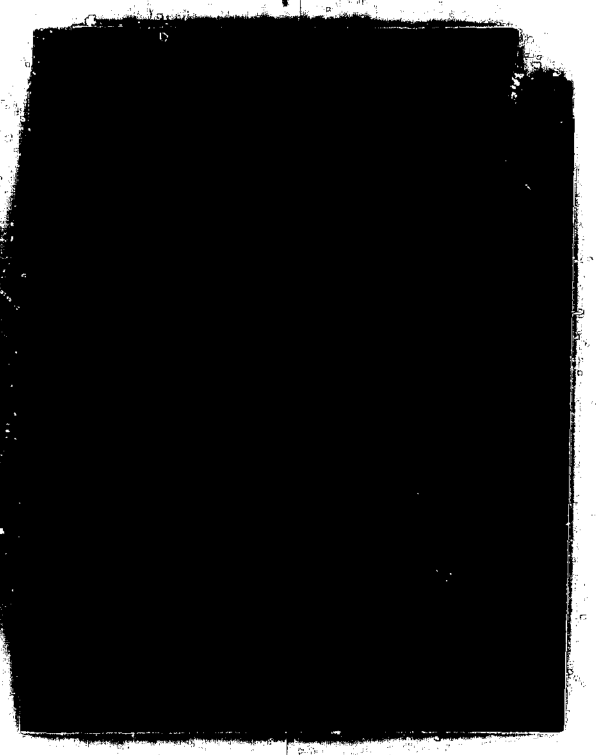

Fig. 12
View of the support cart with the top plate removed. This cart can be used to position the Coincidence Collar around reactor fuel assemblies.

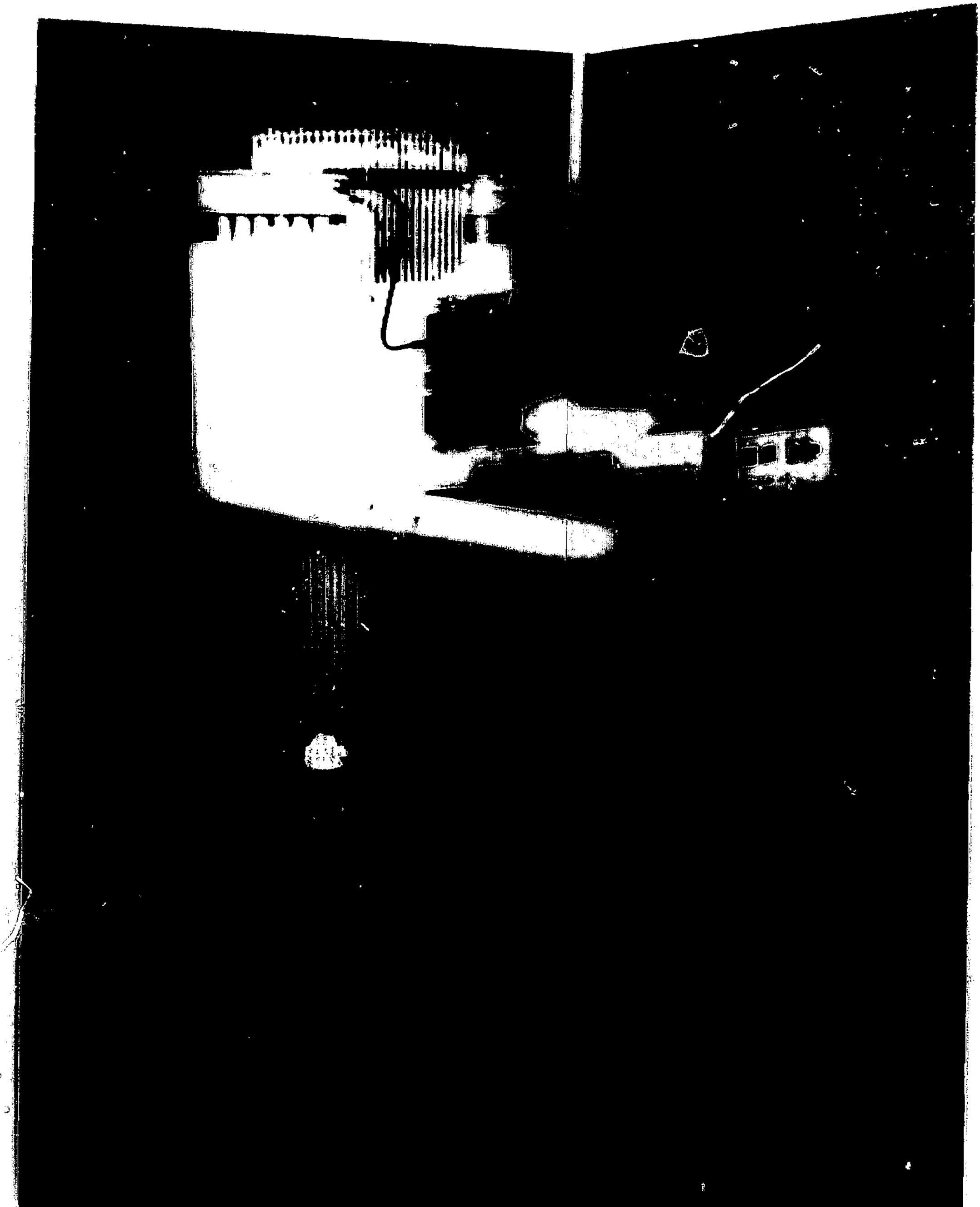

Fig. 13
The complete Coincidence Collar system with the mockup PWR assembly in the measurement position.

III. OPERATION OF ASSAY SYSTEM

A. Sample Categories

The Coincidence Collar has been designed specifically for unirradiated PWR fuel assemblies, but it also can be used for other assemblies such as BWR, heavy water reactor (CANDU), etc. Table II lists some assembly types and the corresponding configuration for the Coincidence Collar. The instrument can be applied to high enrichment uranium (HEU) fuel such as materials test reactor (MTR) assemblies, but a cadmium liner should be added to the interior of the Collar to improve neutron penetrability.

Only two size configurations have been designed into the Coincidence Collar to limit the possible positioning and calibration errors. In the full open position, the clearance hole is 235 x 235 mm. When the side detector banks are moved to the inner screw hole position, the opening is 165 x 235 mm. Each sample type and detector configuration requires a separate calibration.

TABLE II

SAMPLE CATEGORIES FOR COINCIDENCE COLLAR APPLICATION

Sample	Section Shape	Cross Section	Approximate Collar Configuration[a]
PWR Assembly	Square	216 x 216 mm	235 x 235 mm
BWR	Square	130 x 130 mm	165 x 235 mm
CANDU	Cylindrical	100 mm diam.	165 x 235 mm
WWER	Hexagonal	143 x 165 mm	165 x 235 mm
Rod Storage Tray	Rectangular	variable	165 x 235 mm
UF_6/U_3O_8 Cyl.	Cylindrical	variable	235 x 235 mm

[a]The full opening in the Collar has dimensions of 235 x 235 mm, and when the Collar is reduced to the inner screw holes, the opening is 165 x 235 mm.

B. Normal Setup

1. Detector and Cart. For normal applications, the fuel assemblies will be in a vertical storage position and the Coincidence Collar will be positioned on its cart as shown in Fig. 13. If the floor has no steps or other barriers, the unit can be rolled up to the assembly with the detector door open. When the fuel assembly is inside the detector, the door is closed and the measurement can begin. In some cases, the fuel assembly support structure will prevent this and additional steps are required. The detector door is removed easily to facilitate use in tight quarters. In general, it will be necessary to arrange adequate mechanical support with the facility operator before the measurement campaign.

In many cases, the fuel assemblies are stored in poly bags. The bag will not hinder the measurement so it can be left in place.

2. Electronic Setup. The electronic components and connections are identical to the HLNCC. Recommended settings are as follows.

a. hv = 7.5 (1500 V)
b. Discriminator = 3.0 (1.5 V)
c. Gate = 64 μs
d. Time = Desired Run Time (100-1000 s recycle).

Additional details on the electronic components can be found in the HLNCC User's Manual.[4] Appendix B gives the rationale for the 64-μs gate selection.

C. Measurement Steps

The Coincidence Collar can be used in either the active (^{235}U determination) or passive (^{238}U determination) modes. When both measurements are performed, the enrichment or $^{235}U/^{238}U$ ratio is determined. In most cases, only the active measurement is necessary because the ^{235}U verification is of primary interest. When first arriving at a facility, the following steps are recommended.

1. Assemble detector and cart, and use thumb screws to attach detector to cart.
2. Check out electronics as suggested in Ref. 4, and set parameters as listed in Sec. III.B.2.

3. Take a 100-s count with no AmLi source or fuel assembly near unit. The net coincidence rate (R+A) - A, should be statistically equal to zero and the totals rate, T, should be between 10 and 600 counts/s depending on the amount of U_3O_8 in the vicinity.
4. Place the AmLi source in its normal position in the CH_2 detector (see Fig. 1) and observe (100-s run) that the net coincidence rate is statistically zero. The totals rate should be ~1800 counts/s depending on the AmLi source strength.
5. Temporarily remove the AmLi source from the unit and position the Coincidence Collar around a fuel assembly. Take a longer run (~600 s) to determine the fuel assembly coincidence background rate. This should be 10 to 15 counts/s for the net coincidence counts for PWR assemblies. This number depends primarily on the ^{238}U mass and is approximately the same for all of the fuel assemblies of the same mass. It will be subtracted from the induced coincidence counts in the data reduction.
6. Return the AmLi source to the Coincidence Collar and take the active neutron measurement. The total time available for measurement should be subdivided into several shorter intervals to check for noise pickup and data consistency using the HP-97. For example, if 15 min per assembly is available, then set the time for 300 s on the recycle mode and use the HP-97 to average the results and check for statistical consistency.
7. If the ^{238}U content is desired, remove the AmLi source from the detector and place the source in its storage container at least 10 m away from the detector system. Repeat the data collection cycle as used in the active mode.

D. Calibration

1. Standards. The calibration of the Coincidence Counter in an absolute sense is difficult because of the complexity and costs of "standard" fuel

assemblies. The relative calibration of one fuel assembly to the others at a facility is easy to obtain. In general, each major category of fuel (namely, PWR, BWR, etc.) will require its own calibration curve. Within a fuel assembly category such as PWR, there are numerous variations such as number of rods in the array (14 by 14 to 17 by 17) and fuel rod diameter that will require corrections to the calibration curves. These correction factors should be calculated, for most cases, using Monte Carlo computer codes to avoid excessive costs in physical standards preparation.

2. Parameter Sensitivity. The Coincidence Collar has been designed to make the results insensitive to variations in the assembly such as

a. number and position of open channels for reactor control rods,
b. mixture and position of fuel rods with different enrichments,
c. angular orientation of the fuel assembly in the Coincidence Collar,
d. nominal differences in fuel pellet density, and
e. any protective bagging or cardboard on the outside of the fuel assembly.

The Coincidence Collar is somewhat sensitive to

a. stainless steel vs Zircaloy cladding,
b. significant differences in fuel pellet diameter,
c. size of the fuel rod array, and
d. neutron absorbers (that is, burnable poisons) such as Gd_2O_3 commonly found in BWR fuel rods.

3. Sample Region. The Coincidence Collar measures the ^{235}U or ^{238}U content per unit length rather than enrichment. The sampled region is approximately 400 mm long centered in the midplane of the detector body. If the edge of the detector body gets closer than 150 mm to the top or bottom ends of the fuel region, the measured response will decrease because of end leakage of the neutrons. Any region selected inside these end regions should give a constant counting rate if the ^{235}U loading is uniform.

When an overhead crane is available for scanning the fuel assembly through the detector, then the entire assembly can be sampled. The measurement time is the same for the scanning or stationary modes for equivalent statistical precision. If the scanning mode is used, the calibration curve should be obtained in the same manner to take into account the end losses as the assembly enters and leaves the detector. The counting rate in the midsection of the assembly is the same for both the scanning or stationary modes of operation because the prompt fission neutrons dominate the observed coincidence signal, and they are detected on a time scale of ~100 μs.

4. Calibration Normalization. For most applications, it will be impossible to have physical standards available at the facility being inspected, so it will be necessary to relate the inspection measurement to calibration measurements at a "host" facility that has the same or similar type fuel assemblies. The AmLi neutron source can be used as a calibration normalization source to bridge the distance and time between the actual calibration and the field inspection.

At the time of calibration, net AmLi source background (totals and accidental coincidence rates) should be recorded with no fuel assembly in the detector. This records the relative detection efficiency and efficiency squared (accidental rate) for the system at the time of calibration. Because the totals rate is proportional to the efficiency and the coincidence rate proportional to the efficiency squared, the signals can be renormalized to the AmLi background rate at any future time. Because of its long half-life (432 yr), the AmLi source strength is essentially constant for calibration purposes. After several years of source decay, the above-mentioned calibration normalization procedure automatically takes care of any reduction in source strength.

There are two detector configurations: wide for PWR, and narrow for BWR, as given in Table II. The Coincidence Collar must always be calibrated in the same configuration as it is to be used because the efficiency is different for the two configurations. Also, the coincidence counting efficiency is affected by changes in the gate length and predelay, so these settings should not be altered.

To demonstrate the adequacy of the AmLi source normalization technique, the electronic settings of the Coincidence Collar were purposely varied, and both the sample and background counts were performed before and after the variation.

Table III presents the results of the tests. The corrected results (last column) for the BWR assembly agree with the normal results before the perturbation within the counting statistics (~0.5 percent).

Note that this procedure only corrects for electronic problems and not for changes in the neutron interrogation flux, such as an improperly placed AmLi source or the incorrect positioning of the fuel assembly.

5. Calibration Curve Function. The response of the Coincidence Collar is nonlinear primarily because of neutron self-shielding and fission neutron multiplication. Thus, it is necessary to use several fuel assembly standards with different fissile loadings to establish a calibration curve.

A series of measurements using five different fuel assembly enrichments was performed to study the shape of the calibration curve for PWR assemblies. The measurements[6,7] were performed by a joint team of staff members from Los Alamos, IAEA, and Mol, Belgium. The results of the measurements for PWR assemblies containing 17 by 17 rods are shown in Fig. 14. The enrichments varied from 1.8 to 3.4 percent ^{235}U and the graph corresponds to the coincidence response as a function of ^{235}U enrichment. A response function (R) of the form

$$R = k\sqrt{E},$$

TABLE III

COINCIDENCE COLLAR CALIBRATION NORMALIZATION TESTS

Condition	AmLi Background T/s	AmLi Background acc/s	BWR Assembly T/s	BWR Assembly coinc/s	BWR Corrected[a] T/s	BWR Corrected[a] coinc/s
Normal	4699	1414	5493	189.3	5493	189.3
hv reduced						
(1500 → 1450 V)	4573	1340	5385	179.1	5533	189.0
(1500 → 1400 V)	4037	1045	4760	139.2	5540	188.4
Disc-raised						
(2.5 → 3.0)	4608	1394	5430	185.0	5547	187.7
(2.5 → 3.5)	4546	1322	5353	177.7	5533	190.0
(2.5 → 4.0)	4323	1193	5092	159.6	5535	188.8

[a]The correction factor is (AmLi Background, Normal)/(AmLi Background, Changed Condition).

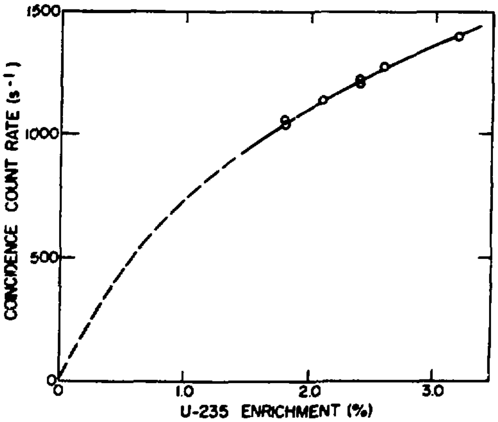

Fig. 14
Active mode coincidence rate vs ^{235}U enrichment for full (17 by 17) PWR fuel assemblies.

where k is a constant and E is the enrichment, gave a reasonably good fit to the data.

More generally, the calibration standards are used to generate the fitting parameters for the selected functional form such as a quadratic equation similar to that used with the HLNCC:

$$R = A_0 + A_1 m + A_2 m^2 \quad ,$$

where R is the real coincidence response and m is the fissile mass per unit length. Once the desired functional form and parameters have been established, day-to-day operation can usually be accomplished using a "normalization" sample or the AmLi source to confirm that the system has not changed. If minor shifts have taken place, a simple renormalization is usually possible.

Once the calibration function and fitting parameters have been established, these can be put in the HP-97 via the magnetic program card. Detailed procedures for doing this will be developed as part of the Coincidence Collar implementation.

IV. PERFORMANCE CHARACTERISTICS

A. Introduction

The performance of the Coincidence Collar depends on the detector configuration and type of fuel assembly. Preliminary data have been collected for both PWR and BWR assemblies. The ability of the measurement to penetrate into the interior regions of the fuel assemblies is of high importance. This has been accomplished through fast-neutron multiplication, even though the primary AmLi interrogation neutrons are thermalized in the CH_2 moderator.

The AmLi source stren‹ .h and the resulting coincidence counting rates are not of high importance because the statistical error is dominated by the accidental coincidence rate.[3] The present source strength of 5 x 10^4 n/s gives about the same statistical error as sources one or two orders of magnitude higher.

In evaluating the performance, I will first describe the system response as a function of fuel rod position, then the ^{235}U enrichment, and finally, the position of the full assembly in the detector.

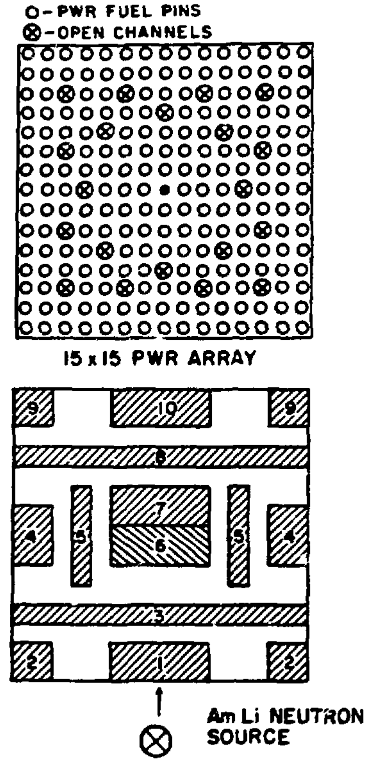

Fig. 15
Cross section of the mockup PWR fuel rod assembly showing rod locations and regions selected for rod substitutions.

B. Rod Substitution Position Sensitivity

1. PWR Results. Tests with the system have been performed on a mockup fuel assembly that has removable rods. The assembly is a 15 by 15 array of PWR fuel rods 1.035 m long. The characteristics of the rods are listed in Table IV.

A series of experiments was performed where rods from different sections of the assembly were removed to determine the position sensitivity to rod substitution. The regions selected for the measurements are shown in Fig. 15, which is a cross section of the rod positions in the PWR array. For each rod configuration, several 1000-s measurements were performed and the coincidence rate was compared with the full array count rate to determine the perturbation

TABLE IV

MOCKUP PWR FUEL ROD CHARACTERISTICS

Array size	15 x 15 (cm width)
Number of rods	204 (21 open channels)
Rod diameter (OD)	10.8 mm
Rod cladding	Zircaloy-2
Uranium enrichment	3.19 percent
Linear ^{235}U loading (assembly)	38.76 g ^{235}U/cm
UO_2 active length	1.035 m
UO_2 density	10.48 g/cm^3

caused by the substitution. The measured perturbation was then divided by the number of rods in the substitution region to obtain the perturbation per rod.

Table V gives the results of the sensitivity measurements for the empty rod and iron substitution cases. The sensitivity limit is defined as the minimum number of rod substitutions that can be detected in a 1000-s measurement time at the 95 percent (2σ) confidence level. The detection limit for empty rod substitution varies from 2.1 to 3.8 rods and is rather uniform at all rod positions including the central region. The iron rod substitution gives better sensitivity because of the thermal-neutron absorption in the iron. The uniformity of response is achieved by balancing three different mechanisms as follows.

1. The front of the assembly near the AmLi interrogation source gets more direct source neutrons than other regions.
2. The back and side regions have higher counting efficiency for the induced fission neutrons because of their close proximity to the ^3He detector banks.
3. The central region gets a greater contribution from fast neutron multiplication than the perimeter regions.

The measured coincidence response corresponds to the combination of these components resulting in a rather uniform sensitivity as given in Table V. The front corners (rod location No. 2) have the most sensitivity of all of the rod positions because of the high thermal-neutron flux and limited shadowing from neighboring rods.

TABLE V

FUEL ROD REMOVAL DETECTION SENSITIVITY FOR A 15 BY 15 PWR ASSEMBLY

Rod Location[a]	Percent Change/Rod Empty	Percent Change/Rod Iron	Rod Detection Limit (2σ)[b] Empty	Rod Detection Limit (2σ)[b] Iron
1	0.35	1.68	3.6	1.0
2	0.64	1.25	2.0	1.0
3	0.41	0.71	3.1	1.8
4	0.41	0.62	3.1	2.0
5	0.55	0.53	2.3	2.4
6	0.57	0.51	2.2	2.5
7	0.53	0.44	2.4	2.9
8	0.36	0.38	3.5	3.3
9	0.48	0.60	2.6	2.1
10	0.46	0.47	2.7	2.7
Average =	0.48	0.71	2.8 Rods	2.2 Rods

[a]Rod removal locations are shown in Fig. 1.

[b]Rod detection limit corresponds to the perturbation per rod removal being equal to twice the standard deviation for a 1000-s measurement.

In effect, the system works like a reactivity gauge for the fuel assembly, and the removal of fissile material from the assembly lowers the neutron reactivity and thus the coincidence response.

Preliminary measurements with depleted uranium rods substituted for the enriched uranium rods indicated a detection limit roughly a factor of 1.6 higher than for the empty pin substitution. This is to be expected because the ^{238}U in the depleted rod contributes to the fast neutron multiplication because some of the fission neutrons have energies above the ^{238}U fission threshold.

By removing the AmLi interrogation source from the Coincidence Collar, passive measurements give the ^{238}U content by coincidence counting the ^{238}U spontaneous fission neutrons. The combination of the ^{235}U and ^{238}U results gives a high level of verification for the fuel assembly.

2. BWR Results. Experiments were performed with a mockup BWR fuel assembly to determine the sensitivity to rod substitution and spatial uniformity of the response. The available BWR assembly has rods enriched to 2.34 percent in ^{235}U, and there are 36 rods in the 6 by 6 array, which is smaller than the

more typical 8 by 8 arrays. Rods were removed from different positions in the array to measure the response as a function of position. In separate measurements, rods filled with lead or iron were substituted into the array to determine the effect of materials with a density similar to UO_2 (10 g/cm^3) on the coincidence counting rate.

Because the BWR assemblies are considerably smaller than PWR assemblies, the side ^{3}He-detector banks were moved toward the center to give a separation of 16.5 cm as shown in Fig. 4. This gives a higher counting efficiency and a better sensitivity to the detection of rod removal. The detector is designed to be adjustable so that it can be used on either PWR or BWR assemblies.

The results of the measurements are shown in Fig. 16 where the array represents the 36 fuel rod locations. The number in each array position corresponds to the percentage of decrease in the coincidence rate when one fuel rod is removed from that position. The top array in Fig. 16 corresponds to the empty rod substitution and shows that the response is very uniform with an average decrease of 2.1 percent for the removal of one pin. The statistical precision of a 1000-s count is 1.1 percent (1σ) compared with 0.63 percent (1σ) for the PWR assembly. The removal of one BWR rod causes a 2.1 percent change in the rate and can be detected at the 95 percent (2σ) confidence level.

The two lower arrays shown in Fig. 16 correspond to lead (cast in steel tubing) and iron rod substitutions. In general, these materials give larger changes than the empty substitution case and thus are easier

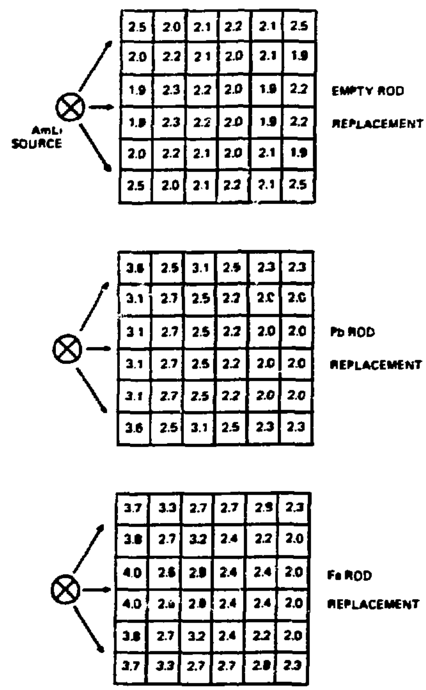

Fig. 16
Schematic diagram of three BWR arrays (6 by 6) showing fuel rod locations relative to the neutron interrogation source in the Coincidence Collar. The numbers in the array are the percent reduction in coincidence count rate caused by the substitution of one rod in the corresponding location.

to detect. The changes are considerably larger on the fro ˆ-ˆe o. the assembly because the thermal-neutron flux is higher there and the absorption of the neutrons by the iron has a large effect.

In general, the substitution of iron or lead to obtain the correct assembly weight can be detected easily by both the active and passive counts. The substitution of normal or depleted uranium rods is a more difficult case to detect because of the fast fission multiplication in the ^{238}U similar to the results with the PWR assembly.

The application of the Coincidence Collar to BWR fuel assemblies is more complicated than for PWR assemblies because of the mixed uranium enrichments in the rods and the possibility of rods containing gadolinium or other burnable neutron poisons. In effect, the active neutron interrogation gives the reactivity of the assembly and both the enrichment and neutron poisons affect the reactivity. The additional information from the passive counting of the assembly helps to clear up the above complications. See Appendix C for more information about measurements when burnable poisons are present.

C. Response vs Loading

When fuel rods are removed from a fuel assembly, the measured response decreases. To observe the shape of this response curve, rods were uniformly removed from a mockup assembly.[6] The results of the measurements are shown in Fig. 17 where the percentage of decrease in the coincidence response (active mode) is plotted as a function of the percentage of decrease in the uranium mass. The relationship is linear over the range tested (0-30 percent fuel rod removal) because of the cancellation of compensating nonlinear effects. That is, as the uranium mass decreases, the interrogation neutron self-shielding decreases, which increases the coincidence response per gram uranium. However, as the mass decreases. the

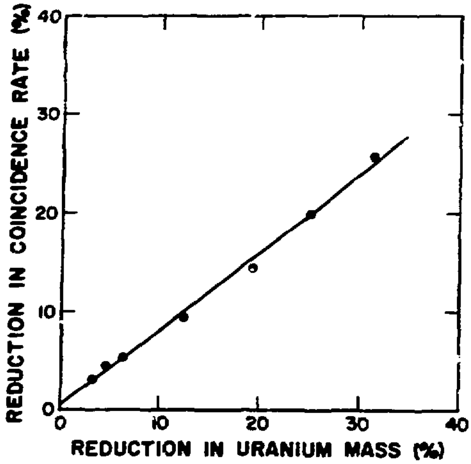

Fig. 17
Active neutron coincidence response as a function of reduction in ^{235}U mass for a uniform distribution of rod removals from a full PWR assembly.

neutron multiplication decreases, which decreases the coincidence response per gram and the two effects nearly cancel each other.

In addition to the active neutron measurements, the AmLi source was removed and passive measurements were made to determine the ^{238}U spontaneous fission rate. The results are shown in Fig. 18 where the percentage of decrease in passive coincidence rate is plotted as a function of the percentage of decrease in uranium mass. The change in the observed coincidence response is greater than for the active case because there are no neutron self-shielding effects in the passive case.

D. Response vs Enrichment

A series of measurements were performed[6] using full-size (17 by 17 rods) PWR assemblies with enrichments ranging from 1.8 to 3.4 percent ^{235}U. The thermal-neutron interrogation is saturated for all of the fuel assemblies; however, the measured response continues to increase as a function of enrichment because the fast neutron multiplication increases with increasing enrichment. The response of the system in the active neutron mode is shown in Fig. 14. Relative ^{235}U loading variations as small as 1.9 percent can be detected in a measurement time of 1000 s. Longer measurements can further reduce the statistical uncertainty.

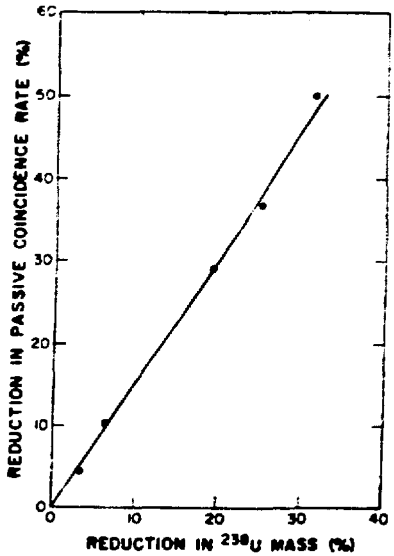

Fig. 18
Passive neutron coincidence response as a function of reduction in ^{238}U mass for a uniform distribution of rod removals from a full PWR assembly.

E. Assembly Position Effects

Measurements were performed to examine the possible error from the incorrect positioning of the fuel assembly. The mockup PWR assembly was positioned at the extreme front position (touching the CH_2), the normal midposition, and the extreme back position (touching the back detector bank) and the normalized coincidence rates were 1.005, 1.000, and 0.993, respectively. Similarly, the normalized coincidence rates for the fuel assembly touching the left side, in the middle, and touching the right side are 1.001, 1.000, and 1.004, respectively. Thus, the expected error from variations in positioning the assembly in the center of the Coincidence Collar is much less than 1 percent. Repeat measurements to investigate the magnitude of this error are described in the following section.

For the BWR assembly, there is a large gap between the back of the assembly and the rear detector bank (see Fig. 4). This makes for a larger variation in the counting rates for the extreme positions. The normalized coincidence rates at the extreme front, midposition, and extreme back were 1.000, 0.970, and 0.936, respectively. These variations are considerably larger than for the PWR assembly because the change in position is much larger (3-6 cm). However, the expected uncertainty from positioning variations is still much less than 1 percent.

F. System Stability and Precision Checks

To measure the system stability and reproducibiltiy, long runs using the recycle mode were made over a period of several weeks. The Coincidence Collar was placed around a PWR assembly and a series of 4,000- to 10,000-s measurements were performed. The results of the measurements are given in Table VI.

Under these ideal conditions of no sample movement and steady background conditions, a standard deviation of better than 0.1 percent can be realized. In recent field work,[6] standard deviations of 0.08 percent (1σ) were obtained in plant working conditions.

TABLE VI

COINCIDENCE COLLAR PRECISION CHECKS

		Precision (1σ)	
Cycle Time	Total Time	Predicted[a]	Observed
37 x 4000 s	1.7 d	0.028 percent	0.039 percent
17 x 4000 s	0.8 d	0.028 percent	0.045 percent
57 x 4000 s	2.6 d	0.028 percent	0.058 percent
17 x 10,000 s	2.0 d	0.018 percent	0.020 percent

[a]Corresponds to expected standard deviation (1σ) from number of counts in the R+A and the A.

In addition to the counting statistical error, fuel assembly positioning variations must be considered. To check these effects, repeat measurements over the period of a week were made on the same PWR assembly. A total of 10 measurements were performed where the Coincidence Collar was removed from the fuel assembly and then repositioned between each run. The observed standard deviation was 0.26 percent which was very close to the counting statistical value of 0.20 percent (1σ). The reason for this good agreement is that the Coincidence Collar has been designed to give a uniform response over the sample region.

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Merlyn Krick and John Foley from Los Alamos, Ahmed Keddar from the IAEA, and Charles Beets from Mol, Belgium, provided many helpful suggestions in the development of this instrument. O. R. Holbrooks was responsible for the mechanical design and fabrication of the Coincidence Collar.

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APPENDIX A

COINCIDENCE COLLAR DESIGN STUDY

The design of the system included experiments to determine the optimum CH_2 thickness for the detector banks. Figure A-1 shows the relative coincidence rate and relative assay error as a function of CH_2 thickness. The detector tubes were centered in the CH_2 slab for this set of data. The goal is to minimize the error rather than to maximize the coincidence rate. The AmLi source neutrons contribute to the statistical error and so it is desirable to decrease the counting rate from these background neutrons. The relative error continues to decrease out to a thickness of 10 cm; however, 8.8 cm was selected because of weight considerations.

After the above CH_2 thickness has been established, it is necessary to determine the best position for the ^3He detectors in the slab of CH_2. To determine this, I moved the ^3He tubes from the front to the back of the slab and at each position performed an active neutron measurement with the PWR assembly (see Fig. A-2) in place. The counting efficiency peaks at a position 3.5 cm back from the inside face which is a little forward of the geometric center. The relative error can be written[3] as

$$E \simeq K \frac{1}{U} \frac{\epsilon_\alpha}{(\epsilon_f)^2} ,$$

where K is a constant, U is the uranium fissile content, ϵ_α is the detection efficiency for AmLi (α,n) background neutrons, and ϵ_f is the detection efficiency for the induced fission neutrons. Thus the relative error E can be reduced by decreasing ϵ_α or increasing ϵ_f. The ratio of $\epsilon_\alpha/\epsilon_f^2$ is minimized at a position of 4.0 cm, which is slightly behind the 3.5-cm peak of ϵ_f^2. This 4-cm distance between the inside face of the CH_2 and the center of the ^3He tube was used in the design of the detector shown in Fig. 1.

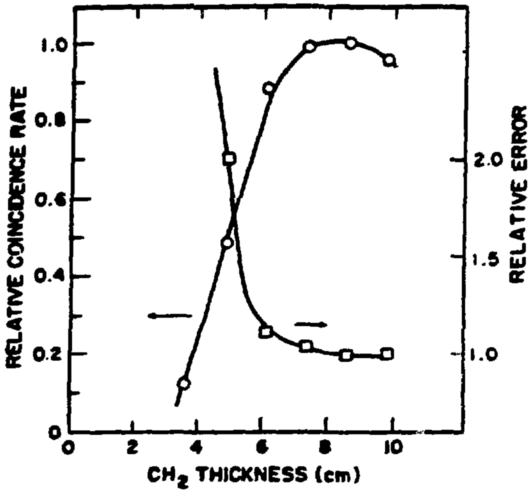

Fig. A-1
Experimental study of the relative coincidence rate and error as a function of CH_2 thickness in the detector slab shown in Fig. 1.

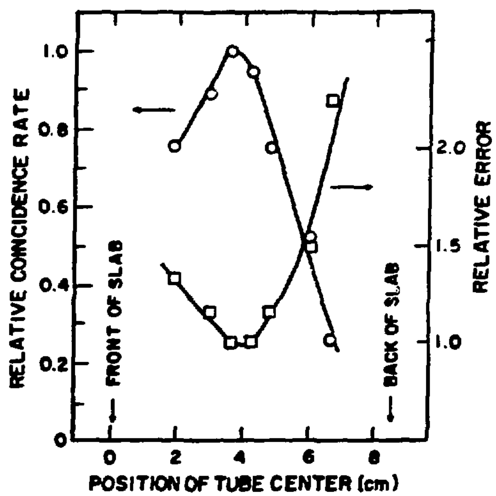

Fig. A-2
Relative coincidence rate and relative error as a function of the position of the ^3He detectors in the side slab of the Coincidence Collar shown in Fig. 1.

APPENDIX B

ERROR CALCULATION AND GATE LENGTH SELECTION

The statistical error in the measurement is dominated by the accidental coincidence rate A and this rate is directly proportional to the gate length G,

$$A = T^2 G$$

for a uniform totals rate T. Thus, it is desirable to keep G as small as possible and still include most of the time-correlated coincidence neutrons.

The standard deviation in the measurement can be approximated by

$$\sigma = \sqrt{(R+A) + A}$$

$$\sigma \approx \sqrt{2A} \quad ,$$

for AmLi source strengths of >5 x 10^4 n/s. It can be shown[3] that the fractional standard deviation is minimum when the gate length

$$G \approx 1.2\,\tau$$

where τ is the neutron die-away time of the system (that is, the mean time for a fission neutron to be captured in detector, matrix, or to leak from the system).

The value of τ is controlled by the thickness of CH_2 around the detectors and the number of ^3He gas tubes.

The die-away time τ can be easily measured in the present unit by varying the gate length with a fuel assembly in the counter. Figure B-1 shows the coincidence rate for gate settings ranging from 8-128 μs and with a fixed predelay of 4.5 μs for the Coincidence Collar and PWR fuel assembly. The response curve has the functional form

$$R = (1 - e^{-G/\tau}) \quad ,$$

where it is normalized to unity for very large gate values. Fitting the data shown in Fig. B-1 gives a value of $\tau \approx 55$ μs and thus the optimum gate setting is 64 μs.

To check the effect of gate setting on the assay error, I have calculated the fractional standard deviation from the data for the different gate settings. Figure B-1 shows the relative error that has been normalized to unity at a 64 μs gate setting. We see that the error increases by ~15 percent for a 32 μs gate and ~4 percent for a 128 μs gate. Thus, the unit normally is operated with a gate setting of 64 μs and it is not necessary to change this value for routine operation. The unit should always be operated with the same gate setting used during the calibration.

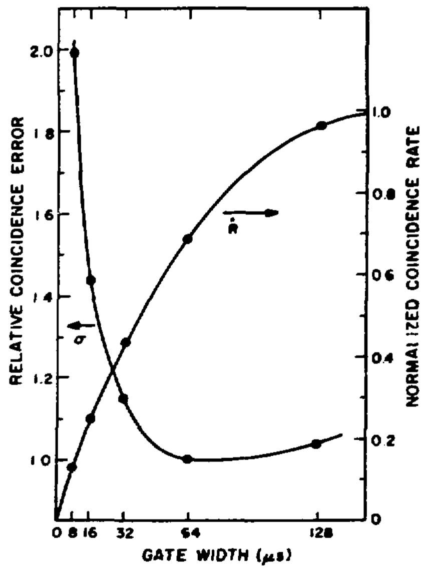

Fig. B-1
Normalized coincidence rate and assay error vs gate width for the Coincidence Collar.

APPENDIX C

BWR ASSAY AND POISON RODS

The application of the Coincidence Collar to BWR fuel assemblies is more complicated than for PWR assemblies because of the mixed uranium enrichments in the rods and the possibility of rods containing gadolinium or other burnable neutron poisons. In effect, the active neutron interrogation gives the reactivity of the assembly, and both the enrichment and the neutron poisons affect the reactivity.

Measurements were performed using the mockup BWR assembly and inserting fuel rods loaded with 2.0 wt% Gd_2O_3 to determine the effect of the burnable poison on the measurements. A rod loaded with Gd_2O_3 decreases the active coincidence response several percent depending on the position of the rod in the assembly. Figure C-1 shows the percent reduction in response caused by the gadolinium-loaded rod for the various rod positions. As expected, the front rows give the largest gadolinium perturbation because of the higher thermal-neutron flux near the AmLi source.

A typical 64-rod BWR assembly contains four gadolinium-loaded pins (or 6.2 percent of the pins) located at interior positions and thus the expected perturbation from the gadolinium should be roughly 5-10 percent. The gadolinium has a relatively small effect in the interior positions because fast neutrons (rather than thermal) cause a large fraction of the fission reactions in the interior region.

To eliminate the gadolinium perturbation on the measurement, a cadmium liner can be added to the inside of the Coincidence Collar. The cadmium absorbs the thermal-neutron component from the interrogation flux and then the gadolinium has no significant effect on the measurement. Table C-I lists the rates and precisions both with and without a 1-mm-thick cadmium liner. Because the statistical error in the cadmium case is about a factor of 6 larger than for the normal case, cadmium liners normally should not be used in the system. However, the cadmium ratio measurement is possible for special cases that require the additional verification. Note that the addition of extra neutron poison such as Gd_2O_3 to the assembly tends to decrease rather than increase the apparent ^{235}U content; so the verification problem is bounded.

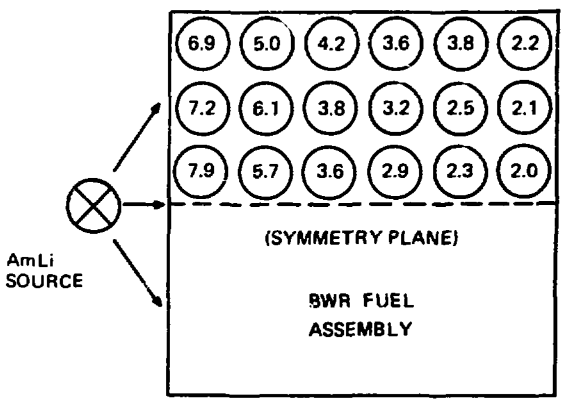

Fig. C-1
Schematic diagram of the BWR array (6 by 6 rods) showing fuel rod locations relative to the neutron interrogation source in the Coincidence Collar. The numbers in the array are the percent reduction in coincidence count rate caused by the substitution of a rod containing 2.0 weight percent Gd_2O_3 in the corresponding location.

TABLE C-I

COINCIDENCE COLLAR RESPONSE FOR BWR ASSEMBLY
WITH AND WITHOUT Cd LINER

	Normal Configuration	Cd Liner Added
Totals Rate (s^{-1})	2350	1120
Net Coincidence Rate (s^{-1})	76	6.3
Coincidence Error for 1000-s run (1σ)	1.1 percent	6.7 percent