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Field Test and Evaluation of the IAEA Coincidence Collar for the Measurement of Unirradiated BWR Fuel Assemblies

H. O. Menlove
A. Keddar*

Participants
H. O. Menlove, Los Alamos National Laboratory
E. Dahn, A. Keddar, A. Kaieda, E. Woelfl, and E. Weidl, International Atomic Energy Agency, A-1400, Vienna, AUSTRIA
L. Kiessling and R. Olsson, Swedish Nuclear Power Inspectorate, Stockholm, SWEDEN
W. Andersson and S. Jonsson, ASEA-ATOM, Vaesteraas, SWEDEN

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*International Atomic Energy Agency, P.O. Box 100, A-1400, Vienna, AUSTRIA

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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FIELD TEST AND EVALUATION OF THE IAEA COINCIDENCE COLLAR FOR THE MEASUREMENT OF UNIRRADIATED BWR FUEL ASSEMBLIES

by

H. O. Menlove and A. Keddar

ABSTRACT

The neutron coincidence counter has been field tested and evaluated for the measurement of boiling-water-reactor (BWR) fuel assemblies at the ASEA-ATOM Fuel Fabrication Facility. The system measures the ^{235}U content per unit length of full fuel assemblies using neutron interrogation and coincidence counting. The ^{238}U content is measured in the passive mode without the AmLi neutron interrogation source. The field tests included both standard production BWR assemblies and a full-size mockup assembly that had removable fuel rods to investigate enrichment and absorber variations. The results of the tests gave a response standard deviation of 0.9% for the active case and 2.1% for the passive case in 1000-s measurement times.

I. INTRODUCTION

As part of the POTAS Program Task A.75, three Class III Coincidence Collars have been supplied to the International Atomic Energy Agency (IAEA) for test and evaluation. This instrument can be used for the verification of unirradiated fuel assemblies either at the fuel fabrication facility or at the reactor site. Previous reports[1,2] have given a description of the Coincidence Collar and its application to PWR fuel assemblies.

This report gives the results of the field test and evaluation of the Coincidence Collar (unit 3) for boiling-water-reactor (BWR) fuel assemblies. The measurements were performed at the ASEA-ATOM Fuel Fabrication Facility, Vaesteraas, Sweden, from November 12-17, 1981

The testing of the unit for BWR assemblies was of particular interest because of the presence of fuel rods with different ^{235}U enrichments and Gd_2O_3 burnable poisons in some of the rods in the assemblies. To check the effects of these parameters, the following tests were performed.

(1) Interrogate the assembly from each of the four different sides for comparison.

(2) Measure the vertical profile of the assembly.

(3) Change the ^{235}U loading and spatial configuration of the different enriched rods.

(4) Change the Gd_2O_3 rod loading.

(5) Change the number of normal rods.

In addition to the above measurements, the ease and time requirements for using the instrument in the plant environment were evaluated.

II. DESCRIPTION OF EQUIPMENT AND SETUP

A. Neutron Source

The present work used the IAEA Coincidence Collar-3, together with its source MRC-AmLi-93. This source has 0.66 Ci of ^{241}Am in the form of AmO_2 with a neutron yield of 4.67×10^4 n/s and the IAEA Certification of Competent Authority USA/D043/S.

B. Measurement Setup

A schematic diagram of the Coincidence Collar in its BWR geometric configuration is given in Fig. 1. For the measurements at ASEA-ATOM, the normal support cart for the collar was not used, because it was more convenient to set the collar directly on the elevated platform located three floors above the ground floor. This position is slightly above the normal storage position of the fuel assemblies.

In this location, it was possible to lower the fuel assemblies through the Coincidence Collar and a hole in the floor using the overhead crane as shown

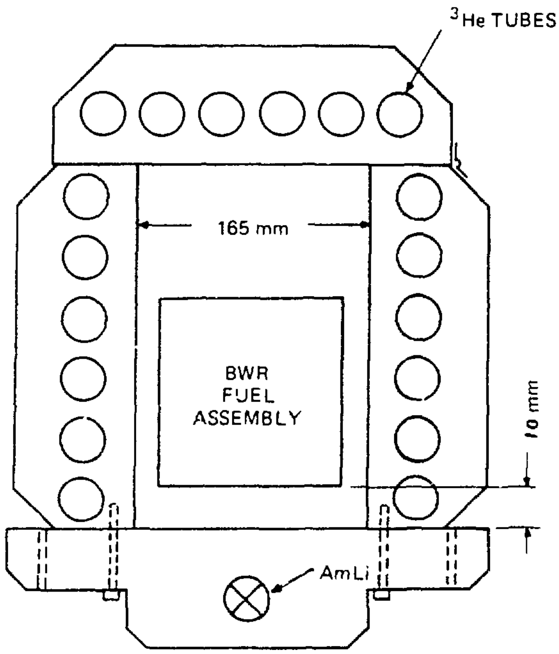

Fig. 1.
Schematic diagram of Coincidence Collar set for BWR fuel assemblies.

in Fig. 2. Figure 3 shows a closer view of the measurement system with a BWR assembly in the measurement position. The assemblies were normally measured inside their Zircaloy-2 water channel box and the plastic bag used to keep the assembly clean. The channel box was positioned approximately 1 cm from the front surface and sides of the Coincidence Collar.

C. Electronic Setup

The electronic components are identical to the High-Level Neutron Coincidence Counter (HLNCC) described in Ref. 3. The recommended settings are

high voltage = 7.5 (1500 V),
discriminator = 3.0 (1.5 V),
gate = 64 μs, and
time = 200-s runs on recycle for available measurement time.

III. DESCRIPTION OF FUEL ASSEMBLIES

A. Test Assemblies

Two different types of normal production fuel assemblies were available at the time of the field test. In addition, a special mockup assembly was put

Fig. 2.
Photograph of BWR fuel assembly being scanned through Coincidence Collar using the overhead crane at the ASEA-ATOM facility. The detector head is positioned over a hole in the floor to accommodate the full length of the fuel assembly.

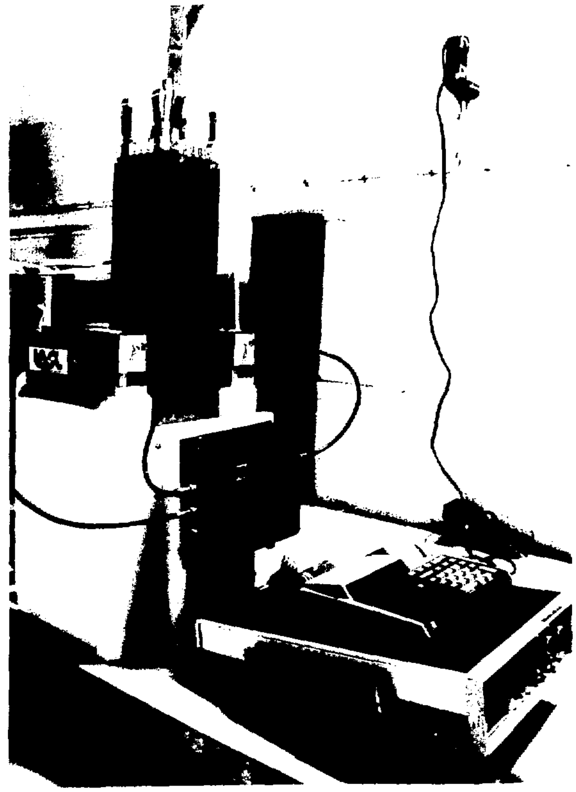

Fig. 3.
Close-up view of the Coincidence Collar and HLNCC electronics package. The BWR fuel assembly has the water channel box removed to show the fuel rods.

together to increase the flexibility of the evaluation. The normal assembly is an 8 x 8 rod array with one empty position resulting in 63 fuel rods. The characteristics of a typical fuel rod are given in Table I, and Table II gives a summary of the assemblies used in the evaluation. The 5 x 5 rod array was made up because there was interest in this size assembly within the Far East section of the IAEA.

B. Mockup Assembly

The mockup assembly was a full 8 x 8 array, 3.68-m-long assembly in a Zircaloy-2 or stainless steel channel box. The fuel rods could be removed to

TABLE I

BWR FUEL ROD CHARACTERISTICS

Active length	3.680 m
Pellet density	10.5 g/cm^3
Pellet diameter	9.94-10.44 mm
Cladding o.d.	12.25 mm
Cladding thickness	0.8 mm
Cladding material	Zircaloy-2
Assembly box	Zircaloy-2

obtain average enrichments ranging from 2.47 to 3.13%. The configuration for the 2.85% average enrichment is shown in Fig. 4. The rods containing Gd_2O_3 are always located on the second or third rows in from the perimeter.

C. Rods Containing Gadolinium

Typically, there are 4 to 6 rods in an assembly that contains 2-4.4 wt% Gd_2O_3. This burnable neutron poison (gadolinium) is used to extend the useful life of the fuel assembly in the reactor for a given initial reactivity. Figure 5 shows a schematic diagram of a rod containing Gd_2O_3. The vertical Gd_2O_3 profile is not uniform so that the burnup profile will flatten in the reactor. The two ends of the fuel rod contain little or no Gd_2O_3 and the bottom section contains more Gd_2O_3 than the top section. This is to compensate for the reactivity loss from neutron leakage near the ends and the boiling water void fraction in the upper region of the reactor core.

IV. MEASUREMENT STEPS

The measurement steps can be separated into the initial check-out and normal operation.

A. Initial Check-Out

(1) If the cart is to be used in the facility, attach the detector to the cart with thumbscrews.

(2) Check out the electronics as suggested in Ref. 3, and set the parameters as listed in Sec. II.C.

(3) Take a 100-s count with no AmLi source or fuel assembly near the unit. The net coincidence rate (R+A)-A, where (R+A) is the reals plus accidentals and A is the accidental rate, should be statistically equal to zero; the totals rate, T, should be between 10 and 600 counts/s, depending on the amount of U_3O_8 in the vicinity.

TABLE II

BWR FUEL ASSEMBLIES USED FOR COINCIDENCE COLLAR EVALUATION

Assembly Type	Average Enrichment	^{235}U (g/cm)	^{238}U (g/cm)	Total Rods	Rods with Gadolinium	Gd_2O_3 (wt%)	Assembly Box
Mockup A	2.85%	13.82	471.1	63	5	4.4	Zr-2
B	2.47%	11.98	472.9	63	5	4.4	Zr-2
C	3.13%	15.18	469.7	63	5	4.4	Zr-2
D	2.85%	13.82	471.1	63	5	4.4	Zr-2
E	2.85%	13.82	471.1	63	3	4.4	Zr-2
F	2.85%	13.82	471.1	63	0	0	Zr-2
5 x 5-A	3.12%	5.76	178.9	24	0	0	Zr-2
5 x 5-B	2.40%	4.44	180.3	24	0	0	Zr-2
T•1(a)	2.91%	14.11	470.8	63	6	4.4	Zr-2
T•1(b)	2.91%	14.11	470.8	63	6	4.4	Zr-2
T•1(c)	2.91%	14.11	470.8	63	6	4.4	Zr-2
T•2(a)	2.82%	13.67	471.2	63	4	2.0	Zr-2
T•2(b)	2.82%	13.67	471.2	63	4	2.0	Zr-2
T•2(c)	2.82%	13.67	471.2	63	4	2.0	Zr-2
T•2(d)	2.82%	13.67	471.2	63	4	2.0	Zr-2
T•2(e)	2.82%	13.67	471.2	63	4	2.0	Zr-2
T•2(f)	2.82%	13.67	471.2	63	4	2.0	Zr-2
T•2(g)	2.82%	13.67	471.2	63	4	2.0	Zr-2

1.98	2.49	2.49	2.49	2.49	1.98	1.98	1.38
2.49	3.37	3.17 Ba	3.50	3.37	2.49	2.49	1.98
3.37	3.37	3.37	2.49	2.49	3.17 Ba	2.49	1.98
3.37	3.50	3.37	1.38	1.38	2.49	3.37	2.49
3.37	3.37	3.37	X	1.38	2.49	3.50	2.49
3.37	3.37	3.37	3.37	3.37	3.37	3.17 Ba	2.49
3.50	3.17 Ba	3.37	3.37	3.50	3.17 Ba	3.37	2.49
2.49	3.37	3.37	3.37	3.37	3.37	2.49	1.98

Fig. 4.
Diagram of the mockup 8 x 8 rod array (A) fuel assembly, where the numbers correspond to the ^{235}U enrichment in the individual pins and Ba corresponds to a rod containing Gd_2O_3 burnable poison.

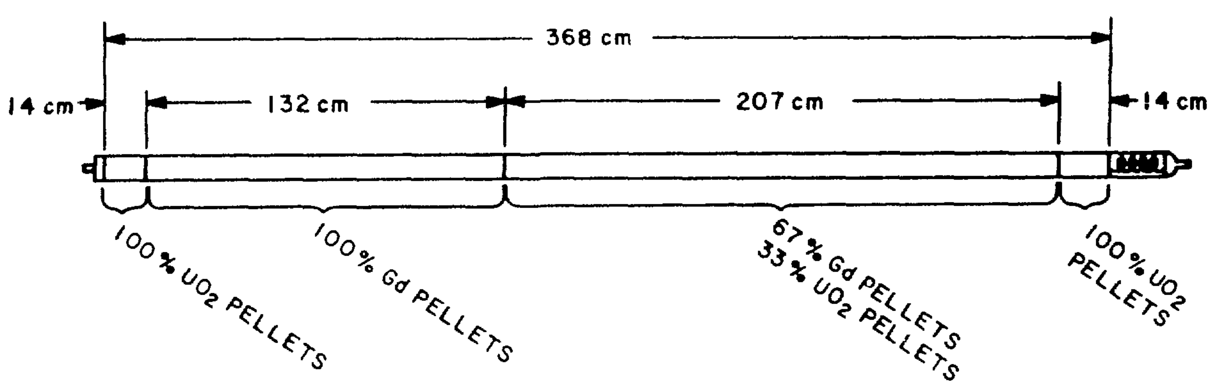

Fig. 5.
Schematic diagram of the axial distribution of pellets in a typical rod containing gadolinium.

(4) Place the AmLi source in its normal position in the polyethylene detector (see Fig. 1) and observe (100-s run) that the net coincidence rate is statistically zero. The net totals rate should be ∿2160 counts/s (BWR detector geometry), 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 (∿300-s) count to determine the fuel assembly coincidence background rate. This should be ∿3 counts/s for the net coincidence counts for BWR 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.

B. Routine Operation

(1) Passive mode (no AmLi) - set the time for 200-s recycle and press the start button on HEC-100 electronics.

(2) After the desired number of cycles (2-3), press the stop button on HEC-100 and the program key B on the HP-97. This will print out the passive results and store the background data for the active assay.

(3) Active mode (with AmLi) - press the start button on HEC-100 to start the 200-s runs.

(4) After the desired number of 200-s cycles (∿5), stop the run and press the program key C on the HP-97. This will print out the active results.

V. IN-PLANT TEST RESULTS

A. In-Plant Neutron Background

The in-plant neutron background measured at the test station was very low. The totals rate was about 20 counts/s, which is an order of magnitude lower than that measured in pressurized-water-reactor (PWR) fabrication facilities. This is because we were about 10 m away from the fuel storage location. The coincidence background was statistically equal to zero. The totals rate from a single BWR assembly inside the Coincidence Collar gave a rate of roughly

45 counts/s. This value was entered into the software program given in Appendix A to make the small passive neutron correction to the coincidence rate. Table III lists the backgrounds and source rates for the tests.

B. Response vs BWR Side Orientation

As seen in Fig. 4, there are normally several different enrichments in a single BWR fuel assembly and these are nonsymmetric as viewed from the different sides. To see if this affects the response, the assembly was measured on all four sides and the results were compared. No differences were observed in the responses within the measurement precision of ±1%.

Previous measurements[1] using a BWR mockup assembly at Los Alamos National Laboratory had indicated that the response from the Coincidence Collar was independent of the position of rods of different enrichments in the assembly. However, the measurement does depend on the number and position of the gadolinium rods. Because the gadolinium rods are always placed in the interior of the BWR assemblies, roughly equidistant from each other, the measured response was the same for all sides of the fuel assembly with the gadolinium rods in place.

C. Response vs Enrichment or ^{235}U Content

The Coincidence Collar measures the ^{235}U or ^{238}U content per unit length, which is proportional to the enrichment for a given type of assembly. 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 20 cm to the top

TABLE III

IN-PLANT NEUTRON BACKGROUND LEVELS

Condition	Totals Rate (s^{-1})	Coincidence Rate (s^{-1})
Room background (third floor)	20	0
Single BWR assembly (no AmLi)	45 (net)	3.2
AmLi-93 (no fuel assembly)	2160	0
BWR (2.82%) assembly (bottom)	2350 (gross)	86.3

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 and Gd_2O_3 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 with 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 a given section of the assembly is the same for both the scanning or stationary modes of operation.

The measurements on each assembly were performed using several runs of 200 s each depending on available time. No personnel were required to be in attendance during the cyclic measurements. For each assembly, the measurements were performed both with and without the AmLi source to obtain both the ^{235}U and ^{238}U values.

The results of the measurements are listed in Table IV for the active neutron case using Coincidence Collar-3. Typically, five runs of 200 s each were used to obtain the results; however, some of the elements were measured for longer periods corresponding to lunch breaks and overnight runs. All of the assemblies listed in Table II were measured during the test. The average net coincidence response and the scatter (standard deviation, S) about the mean are listed in Table IV. Table V gives the coincidence results for the mockup fuel assemblies.

A least squares fit was made to the mockup coincidence data using a quadratic function. This function was then used to obtain the ^{235}U enrichments of the production assemblies listed in Table IV. Details concerning the calibration curve and the quadratic function parameters are given in Sec. VI.

Figure 6 shows the coincidence response as a function or enrichment for the active case. The response increases with enrichment and is not saturated. This is due, in part, to fast neutron multiplication. There is no significant variation as a function of assembly storage location and the proximity of neighboring assemblies.

The gadolinium loading in the BWR assemblies decreases the observed response. Also, the gadolinium concentration is higher in the bottom half of the fuel assemblies than in the top. The two curves shown in Fig. 6 correspond to the top and bottom regions. The separation in the two curves is a measure of the number of gadolinium-loaded rods.

TABLE IV

ACTIVE ASSAY OF BWR FUEL ASSEMBLIES

Assembly	Av ^{235}U	Run Time (s)	Coincidence Rate Top (s^{-1})	Coincidence Rate Bottom (s^{-1})
T·1(a)	2.91%	3 x 200	82.42 ± 1.07	77.47 ± 1.09
T·1(b)	2.91%	5 x 200	82.44 ± 0.80	77.50 ± 0.77
T·1(c)	2.91%	10 x 200	83.29 ± 0.62	77.27 ± 0.58
			x = 82.72	x = 77.41
			S = 0.50	S = 0.13
		Assay Value[a] =	2.93%	2.86%
		% diff. $\frac{\text{Meas.-Tag}}{\text{Tag}} \times 100$ =	0.69%	-1.71%
T·2(a)	2.82%	7 x 200	---	85.30 ± 0.74
T·2(b)	2.82%	5 x 200	90.00 ± 0.90	84.72 ± 0.80
T·2(c)	2.82%	6 x 200	88.93 ± 0.89	85.80 ± 0.51
T·2(d)	2.82%	5 x 200	---	87.29 ± 0.87
T·2(e)	2.82%	10 x 200	---	87.85 ± 0.62
T·2(f)	2.82%	10 x 200	---	86.91 ± 0.70
T·2(g)	2.82%	9 x 200	---	86.20 ± 0.70
			x = 89.47	x = 86.30
				S = 1.12
		Assay value[a] =	2.83%	2.83%
		% diff. $\frac{\text{Meas.-Tag}}{\text{Tag}} \times 100$ =	0.35%	0.35%

[a]Assay value from calibration curve for mockup assembly after correction for differences in Gd_2O_3 loading.

TABLE V

DATA SUMMARY FOR MOCKUP FUEL ASSEMBLIES

Assembly		Av ^{235}U	Gd Rods	Run Time (s)	Coincidence Rate Top (s^{-1})	Coincidence Rate Bottom (s^{-1})
Mockup	A	2.85%	5	5 x 200	83.97 ± 0.84	80.83 ± 0.81
	B	2.47%	5	5 x 200	76.64 ± 0.77	73.41 ± 0.73
	C	3.13%	5	5 x 200	91.25 ± 0.91	86.75 ± 0.87
	D	2.85%	5	5 x 200	83.97 ± 0.84	80.83 ± 0.81
	E	2.85%	3	5 x 200	---	91.41 ± 0.91
	F	2.85%	0	10 x 200	---	105.3 ± 0.90
(CD)	F	2.85%	0	6 x 10 000	---	8.4 ± 0.08
(CD)	D	2.85%	5	9 x 600	---	7.4 ± 0.20
(CD)	T•2	2.82%	4	13 x 600	---	7.8 ± 0.11
5 x 5	G	3.12%	0	6 x 10 000	---	51.35 ± 0.12
5 x 5	H	2.40%	0	13 x 600	---	42.12 ± 0.34

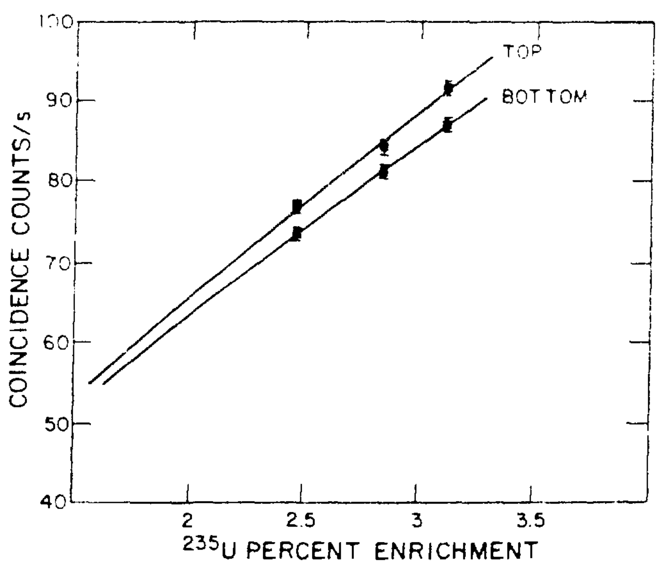

Fig. 6.
Active measurements results for different average enrichments in the mockup fuel assembly. The top and bottom curves correspond to the top and bottom regions of the fuel assembly with different Gd_2O_3 loadings.

D. Passive Results

When the AmLi source is removed from the detector, the passive coincidence rate is proportional to the ^{238}U mass by means of the spontaneous fission neutrons. For the 8 x 8 BWR assemblies, the uranium mass and the enrichment did not change enough to significantly change the passive response, which was 3.18 counts/s. Because this is only a small fraction of the active response that ranges from 80 to 100 counts/s, the passive rate was not measured for each of the assemblies, and the constant rate (3.18) was subtracted from the active rate to get the net active rate.

When the uranium mass or rods are removed from the assembly, the passive rate drops because of the reductions in the ^{238}U source strength and in the fast-neutron multiplication and because of the decrease in the reflection of neutrons from the top and bottom of the measurement zone. Figure 7 plots the passive coincidence response for both the 8 x 8 (63 rods) and 5 x 5 (24 rods) assemblies. Also shown on the plot is a data point for a 6 x 6 rod assembly that was measured at Los Alamos before shipping Coincidence Collar-3 to the agency.

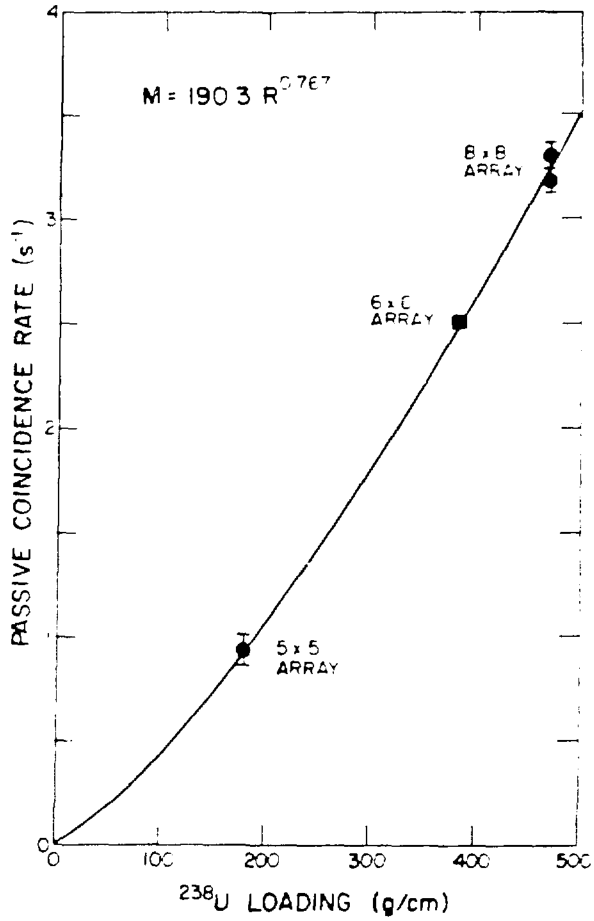

Fig. 7.
Passive measurement results for mockup assemblies containing different numbers of fuel rods. The data for the 6 x 6 array were taken at Los Alamos before the ASEA-ATOM exercise.

The statistical precision for the 8 x 8 assembly was 1.8% for 1000 s of run time in the passive mode. The gadolinium rods do not affect the passive measurement; because the signal is from fast fission neutrons, the thermal neutron absorber (gadolinium) has no effect.

E. Effects of Gadolinium Rods and Cadmium Sheet

To evaluate the effect of the rods containing gadolinium on the active response, the 8 x 8 mockup assembly was changed to contain 5, 3, and 0 gadolinium rods. In each case, the gadolinium rod was replaced by a rod containing the same ^{235}U enrichment (3.17%) but without gadolinium. The results of the active measurements are shown in Fig. 8, where we see that one gadolinium ($\sim$4.4 wt% Gd_2O_3) rod reduces the active response by about 5%. For a rod containing less Gd_2O_3 (for example, 2 wt%), the reduction is a little less but the effect is nonlinear with Gd_2O_3 mass because the rods are nearly "black" or saturated for thermal neutron absorption.

The perturbation on the measurement from the Gd_2O_3 can be mostly eliminated by using thin cadmium sheet liners (0.4 mm thick) on the inside surface of the sample chamber. The cadmium removes the thermal neutrons from the interrogation flux and thus the thermal neutron poison (Gd_2O_3) has no significant effect. The bottom curve in Fig. 8 shows that there is little difference in the responses with zero or five Gd_2O_3 rods when the cadmium sheet is in place.

However, the cadmium reduces the signal rate, and thus the measurement time to reach a given precision is increased. For example, the standard deviation with cadmium is 4.0% in 1000 s as compared with 0.9% in 1000 s with no cadmium. Because the cadmium increases the required measurement time, it should be used only as a

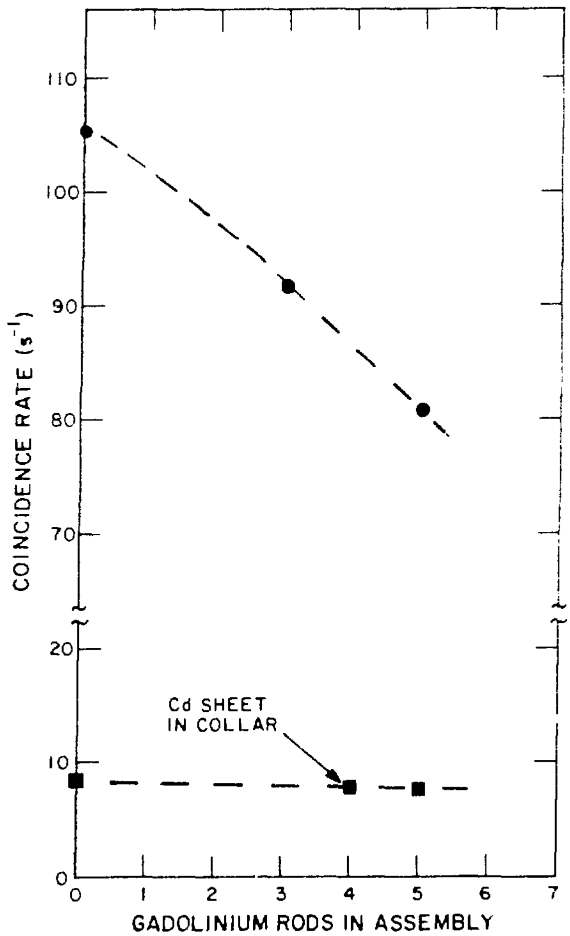

Fig. 8.
Coincidence rate as a function of the number of Gd_2O_3 rods both with (bottom curve) and without (top curve) a cadmium liner on the inside of the collar.

potential check on the operator-declared gadolinium content and not for routine use.

Because the gadolinium loading is greater in the bottom than in the top half of the assembly, the bottom-to-top ratio gives a second potential check on the gadolinium content. For example, if the Gd_2O_3 were removed to give a higher reading for the average ^{235}U enrichment, then the bottom and top measurements would be the same, as opposed to the normal difference of ~5% as shown in Fig. 6.

F. Production Assembly Results

Two types of production assemblies were available for the tests; type 1 containing six rods with 4.4 wt% Gd_2O_3, and type 2 containing four rods with 2.0 wt% Gd_2O_3. Several of these assemblies were measured as shown in Table IV. The responses showed a scatter of ~1%, which is consistent with the statistical expectations for measurement times of 800 to 1000 s. If shorter measurement times are desired, the precision will increase as the square root of the time. For example, a 300-s measurement will give a standard deviation of ~1.7%.

The calibration results from the mockup assembly were used to assay the production assemblies. A least squares fit was made to the data for top and bottom zones to establish the two calibration curves shown in Fig. 9. The measured data from the production assemblies were then corrected for the differences in Gd_2O_3 using Fig. 8, and the responses were fit to the mockup calibration curves (Fig. 9) to determine the ^{235}U content. The average difference between collar assay value and the tag value was 0.6% for the T•1 type assemblies and 0.35% for the T•2 assemblies.

G. End Effects

Measurements were performed to determine the "end effects" when the fuel assembly is scanned completely through the Coincidence Collar. The overhead crane was used to move the fuel assembly in increments of 10 cm near the top and bottom ends of the fuel assembly.

The results of the measurement are shown in Fig. 10, where the coincidence response corresponds to assembly T•2 for the top measurement and mockup A assembly for the bottom region. To avoid end effects, the top or bottom of the collar should not get closer than 15-20 cm to the ends of the active fuel region.

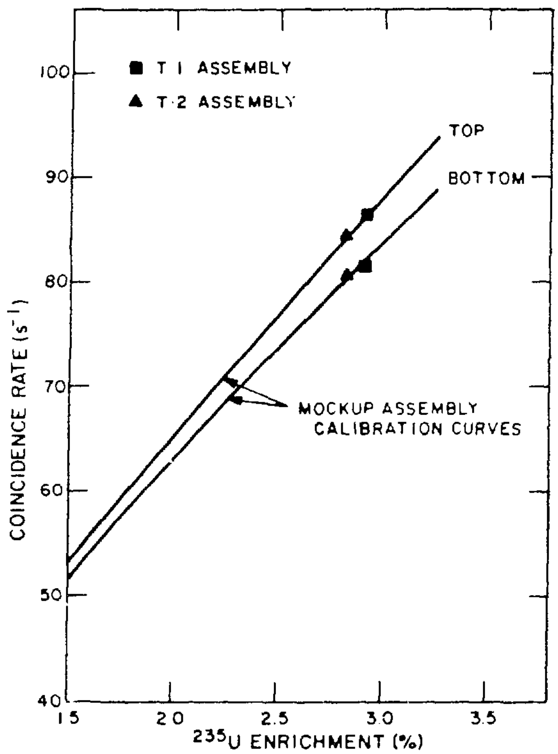

Fig. 9.
The results from the production assembly measurements compared with the calibration curves obtained from the mockup assembly.

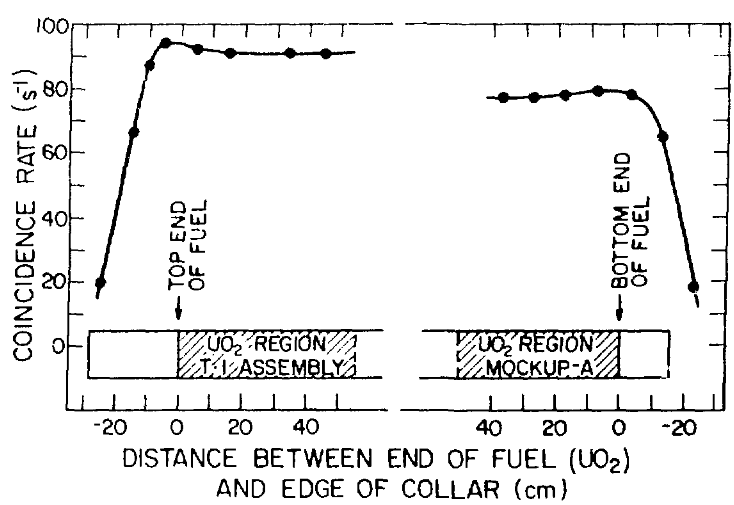

Fig. 10.
Axial scans of the mockup assembly (A) and the production assembly (T·1) near the bottom and top ends of the active fuel (UO_2) regions. The slight rise in the response near the end is caused by the absence of Gd_2O_3 in the last 14 cm of the fuel column.

For fuel assemblies with no gadolinium in the pellets near the ends of the rod, the end response shows a slight increase before dropping off when the fuel ends. This effect first alerted us to the variable loading along the length of the gadolinium rods.

H. 5 x 5 Rod Results

The 5 x 5 rod loading is not a normal BWR configuration, but BWR rods stored in this configuration are under IAEA safeguards. Because of the atypical nature of this configuration, the results are detailed in Appendix B.

I. Precision and Stability

To check the stability and precision of the system, long runs were performed overnight and during the weekend. The results of the long-term stability checks are given in Table VI. No electrical noise was observed in the system during the in-plant tests.

The predicted standard deviation (σ) is calculated from the expression

$$\sigma = \frac{\sqrt{(R+A)+A}}{R} \times 100\% \quad .$$

The software program calculated the mean and the standard deviation S from the observed scatter about the mean.

The observed scatter is about 0.1% higher than the predicted σ from counting statistics, which is consistent with previous measurements under laboratory test conditions.

TABLE VI

IN-PLANT STABILITY AND PRECISION MEASUREMENTS

Assembly	Run Time	Standard Deviation (Coinc.) Observed (S)	Standard Deviation (Coinc.) Predicted (σ)
Mockup A	15 x 4000 s (overnight)	0.63%	0.52%
T·2	15 x 4000 s (overnight)	0.59%	0.49%
Mockup B	24 x 10 000 s (weekend)	0.43%	0.35%

VI. CALIBRATION

The active assay data for the different enrichments are shown in Fig. 6. To take advantage of HP-97 software programs used with the HLNCC,[3] a quadratic function was used to fit the data.

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

where R is the coincidence response, M is the fissile content per unit length (or enrichment), and A_0, A_1, and A_2 are constants.

For the top region, the constants determined from fitting the data from Coincidence Collar-3 for the 8 x 8 rod mockup BWR assembly (5 rods with Gd_2O_3) are given.

$$\left.\begin{aligned} A_0 &= -0.523 \\ A_1 &= 0.03458 \\ A_2 &= 0.0000616 \end{aligned}\right\} \quad {}^{235}\text{U enrichment (top zone)}$$

$$\left.\begin{aligned} A_0 &= -2.535 \\ A_1 &= 0.1676 \\ A_2 &= 0.000299 \end{aligned}\right\} \quad {}^{235}\text{U grams per cm (top zone)}$$

These two sets of constants are related by the ratio of

$$\frac{13.67\ \text{g}\ {}^{235}\text{U per cm}}{2.82\%\ {}^{235}\text{U}} = 4.848 \quad .$$

Thus, if one fits for the enrichment, the ^{235}U mass per centimeter can be determined by multiplying by 4.848 for this particular type fuel assembly. The advantage of using the mass per unit length is that one assembly type can be related to other assembly geometries (for example, 7 x 7 arrays). The advantage of using the enrichment is that enrichment data are normally supplied by the operator during inspection.

The constants listed above were determined from a least squares fit of the data, where we inserted a point near zero ^{235}U enrichment (0.01%) of 14 counts/s. This was estimated from theoretical considerations of the fast neutron fissions in the ^{238}U mass. The reason for the artificial data point was to better anchor the quadratic function near the zero ^{235}U mass end, and thus to reduce the uncertainties in the calibration curve.

For the bottom region, we give the corresponding constants.

$$\left.\begin{array}{l} A_0 = -0.458 \\ A_1 = 0.03192 \\ A_2 = 0.0001097 \end{array}\right\} \quad \begin{array}{l} ^{235}U \text{ enrichment} \\ \text{(bottom region)} \end{array}$$

$$\left.\begin{array}{l} A_0 = -2.220 \\ A_1 = 0.1547 \\ A_2 = 0.000532 \end{array}\right\} \quad \begin{array}{l} ^{235}U \text{ grams per cm} \\ \text{(bottom region)} \end{array}$$

The above calibration constants correspond to 8 x 8 rod assemblies (63 rods) containing five rods loaded with Gd_2O_3 (4.4 wt%). For applications to assemblies with different gadolinium loadings, it is necessary to correct the measured response using the curve in Fig. 8. The gadolinium rod loadings are normally the same for all the assemblies in a given reactor core loading.

Any future measurements of BWR assemblies with Coincidence Collar-3 can be related to the above calibration parameters by using the AmLi source normalization procedure described in Ref. 1. By counting the net T for AmLi-93 (no fuel in counter) at the time of calibration, future electronic shifts in the rates can be corrected by again counting the same AmLi source.

For the present exercise, the AmLi-93 rate is

T = 2160 counts/s.   Coincidence Collar-3
AmLi-93

The corresponding enrichment is given by

$$M = A_0 + A_1R + A_2R^2 \quad ,$$

where the A's are the calibration constants and R is the net coincidence rate in counts per second.

The normalization constant is defined as

$$k = \left[\frac{T(\text{original})}{T(\text{current})}\right]^2 \quad ,$$

or

$$k = \left[\frac{2160}{T(\text{current})}\right]^2 \quad ,$$

and

$$R_{(\text{Norm})} = k\ R_{(\text{current})} \quad .$$

The enrichment of an unknown BWR assembly can be calculated from the equation

$$M = -0.458 + 0.03192(kR) + 0.0001097(kR)^2$$

for the bottom region of the fuel assembly. Similarly, the top region calibration constants are used for measurements in the top fuel region. Normally, only the bottom region of the assembly would be measured, with the inspector checking the top region if additional verification of the gadolinium loading seemed warranted.

1. Example Calculation. (Hypothetical future data)

Net totals rate = 2040 counts/s (source alone)

Coincidence rate R = 81.0 counts/s (bottom region of assembly)

Number of Gd_2O_3 (4.4 wt%) rods = 4 (vs 5 for calibration parameters)

Reduce the response by 81.0/1.05 for the gadolinium difference (4 vs 5 rods)to get R(gadolinium corr.) = 77.14 counts/s. Next, to account for the electronic shift, calculate

$$k = \left[\frac{2160}{2040}\right]^2 = 1.121 \quad .$$

Then the enrichment is

$$M = 0.458 + 0.03192\,(kR) \quad 0.0001097(kR)^2$$

or

$$M = 3.12\%\ {}^{235}U \quad .$$

In general, this calculation will be automated in the HP-97 calculator.

VII. CONCLUSIONS AND RECOMMENDATIONS

A. Electrical Noise and Neutron Background

No electrical noise or interference problems were observed at the plant. The collar had properly shielded cables and there was fresh desiccant in the hv boxes.

Room neutron levels were small and interfered with neither the active nor passive measurements. There were no problems in measuring the passive coincidence signal to check the ^{238}U.

B. Precision and Stability

1. Active Assay for ^{235}U. The statistical precision for a 1000-s run was $\sim$0.9% (1σ). For longer counting periods of $\sim$1 h, the precision was about 0.4%.

2. Passive Results for ^{238}U. The counting rates for the passive measurements are much lower than for the active case. The statistical standard deviation was $\sim$3.3% (400 s).

C. Information Needed from Operator

(1) Number of gadolinium rods, wt% Gd_2O_3, and axial distribution
(2) Average ^{235}U enrichment of fuel assembly
(3) Active length of fuel region

D. What is Obtained

(1) Uranium-235 enrichment (or ^{235}U/cm) relative to calibration with same type assembly (1σ = 1% in 800 s) or (1.4% in 400 s).
(2) Absolute ^{235}U enrichment by fitting to general calibration curve for 8 x 8 assembly plus gadolinium correction. ($1\sigma \sim$ 2-3% in 400 s).
(3) Check on Gd_2O_3 content by ratio of top to bottom.
(4) Absolute ^{238}U content by passive count. ($1\sigma \sim$ 3.3% in 400 s) independent of gadolinium loading.
(5) Results do not depend on enrichment configuration or pellet density.
(6) Results do not depend on plastic bagging or Zircaloy channel; however, the stainless steel storage channels significantly (12%) reduce the response.
(7) For fixed average enrichment, the number of gadolinium rods can be determined in 300 to 400 s.

E. Recommendations

Assemblies that differ from the present assemblies can still be measured to obtain the relative loading of a group of fuel assemblies. Repeat measurements over a period of time verify that the assemblies have not been tampered with. Assemblies that differ from the calibration assemblies are still measured using the inappropriate calibration curve, but the uncertainty in the absolute result will be somewhat larger. Calculations are performed to reduce this uncertainty.

(1) For routine measurements, some fabrication facilities will require a custom-built cart or support mechanism for the collar.

(2) Coincidence Collar-3, together with AmLi source MRC-AmLi-93, is calibrated for the verification of BWR fuel assemblies.

(3) In general, each major category of fuel (for example, PWR and BWR) will require its own calibration curve. Within a fuel assembly category such as BWR, there are variations such as rod number in the array (6 x 6 to 8 x 8) and fuel rod diameter, which will require small 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.

REFERENCES

1. H. O. Menlove, "Description and Performance Characteristics for the Neutron Coincidence Collar for the Verification of Reactor Fuel Assemblies," Los Alamos National Laboratory report LA-8939-MS (ISPO-142) (1981).

2. H. O. Menlove, A. Keddar, J. Griggs, C. Beets, P. Bemelmans, and P. Boermans, "Optimization of NDA Measurements in Field Conditions for Safeguards Purposes," Studiecentrum voor Kernenergie CEN/SCK. Mol, Belgium, report BLG 553 (January 1982).

3. M. S. Krick and H. O. Menlove, "High-Level Neutron Coincidence Counter (HLNCC): USERS MANUAL," Los Alamos Scientific Laboratory report LA-7779-M (ISPO-53) (June 1979).

APPENDIX A

DATA COLLECTION AND STATISTICAL ANALYSES PROGRAM USING THE HP-97 CALCULATOR

A software program was written and tested during the present exercise at the BWR facility. Its purpose was to collect data in the cyclic mode and calculate the estimated standard deviation from the number of counts.

$$\sigma\% = \frac{\sqrt{(R + A) + A}}{R} \times 100\% \quad ,$$

as well as the mean responses (T and R) and the observed scatter (S), about the mean. At the end of n runs (or cycles), the standard deviation for the total counting time is calculated from

$$\frac{\sigma\%}{\sqrt{n}} \quad .$$

The inspector has a comparison of

σ% (predicted deviation)

with

S% (observed scatter)

at the time of the measurements.

In the program, subroutine B is used for the passive measurement, and the passive coincidence results are stored for background subtraction in subroutine C, which is used for the active measurement. The background correction factors are written directly into the program and no entries are required from the user. A totals rate background from the assembly in the collar is taken as 45 counts/s for all of the assemblies and BWR collars. This value should not be changed as long as the present calibration constants are in use. This is true also for the passive background correction factor of 0.0138. An example of the readout format is given in Table A-I.

Only two results from the data output are required for the mass analysis and these are

$$R = 81.0 \text{ counts/s} \pm 0.90\% \text{ (typical)}$$

for the active (^{235}U) assay, and

$$R = 3.2 \text{ counts/s} \pm 2.1\%$$

for the passive (^{238}U) assay.

The program listing and explanation of the HP-97 Data Collection and Statistical Analyses Program are given in Table A-II. The subprogram D in the software has been updated (July 1982) to include the mass calculation with the power function $M = aR^b$ calibration curve, where a = 0.03177 and b = 1.399. These constants are appropriate for AmLi-93 and an 8 x 8 rod BWR assembly containing six rods with 4.4 wt% Gd_2O_3.

TABLE A-I

DATA READOUT FORMAT FOR HP-97 DATA COLLECTION
PROGRAM FOR A 2.4%-ENRICHED PWR ASSEMBLY

Passive Mode

200.00	***	- time (s)
56.59	***	- T/s
2.66	***	- (R + A)/s
0.16	***	- A/s
2.65	***	- R/s
4.59	***	- σ%
1.00	***	- n
200.00	***	2nd run
61.32	***	
3.04	***	
0.30	***	
2.74	***	
4.71	***	
2.00	***	
200.00	***	3rd run
55.51	***	
3.08	***	
0.19	***	
2.89	***	
4.42	***	
3.00	***	

Press B

57.5[illegible]	***	- $\bar{T}$/s
2.61	***	- $\bar{R}$/s
3.23	***	- S%
238000000.0		- U-238
2.63	***	- $\bar{R}$ corr.
397.33	***	- $\sigma/\sqrt{n}$ %
[illegible]	***	

Press D

14.04	***	- M(g ^{235}U/cm)
0.20	***	- ΔM(g)
3.04	***	- % U-235

Active Mode

200.000	***	- time (s)
2169.245	***	- T/s
373.900	***	- (R + A)/s
301.935	***	- A/s
71.965	***	- R/s
2.554	***	- σ%
1.000	***	- n
200.000	***	2nd run
2143.530	***	
366.385	***	
292.395	***	
73.590	***	
2.453	***	
2.000	***	
200.000	***	3rd run
2127.500	***	
362.160	***	
290.575	***	
71.585	***	
2.524	***	
3.000	***	
200.000	***	4th run
2123.330	***	
363.285	***	
292.615	***	
70.670	***	
2.563	***	
4.000	***	

Press C

2136.734	***	- $\bar{T}$/s
72.215	***	- $\bar{R}$/s
2.438	***	- S%
235000000.0		- U-235
69.583	***	- $\bar{R}$ net
0.969	***	- $\sigma\%/\sqrt{n}$

TABLE A-II

HP-97 DATA COLLECTION AND STATISTICAL ANALYSIS PROGRAM

Step	Instruction	Comment
001	*LBLA	- Data in
002	RCL1	
003	PRTx	- Time (s)
004	RCL2	
005	RCL1	
006	÷	
007	PRTx	- T/s
008	RCL3	
009	RCL1	
010	÷	
011	PRTx	- (R + A)/s
012	RCL4	
013	RCL1	
014	÷	
015	PRTx	- A/s
016	RCL3	
017	RCL4	
018	-	
019	RCL1	
020	÷	
021	PRTx	- R/s
022	STO6	
023	RCL3	
024	RCL4	
025	+	
026	√X	
027	RCL3	
028	RCL4	
029	-	
030	÷	
031	1	
032	0	
033	0	
034	×	
035	PRTx	- σ%
036	STO5	
037	RCL2	
038	RCL1	
039	÷	
040	ENT↑	
041	RCL6	
042	Σ+	
043	PRTx	- run no.(n)
044	STO9	
045	SPC	
046	RTN	
047	*LBLB	- Passive Mode-key B
048	$\bar{x}$	
049	X⇄Y	
050	PRTx	- $\bar{T}$/s
051	STO8	
052	X⇄Y	
053	PRTx	- $\bar{R}$/s
054	STOA	
055	S	
056	RCLA	
057	÷	
058	1	
059	0	
060	0	
061	×	
062	PRTx	- S% (scatter)
063	2	
064	3	
065	8	
066	0	
067	0	
068	0	
069	0	
070	0	
071	0	
072	PRTx	- U-238 (ID)
073	RCL8	
074	0	BWR background Passive T/s
075	4	
076	5	
077	-	
078	.	
079	0	
080	1	
081	3	
082	8	
083	×	
084	RCLA	
085	X⇄Y	
086	-	
087	PRTx	- $\bar{R}$/s (corrected)
088	RCL5	
089	RCL9	
090	√X	
091	÷	
092	PRTx	- $\sigma/\sqrt{n}$ %
093	SPC	
094	GSBE	
095	CLX	
096	RTN	
097	R/S	

TABLE A-II (cont.)

```
098  *LBLC - Active Mode-key C
099     x̄
100    X⇄Y
101   PRTX - T̄/s
102    X⇄Y
103   PRTX - R̄/s
104   STO7
105     S
106   RCL7
107     ÷
108     1
109     0
110     0
111     x
112   PRTX - S% (scatter)
113     2
114     3
115     5
116     0
117     0
118     0
119     0
120     0
121     0
122   PRTX - U-235 (ID)
123   RCL7
124   RCLA - Passive R background
125     -
126   PRTX - net R̄/s
127   STOB
128   RCL5
129   RCL9
130    √X
131     ÷
132   PRTX - σ/√n %
133   STO3
134    SFC
135   GSBE
136    CLX
137    RTN
138    R/S
```

```
139  *LBLD - Mass Calc.-key D
140   RCLB
141   RCLC
142     x
143     1  )
144     .  |
145     3  |
146     9  } b (BWR)
147     9  |
148    y^x )
149     .  )
150     0  |
151     3  } a (BWR)
152     1  |
153     7  |
154     7  )
155     x
156   RCLD
157     x
158   PRTX - M(g 235U/cm)
159    P⇄S
160   STO5
161   RCL3
162     1
163     0
164     0
165     ÷
166     x
167     1
168     .
169     4
170     x
171   PRTX - ΔM(g 235U/cm)
172   RCL5
173   RCLE
174     x
175   PRTX - % 235U
176    SFC
177   GSBE
178    CLX
179    RTN
--------------------------------
180  *LBLE- Storage reference
181     0         (optional)
182   STO4
183   STO5 - σ,σ/√n
184   STO6 - R/s
185   STO7 - R/s
186   STO8 - T/s
187   STO9 - n
188    P⇄S
189    RTN
190    R/S
```

APPENDIX B

CALIBRATION FOR 5 x 5 ROD ARRAYS

The response functions given in Sec. VI apply only to 8 x 8 rod BWR assemblies. A series of measurements were performed to extend the calibration to 5 x 5 rod arrays. Rods were removed from the mockup assembly to obtain the 5 x 5 rod configuration shown in Fig. B-1. The average enrichments and masses for this reduced loading are given in Table B-I.

For the measurements, the assembly was positioned in the collar so that the plastic bagging around the Zircaloy channel was just touching the inside face of the polyethylene in the collar. The coincidence responses for the two enrichments are listed in Table V, and Fig. B-2 shows a plot of the results vs enrichment. None of the rods contained Gd_2O_3, so there is no difference between the bottom and top rates. The 8 x 8 response is shown on the same graph for comparison.

If the responses are compared in terms of g ^{235}U/cm rather than per cent enrichment, the differences between different type assemblies are less. Actually, the instrument measures the fissile loading per unit length. Figure B-3 shows the 5 x 5 results together with 8 x 8 data plotted as a function of loading per unit length. The 6 x 6 array results were obtained at Los Alamos before shipping the collar to the IAEA. In this case, all of the configurations fall on a common calibration curve.

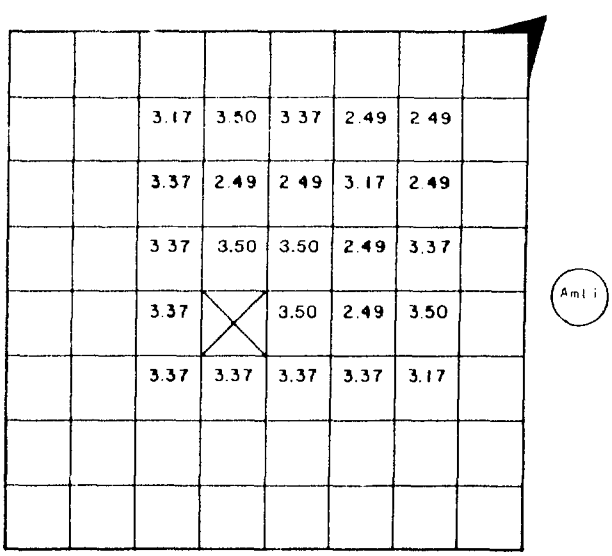

Fig. B-1.
Rod loading configuration for the 5 x 5 rod array with an average enrichment of 3.12% ^{235}U. The AmLi circle indicates the orientation of the neutron interrogation source.

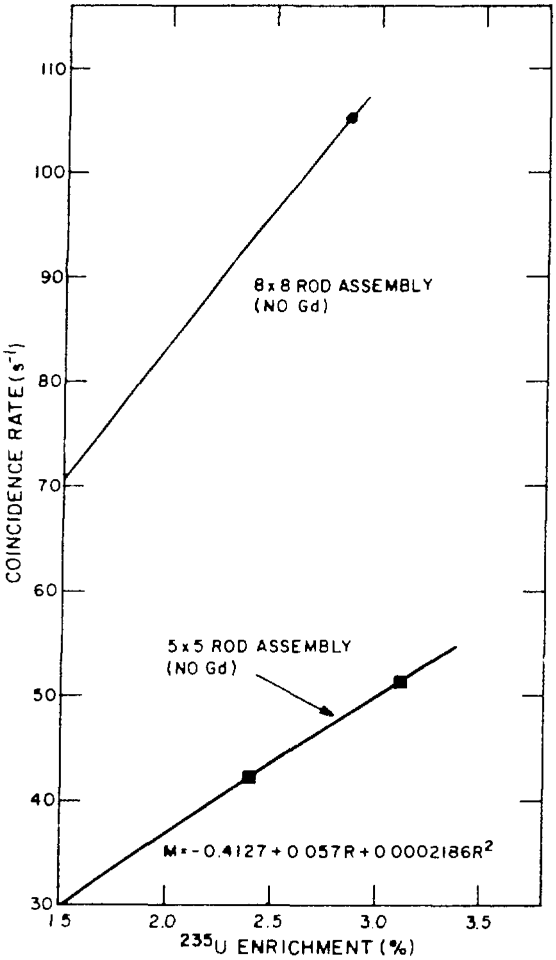

Fig. B-2.
Plot of the coincidence rate as a function of ^{235}U enrichment for the different arrays.

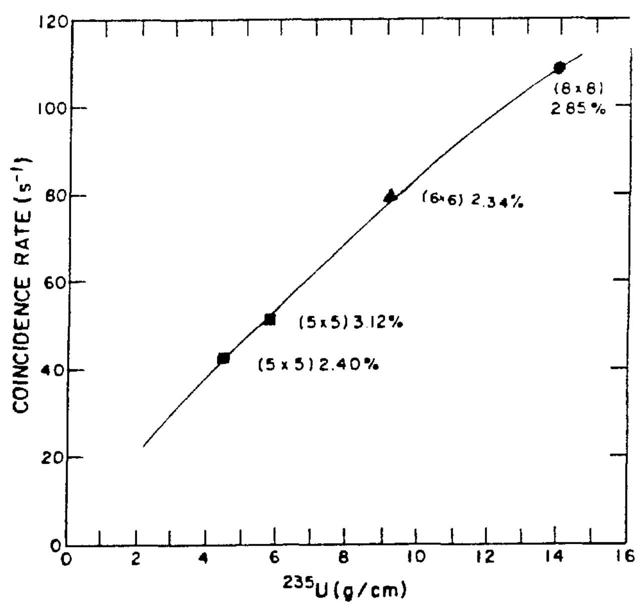

Fig. B-3.
Plot of the coincidence rate as a function of g ^{235}U/cm for different rod arrays.

The calibration constants for the 5 x 5 rod array are given in the equation

$$M = - 0.4127 + 0.05757R + 0.0002186R^2 \quad .$$

These constants are for ^{235}U enrichment when using Coincidence Collar-3 (MRC-AmLi-93), where the source totals rate is 2160 counts/s. The same normalization procedure described in Sec. VI can be used to relate these coefficients to future measurements.

Table B-I gives the results for the different number of rods in the array together with the loading in terms of g ^{235}U/cm. Note that the fuel pellet diameter for the 6 x 6 rod mockup at Los Alamos was 14.2 mm compared with an average of 10.3 mm for the ASEA-ATOM rods. None of these assemblies contained gadolinium rods.

TABLE B-I

MEASUREMENT RESULTS FOR DIFFERENT BWR ROD ARRAYS

Assembly	Array	No. of Rods	Average Per Cent ^{235}U	^{238}U g/cm	^{235}U g/cm	Coincidence Rate Passive	Coincidence Rate Active
Mockup B	5 x 5	24	2.40	178.9	4.44	---	42.12
Mockup A	5 x 5	24	3.12	180.3	5.76	0.93	51.35
Mockup F	8 x 8	63	2.85	471.1	13.82	3.2	105.3
Los Alamos Mockup	6 x 6	36	2.34	382	9.15	2.51	79.4