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CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

OPTIMIZATION OF NDA MEASUREMENTS IN FIELD CONDITIONS FOR SAFEGUARDS PURPOSES

H. MENLOVE, A. KEDDAR, J. GRIGGS, C. BEETS, P. BEMELMANS, P. BOERMANS

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Contract RB/2274 - Third Progress Report

Chief Scientific Investigator : C. Beets

Contributors : H. Menlove*
A. Keddar**
J. Griggs**
P. Bemelmans***
P. Boermans****

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* LASL, Los Alamos Scientific Laboratory
** IAEA, International Atomic Energy Agency
*** CEN/SCK, Centre d'Etude de l'Energie Nucléaire
**** FBFC, Franco-Belge de Fabrication de Combustibles.

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Summary. - This report describes the results of a field test and evaluation of the Coïncidence Collar for PWR fuel assemblies performed at the Franco-Belge de Fabrication de Combustibles (FBFC) facility in Dessel, Belgium from June 10-17, 1981. Comparisons are made with the results using the Prototype Neutron Coïncidence Collar at the same facility described in the BLG-548 report.
The main results are the following:

1. Active Assay for ^{235}U. - The standard deviation for a 1000 s run varied from 0.6 - 0.9 %, depending on the type assembly. For longer counting periods, the ultimate precision was about 0.1 % for repeat runs with a fixed geometry. The response curve is not saturated and continues to increase versus the enrichment increases through the normal range of LWR fuel.

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 about 1.4 % (1000 s) but the results were influenced by neutron background variations.

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Samenvatting. - Dit rapport geeft een beschrijving van de resultaten van een proefneming met de «Coïncidence Collar» voor de niet-destructieve meting van PWR-splijtstofassemblages. Deze proefneming werd van 10 tot 17 juni 1981 uitgevoerd in de fabriek Franco-Belge de Fabrication de Combustibles (FBFC) te Dessel, België. De resultaten worden vergeleken met dezen die met het prototype van de Coïncidence Neutron Collar bekomen werden in dezelfde fabriek en gepubliceerd werden in het rapport BLG-548.
De voornaamste resultaten worden hierna gegeven:

1. Actieve proef voor ^{235}U - De standaardafwijking voor een proef gedurende 1000 s varieerde van 0,6 tot 0,9 %, naargelang het assemblagetype. Voor langere telperiodes bedroeg de uiteindelijke nauwkeurigheid 0,1 % voor herhaalde proeven in een vaste geometrie. De antwoordcurve is niet verzadigd en blijft groeien in functie van de verrijking voor het domein van de verrijkingen die gebruikt worden voor de fabricage van LWR-splijtstof.

2. Passieve proef voor ^{238}U - De telsnelheden voor de passieve metingen zijn beduidend lager dan deze voor de actieve metingen. De standaardafwijking bedraagt ongeveer 1,4 % voor 1000 s, maar de resultaten worden beïnvloed door variaties van de parasitaire achtergrond.

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Resumé. - Ce rapport décrit les résultats d'une expérience en usine du dispositif «Coïncidence Collar» pour mesurer de façon non-destructive les assemblages du type PWR. L'expérience a été réalisée à l'usine Franco-Belge de Fabrication de Combustibles (FBFC), Dessel,Belgique du 10 au 17 juin 1981. Les résultats sont comparés aux résultats précédents utilisant le prototype du dispositif «Neutron Coïncidence Collar» et qui sont publiés dans le rapport BLG-548.
Les résultats principaux sont les suivants:

1. Essai actif pour ^{235}U. - L'écart type pour un essai de 1000 s varie de 0,6 à 0,9 %, en fonction du type d'assemblage. Pour des périodes de comptage plus longues la précision ultime était voisine de 0,1 % pour des essais répétés en géométrie fixe.
La courbe de réponse n'est pas saturée et continue à s'accroître en fonction de l'enrichissement pour le domaine des enrichissements utilisés dans la fabrication des combustibles LWR.

2. Essai passif pour ^{238}U. - Les taux de comptage pour les mesures passives sont beaucoup plus bas que pour les mesures actives. L'écart-type est d'environ 1.4 % pour 1000 s mais les résultats sont affectés par les variations du fond parasite.

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I. INTRODUCTION

The Coincidence Collar[1-2] has been developed for the verification of fissle content in fresh fuel assemblies. Measurements can be performed at fuel fabrication facilities or at reactor sites after the fuel shipment is received. Three class III Coincidence Collars have been supplied to the IAEA under Task A-75 for test and evaluation.

The assay method employs an AmLi neutron source to induce fission reactions in the fuel assembly and coincidence counting of the resulting fission reaction neutrons. This coincidence counting eliminates the undesired neutron counts from the random AmLi interrogation source (4.5×10^4 n/s) and room background neutrons. When no interrogation source is present, the passive neutron coincidence rate gives a measure of the ^{238}U through the spontaneous fission reactions. This Coincidence Collar technique can be applied to the fissile content determination in heavy-water-reactor (HWR), boiling-water-reactor (BWR), and pressurized-water-reactor (PWR) fuel assemblies.

This report gives the results of the field test and evaluation of the Coincidence Collar for PWR fuel assemblies performed at the Franco-Belge de Fabrication de Combustibles (FBFC) facility in Dessel, Belgium from June 10-17, 1981. Comparisons are made with the results using the Prototype Coincidence Collar[3] at the same facility in June 1980.

II. DESCRIPTION OF COINCIDENCE COLLAR EQUIPMENT

A. Detector Head

Two neutron Coincidence Collars were used in the present work (C-Collar 1 and C-Collar 2), and a schematic diagram of the detector head is shown in Fig.1. There are three groups of ^{3}He detectors with six tubes in each bank imbedded in a CH_2 slab. The active length of each tube is 33 cm, the overall height of the unit is about 45 cm, and the weight is approximately 27 kg.

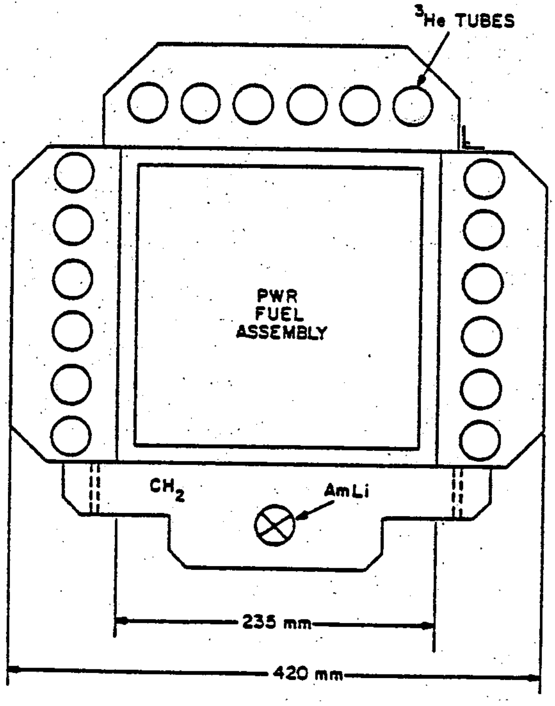

Fig.1. Schematic diagram of Coincidence Collar showing the location of the AmLi neutron source and the ^{3}He detectors.

The detector shown in Fig.1 can be adjusted for both PWR and BWR fuel assemblies. The configuration shown corresponds to the PWR geometry. For BWR assemblies, the sides of the detector are moved toward the center and the BWR assembly is positioned about 2 cm from the front face.

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 sources. 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 to facilitate handling and removal from the Coincidence Collar for the passive portion of the assay.

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 : Americium 241

Source Container Description : MRC Model 2724-Bt

Shipping Container : 10-gal drum, 6M-1026 USDOT Spec. 6m, Type D

IAEA Certification of Competent Authority : USA/D043/S

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.

C. Electronic Setup

The electronic components and connections are identical to the High-Level Neutron Coincidence Counter (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]

D. Detector Cart

For normal applications, the fuel assemblies will be in a vertical storage position and the Coincidence Collar will be positioned on its cart. 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 easily removed to facilitate use in tight quarters. In general, it will be necessary to arrange adequate mechanical support with the facility operator before the measurement compaign.

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: 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.

In many cases, the fuel assemblies are stored in poly bags or cardboard covers. These will not perturb the measurement so they can be left in place.

III. 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. When first arriving at a facility, the following steps are recommended:(1)

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 Section II.C.
3. Take a 100-s count with no AmLi source or fuel assembly near 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 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 (∿300 s) to determine the fuel assembly coincidence background rate. This should be 10-15 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 are available, then set the time for 200 s on the recycle mode and use the HP-97 to average the results and check for statistical consistency using the program described in appendix A.

IV. DESCRIPTION OF FUEL ASSEMBLIES

The fuel assemblies available for measurement at the FBFC facility included a range of ^{235}U enrichments from 1.80-3.2%. For all of the measurements, the elements consisted of a 17 by 17 array with 25 open holes for control rod insertion as illustrated in Fig.2. The assemblies that were measured are listed in Table II. For comparison, we have listed the fuel assemblies measured during the June 1980 exercise using the prototype Coincidence Collar. Also listed is the mockup for PWR assembly located at Los Alamos that was used to give a preliminary calibration point for all three of the IAEA Coincidence Collars.

Most of the fuel assemblies were inside a plastic protective bag, and about half the assemblies had an additional layer of cardboard around the plastic bag.

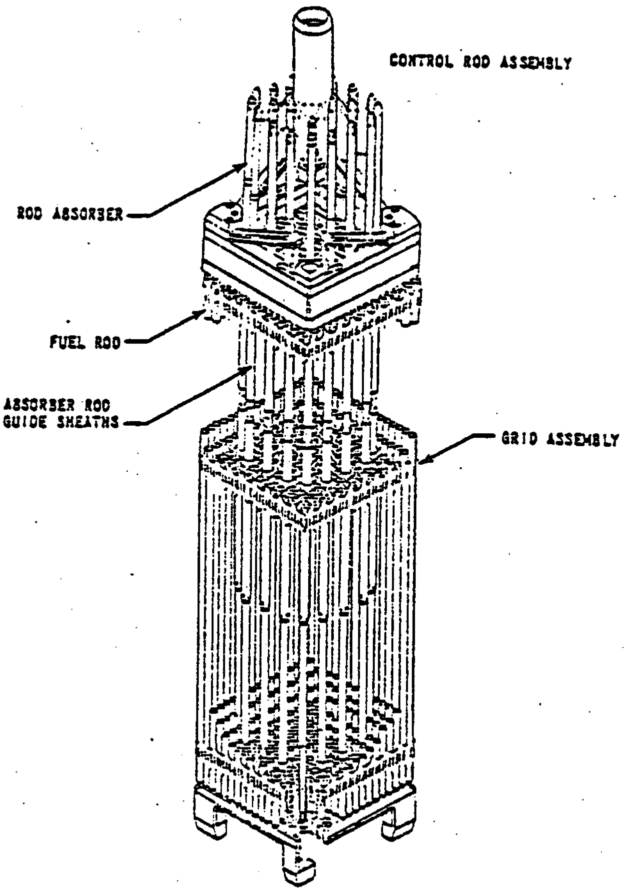

Fig.2. Diagram of typical PWR fuel assembly section from Ref.5 showing position of control elements.

TABLE II

CHARACTERISTICS OF PWR ASSEMBLIES MEASURED WITH THE COINCIDENCE COLLAR

No. of Elements	Nominal Enrichment	Array	No. Rods	Pellet Diam (mm)	g ^{235}U/cm	g ^{238}U/cm
June 1981 Exercise						
5	1.8 %	17 x 17	264	8.2	26.1	1423
6	2.4 %	17 x 17	264	8.2	34.8	1415
5	3.1 %	17 x 17	264	8.2	45.0	1404
4	3.25%	17 x 17	264	8.2	47.1	1402
June 1980 Exercise (Prototype Coincidence Collar)						
2	1.8 %	17 x 17	264	8.2	26.1	1423
1	2.1 %	17 x 17	264	8.2	30.4	1419
2	2.4 %	17 x 17	264	8.2	34.8	1415
1	2.6 %	17 x 17	264	8.2	37.7	1412
1	3.2 %	17 x 17	264	8.2	46.4	1404
1	3.35%	14 x 14	179	9.3	42.3	1220
Los Alamos Assembly (1980)						
1	3.19%	15 x 15	204	9.3	38.7	1177

V. TEST RESULTS

A. Noise Investigations

The equipment was set up at several different locations in the plant, and background runs were performed. No noise pickup was observed even though many different types of electrical apparatus (drills, cranes, forklifts, compressors, welders, etc.) were in operation in the same room.

B. Neutron Backgrounds

Neutron backgrounds were measured with the Coincidence Collar at several different locations in the plant. For these measurements, the AmLi source was removed to a remote location. The results of the background checks are shown for comparison. It is clear that the room backgrounds are negligible for the coincidence counting, but is necessary to subtract the coincidence background from the assembly in the detector.

Adding Cadmium (1-mm-thick) to the <u>outside</u> of the detector did not significantly reduce the room neutron background.[3] This indicates that the neutron flux from the large quantity of U_3O_8 in the assemblies is hard (i.e., epi-cadmium) and there is no need to place cadmium shielding on the units.

TABLE III

IN-PLANT NEUTRON BACKGROUND LEVELS

Locations	Totals Rate (s^{-1})	Coincidence Rate (s^{-1})
Near assembly washing pit	150	0
At edge if assembly storage forest	400	0
At center of assembly storage forest	484	0
Around single PWR assembly (no AmLi)	∿ 150 net	∿ 12
AmLi-MRC-91 (no fuel assembly)	1700	0
AmLi-MRC-91 (1.8% PWR assembly)	2100	∿100

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 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.

At the FBFC facility, each assembly was measured at a position ∿ 1m from the bottom end of the assembly. This was accomplished by using the Collar support cart and rolling the cart on a special support platform that was fabricated by CEN/SCK to raise the cart above the step (∿20 cm) at the floor level. The same cart was used during the 1980 exercise. In general, each facility where the Coincidence Collar is to be used will have to be examined for a convenient support mechanism for the Coincidence Collar.

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-1. 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 break, mental lapses, and overnight runs. Three of four different assemblies of each enrichment as listed in Table IV were measured. The average net coincidence response and the scatter (standard deviation, S) about the mean are listed in Table IV.

A least-squares fit was made to the coincidence data using a quadratic function to obtain the relative ^{235}U enrichment (En). Table IV gives the measured relative enrichments and the observed standard deviation about the mean value. The average difference between the given enrichments and the measured values was 1.8%. Part of this variation is caused by counting statistics and curve fitting errors, and part is from the variation in the nominal enrichment values. Details concerning the calibration curve and the quadratic function parameters are given in Sec. VI-B.

TABLE IV

ACTIVE RESULTS FOR U-235 CONTENT IN PWR FUEL ASSEMBLIES (C-Collar-1)

Assembly N°	U-235 Enrichment	Coincidence Rate (s^{-1})	Measured Relative U-235
1	1.8%	95.0	1.75
2	1.8%	95.2	1.76
3	1.8%	95.5	1.78
		X = 95.23	E_n = 1.76%
		S = 0.25	S = 0.02%
4	2.4%	111.8	2.51
5	2.4%	111.5	2.49
6	2.4%	110.9	2.47
		X = 111.40	E_n = 2.49%
		S = 0.46	S = 0.02
7	3.1%	122.4	3.06
8	3.1%	124.2	3.16
9	3.1%	123.3	3.11
10	3.1%	121.9	3.04
		X = 122.95	E_n = 3.09%
		S = 1.01	S = 0.05
11	3.25%	123.2	3.11
12	3.25%	126.0	3.27
13	3.25%	125.7	3.25
		X = 125.00	E_n = 3.21%
		S = 1.54	S = 0.09

Ave. difference $\frac{\text{Tag - Meas.}}{\text{Tag}} \times 100 = 1.8\%$

Fig. 3. shows the coincidence response as a function or enrichment for the active case. It can be seen that the response increases with enrichment and the response is not saturated. This is probably 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.

After completing the calibration work for Coincidence Collar-1, similar measurements were performed using coincidence Collar-2.For comparison purposes, the results of the June 1980 exercise using the prototype Coincidence Collar are listed also in Table V. For both of these detector systems, the coincidence rates have been normalized by the ratio of their AmLi source yields to AmLi-1 so that all of the data could be fit to the calibration curve obtained from Coincidence Collar-1. The results of the fit are given in the last column of Table V.

The average difference between the measured values and the given values was 2.97% for Coincidence Collar-2 and 1.4% for the prototype unit. These data show that the shape of the calibration curve does not change significantly for different collar systems, and a single data point (or standard) can be used to establish the calibration normalization.

D. Passive Results

For the passive measurement of ^{238}U, the neutron backround level from neighboring assemblies is important. The effect of the background on the coincidence response comes from induced fissions in the assembly being measured. The increased background neutrons in the high-density storage regions can enter the assembly being measured with the Coincidence Collar and induce fission reactions. These fission events are then detected by the Coincidence Collar as net real coincidences. This effect appears to be a few coincidence counts per second. In the active case, the induced rate is greater ∿ 100 counts/s and the background is only a small correction; however, for the passive counting, the spontaneous fission coincidence rate is ∿ 12 counts/s and the bacground is important. For future applications of the Collar in the <u>passive</u> mode, the background levels should be reduced, or measured to get more accurate results.

The present passive coincidence data were correctedfor background induced fissions by using the totals rate as a measure of the background. To determine the background correction factor, a given fuel assembly was measured with varying neutron background conditions. Because the assemblys should give the same passive coincidence count, a background correction factor of 0.0138 coincidence count per totals count was established. Applying this factor to all of the fuel assemblies resulted in a much more uniform set of data, as shown in Table VI.

The results of the passive measurements are shown in Fig.4, where none of the data have been normalized. The passive response is primarly coming from the ^{238}U, which does not significantly change for the enrichment range of the present work. Thus, the passive curve in Fig. 4 does not go to zero response at zero enrichment. The slight upturn in the curve for increasing enrichments is caused by multiplication of the neutrons by induced fissions in the ^{235}U. For normal applications, the totals rate is automatically recorded along with the coincidence rate, so the passive correction to the coincidence response is easily automated in the HP-97 software. The corrected passive coincidence rate (R_{corr}) is calculated using the expression

$$R_{corr} = R - 0.0138\ (T - 150\ ),$$

where R is the measured coincidence rate and T is the totals rate per second. The 150 counts/s is from the assembly in the detector, so it is subtracted from T to get the net room background. This equation is used in the HP-97 software program given in Appendix A.

The passive measurements were of lower priority than the active measurements and so less time was taken for the passive measurements. Typically, three runs of 200 each. The standard deviation estimated from the number of counts is approximately 2.0% however, the observed scatter in the data for different assemblies of the same enrichment was 3-9% (see Table VI), reflecting additional errors from uncertainties in the background correction.

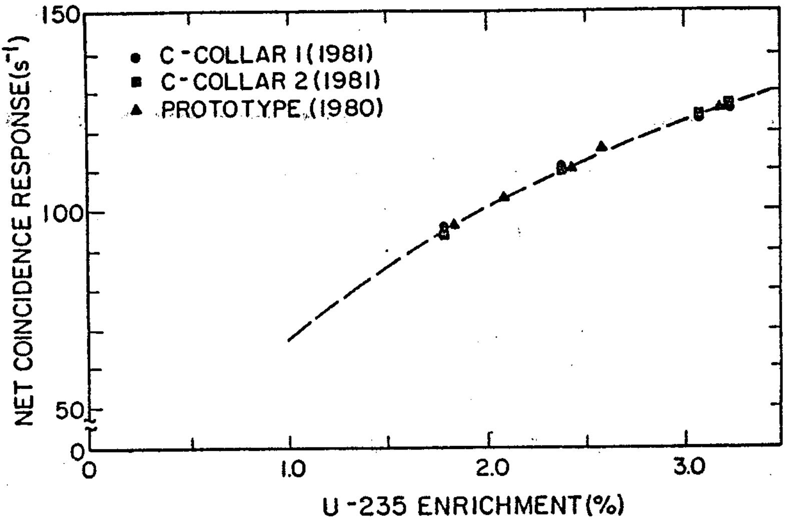

Fig.3. Active neutron coincidence response as a function of enrichment for 17 by 17 PWR assemblies.

TABLE V

ACTIVE RESULTS FOR U-235 CONTENT

Assembly Number	Nominal U-235	Coincidence Rate (s^{-1})	AmLi - Norm.[a] Rate (s^{-1})	Measured[b] U-235 (%)
June 1981 Exercise (Coincidence Collar - 2)				
2	1.8%	96.1	93.3	1.68
5	2.4%	113.0	109.6	2.40
14	2.4%	116.6	113.1	2.57
10	3.1%	127.7	123.9	3.14
15	3.1%	128.0	124.1	3.16
16	3.25%	129.6	125.7	3.25

$$\text{Ave. difference} = \frac{\text{Tag - Meas.}}{\text{Tag}} \times 100\% = 2.9\%$$

Assembly Number	Nominal U-235	Coincidence Rate (s^{-1})	AmLi - Norm.[a] Rate (s^{-1})	Measured[b] U-235 (%)
June 1980 Exercise (Prototype Coincidence Collar)				
I	1.8	1058	95.9	1.79
V	1.8	1049	95.1	1.75
VII	2.1	1140	103.4	2.11
II	2.4	1217	110.3	2.43
VI	2.4	1201	108.9	2.37
IV	2.6	1272	115.3	2.69
III	3.2	1384	125.5	3.24

$$\text{Ave. difference} = \frac{\text{Tag - Meas.}}{\text{Tag}} \times 100\% = 1.4\%$$

a) Normalized to AmLi-1 rate.

b) Fit to calibration curve of Coincidence Collar-1.

TABLE VI

PASSIVE RESULTS FOR U-238 CONTENT IN PWR FUEL ASSEMBLIES

Assembly No.	R-235 Enrichment	Totals Rate (s^{-1})	Coincidence Rate (s^{-1})	Corr. Coincidence Rate (s^{-1})
C-Collar-1				
1	1.8%	321	12.0	9.7
2	1.8%	551	15.4	10.8
3	1.8%	570	16.2	10.4
				$\bar{X}$ = 10.3
				S = 0.56
4	2.4%	463	10.3	12.0
5	2.4%	565	16.3	10.6
6	2.4%	537	16.5	11.1
				$\bar{X}$ = 11.23
				S = 0.71
7	3.1%	378	15.1	12.0
8	3.1%	502	17.6	12.8
9	3.1%	617	19.2	12.8
10	3.1%	631	19.2	12.6
				$\bar{X}$ = 12.55
				S = 0.38
11	3.25%	634	20.4	13.7
12	3.25%	571	17.8	12.0
13	3.25%	593	17.6	11.5
				$\bar{X}$ = 12.40
				S = 1.15
C-Collar-2				
2	1.8%	565	16.0	10.3
5	2.4%	583	16.9	10.9
14	2.4%	674	19.3	12.1
10	3.1%	652	18.8	11.9
15	3.1%	521	16.7	11.6
16	3.25%	580	18.2	12.3

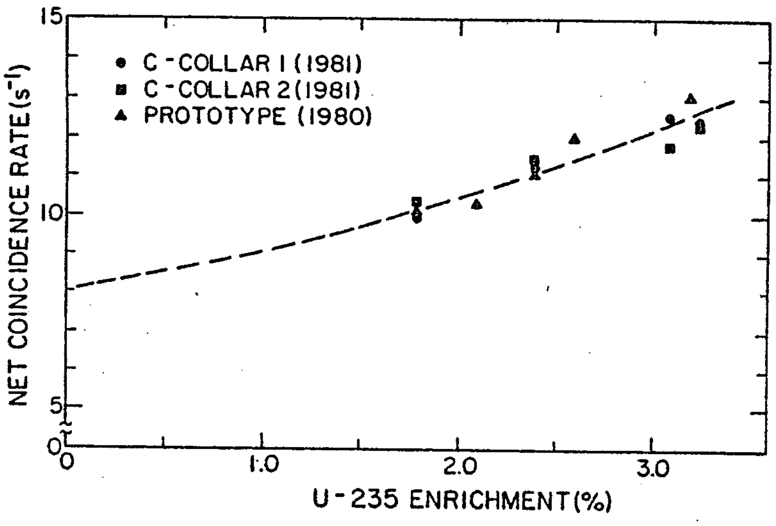

Fig.4. Passive neutron coincidence response as a function of enrichment for 17 by 17 PWR assemblies.

E. Effect of Neutron Absorbers in the Assemblies

Several of the fuel assemblies that were measured the first day gave lower than expected results in the active mode; however, the passive were not low. Subsequent checking of the records for these anomalous assemblies confirmed that they contained control rods loaded with Cadmium or boron, causing the low readings. These materials absorb the thermalized interrogation neutrons (active mode), but they do not significantly affect the fast-neutrons from spontaneous fission (passive mode). The location of the control rods is shown in Fig.2

Before finding out about the poisoned controls rods, we made several measurements both with and without the cardboard liners to see if it had any effect on the results. We found no change (<1%) from the insertion of the cardboard liners around the assemblies.

F. In-Plant Precision and Stability

The Coincidence Collar had previously demonstrated very good stability and precision in laboratory tests. To check the performance under in-plant conditions, cyclic runs were taken on each assembly and compared with the counting statistical error determined from

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

For most of the active mode measurements, multiple 200 s runs were made and the software program (see Appendix A) automatically calculated the mean and standard deviation (S) in the coincidence results. These results are given in Table VII together with the estimate of σ from the above equation. The excellent agreement in two approaches indicates that there were no electrical noise problems or instabilities in the electronics.

TABLE VII

IN-PLANT STABILITY AND PRECISION TESTS (ACTIVE MODE)

Enrichment	Single Run Time (s)	No. of Runs	Observed S for 200 s	Estimated 1 σ for 200 s	Estimated 1 σ for 1000 s
1.8%	200	60	2.0	1.88	0.84
2.4%	200	25	1.6	1.68	0.75
3.1%	200	30	1.5	1.59	0.71
3.25%	200	20	1.7	1.58	0.71

To determine the precision that could be obtained using longer run times, overnight runs were made on two of the assemblies and the results are given in Table VIII. A run time of 5000 s gives a predicted error of ∿ 0.3% (1σ) and the observed scatter was a little less than this as given in Table VIII.

TABLE VIII

IN-PLANT LONG TERM STABILITY AND PRECISION TESTS
FOR COINCIDENCE COLLAR

Assembly No.	U-235 Content	Run Time	Standard Deviation (Coincidence) Observed	Standard Deviation (Coincidence) Predicted
8	3.1%	12 x 5000 s (overnight)	0.32%	0.38%
10	3.1%	11 x 5000 s (overnight)	0.19%	0.33%

The precision can be reduced below 0.3% by using even longer counting times. We estimate from prior work(1) that the precision limit is ∿ 0.1% at which time systematic errors will start to dominate the statistical errors.

VI. CALIBRATION

The Coincidence Collar responds somewhat differently to a reduction in ^{235}U mass from the following: (1) uranium mass removal e.g., fuel rod removal, and (2) ^{235}U enrichment change. For case (1) the response function is almost linear so a 10% mass change gives ∿ 10% response change; whereas, in case (2) the response function is nonlinear and a 10% ^{235}U enrichment change results in less than a 10% change in the measured response. These cases will be considered separately in the following sections.

A. Uranium Mass Removal

When uranium rods are removed from the assembly and substituted by empty rods or rods containing nonfissionable material, the coincidence response changes as shown in Fig.5. These data were taken during the June 1980 exercise at CEN/SCK(3) using a mockup PWR assembly with removable rods.

The response function can be approximated by a straight line relating the mass reduction to the response reduction. If the calibration line has negligible uncertainty, then a 1% coincidence response error translates to ∿ 1% uncertainty in the uranium mass.

However, rod removal is not the normal case that the inspector is faced with. More typically, the ^{235}U enrichment can vary for a given type fuel assembly. This case was the focus for the present calibration work and the results are given in the next section.

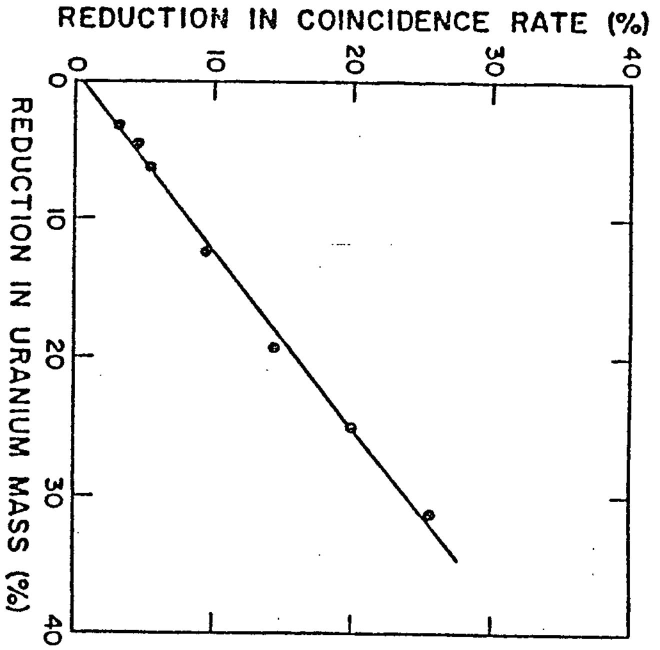

Fig.5. Active neutron coincidence response as a function of reduction in ^{235}U mass for a uniform distribution of rod removals from a full PWR fuel assembly.

B. Enrichment Calibration.

The active assay data for the different enrichments are shown in Fig. 3.
To take advantage of HP-97 software programs used with the HLNCC,[4] a quadratic function was used to fit the data

$$M = A_0 + A_1 + A_2R^2 ,$$

where R is the coincidence response M is the fissile content per unit length (e.g., enrichment), and A_0, A_1, A_2 are constants. The software program that can be used in the field to fit the data is given in Appendix B.

The constants determined from fitting the data from C-Collar-1 for the 17 by 17 array PWR assemblies are :

$$\left.\begin{aligned} A_0 &= -0.074850 \\ A_1 &= -0.003313 \\ A_2 &= 0.0002366 \end{aligned}\right\} \quad {}^{235}\text{U enrichment}$$

or

$$\left.\begin{aligned} A_0 &= -1.08157 \\ A_1 &= -0.048485 \\ A_2 &= 0.003435 \end{aligned}\right\} \quad {}^{235}\text{U mass per cm}$$

These two sets of constants are related by the ratio of

$$\frac{26.1\text{ g }{}^{235}\text{U per cm}}{1.8\text{ per cent }{}^{235}\text{U}} = 14.5$$

Thus, if one fits for the enrichment, the ^{235}U mass per centimeter can be determined by multiplying by 14.5 for this particular type fuel assembly. The advantage of using the mass per unit lenght is that one assembly type can be related to other assembly geometries (e.g., 15 by 15 arrays). The advantage of using the enrichment is that enrichment data is 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 (0.001%) of 27 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.

The calibration curve for Coincidence Collar-2 was determined with less accuracy than Coincidence Collar-1. However, the shape of the curves should be the same, and only a normalization constant is needed to account for the different AmLi source strength and detector efficiency. The coincidence counting rates from unit 2 are 1.031 times larger than for unit 1.
Thus the ^{235}U mass can be calculated from the expression

$$M = A_0 + A_1 \left(\frac{R}{1.031}\right) + A_2 \left(\frac{R}{1.031}\right)^2 ,$$

where A_0, A_1, and A_2 are the same constants as were determined for Coincidence Collar-1.

An advantage of this normalization approach is that the original calibration on any of the Coincidence Collars can be related to future measurements in different facilities by the AmLi source normalization described in Ref. 1. By counting the net T for the AmLi source (no fuel assembly in the counter) at the time of calibration, then future electronic shifts in the rates can be corrected for. This is similar to the use of the ^{252}Cf calibration source in the HLNCC[4].

For the present calibration exercise at FBFC the AmLi background rates were

$$T = 1691 \text{ counts/s} \qquad \text{C-Collar-1, AmLi-91}$$

and

$$T = 1743 \text{ counts/s} \qquad \text{C-Collar-2, AmLi-92}$$

The corresponding enrichment calibration parameters are :

$$M = -0.074850 - 0.003313\ R_1 + 0.0002366\ R_1^2$$

for C-Collar-1 and

$$M = -0.074850 - 0.003213\ R_2 + 0.0002226\ R_2^2$$

for C-Collar-2 where R_1 and R_2 are the net real coincidence counts per second for units 1 and 2, respectively.

$$R_{(Norm)} = R_{(Current)} \left[\frac{T(Original)}{T(Current)}\right]^2 ,$$

where R is the coincidence response with the unknown fuel assembly and T is the net totals rate for the AmLi source alone (i.e., no fuel assembly). The totals rates are squared because T is proportional to the efficiency; whereas R is proportional to the efficiency squared. The coincidence gate must be 64 µs for all of the measurements.

In summary, at the start of future verification work, the room background is first measured (100 s) and then subtracted from the AmLi background (100 s) to give the net T (current). This is then ratioed with T (original) to define the normalization constant.

$$k_1 = \left[\frac{T(Original)}{T(Current)}\right]^2 = \left[\frac{1691}{T(Current)}\right]^2 ,$$

for C-Collar-1.

The enrichment of the unknown PWR assembly is then calculated from the equation

$$M = -0.074850 - 0.003313\ (k_1R_1) + 0.0002366\ (k_1R_1)^2 .$$

Similarly, for C-Collar-2,

$$k_2 = \left[\frac{1743}{T(Current)}\right]^2 ,$$

$$M = -0.074850 - 0.003213\ (k_2R_2) + 0.0002226\ (k_2R_2)^2 .$$

The present data collection program given in Appendix A calculates the mean R values and the calculation of M using the above expression is done separately by the inspector. Future software programs can be supplied as part of an implementation task to combine the calculation of M into the data collection program.

1. Example
C-Collar-2 (June 1981)
3.25% enriched PWR assembly
Mean R = 129.6 counts/s (see Table VIII)
$K_2 = 1.000$

$$M = -0.074850 - 0.003213(129.6) + 0.0002226(129.6)^2$$
$$M = 3.24\% \ ^{235}U.$$

VII. CONCLUSIONS AND RECOMMENDATIONS

A. Rod Removal Sensitivity

The sensitivity limit (2σ) for rod removal was 3.5 rods or 1.36% of the ^{235}U content for a 1000-s measurement independent of location in the assembly. The ^{238}U sensitivity limit was 1.9% of the uranium mass for a 1000-s measurement if the neutron background levels are low. This ^{238}U sensitivity degrades to 3-5% for in-plant conditions with a variable neutron background. These limits were established during the June 1980 exercise[3] and confirmed during the present work.

B. Electrical Noise and Neutron Background

No electrical noise problem was observed at the FBFC plant. The Coincidence Collar had properly shielded cables and desiccant in the high-voltage preamp and junction boxes.

Room neutron background levels were small for the active assay of the ^{235}U. There was some influence from neutron backgrounds at the FBFC facility for the ^{238}U passive results. To make use of this passive method, it will be necessary to have low-neutron background conditions. Alternatively, the background can be measured and the data corrected.

C. Precision and Stability

1. Active Assay for ^{235}U.

The statistical precision for a 1000 s run varied from 0.6 - 0.9% (σ), depending on the type assembly. For longer counting periods, the ultimate precision was about 0.1% for repeat runs with a fixed geometry.

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 ∿ 1.4% (1000 s) but the results were influenced by neutron-background variations.

D. Response vs Enrichment or ^{235}U Loading

The response curve is not saturated and continues to increase vs the enrichment increases through the normal range of LWR fuel. Relative loading variations as small as 1.9% can be detected in a measurement time of 1000 s. Longer measurements can further reduce the statistical uncertainties.

The measurements at the fuel fabrication facility had the following operational advantages:

1. No fuel assemblies handling or movement was required of the plant operator.
2. The fuel assemblies were not touched during the measurements.
3. No personnel were in attendance during the longer and cyclic measurements.
4. The protective plastic bagging and cardboard was not removed from the fuel assemblies for the measurements.

Calibration constants have been determined (see Sec. VI, B) and normalization procedures established to make it possible to make absolute measurements on 17 by 17 PWR assemblies in the future using C-Collar-1 and C-Collar-2.

Assemblies that differ from the present assemblies can still be measured to obtain the <u>relative</u> loading of a group of fuel assemblies. Repeat measurements over a period of times can verify that the assemblies have not been tampered with. Assemblies that differ from the calibration assemblies can still be measured using the inappropriate calibration curve, but the uncertainty in the absolute result will be somewhat larger. See Appendix C for an example of this. Calculations can be performed to reduce this uncertainty.

E. Recommendations

1. For routine measurements, a custom designed support mechanism for the Coincidence Collar will be required at facilities where the normal cart cannot roll on the floor at the base of the fuel assemblies.
2. The Coincidence Collar has been specifically designed for unirradiated PWR fuel assemblies, but it also can be used for other assemblies such as BWR, CANDU, WWER, etc. Field tests are required to evaluate the Coincidence Collar for these additional applications.
3. In general, each major category of fuel (e.g., 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 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.
4. Coincidence Collar-1 and Coincidence Collar-2 are calibrated and ready for implementation at PWR fuel fabrication facilities or reactor sites.

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 FBFC facility. The purpose of the program was to collect data in the cyclic mode, calculate the estimated standard deviation from the number of counts.

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

as well as the mean responses, T and R, and the observed scatter (5), about the mean. At the end of n runs (or cycles), the standard deviation for the total counting time is calculated from

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

This gives the inspector 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 that is used for the active measurements. The background correction factors are directly written into the program and no entries are required from the user.
A totals rate background from the assembly in the collar is taken as 150 counts/s for all of the assemblies and collars. This value should not be changed as long as the present calibration constants (see Sec.VI.B) are in use. This is true also for the passive correction factor of 0.0238

The steps for <u>routine assay</u> are:

1. Passive mode (no AmLi) - set time for 200-s recycle and press start button on HEC-100 electronics.
2. After the desired number of cycles (2-3), press stop button and program key B on HP-97. This will print out the passive results and store the background data for the active assay.
3. Active mode (with AmLi) - press 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 program key C on HP-97. This will print out the active results.

An example of the readout format is given in Table A-1.
Only two results from the data output are required for the mass analysis and these are:

$$R = 116.59 \text{ counts/s} \pm 0.76\%$$

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

$$R = 12.05 \text{ counts/s} \pm 1.65\%$$

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

The progam listing and explanation of the HP-97 Data Collection and Statistical Analyses Program are given in Table A.2.

TABLE A-1

Data Readout Format for HP-97 Data Collection Program for a 2.4% Enriched PWR Assembly

Passive Mode

```
      200.00  ***  — time(s)
      673.35  ***  — t/s
       48.11  ***  — R + A/s
       29.13  ***  — A/s
       18.99  ***  — R/s
        3.27  ***  — σ%
        1.00  ***  — n

      200.00  ***  }
      677.72  ***  }
       49.36  ***  }
       29.70  ***  }  2nd run
       19.66  ***  }
        3.26  ***  }
        2.00  ***  }

      200.00  ***  }
      677.12  ***  }
       48.83  ***  }
       28.97  ***  }  3rd run
       19.86  ***  }
        3.14  ***  }
        3.00  ***  }

      200.00  ***  }
      665.51  ***  }
       47.06  ***  }
       28.43  ***  }  4th run
       18.64  ***  }
        3.30  ***  }
        4.00  ***  }
Press B →
      674.42  ***  — T̄/s
       19.28  ***  — R̄/s
        2.95  ***    s%
 235000000.0         U-238
       12.65  ***    R̄ corr
        1.65  ***    σ% /√n
```

Active Mode

```
      200.00  ***  —  time(s)
     2675.93  ***  —  t/s
      596.99  ***  —  R + A/s
      460.73  ***  —  A/s
      136.26  ***  —  R/s
        1.69  ***  —  σ%
        1.00  ***  —  n

      200.00  ***  }
     2677.51  ***  }
      594.75  ***  }
      459.23  ***  }  2nd run
      135.52  ***  }
        1.69  ***  }
        2.00  ***  }

      200.00  ***  }
     2676.37  ***  }
      596.45  ***  }
      457.87  ***  }  3rd run
      138.58  ***  }
        1.66  ***  }
        3.00  ***  }

      200.00  ***  }
     2566.31  ***  }  4th run
      587.07  ***  }
      452.35  ***  }
      134.72  ***  }
        1.69  ***  }
        4.00  ***  }

      200.00  ***  }
     2662.58  ***  }
      587.55  ***  }
      453.33  ***  }  5th run
      134.23  ***  }
        1.70  ***  }
        5.00  ***  }
Press C →
     2670.76  ***  — T̄/s
      135.87  ***    R̄/s
        1.25  ***    S%
 235000000.0 ————— u - 235
      116.59  ***  — R̄ net
        0.76  ***  — σ% /√n
```

TABLE A-2

HP-97 Data Collection and Statistical Analysis Program

Program Step			Function
001	*LBLA	21 11	
002	RCL1	36 01	
003	PRTX	-14	— time (s)
004	RCL2	36 02	
005	RCL1	36 01	
006	÷	-24	
007	PRTX	-14	— T/s
008	RCL3	36 03	
009	RCL1	36 01	
010	÷	-24	
011	PRTX	-14	— (R + A)/s
012	RCL4	36 04	
013	RCL1	36 01	
014	÷	-24	
015	PRTX	-14	— A/s
016	RCL3	36 03	
017	RCL4	36 04	
018	-	-45	
019	RCL1	36 01	
020	÷	-24	
021	PRTX	-14	— R/s
022	STO6	35 06	
023	RCL3	36 03	
024	RCL4	36 04	
025	+	-55	
026	√X	54	
027	RCL3	36 03	
028	RCL4	36 04	
029	-	-45	
030	÷	-24	
031	1	01	
032	0	00	
033	0	00	
034	×	-35	
035	PRTX	-14	— σ%
036	STO5	35 05	
037	RCL2	36 02	
038	RCL1	36 01	
039	÷	-24	
040	ENT↑	-21	
041	RCL6	36 06	
042	Σ+	56	
043	PRTX	-14	— run no. (n)
044	STO9	35 09	
045	SPC	16-11	
046	RTN	24	
047	*LBLC	21 13	— Active Mode - Key C
048	$\bar{x}$	16 53	
049	X⇄Y	-41	
050	PRTX	-14	— $\overline{T}$/s
051	X⇄Y	-41	
052	PRTX	-14	— $\overline{R}$/s
053	STO7	35 07	
054	S	16 54	— Standard deviation, S
055	RCL7	36 07	
056	÷	-24	
057	1	01	
058	0	00	
059	0	00	
060	×	-35	
061	PRTX	-14	— s%
062	2	02	u-235 label
063	3	03	
064	5	05	
065	0	00	
066	0	00	
067	0	00	
068	0	00	
069	0	00	
070	0	00	
071	PRTX	-14	
072	RCL7	36 07	
073	RCLA	36 11	— Passive $\overline{R}$ background
074	-	-45	
075	PRTX	-14	— net $\overline{R}$/s

Program Step			Function
076	RCL5	36 05	
077	RCL9	36 09	
078	√X	54	
079	÷	-24	
080	PRTX	-14	— $\sigma/\sqrt{n}$ %
081	SPC	16-11	
082	GSBE	23 15	— data storage
083	CLX	-51	
084	RTN	24	
085	*LBLB	21 12	Passive Mode - key B
086	$\bar{x}$	16 53	
087	X⇄Y	-41	
088	PRTX	-14	— $\overline{T}$/s
089	STO8	35 08	
090	X⇄Y	-41	
091	$\bar{x}$	16 53	
092	PRTX	-14	— $\overline{R}$/s
093	STOA	35 11	
094	S	16 54	
095	RCLA	36 11	
096	÷	-24	
097	1	01	
098	0	00	
099	0	00	
100	×	-35	
101	PRTX	-14	— s%
102	2	02	
103	3	03	
104	8	08	u - 238 label
105	0	00	
106	0	00	
107	0	00	
108	0	00	
109	0	00	
110	0	00	
111	PRTX	-14	
112	RCL8	36 08	
113	1	01	passive T background
114	5	05	
115	0	00	
116	-	-45	
117	.	-62	induced fission correction factor
118	0	00	
119	1	01	
120	3	03	
121	6	06	
122	×	-35	
123	RCLA	36 11	
124	X⇄Y	-41	
125	-	-45	
126	PRTX	-14	$\overline{R}$/s (corrected)
127	RCL5	36 05	
128	RCL9	36 09	
129	√X	54	
130	÷	-24	
131	PRTX	-14	— $\sigma/\sqrt{n}$ %
132	SPC	16-11	
133	GSBE	23 15	— data storage
134	CLX	-51	
135	RTN	24	
136	R/S	51	
137	*LBLE	21 15	Storage reference (optional)
138	0	00	
139	STO4	35 04	
140	STO5	35 05	— σ%
141	STO6	35 06	— R/s
142	STO7	35 07	— $\overline{R}$/s
143	STO8	35 08	— $\overline{T}$/s
144	STO9	35 09	— n
145	P⇄S	16-51	
146	RTN	24	
147	R/S	51	

APPENDIX B

PROGRAMM LSQUAD

The following least-squares program (LSQUAD) was taken from Ref.6 where it was supplied for use with the HLNCC. This program has been used with the Coincidence Collar to obtain the calibration constants A_0, A_1, and A_2.

<u>Purpose</u>: To perform an unweighted least-squares fit to the equation

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

where M is the sample mass and R is detector response.

<u>Comment</u>: The calculations are performed according to the equations in <u>Bevington's Data Reduction and Error Analysis for the Physical Sciences</u>, (McGraw-Hill, 1969), pp. 134-137

<u>Procedure</u>:

1. Press "A" to initialize.
2. Enter data pairs, (R_I, M_i) as follows:
   a) Enter R_i
   b) Press "ENTER"
   c) Enter M_i
   d) Press "B".

   The data will be printed for reference.
3. Press "D" to calculate parameters. The parameters are printed in the order A_0, A_1, A_2

<u>Extra Feature</u>: After the fitting parameters have been calculated, M can be calculated for R as follows.

1. Enter R
2. Press "E"
3. M is displayed

A complete listing of the program LSQUAD is given on the following page.

APPENDIX C

CALIBRATION FOR DIFFERENT TYPES OF FUEL ASSEMBLIES

The response functions given in this report apply only to 17 by 17 rod PWR fuel assemblies. Of course, there is interest in using the Coincidence Collar on other types of fuel assemblies in which case separate calibration curves are required for accurate measurements.

To investigate the error involved in mixing assembly types, measurements made with the 15 by 15 rod mockup PWR assembly at Los Alamos were compared with the data from the 17 by 17 rod assemblies at FBFC. The characteristics of the mockup assembly are given in Table C-1.

PROGRAMM LSQUAD

```
001   *LBLA
002   DSP9
003   CLRG
004    R/S
005   *LBLB
006   STO0
007     R↓
008   STO1
009   GSBC
010   RCL0
011   X=0?
012   GTOD
013      1
014   ST+9
015    R/S
016   GTOB
017   *LBLC
018   RCL1
019   PRTX
020   RCL0
021   PRTX
022    SPC
023   RCL0
024   ST+3
025   RCL1
026   ST÷2
027    X^2
028   ST+4
029   RCL1
030      x
031   ST+5
032   RCL1
033      x
034   ST+6
035   RCL0
036   RCL1
037      x
038   ST+7
039   RCL1
040      x
041   ST+8
042    RTN
043   *LBLD
044   RCL9
045   RLC4
046      x
047   RCL6
048      x
049      2
050   RCL2
051      x
052   RCL5
053      x
054   RCL4
055      x
056      +
057   RCL4
058      3
059    Y^X
060      -
061   RCL5
062    X^2
063   RCL9
064      x
065      -
066   RCL2
067    X^2
068   RCL6
069      x
070      -
071   STOD
072   RCL3
073   RCL4
074      x
075   RCL6
076      x
077   RCL2
078   RCL5
079      x
080   RCL8
081      x
082      +
083   RCL7
084   RCL5
085      x
086   RCL4
087      x
088      +
089   RCL4
090    X^2
091   RCL8
092      x
093      -
094   RCL5
095    X^2
096   RCL3
097      x
098      -
099   RCL7
100   RCL2
101      x
102   RCL6
103      x
104      -
105   RCLD
106      ÷
107    SPC
108   PRTX
109   STOA
110   RCL9
111   RCL7
112      x
113   RCL6
114      x
115   RCL3
116   RCL5
117      x
118   RCL4
119      x
120      +
121   RCL2
122   RCL8
123      x
124   RCL4
125      x
126      +
127   RCL4
128    X^2
129   RCL7
130      x
131      -
132   RCL8
133   RCL5
134      x
135   RCL9
136      x
137      -
138   RCL2
139   RCL3
140      x
141   RCL6
142      x
143      -
144   RCLD
145      ÷
146   PRTX
147   STOB
148   RCL9
149   RCL4
150      x
151   RCL8
152      x
153   RCL2
154   RCL7
155      x
156   RCL4
157      x
158      +
159   RCL2
160   RCL5
161      x
162   RCL3
163      x
164      +
165   RCL4
166    X^2
167   RCL3
168      x
169      -
170   RCL7
171   RCL5
172      x
173   RCL9
174      x
175      -
176   RCL2
177    X^2
178   RCL8
179      x
180      -
181   RCLD
182      ÷
183   STOC
184   PRTX
185    SPC
186    SPC
187    SPC
188    SPC
189    SPC
190    R/S
191   *LBLE
192   STOE
193    X^2
194   RCLC
195      x
196   RCLB
197   RCLE
198      x
199      +
200   RCLA
201      +
202    R/S
```

TABLE C-1

MOCKUP PWR FUEL ROD CHARACTERISTICS

Array size	15 by 15 (cm width)
Number of rods	204 (21 open channels)
Rod diameter (OD)	10.8 mm
Rod cladding	zircaloy-2
Uranium enrichment	3.19%
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

Because the geometries of the two assemblies are different, the comparison should be done in terms of g ^{235}U/cm rather than enrichment. Figure C.1 shows a plot of the 17 x 17 rod PWR data together with the 15 x 15 assembly data point. In this particular case, the 15 x 15 rod assembly is only ∿ 3% higher than the curve from the 17 x 17 assemblies. However, measurements during the June 1980 exercise[3] at FBFC gave results for a 14 x 14 rod assembly that were ∿ 14%, lower than would be expected from the curve for the 17 x 17 rod assemblies. In general, calibration curves should be generated for assemblies with similar characteristics. Computer calculations can be used to extend the coverage of the calibration curves and to reduce the requirements for physical standards.

APPENDIX D

NEUTRON ABSORBERS IN THE FUEL ASSEMBLIES

Because thermal neutrons are used for the active assay, the presence of neutron absorbers such as cadmium and boron in the assembly will decrease the response of the Coincidence Collar. During the June 1981 fiels test at the FBFC facility, four of the PWR fuel assemblies contained control elements with varying amounts of thermal neutron absorbers that reduced the response from 20 to 40%.

Initially, we did not know that the absorbers were present in some of the fuel assemblies, but after measuring the low responses, subsequent check of the records confirmed that was the case.

Figure D.1 shows the data points for the anomalous assemblies together with the normal calibration curve. For the 2.4% enriched assemblies, it is possible to distinguish the difference between the assembly loaded with 9 poison elements from the one with 12 poison elements.

The passive ^{238}U measurement does not rely on thermal neutrons and so the measurement is not sensitive to the presence of thermal-neutron poisons. In general, the combined information of T and R in both the active and passive modes gives a high level of confirmation that the assembly has the stated loading.

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