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TITLE: IMPLEMENTATION OF THE ACTIVE NEUTRON COINCIDENCE COLLAR
FOR THE VERIFICATION OF UNIRRADIATED PWR AND BWR FUEL
ASSEMBLIES

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IMPLEMENTATION OF THE ACTIVE NEUTRON COINCIDENCE COLLAR
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FUEL ASSEMBLIES*

ABSTRACT

An active neutron interrogation technique has been developed for the measurement of the ^{235}U content in fresh fuel assemblies. The method employs an AmLi neutron source to induce fission reactions in the fuel assembly and coincidence counting of the resulting fission reaction neutrons. When no interrogation source is present, the passive neutron coincidence rate gives a measure of the ^{238}U by the spontaneous fission reactions. The system can be applied to the fissile content determination in fresh fuel assemblies for accountability, criticality control, and safeguards purposes.

Field tests have been performed by International Atomic Energy Agency (IAEA) staff using the Coincidence Collar to verify the ^{235}U content in light-water-reactor fuel assemblies. The results gave an accuracy of 1-2% in the active mode (^{235}U) and 2-3% in the passive mode (^{238}U) under field conditions.

1. INTRODUCTION

Determination of the fissile content in unirradiated fuel assemblies is important for nuclear material accountability and

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safeguards. Measurements are needed at the fuel fabrication facility and at the reactor site when the fuel shipment is received or the inventory is verified.

This paper describes the implementation of the active neutron Coincidence Collar[1] that has been developed for measurement of the ^{235}U content in fresh fuel assemblies. The 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 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.

Previous work[1,2] has demonstrated that the Coincidence Collar can detect fuel rod substitutions in the interior of the fuel assembly by using mockup fuel assemblies with removable rods. The present paper gives the results of using the Coincidence Collar to verify the fissile content in boiling-water-reactor (BWR) and pressurized-water-reactor (PWR) fuel assemblies.

2. SYSTEM DESCRIPTION

The Coincidence Collar consists of three banks of ^3He tubes and an AmLi source imbedded in a high-density polyethylene body as shown in Figs. 1 and 2. The 18 ^3He neutron detector tubes (4 atm pressure) are 2.54 cm in diameter and 33 cm long

(active length). For the measurement of BWR fuel elements, the sides of the detector are adjusted inward.

The polyethylene body performs three basic functions in the system: (1) general mechanical support, (2) interrogation source neutron moderation, and (3) slowing down of induced fission neutrons prior to their detection in the ^3He tubes. For inspection applications, it is desirable to make the system portable. The weight of the present detector head is ~ 25 kg.

The AmLi interrogation source produces random neutrons (not time correlated) with an average energy of ~ 300 keV. The present Coincidence Collar uses a source fabricated by Monsanto Research Corp. (Model 2724-BT) with a yield of 4.5×10^4 n/s.

The electronics used with the Coincidence Collar are the same as that used with the High-Level Neutron Coincidence Counter (HLNCC).[3] This unit contains high- and low-voltage power supplies, six amplifier-discriminator lines, a microprocessor, and shift-register[4] coincidence logic. The electronic unit is directly interfaced to an HP-97 programmable calculator. The microprocessor is used to read out the run time, total counts, reals plus accidental counts, and accidental counts to the HP-97. The HP-97 is used to reduce the data using the software program selected by the operator.

The complete assay system is shown in Fig. 3, including the detector body, electronic unit, HP-97 calculator, and support cart. For applications, the cart is moved next to a fuel assembly, as shown in Fig. 3. The back detector bank of the unit

is hinged (see Fig. 1) to aid in positioning the system around the fuel assembly.

3. FIELD TEST RESULTS

3.1 PWR Assembly Verification

To evaluate the performance of the Coincidence Collar under in-plant conditions, measurements were performed by the IAEA and Los Alamos National Laboratory staff at both PWR and BWR fuel fabrication facilities. The measurements for PWR fuel assemblies took place at the Franco-Belge de Fabrication de Combustibles (FBFC) facility in Dessel, Belgium.[2]

The fuel assemblies available for measurement at the FBFC facility included a range of ^{235}U enrichments from 1.8-3.2%. For all of the measurements, the elements consisted of a 17- by 17-rod array with 25 open holes for control rod insertion. Most of the fuel assemblies were inside plastic protective bags, and about half the assemblies had an additional layer of cardboard around the plastic bag.

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 with and without the AmLi source to obtain both the ^{235}U and ^{238}U values. Sixteen different fuel assemblies were measured.

The response curve, shown in Fig. 4, is not saturated and continues to increase as the enrichment increases through the

normal range of light-water-reactor (LWR) fuel. The statistical precision (1 σ) is 0.7% and 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 PWR fuel fabrication facility had the following operational advantages: (1) no fuel assembly handling or movement was required of the plant operator, (2) the fuel assemblies were not touched during the measurements, and (3) the protective plastic bagging and cardboard were not removed from the fuel assemblies for the measurements.

3.2. BWR Fuel Assembly Verification

The field test[5] for BWR fuel assemblies was performed at the ASEA-Atom Fabrication Facility in Vaesteraas, Sweden. For the measurements, ASEA-Atom furnished a series of two different types of BWR production fuel assemblies as well as a full-size test assembly that could be reloaded to achieve different test configurations. The parameters that were changed included the enrichment, spatial configuration, number of rods, and the gadolinium (burnable poison) content.

3.2.1. Response vs BWR Side Orientation

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 $\pm 1\%$.

Previous measurements[1] using a BWR mockup assembly at Los Alamos 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.

3.2.2. 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 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 loading are uniform.

When an overhead crane is available for scanning the fuel assembly through the detector, 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 results of the measurements are listed in Table I for the active neutron case using the Coincidence Collar. 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. The average net coincidence response and the scatter (standard deviation, S) about the mean are listed in Table I. The statistical precision for the BWR assemblies was 1.0% (1σ) for 1000 s of measurement time.

Figure 5 shows the coincidence response as a function of enrichment for the active case. It can be seen that the response increases with enrichment and the response 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. 5 correspond to the top and bottom regions. The separation in the two curves is a measure of the number of gadolinium-loaded rods.

3.2.3. Passive Results

When the AmLi source is removed from the detector, the passive coincidence rate is proportional to the ^{238}U mass via

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, which ranges from 80-100 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 reduction in the ^{238}U source strength and because of the reduction in the fast-neutron multiplication and the decrease in the reflection of neutrons from the top and bottom of the measurement zone.

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, and the thermal neutron absorber (gadolinium) has no effect.

3.2.4. 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. 6, where we see that one

gadolinium (~ 4.4 wt% Gd_2O_3) rod reduces the active response by about 5%.

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. 6 shows that there is little difference in the responses with 0 or 5 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 1.0% in 1000 s with no cadmium. Because the cadmium increases the required measurement time, it should only be used as a potential check on the operator's declared gadolinium content and not for routine use.

Because the gadolinium loading is greater in the bottom than 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 $\sim 5\%$ as shown in Fig. 5.

3.2.5. Production Assembly Results

Two types of production assemblies were available for the tests; type 1 (T-1) containing six rods with 4.4 wt% Gd_2O_3 and type 2 (T-2) containing four rods with 2.0 wt% Gd_2O_3 . Several of these assemblies were measured as shown in Table I. The responses showed a scatter of ~1%, which is consistent with the statistical expectations for measurement times of 800-1000 s.

The calibration results from the mockup assembly were used to assay the production assemblies. A least squares fit to the data for the top and bottom zones established the two calibration curves shown in Fig. 5. The measured data from the production assemblies were then corrected for the differences in Gd_2O_3 using Fig. 6, and the responses were fit to the mockup calibration curves to determine the ^{235}U content. The average difference between the collar assay value and the tag value was 0.6% for the T-1 assemblies and 0.35% for the T-2 assemblies.

3.3. Exxon Nuclear, Richland, Washington - Implementation

To qualify the Coincidence Collar for future inspection applications, an exercise was performed at the Exxon Nuclear fabrication facility in Richland, Washington. The measurements included both BWR and PWR production assemblies. The BWR assemblies were all 8 x 8 rod arrays containing eight gadolinium rods (4.0 wt% gadolinium metal) and two water-filled rods. The PWR assemblies were standard 17- by 17-rod arrays with 25 empty channels.

The previous tests and evaluations using the collar were to collect data and establish calibration curves. For inspector application, the calibration parameters are entered into the software and a calibration function is used to calculate the loading density ($\text{g } ^{235}\text{U}/\text{cm}$) and the ^{235}U enrichment. This calculation and the error analysis are also done in the HP-97 software program.

4. FIELD CALIBRATION

Calibration of the Coincidence Counter in an absolute sense is difficult because of the complexity and costs of "standard" fuel assemblies. Normalization procedures have been developed[1] to reduce the requirements for physical standards.

4.1. Parameter Sensitivity

The Coincidence Collar has been designed to make the results insensitive to variations in the assembly, such as

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

The Coincidence Collar is somewhat sensitive to

- (a) stainless steel vs Zircaloy cladding,
- (b) large differences in fuel pellet diameter, and
- (c) size of the fuel-rod array.

4.2. Calibration Normalization

For most applications, it will not be possible to have physical standards available at the facility being inspected, so it will be necessary to relate the inspection measurement to calibration measurements at a "host" facility that has the same or similar type fuel assemblies. The AmLi neutron source can be used as a calibration normalization source[1] to bridge the distance and time between the actual calibration and the field inspection.

There are two detector configurations: wide for PWR and narrow for BWR. The Coincidence Collar must always be calibrated in the same configuration as it is to be used, because the efficiency is different for the two configurations.

4.3. Calibration Curve Function

The response of the Coincidence Collar is nonlinear, primarily because of neutron self-shielding and fission neutron multiplication. Thus, it is necessary to use several fuel assembly standards with different fissile loadings to establish a calibration curve. The calibration data collected at FBFC and ASEA-Atom for PWR and BWR assemblies, respectively, were fit

with quadratic and power function calibration curves. The best fit was obtained with a power function of the form

$$M = aR^b ,$$

where M is the fissile content (^{235}U g/cm), R is the corrected real coincidence rate, and a and b are the fitting constants. The advantage of using the mass per unit length rather than enrichment is that one fuel assembly type (for example, a 17 by 17 array) can be related to other fuel assembly geometries (for example, a 15 by 15 array) of the same type.

Figure 7 shows the least squares fit of the power function calibration curve to the BWR data. Also shown are the 95% confidence intervals obtained from the fit.

This calibration function was used to measure "unknown" fuel assemblies at the Exxon Nuclear fabrication facility. The results of the measurements are given in Table II, where the calibration parameters had been obtained from the data previously collected at FBFC and ASEA-Atom. The agreement is within the statistical expectation of 1-2%.

5. CONCLUSIONS

For relative measurements of similar fuel assemblies in a facility, the overall accuracy (1 σ) for ^{235}U content is 1-2%. For absolute measurements using calibration parameters from other facilities and fuel assemblies, the accuracy should be in the range of 2-4%, depending on how closely the standards match

the unknowns and how carefully the calibration has been performed. The calibration curve shape parameters should be the same for all BWR and PWR fuel assemblies and only the normalization constant need be adjusted for different equipment and facilities.

The impact on the nuclear facilities has been minor, and no problems or negative comments have been observed. There is no need to touch the fuel assemblies, and the facility operator can position the collar, if desired.

The combined passive and active measurements giving both ^{238}U and ^{235}U content make the verification very tamper resistant. The equipment can be used with little or no calibration effort to give a relative measurement or an attribute check, and with careful calibration, it can give a variable measurement. The equipment has been demonstrated to be suitable for use in the verification of BWR and PWR fuel assemblies. In-plant neutron backgrounds do not adversely affect the measurement because the neutron coincidence counting essentially eliminates the background neutrons.

Future efforts will be directed toward the possible use of the Coincidence Collar for WWER, MTR, and CANDU type fuel assemblies as well as storage trays of fuel rods. Computer calculations will be performed to extend the range of the calibration curves and to reduce the number of physical standards required.

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FIGURE CAPTIONS

Fig. 1. Schematic diagram of Coincidence Collar showing the AmLi neutron source, the ^3He detector banks, and the polyethylene moderator material. The detector bank opposite the neutron source pivots open on the hinge to accommodate PWR, BWR, or HWR fuel assemblies.

Fig. 2. Coincidence Collar detector head with AmLi neutron source for active assay of LWR fuel assemblies.

Fig. 3. The Coincidence Collar in measurement position around a mockup PWR fuel assembly, showing HEC-100 electronics, HP-97 calculator, and support cart.

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

Fig. 5. The results from the production assembly measurements compared with the calibration curves obtained from the mockup assembly.

Fig. 6. 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.

Fig. 7. Power function calibration curve for BWR fuel assemblies showing 95% confidence limits.

TABLE I
ACTIVE ASSAY OF BWR FUEL ASSEMBLIES

Assembly Type	Ave. 235 _U	Run Time (s)	Coincidence Rate	
			Top (s ⁻¹)	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. $\frac{\text{Meas.} - \text{Tag}}{\text{Tag}} \times 100$	= 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. $\frac{\text{Meas.} - \text{Tag}}{\text{Tag}} \times 100$	= 0.35%	0.35%

^aAssay value from calibration curve from mockup assembly after correction for differences in Gd₂O₃ loading.

TABLE II
ACTIVE ASSAY RESULTS AT EXXON NUCLEAR

<u>Assembly Type</u>	<u>Run Time (s)</u>	<u>Measured Mass</u>		<u>Tag Value</u>		<u>Difference (%)</u>
		<u>(g ²³⁵U/cm)</u>	<u>(% ²³⁵U)</u>	<u>(g ²³⁵U/cm)</u>	<u>(% ²³⁵U)</u>	
BWR 1	12 x 200	14.90	3.23	14.92	3.236	0.1
BWR 2	7 x 200	14.88	3.23	14.92	3.236	0.2
PWR 1	10 x 200	38.90	3.54	40.0	3.645	2.8

Fig. 1. Schematic diagram of Coincidence Collar showing the AmLi neutron source, the ^3He detector banks, and the polyethylene moderator material. The detector bank opposite the neutron source pivots open on the hinge to accommodate PWR, BWR, or HWR fuel assemblies.

Incidence Collar detector head with AmLi neutron source for

Fig. 3. The Coincidence Collar in measurement position around a mockup PWR fuel assembly, showing EC-100 electronics, HP-97 calculator, and support cart.

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

Fig. 5. The results from the production assembly measurements compared with the calibration curves obtained from the mockup assembly.

Fig. 6. 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.

C-Collar-3 BWR Calibration

Fig. 7. Power function calibration curve for BWR fuel assemblies showing 95% confidence limits.