LA-11965-MS
(ISPO-323)

NOV 0 2 1990

LA--11965-MS

DE91 001718

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UNITED STATES PROGRAM
FOR TECHNICAL ASSISTANCE TO IAEA SAFEGUARDS

POTAS

DEPARTMENT OF STATE
DEPARTMENT OF ENERGY
ARMS CONTROL AND DISARMAMENT AGENCY
NUCLEAR REGULATORY COMMISSION

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Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

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(ISPO-323)

UC-000
Issued: November 1990

Neutron Collar Calibration and Evaluation for Assay of LWR Fuel Assemblies Containing Burnable Neutron Absorbers

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NEUTRON COLLAR CALIBRATION AND EVALUATION FOR ASSAY OF LWR FUEL ASSEMBLIES CONTAINING BURNABLE NEUTRON ABSORBERS

by

H. O. Menlove, J. E. Stewart, S. Z. Qiao, T. R. Wenz, and G. P. D. Verrecchia

ABSTRACT

The neutron coincidence collar is used to verify the uranium content in light water reactor fuel assemblies. An AmLi neutron source actively interrogates the fuel assembly to measure the ^{235}U content and the ^{238}U content can be verified from a passive neutron coincidence measurement. This report gives the collar calibration data for pressurized water reactor (PWR) and boiling water reactor (BWR) fuel assemblies both with and without cadmium liners. Calibration curves and correction factors are presented for neutron absorbers (burnable poisons) and various fuel assembly sizes. The data were collected using the Los Alamos BWR and PWR test assemblies as well as fuel assemblies from several fuel fabrication facilities.

I. INTRODUCTION

Neutron collars* (UNCLs)[1] are being used for routine inspection activities by both the International Atomic Energy Agency (IAEA) and the Commission of the European Communities (CEC) Safeguards Directorate, Luxembourg (EURATOM). This activity has led to increased requirements for an absolute calibration for each of the collars and a procedure to carry over the calibration to different nuclear facilities. Achieving this kind of standardization is complex because the fuel assemblies include many different enrichments, pin configurations, fuel masses, and burnable poison loadings.

To obtain an absolute calibration of the UNCL requires measuring a group of standard boiling water reactor (BWR) and pressurized water reactor (PWR) fuel assemblies that cover a wide range of fuel enrichments and dimensions. During past calibration work, data of this type were obtained for PWR fuel at Franco-Belge de Fabrication de Combustibles (FBFC),[2] for BWR fuel at ASEA-Atom[3] in Sweden in 1982, and for both types of fuel at Exxon Nuclear at Richland, Washington, during 1984-1985.[4] However, calibration data for fuel assemblies containing burnable poison rods were not obtained during this early work.

More recently, the use of burnable poison rods in both BWR and PWR fuel assemblies has greatly increased. This has made it necessary to recalibrate the collar for the case of poison rod assemblies. To gain independence from the operator's declaration for the number of poison rods, cadmium (Cd) liners have been included with the collar, and a combination of measurements with and without the Cd liners can be used to verify the amount of burnable poison in the assemblies.

The Cd liners remove the low energy (thermal) neutrons from the interrogation spectrum and thus reduce the poison rod perturbation to the assay by about a factor of 10. If the measurements are performed using **only** the Cd liner mode, the measurement **variations** caused by the poison rods can be neglected in some cases. However, long measurement times (20-40 min) are required in the Cd mode, so it is more practical to measure most of the assemblies in the no-Cd mode. A ratio of measurements with and without the Cd liners (Cd ratio) can be used to verify the operator's burnable poison declaration. Both calibrations with and without Cd liners will be given in this report.

During 1989, a new version of the collar the (UNCL-II) was introduced to reduce measurement times and to take advantage of the high reliability and stability that is possible with the new AMPTEK electronics.[5] This unit has a fixed body size, so separate detector heads are used for PWR and BWR fuel assemblies. A description of the UNCL-II will be given in this report.

This report summarizes calibration information needed for the PWR and BWR calibration work. After the absolute calibration has been performed for a particular collar, a common reference checkpoint is needed to cross-calibrate additional collars for both fuel types. We performed such a cross-calibration using the Los Alamos National Laboratory prototype fuel assemblies.

The new fuel assembly designs have a wide variation in poison rod loadings and variable enrichments. Results are presented in this report to better quantify the corrections for these variations.

Table I lists collars that are included in the present cross-reference and calibration.

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*IAEA designation is UNCL (Uranium Neutron Collar—Light Water Reactor Fuel). EURATOM designation is NCC (Neutron Coincidence Collar).

Table I. Neutron Collar Listing

Collar	Fabricator's Source No.	Mod	Fabricator (AMPTEK Upgrade)	Location
LANL-3	N/A	II	LANL	LANL
LANL-4	N/A	II	LANL	LANL
IAEA-BWR/1	88-049-01	II	JOMAR	IAEA/Japan
IAEA-BWR/2	88-049-02	II	JOMAR	IAEA/Japan
IAEA-PWR/3	88-049-03	II	JOMAR	IAEA/Japan
IAEA-PWR/4	88-049-04	II	JOMAR	IAEA/Japan
LANL-1	N/A	I	LANL	LANL
IAEA-4887/1	--	I	NNC	IAEA/Vienna
IAEA-4887/3	88-0739C	I	NNC	IAEA/Korea
IAEA-4887/4	88-049-10	I	JOMAR	IAEA/Vienna
IAEA-4887/5	--	I	JOMAR	IAEA/Vienna
IAEA-4887/7	--	I	NNC	IAEA/Vienna
IAEA-4887/8	--	I	JOMAR	IAEA/Vienna
IAEA-4887/spare	--	I	NNC	IAEA/Vienna
IAEA-88-049-08	88-049-08	I	JOMAR	IAEA/Vienna
IAEA-88-049-09	88-049-09	I	JOMAR	IAEA/Vienna
EUR (BWR/PWR-3)	--	I	JOMAR	EUR/Lux.
EUR (BWR/PWR-5)	--	I	JOMAR	EUR/Lux.
EUR (JOMAR 1988)	Pur. 1988	I	JOMAR	EUR/Lux.

II. NEUTRON SOURCE-SAMPLE COUPLING

The response from the UNCL is directly proportional to the AmLi neutron source intensity and the source-sample coupling. However, the response varies as the square of the detector efficiency. Thus it is important to keep track of the source and the sample spacing in the UNCL. The normal procedure is to keep an assigned source with a specific UNCL. However, in some field applications, it is necessary to substitute a different source because of transportation and licensing problems. In case of substitution, the AmLi source yields and ratios given in Table II can be used to correct the response. The response varies linearly with the source strength.

Table II. AmLi Source Yield Comparison

Source No.	Absolute Yield[a] (n/s)	Yield Relative to MRC-95	Location
MRC-67	2.20×10^4	0.554	Los Alamos
MRC-68	1.14×10^5	2.872	Los Alamos
MRC-75	6.98×10^3	0.1760	IAEA
MRC-77	6.45×10^3	0.1633	IAEA
MRC-79	4.38×10^4	1.107	IAEA
MRC-80	4.21×10^4	1.062	IAEA
MRC-81	4.11×10^4	1.037	IAEA
MRC-82	3.79×10^4	0.956	IAEA
MRC-91	3.83×10^4	0.995	IAEA
MRC-92	3.94×10^4	0.996	IAEA
MRC-93	4.13×10^4	1.042	IAEA
MRC-94	4.01×10^4	1.013	Los Alamos
MRC-95	3.96×10^4	1.000	Los Alamos
MRC-96	4.00×10^4	1.009	Los Alamos
MRC-99	7.53×10^4	1.899	Los Alamos
MRC-100	7.31×10^4	1.845	Los Alamos
MRC-104	4.53×10^4	1.144	IAEA
MRC-105	4.38×10^4	1.106	IAEA
MRC-110	4.15×10^4	1.048	IAEA
MRC-111	4.48×10^4	1.132	IAEA
MRC-112	4.56×10^4	1.150	IAEA
MRC-113	4.80×10^4	1.211	Los Alamos/IAEA
MRC-114	4.62×10^4	1.164	Los Alamos/IAEA
MRC-115	5.10×10^4	1.287	Los Alamos
MRC-116	5.17×10^4	1.305	Los Alamos
MRC-117	4.83×10^4	1.220	Los Alamos
MRC-118	4.83×10^4	1.220	Los Alamos
MRC-121	6.46×10^4	1.628	EURATOM
C-119	4.52×10^4	1.142	EURATOM
C-171	4.78×10^4	1.207	IAEA
C-172	4.72×10^4	1.193	IAEA
C-173	4.79×10^4	1.190	IAEA/Japan
C-176	4.96×10^4	1.255	EURATOM
C-180	5.03×10^4	1.270	EURATOM
C-181	4.80×10^4	1.211	EURATOM
C-182	4.73×10^4	1.193	EURATOM
C-183	4.66×10^4	1.176	EURATOM
C-186	4.00×10^4	1.009	IAEA
C-188	4.21×10^4	1.063	IAEA
C-268	3.97×10^4	1.003	IAEA
C-270	5.48×10^4	1.382	EURATOM
C-271	4.64×10^4	1.169	EURATOM
C-272	4.00×10^4	1.009	IAEA
C-282	5.84×10^4	1.474	EURATOM
C-283	5.71×10^4	1.439	EURATOM
C-287	5.70×10^4	1.440	EURATOM
C-297	4.36×10^4	1.102	EURATOM
C-298	4.42×10^4	1.108	EURATOM
C-299	4.52×10^4	1.138	EURATOM
C-300	4.40×10^4	1.109	EURATOM
C-470	4.48×10^4	1.132	IAEA
C-471	4.57×10^4	1.153	IAEA
C-472	4.50×10^4	1.136	IAEA
C-473	4.42×10^4	1.116	IAEA
C-474	1.01×10^5	2.554	IAEA
C-475	1.04×10^5	2.627	IAEA
C-476	1.02×10^5	2.580	IAEA
C-477	1.03×10^5	2.600	IAEA
C-539	9.90×10^4	2.499	IAEA
C-540	9.94×10^4	2.511	IAEA
C-541	1.03×10^5	2.610	IAEA
C-542	9.77×10^4	2.468	IAEA

[a] The absolute yield is based on the ratio of the totals rate to ^{252}Cf (CR-5) in the center of a two-ring AWCC. The efficiency for the ratio of AmLi/Cf was 1.055 based on MCNP calculations. The yields correspond to January 1, 1989.

The previous AmLi sources used with the UNCL units had a yield of ~5 x 10^4 n/s; however, the newer UNCLs have source strengths of ~9 x 10^4 n/s to better override the neutron background from the fuel assembly. For the Cd-mode interrogation, the induced signal rate is an order of magnitude less than for the no-Cd mode; therefore, the stronger source helps to reduce measurement times by increasing the signal/background ratio.

The source-sample coupling is fixed by positioning the fuel assembly face 1 cm away from the polyethylene (CH_2) side holding the AmLi source. The AmLi source has a fixed position in the UNCL.

III. DETECTORS

Detector and electronic counting efficiency depend on three components: the ^{3}He tube detectors, the sample-detector solid angle, and the electronics. The first of these is essentially constant for a given system, whereas the solid angle and the electronics can change from one setup to the next. If the same electronics are used from one application to the next and the high-voltage setting is not altered, experience shows we can expect to obtain better than 1% stability in the totals rate.

One of the primary sources of error in using the UNCL in the past has been improper field assembly of the four sides. When these sides are misaligned, the detector's efficiency changes. Also, in some nuclear fuel facilities, there has not been adequate clearance to open and close the hinged door of the UNCL.

To help eliminate these problems and to decrease the required measurement times, the UNCL-II was introduced in July 1989.

UNCL-II Design

The UNCL-II has the following characteristics that are different from the UNCL:

- Separate detectors for BWR and PWR assemblies with a single U-shaped AMPTEK[5] junction box,
- A lift-out door containing the AmLi neutron source, and
- Higher detector efficiency than the original UNCL.

The new detector schematic design is shown in Fig. 1 for PWR together with that of the original UNCL. Figure 2 is a photograph of the UNCL-II with the AMPTEK box lid removed. Figure 3 is a diagram of the original UNCL (top) and the new UNCL-II (bottom) corresponding to BWR-size fuel. Figure 4 shows the experimental setup with the collar positioned on a BWR fuel assembly. Table III gives the specifications for the old and new systems.

The detector tubes are set to operate with HV = 1680 V and a gate of 64 μs, which is the same as for the HLNC-II.

The deadtime of the UNCL is negligible, so the deadtime coefficient is set equal to zero ($\delta = 0$) for **both** calibration and assay.

IV. CALIBRATION METHODS

During the past several years, neutron coincidence collars have been calibrated from reference fuel assemblies in Belgium (PWR),[2] Sweden (BWR),[3] and at the Exxon Nuclear[4] facility (PWR and BWR). Various ^{235}U enrichments were used to establish the shape of the calibration

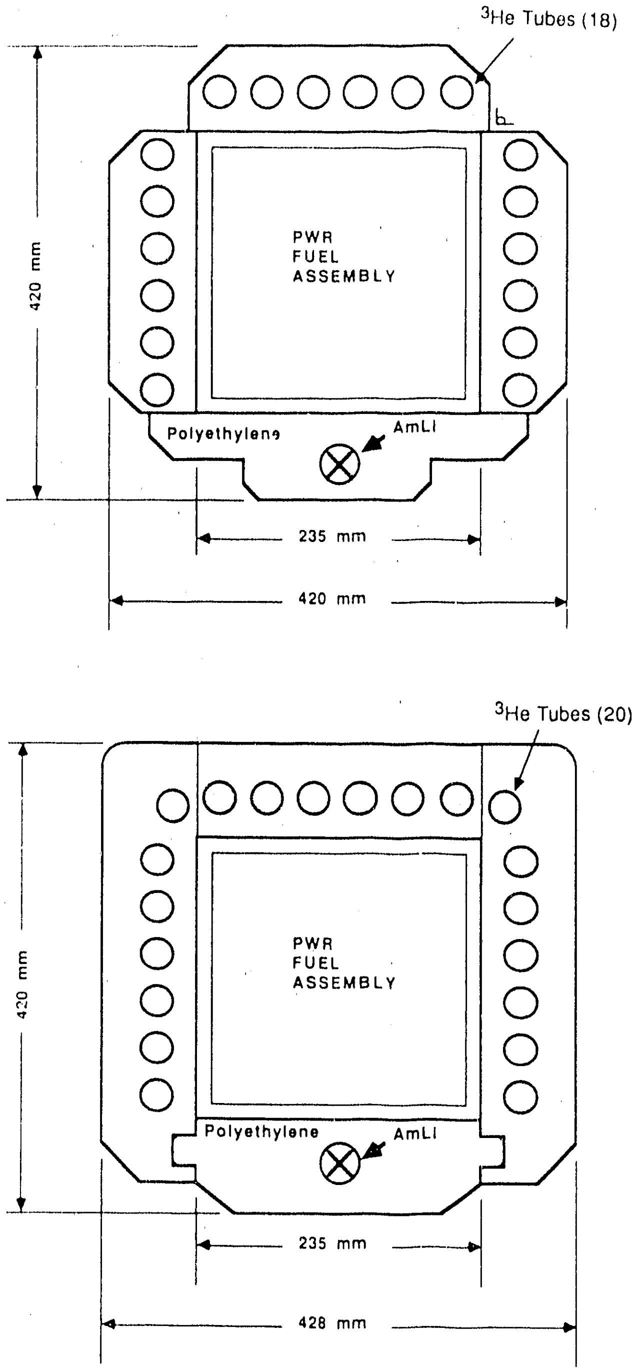

Fig. 1. Schematic diagram of original UNCL (top) and the new UNCL-II (PWR size) at the bottom of the figure.

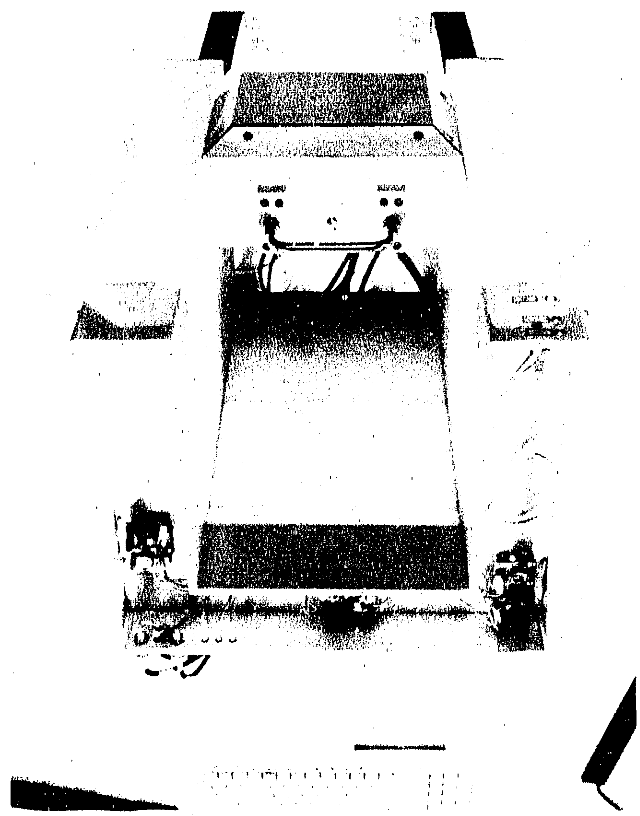

Fig. 2. Photograph of the UNCL-II with the lid removed to show the three AMPTEK amplifier boards. The lift-out door contains the AmLi source.

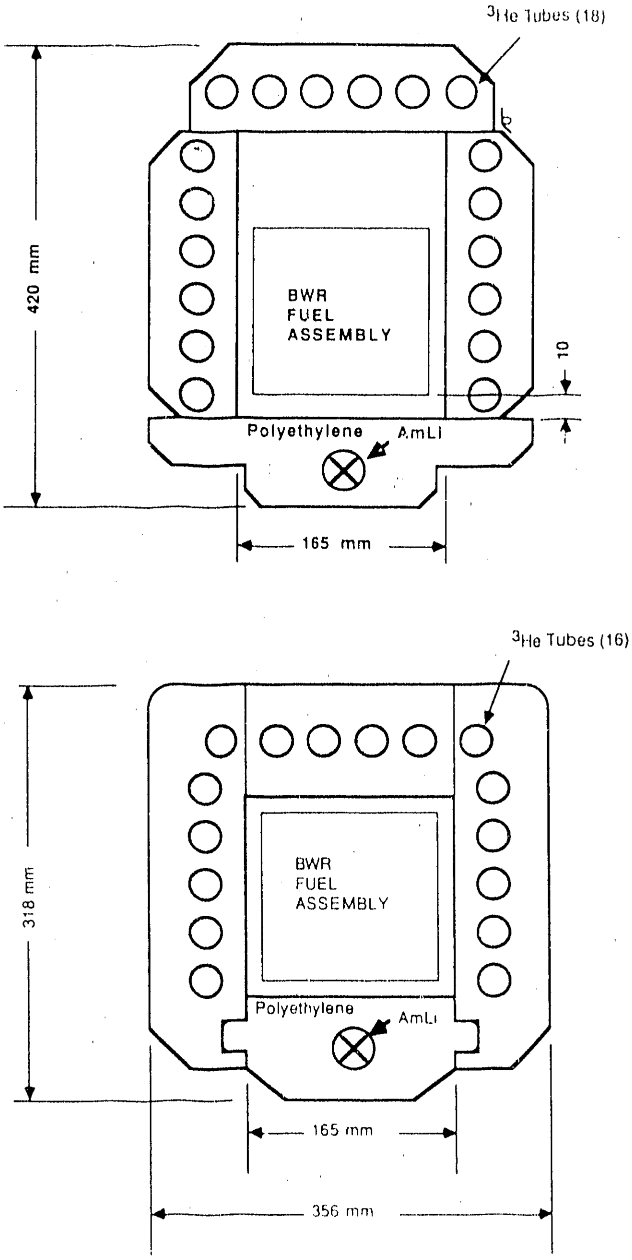

Fig. 3. Schematic diagram of the original UNCL (top) and the new UNCL-II (BWR size) at the bottom of the figure.

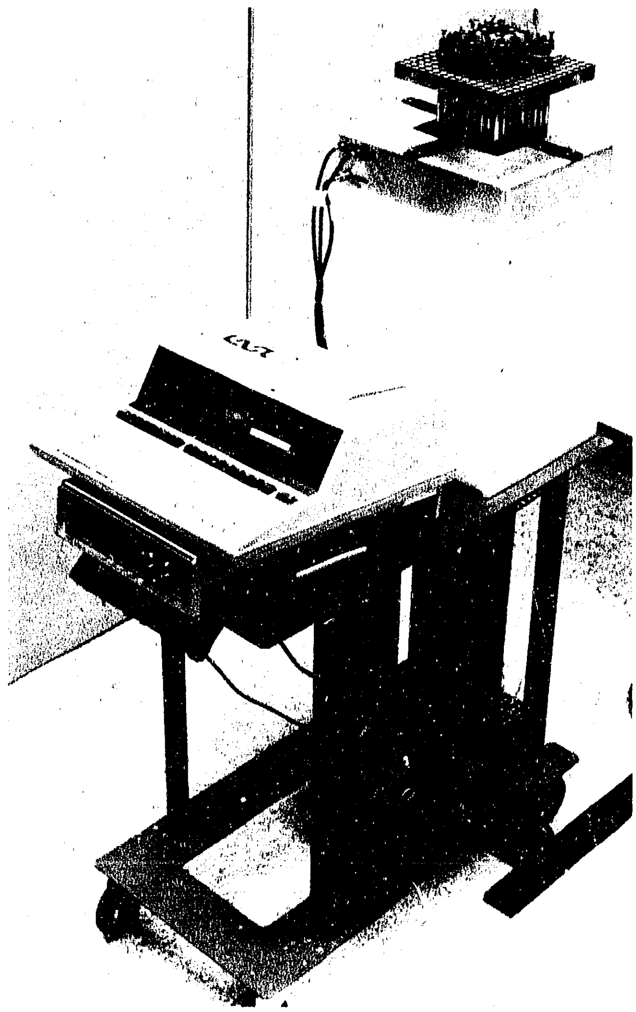

Fig. 4. Photograph of the UNCL-II (BWR size) with Cd liners in place and the LANL mockup BWR fuel assembly.

Table III. Specifications for UNCL and UNCL-II

Item	UNCL[a]	UNCL-II
^3He tube model	RS-P4-0813-101	RS-P4-0813-101
Gas filled ^3He (Ar + CH_4)	4 bar	4 bar
Active diam x length	25 x 330 mm	25 x 330 mm
Number of tubes (PWR)	18	20
Number of tubes (BWR)	18	16
AMPTEK amplifiers	3	3
Sample cavity size (PWR)	235 x 235 mm	235 x 235 mm
Sample cavity size (BWR)	165 x 235 mm	165 x 165 mm
Overall height (PWR and BWR)	509 mm	515 mm
Outside dimensions (PWR)	420 x 420 mm	428 x 420 mm
Outside dimensions (BWR)	350 x 420 mm	356 x 345 mm
Weight (PWR)	38 kg	48 kg
Weight (BWR)	38 kg	39 kg

[a]The UNCL corresponds to the AMPTEK upgraded units.

function, and the AmLi neutron sources and/or ^{252}Cf sources were measured to establish the relative counting efficiency.

None of the previous calibrations included accurate Cd mode calibrations for assemblies with burnable poisons. In this report we have used the Los Alamos BWR and PWR reference assemblies to establish the shape of the calibration curves and to determine the burnable poison corrections. Calibration curves have been established both with and without Cd liners.

We have established that all UNCL units have the same calibration curve shape for a given type of fuel and the detector heads only differ in the absolute magnitude of the reals (R) response depending on their source and detection efficiency. It is impractical to measure the full mass and enrichment range to establish separate calibration functions for all UNCL units, so we will establish the shape of the calibration function using a single UNCL-II and then cross-calibrate all other UNCL units to the reference detector or to the reference fuel assemblies with a single mass loading.

The standard PWR and BWR reference assemblies at Los Alamos will be used for this cross-calibration purpose. Alternatively, UNCL units can be cross-referenced in the field by measuring a production fuel assembly with both uncalibrated and calibrated collars. In all cases, the **shape** of the calibration curve will remain fixed.

For past calibrations of the UNCL, we have used a function of the form

$$M = a(R)^b \ ,$$

where M is the mass per unit length (g ^{235}U/cm) and a and b are calibration constants. We decided to leave a and b fixed for a given type of fuel assembly for all of the different collars and then correct the measured R to match the original calibration conditions.

More recent measurements have shown that the UNCL calibration can be fit over a wider range of ^{235}U loadings with a function of the form

$$R = \frac{aM}{1 + bM} \ .$$

To be more consistent with software and error analysis that have been developed for the HLNC by the IAEA, we have changed the equation to R as a function of M.

This new function will be used for the upgraded UNCLs and the UNCL-II (both Cd and no-Cd modes).

In addition to M (g ^{235}U/cm), the response R is a function of:

- AmLi source strength -- k_0
- Electronics drift -- k_1
- Detector efficiency, ε -- k_2
- Burnable poison, Gd_2O_3 -- k_3
- Heavy metal loading, g U/cm -- k_4
- Other conditions -- k_5 .

When these variables differ from our calibration condition, it is necessary to correct the measured response by

$$kR = (k_0 \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5)\, R \ .$$

This approach assumes that all corrections are independent of each other. This is not strictly true but is sufficiently accurate for implementation.

When the assay conditions are the same as the calibration conditions, then the k terms are unity.

By conditioning our response (kR) to the calibration condition, we can use fixed a and b parameters, and k_3 and k_4 are defined by correction formulas.

V. REFERENCE ASSEMBLIES

Both PWR and BWR reference assemblies are available at Los Alamos for general calibration purposes. The specifications for these assemblies are given in Table IV. The responses measured from these two reference assemblies have been compared with fuel assembly measurements at several fuel fabrication facilities[4,6,7,8] and the agreement has been good (±1%).

TABLE IV. Characteristics of Los Alamos BWR and PWR Fuel Assemblies

	BWR	PWR
Array size	9 x 9	15 x 15
Number of rods	76	204
Number of open channels	5	21
Rod diameter	10.8 mm	10.8 mm
Rod cladding	Zircaloy 2	Zircaloy 2
UO_2 active length	1.035 m	1.035 m
UO_2 density	10.48 g/cm^3	10.48 g/cm^3
Linear ^{235}U loading assembly	14.44 g ^{235}U/cm	38.76 g ^{235}U/cm
Uranium enrichment	3.19%	3.19%
Heavy metal loading	453 g U/cm	1215 g U/cm
Number of depleted rods	76	204
Number of poison rods (max.)	12	12

For the LANL reference assemblies, we have the capability to substitute depleted uranium (DU) rods for enriched uranium (EU) rods, and also to substitute up to 12 burnable poison (BP) rods into any rod location in the array. The poison rod specifications are given in Table V.

The DU for EU substitution feature allows us to generate the shape of the *R* vs *M* curve for a constant uranium density (1215 g U/cm for PWR, and 453 g U/cm for BWR).

The poison rod substitution gives us the formula for k_3, and the heavy metal loading correction (k_4) is obtained from Monte Carlo (MCNP)[9] computer calculations with experimental cross-checks by changing the heavy metal loading in the assembly.

VI. CALIBRATION

A. Calibration Types

For safeguards verification purposes two different conditions could apply to the UNCL calibration. These are (1) EU rod removal with no uranium (DU) substitution, or (2) EU rod removal with DU rod substitution. We will focus on this second case because it corresponds to the normal plant condition of a full assembly with variable or unknown ^{235}U enrichment. The UNCL is more sensitive to case (1) than (2), so by calibrating for case (2), we will be conservative in our verification sensitivity limits.

The passive assay (no AmLi sources) checks the ^{238}U loading by measuring the spontaneous fission rate, so we obtain a rough check that calibration case (2) is valid. That is, we can verify that the total heavy metal (g U/cm) loading is as declared.

TABLE V. PWR and BWR Poison Rod Specifications

Number of rods	12
Rod active length	1040 mm
Cladding material	Zr-4
Rod diameter	10.8 mm
Pellet diameter	9.0 ± 0.3 mm
Pellet enrichment	3.27%
U/UO_2	0.8441
U/rod	571 g
^{235}U/rod	18.72 g
Gd_2O_3/rod	40.6 g
Gd/rod	35.2 g
Gd weight percent of fuel	5.2%
^{235}U linear loading	0.18 g ^{235}U/cm

B. Calibration Conditions

In the following sections of this report, we will develop calibration curves for four different conditions:

- PWR - no Cd liners,
- PWR - Cd liners,
- BWR - no Cd liners, and
- BWR - Cd liners.

In addition, we will give a method to use the Cd ratio to verify the operator's declaration as to the number of poison rods in the assembly.

For most applications, we expect the inspectors to use the UNCL in the no-Cd mode to save time in the plant, and to measure with Cd liners only one or two assemblies of a given type to verify the poison rod declaration or to directly measure the k_3 factor.

C. Calibration Cross-Reference

The reference fuel assembly was carefully measured for a wide range of fuel loadings and enrichment variations using a reference UNCL. This established the shape of the calibration curve. Additional new collars will be cross-referenced to the reference collar or reference fuel assembly at a single loading. This cross-reference can be performed using the standard assemblies at LANL or using a production assembly in the field. With this procedure, all collars use the same calibration parameters after correcting the responses to the calibration condition.

D. Sample Variables for Calibration

In addition to the ^{235}U loading, sample variables that affect the assay are the BP content and the heavy metal loading. Changes in the UNCL response relative to the calibration assemblies are accounted for using the k_3 and k_4 factors that were defined in Section IV. Some variables that have **negligible** effect on the assay are the number of rods, the number of empty rods, the number of empty water rods, the rod diameter, the pellet size and density, and the type of zircaloy cladding. Stainless steel cladding will depress the measured response, but this type of cladding is not used in commercial LWR fuel. Also, cardboard or plastic bags that cover the fuel assembly give a small perturbation to the no-Cd-mode assay, but the bags increase the response by a few percent for the Cd-mode assay. Sample changes of this type are corrected by the k_5 term.

VII. PWR CALIBRATION RESULTS

A. PWR—No Cd Liners

In the past, calibrations have been made at fabrication plants with the standard UNCL configuration without Cd liners. However, the enrichment and mass ranges were limited. We are now using the PWR assembly specified in Table IV to define our basic calibration shape.

The data were obtained using the LANL-1 (UNCL), the LANL-3 (UNCL-II), and the standard AmLi (MRC-95) interrogation sources. These data allowed us to check for any differences in the calibration shapes between the original collar (LANL-1) and the new collar (LANL-3).

Calibration measurement data were obtained by replacing EU rods by DU rods uniformly across the fuel assembly. Prior measurements[7] had shown that the relative location of the EU and DU rods did not affect the results.

The measurement precision in R for a 1000-s count time is 0.6% for LANL-1 and 0.5% for LANL-3. Most calibration measurements were for 5 x 1000 s or longer.

The measurements as a function of ^{235}U loading are given in Table VI. The new unit (LANL-3) has a higher efficiency than the UNCL and the average ratio of the responses (new/old) was 1.52. **We see from Table VI that the ratio of the two collars is constant ($\pm$1%) over the entire loading range.**

Table VI lists the nine mass loadings used for the new collar (LANL-3) and six mass loadings used for the old collar (LANL-1). The measured reals using MRC-95 have been increased by 1.5% to correct for the neutron absorption in the stainless steel guide tubes (see Table VII).[10]

The mass residuals given in Table VI were obtained from the computer fit to the 15 fuel assembly loadings with the heavy metal mass constant at 1215 g U/cm. The highest enrichment loading was measured six different times over a 9 month period, and it was given a correspondingly higher weighting in the fitting procedure.

Because LANL-3 (UNCL-II) is the new reference collar, we have normalized the data from LANL-1 by the average ratio to superimpose the two results. Figure 5 shows a plot of the two data sets with a fitted (Deming) function of the form

$$R = \frac{aM}{1 + bM}$$

where

$a = 9.646 \pm 0.216$
$b = 0.0261 \pm 0.0013$

Table VI. PWR Calibration Data for Reference Calibration Curve—No Cd Case

Assembly Number	$\frac{g\ ^{235}U}{cm}$	R* (s^{-1})	Mass Residuals** (%)
LANL-3 (UNCL-II)			
1	16.04	111.1	+1.9
2	21.72	132.0	-1.2
3	27.40	149.7	-2.9
4	29.18	158.8	-0.6
5	30.95	164.1	-0.6
6	33.08	173.4	+1.2
7	34.50	176.0	+0.5
8	36.63	180.8	+0.1
9	38.76	186.5	+0.4
LANL-1 (UNCL), Normalized (k = 1.5216)			
1	20.30	127.7	-0.2
2	23.85	145.3	+2.4
3	27.40	152.8	-0.9
4	30.95	162.3	-1.7
5	34.47	173.4	-0.9
6	38.76	187.0	+0.6

a = 9.646 ± 0.216
b = 0.0261 ± 0.0013

a:a 4.66 x 10^{-2}

a:b 2.78 x 10^{-4}

b:b 1.69 x 10^{-6}

$$R = \frac{aM}{1 + bM}$$

*The net R values have been increased by a factor of 1.015 to correct for the neutron absorption in the SS guide tubes in the LANL PWR assembly. AmLi source MRC-95 was used for the measurements.

**The mass residuals were obtained from a Deming fit of the combined data set with a fixed percent weighting of 0.5% for all the points except for 38.76 g ^{235}U/cm where the weight was 0.29%.

Table VII. Response Corrections for Stainless Steel Guide Tubes in LANL Mockup Assemblies

	PWR	BWR[a]
No Cd	1.015	1.004
Cd	1.010	1.002

[a]MCNP calculations were performed for the PWR case and a linear extrapolation was used to estimate the BWR case.

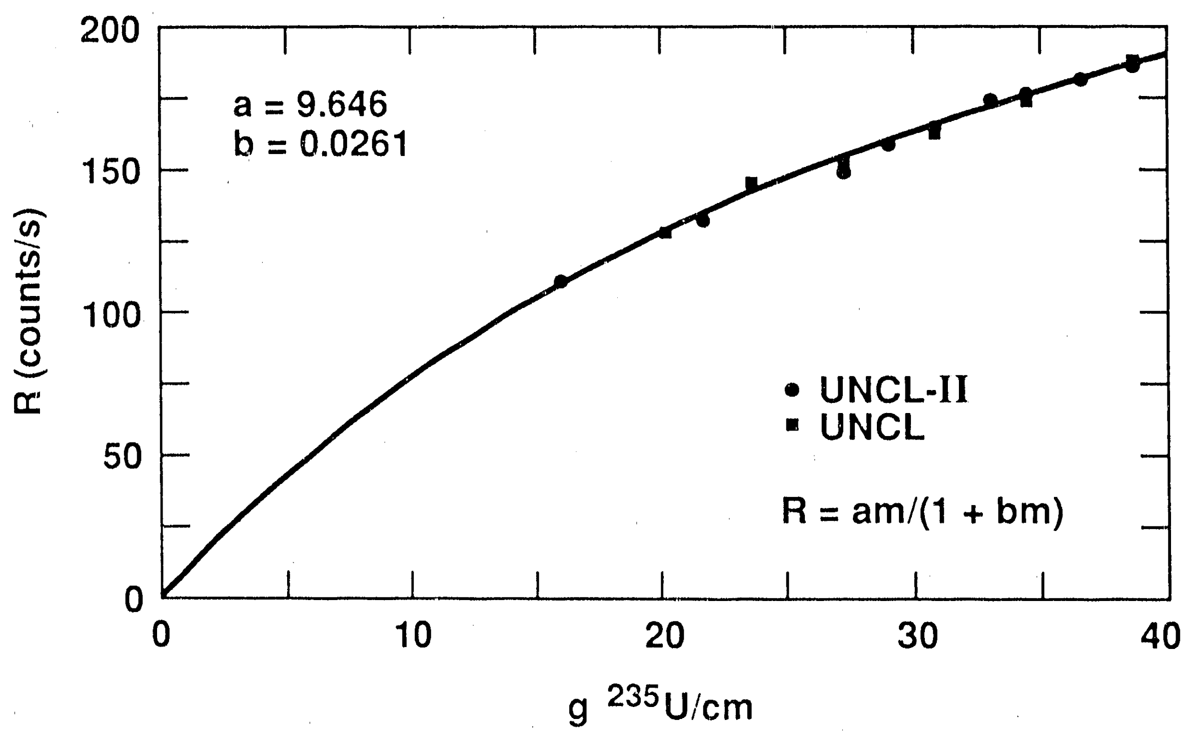

Fig. 5. The PWR calibration reference curve (no Cd) with the UNCL data normalized to the UNCL-II (LANL-3) collar (source MRC-95, 89-10-17).

with covariances

$a{:}a$ 4.66×10^{-2}
$a{:}b$ 2.78×10^{-4}
$b{:}b$ 1.69×10^{-6} .

The average absolute mass residual was 1.0%, which is consistent with the measurement precision (~0.2%-0.5%) for the individual points.

The LANL PWR and BWR mockup fuel assemblies contain 21 and 5 stainless steel guide tubes, respectively. These guide tubes absorb a small fraction (~1%) of the interrogation neutrons; whereas, commercial fuel assemblies normally have zircaloy guide tubes that have negligible neutron absorption. MCNP calculations[10] were performed to determine a correction factor for the absorption and the results are given in Table VII.

We increased the measured reals for the LANL calibrations by the factors in Table VII before fitting the reference calibration curves for PWR and BWR fuel assemblies. Thus, any future measurements using the LANL reference assemblies should be corrected by the factors in Table VII before comparison with the reference calibration curves.

B. PWR—Cd Liners

When Cd liners are used, there is less neutron self-shielding in the fuel assembly and the results yield a more linear calibration function. The Cd liners significantly reduce the response compared with the case with no Cd liners; however, the linear calibration curve reduces the magnitude of the error propagation.

The Cd-mode-measurement results as a function of ^{235}U loading are given in Table VIII for both LANL-1 and LANL-3. We see that the ratio of R for the two collars is almost constant ($\pm$ 1%) as a function of ^{235}U mass.

When the LANL-1 results are normalized to the LANL-3 data, we get the combined result that is plotted in Fig. 6. The fitted function is of the form

$$R = \frac{aM}{1 + bM} ,$$

where

$a = 0.4373 \pm 0.0047$
$b = 0.0067 \pm 0.00048$

with covariances

$a{:}a$ 2.28×10^{-5}
$a{:}b$ 2.18×10^{-6}
$b{:}b$ 2.29×10^{-7} .

The average absolute mass residual was 1.01%, which is a little larger than the measurement precision. The Cd-mode results are somewhat dependent on the thickness and coverage of the Cd liners, and because each collar has its own Cd liners, the results can be slightly different from

Table VIII. Reference PWR Calibration Data Cd Liner Case

Assembly Number	$\frac{g\ ^{235}U}{cm}$	R* (s^{-1})	Mass Residuals (%)
LANL-3 (UNCL-II)			
1	10.36	4.29	+1.3
2	16.04	6.11	-3.6
3	21.72	8.29	+0.0
4	27.40	10.14	+0.2
5	29.18	10.69	+0.2
6	30.95	11.34	+1.2
7	33.08	11.86	+0.2
8	34.50	12.29	+0.3
9	36.63	13.10	+1.8
10	38.76	13.56	+0.8
LANL-1 (UNCL), Normalized (k = 1.62)			
1	9.65	3.93	-0.8
2	13.20	5.39	+1.6
3	16.75	6.63	+0.7
4	20.30	7.81	+0.0
5	23.85	9.13	+1.5
6	27.40	10.07	-0.5
7	30.95	11.12	-0.8
8	34.47	11.97	-2.3
9	38.76	13.27	-1.4

a = 0.4373 ± 0.0048
b = 0.00671 ± 0.00048

a:a 2.28×10^{-5}

a:b 2.18×10^{-6}

b:b 2.29×10^{-7}

$$R = \frac{aM}{1 + bM}$$

*The net R values have been increased by a factor of 1.010 to correct for neutron absorption in the stainless steel guide tubes. Source MRC-95 was used.

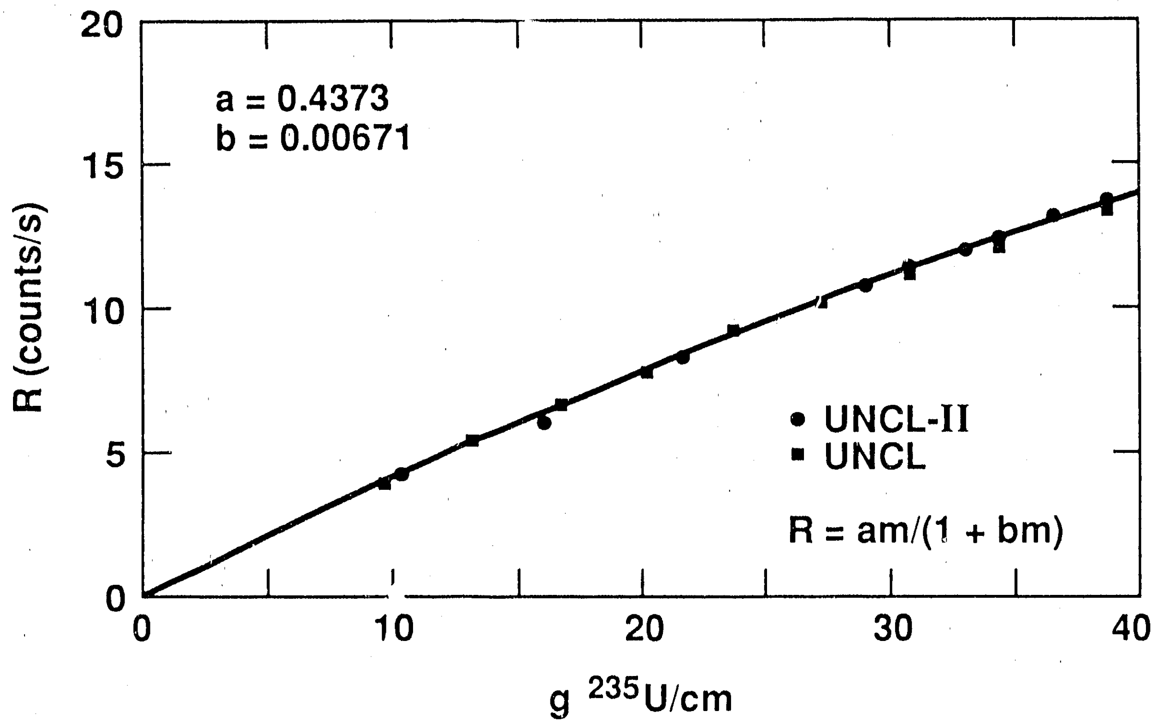

Fig. 6. The PWR reference calibration curve (Cd mode) with the UNCL data normalized to the UNCL-II (LANL-3) collar (source MRC-95, 89-10-17).

collar to collar. The Cd liners used during the calibration should stay with the collar for all field applications.

VIII. BWR CALIBRATION RESULT

A. BWR—No Cd Liners

The specifications for the BWR assembly are listed in Table IV. The measurement procedure was the same as for the PWR assembly.

The results for the BWR case are listed in Table IX for the LANL-4 collar (UNCL-II).

After normalizing the responses by 1.004 to correct for the stainless steel guide tubes, we have plotted the data in Fig. 7. The fitted function is

$$R = \frac{aM}{1 + bM} ,$$

where

$$a = 24.91 \pm 0.331$$
$$b = 0.0680 \pm 0.0021$$

Table IX. Reference BWR Calibration Data No Cd Liner (LANL-4, MRC-95)

Assembly Number	$\frac{g\ ^{235}U}{cm}$	R* (s^{-1})	Mass Residuals (%)
1	3.79	75.60	+1.1
2	5.92	103.0	-1.7
3	8.05	129.2	+0.1
4	10.18	149.4	+0.1
5	10.89	155.7	+0.3
6	11.60	159.3	-1.0
7	12.31	166.2	-0.1
8	13.02	172.6	+0.7
9	13.73	175.8	-0.3
10	14.44	181.8	+0.5

a = 24.91 ± 0.33
b = 0.0680 ± 0.0021

a:a 1.09×10^{-1}

a:b 6.85×10^{-4}

b:b 4.45×10^{-6}

$$R = \frac{aM}{1 + bM}$$

*The net R was increased by 1.004 to correct for the neutron absorption in the five stainless steel guide tubes.

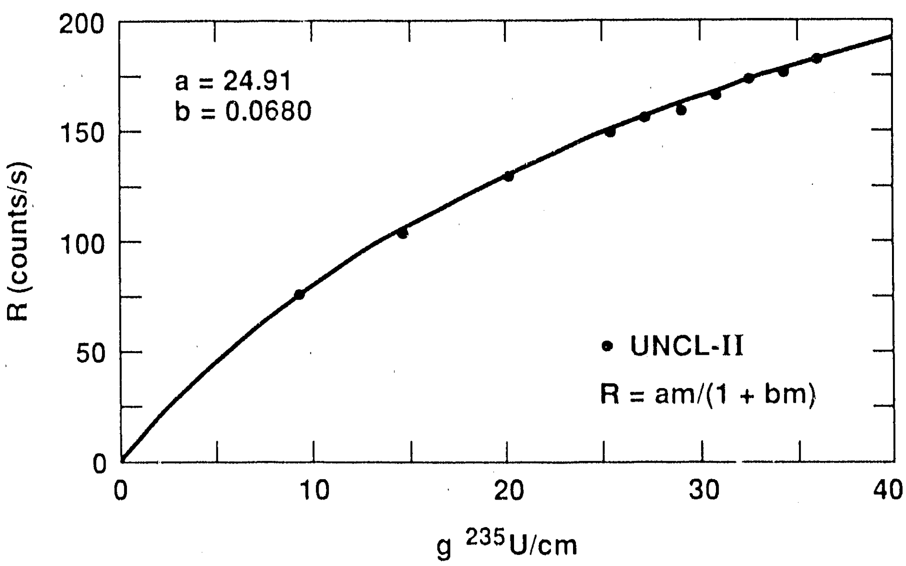

Fig. 7. The BWR reference calibration curve (no Cd) using UNCL-II (LANL-4) collar (source MRC-95, 89-10-17).

with covariances

$a{:}a$ 1.09 x 10^{-1}
$a{:}b$ 6.85 x 10^{-4}
$b{:}b$ 4.45 x 10^{-6} .

The average absolute mass residual was 0.6%, which is consistent with the measurement precision.

To compare the calibration shape of the old style BWR collars with the new design, we measured the LANL BWR mockup assembly with both the old (EURATOM NCC3) and the new (LANL-4) collars as a function of g ^{235}U/cm. The results are given in Table X, and we see that the normalized responses differ by less than ±1.5% over the mass range from 5.92 to 14.44 g ^{235}U/cm.

To compare the shape of our new calibration curve to our old calibration curve in reference LA-11229-MS, we have calculated the responses for two of our current mass loadings (12.31 and 14.44 g ^{235}U/cm) using the old function $M = aR^b$ to get the R values of 70.81 and 79.36. The ratios of the new UNCL-II responses to the old collar responses are 2.38 and 2.32 for the two mass values given above. After adjusting the calculated R for the six gadolinium rods in the old calibration curve, the reals ratio of the new/old collars is ~1.8. The slight change in slope between the old and new collars is not important for BWR assemblies because of the small mass variation in commercial BWR power reactors. The good shape agreement given in Table X indicates that the above shape differences are probably caused by the limited mass range of the original standards.

B. BWR—Cd Liners

The results with Cd liners are similar to the PWR Cd-mode results. The calibration is more linear than for the no-Cd case.

The net R values are listed in Table XI; we increased the value of R by a factor of 1.002 to correct for neutron absorption in the stainless steel guide tubes. Figure 8 gives the Cd-mode calibration curve for the fixed heavy metal loading of 453 g U/cm. The mass residuals were obtained from a Deming fit of the 10 data points. The fitted function is

$$R = \frac{aM}{1 + bM} ,$$

Table X. Calibration Curve Shape Comparison for UNCL and UNCL-II BWR Collars

g ^{235}U / cm	UNCL R (s^{-1})	UNCL R(norm) (s^{-1})	UNCL-II R (s^{-1})	Ratio new/old norm.
14.44	163.1	181.4	181.5	1.001
12.31	148.8	165.5	167.0	1.009
8.76	122.2	135.9	136.8	1.002
5.21	87.57	97.4	95.9	0.985

Table XI. Reference BWR Calibration Data
Cd Liner (LANL-4, MRC-95)

Assembly Number	$\frac{g\ ^{235}U}{cm}$	R* (s^{-1})	Mass Residuals (%)
1	3.79	2.75	-1.9
2	5.92	4.39	+1.9
3	8.05	5.82	+0.7
4	10.18	7.20	-0.1
5	10.89	7.60	-0.9
6	11.60	8.07	-0.8
7	12.31	8.62	+0.4
8	13.02	9.05	+0.1
9	13.73	9.48	-0.1
10	14.44	10.02	+0.8

a = 0.7582 ± 0.0105
b = 0.00705 ± 0.00126

a:a 1.12 x 10^{-4}

a:b 1.31 x 10^{-5}

b:b 1.57 x 10^{-6}

$$R = \frac{aM}{1 + bM}$$

*The net *R* was increased by 1.002 to correct for the neutron absorption in the five stainless steel guide tubes.

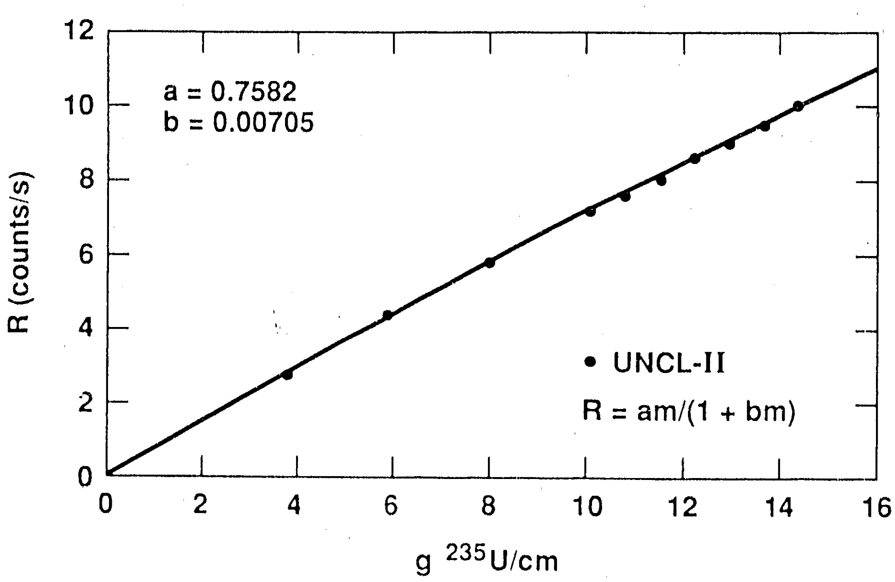

Fig. 8. The BWR reference calibration curve (Cd mode) using UNCL-II (LANL-3) collar (source MRC-95, 89-10-17).

where

$a = 0.7582 \pm 0.0105$
$b = 0.00705 \pm 0.00126$

with covariances

$a{:}a$ 1.12×10^{-4}
$a{:}b$ 1.31×10^{-5}
$b{:}b$ 1.57×10^{-6} .

The average absolute mass residual was 0.77%.

IX. CORRECTION FACTORS

To use the calibration of the reference collar for additional collars, it is necessary to condition the signal R from the new collars to the calibration conditions. In the introduction we defined the constant $k = k_0 \bullet k_1 \bullet k_2 \bullet k_3 \bullet k_4 \bullet k_5$ that is used to condition the response from **any** UNCL to the calibration condition. The following sections give the correction factors for both PWR and BWR assemblies. The first two factors (k_0 and k_1) are the same for PWR and BWR assemblies.

A. k_0—AmLi Source

This is a simple correction for source decay and to allow the change from the normal AmLi source assigned to the particular UNCL to a different source. The correction is

$$R_0 = \frac{\text{original source yield}}{\text{new source yield}} e^{+\lambda \Delta t} ;$$

the source yield ratios are given in Table I. The AmLi source decay constant is λ, and Δt is the time in years since the original calibration.

The AmLi source decays with a half-life of 432 y so the yield vs time decreases by $e^{-\lambda \Delta t}$ where $\lambda = 0.0016\ y^{-1}$ and Δt is the time interval in years. The decay is 0.16% per year, but it can be neglected for $\Delta t \leq 2\ y$. The calibration coefficients are based on the induced fission rate from the AmLi at the time of calibration. After several years (Δt) of source decay, there are less induced fissions, so the newly measured response must be corrected back to the source strength at the calibration date.

For example, if for a particular collar the source used for cross-referencing was C-172 and the applied source was MRC-112 then (see Table I),

$$k_0 = \frac{(C\text{-}172/MRC\text{-}95)\, e^{\lambda \Delta t}}{(MRC\text{-}112/MRC\text{-}95)} = \frac{1.193\, e^{\lambda \Delta t}}{1.150} = 1.04\, e^{\lambda \Delta t} .$$

Because the decay rate for all the AmLi sources is the same, the yield ratios given in Table I are invariant with time.

B. k_1—Electronics Change

If the counting efficiency of the UNCL has changed, the measurement of the AmLi source gives the correction

$$k_1 = \left(\frac{T_0 e^{-\lambda_1 \Delta t}}{T_{new}}\right)^2$$

for AmLi or

$$k_1 = \left(\frac{R_0 e^{-\lambda_2 \Delta t}}{R_{new}}\right)$$

for ^{252}Cf, where T_0 and R_0 are the totals and reals rates at the time of the calibration cross-reference. The decay constants are $\lambda_1 = 0.0016$ y^{-1} for AmLi and $\lambda_2 = 0.2623$ y^{-1} for ^{252}Cf and Δt is the elapsed time from calibration in years.

Because of experimental uncertainties in T_0 and T_{new}, if

$$|k_1 - 1| \leq 0.04 \text{ (that is, a totals change of } \leq 2\%) ,$$

then set k_1 (elect.) = 1.000.

The new AMPTEK electronics are very stable with counting efficiency drifts of much less than 1%, so this factor will normally be unity.

C. k_2—Detector Efficiency and Source Yield

The detectors differ in their intrinsic efficiency and source-sample coupling. This is measured by counting the same fuel assembly with the reference collar and the uncalibrated collar. The resulting reals ratio defines

$$k_2 = \frac{R_0 \text{ (Ref. collar, ref. source)}}{R_0 \text{ (new collar, assigned AmLi)}} ;$$

the R_0 corresponds to the reals rate at the time of calibration cross-reference.

The cross-reference factors for k_2 were determined by measuring both the reference collars and the additional collars on the standard (full) PWR and BWR fuel assemblies at LANL.

1. Cross-Reference Factors—No Cd. Table XII lists the cross-reference parameters for the PWR assemblies for which the reference collar is LANL-3 (UNCL-II), and Table XIII lists the similar information for BWR assemblies where the reference collar is LANL-4 (UNCL-II). The calibration constants a and b correspond to the equation

$$kR = \frac{aM}{1 + bM} ;$$

M is the number of g ^{235}U/cm.

Table XII. PWR Calibration Cross-Reference Data for UNCL (AMPTEK Upgrades) and UNCL-II—No Cd Mode

Collar Unit	Passive ^{252}Cf ε (%)	AmLi Source	T_0 Date (y/m/d)	T_0 (empty) MRC-XX (s^{-1})	R_0 (XX) (s^{-1})	k_2 $\frac{R_0\text{ (LANL-3)}}{R_0\text{ (XX)}}$	[1215 g U/cm] a	b	A (a/k_2)
LANL-3 (ref.)	12.6	MRC-95	89-10-17	2095	183.0	1.000	9.646	0.0261	9.646
LANL-1	10.3	MRC-95	89-02-26	1591	118.3	1.547	9.646	0.0261	6.235
IAEA-4887/1	9.88	MRC-95	89-03-20	1566	117.7	1.555	9.646	0.0261	6.203
IAEA-4887/3	10.3	MRC-95	88-10-01	1567	118.2	1.548	9.646	0.0261	6.231
IAEA-4787/4	9.36	MRC-95	90-02-27	1513	106.2	1.723	9.646	0.0261	5.598
IAEA-4887/5	9.78	MRC-95	90-08-06	1587	117.4	1.559	9.646	0.00261	6.187
IAEA-4887/7	10.1	MRC-95	89-03-22	1554	119.0	1.538	9.646	0.0261	6.272
IAEA-4887/8	10.0	MRC-95	90-01-10	1598	121.4	1.507	9.646	0.0261	6.399
IAEA-4887/Spare	9.82	MRC-95	89-03-28	1583	120.5	1.519	9.646	0.0261	6.350
IAEA-88-049-08	10.0	MRC-95	90-01-12	1598	121.4	1.507	9.646	0.0261	6.401
IAEA-88-049-09	9.33	MRC-95	90-02-20	1564	107.2	1.707	9.646	0.0261	5.651
IAEA-PWR/3 (UNCL-II)	12.6	MRC-95	90-02-28	2314	176.5	1.037	9.646	0.0261	9.302
IAEA-PWR/4 (UNCL-II)	12.6	MRC-95	90-03-06	2303	178.0	1.028	9.646	0.0261	9.383
EUR (PWR-5)	--	MRC-95	89-10-30	1565	127.7	1.433	9.646	0.0261	6.731
EUR (JOMAR 1988)	10.3	MRC-95	88-01-09	1590	126.0	1.452	9.646	0.0261	6.643

2. **Cross-Reference Factors—Cd Mode.** If the Cd-mode calibration curves are used, then the cross-reference factors are

$$k_2 = \frac{R_0\text{ (reference UNCL)}}{R_0\text{ (XX)}} \quad .$$

3. **Cross-Reference Factor Transposition into the Calibration Coefficient.** In the k factor the cross-reference factor k_2 is the primary, detector-specific calibration term. The current IAEA software is set up to store the detector calibration factors in the calibration coefficient file. Thus, to accommodate the existing software structure we can transpose the k_2 factor out of k and into a in the calibration equation given above.

By dividing both sides of the equation by k_2 we define

$$K \equiv k/k_2 \ ,$$
$$A \equiv a/k_2 \ ,$$

and the transformed calibration equation is

$$KR = \frac{AM}{1 + bM} \quad .$$

Table XIII. BWR Calibration Cross-Reference Data for UNCL (AMPTEK Upgrades) and UNCL-II—No Cd Mode

Collar Unit	Passive ^{252}Cf ε (%)	AmLi Source	T_0 Date (y/m/d)	T_0 (empty) MRC-XX (s^{-1})	R_0 (XX)[a] (s^{-1})	k_2 $\frac{R_0 (LANL\text{-}4)}{R_0 (XX)}$	[453 g U/cm] a	b	A (a/k_2)
LANL-4 (ref.)	15.4	MRC-95	89-10-17	2717	180.8	1.000	24.91	0.0680	24.91
LANL-1	13.5	MRC-95	TBD	TBD	TBD	TBD	24.91	0.0680	TBD
IAEA-4887/1	13.3	MRC-95	89-03-28	1900	102.7	1.760	24.91	0.0680	14.15
IAEA-4887/3	13.5	MRC-95	88-09-10	1880	TBD	TBD	24.91	0.0680	TBD
IAEA-4887/4	12.4	MRC-95	90-02-27	1844	93.12	1.942	24.91	0.0680	12.83
IAEA-4887/5	13.2	MRC-95	90-08-08	1937	104.5	1.730	24.91	0.0680	14.40
IAEA-4887/7	13.4	MRC-95	89-03-27	1871	105.1	1.720	24.91	0.0680	14.48
IAEA-4887/8	13.3	MRC-95	90-01-10	1941	106.8	1.693	24.91	0.0680	14.71
IAEA-4887/Spare	13.4	MRC-95	89-03-28	1913	103.7	1.743	24.91	0.0680	14.29
IAEA-88-049-08	13.3	MRC-95	90-01-12	1940	106.8	1.693	24.91	0.0680	14.71
IAEA-88-049-09	12.4	MRC-95	90-02-20	1939	93.14	1.941	24.91	0.0680	12.83
IAEA-BWR/1 (UNCL-II)	15.4	MRC-95	90-02-21	2693	180.9	1.000	24.91	0.0680	24.91
IAEA-BWR/2 (UNCL-II)	15.4	MRC-95	90-02-22	2684	180.5	1.002	24.91	0.0680	24.86
EUR (BWR-3)	--	MRC-95	89-10-30	1959	110.7	1.632	24.91	0.0680	15.26
EUR (BWR-5)	--	MRC-95	89-10-30	1920	110.2	1.641	24.91	0.0580	15.81

[a] The net reals rate corresponds to the 9 x 9 BWR assembly at LANL with 76 rods and 14.4 g ^{235}U/cm.

In Tables XII, XIII, XIV, and XV, the calibration coefficient is replaced by a/k_2 and

$$K = \frac{b}{k_2} = k_0 \cdot k_1 \cdot k_3 \cdot k_4 \cdot k_5 \quad .$$

It is still necessary to use the information in the cross-reference tables to establish the calibration reference values, T_0, for the reference AmLi source and the dates for determining source decay. These factors are listed in Table XII for PWR assemblies and Table XIII for BWR assemblies.

D. k_3—Burnable Poisons

The corrections k_0, k_1, and k_2 are the same for both PWR and BWR assemblies. However, the correction k_3 for burnable poisons is different for PWR and BWR because of the full assembly size differences.

Table XIV. PWR Calibration Cross-Reference Data for UNCL (AMPTEK Upgrades) and UNCL-II—Cd Mode

Collar Unit	AmLi Source	T_0 Date (y/m/d)	T_0 (empty)[a] MRC-XX (s^{-1})	R_0 (XX) (s^{-1})	k_2 $\frac{R_0\ (LANL\text{-}3)}{R_0\ (XX)}$	[1215 g U/cm] a	b	A (a/k_2)
LANL-3 (ref.)	MRC-95	89-10-17	2095	13.17	1.000	0.4373	0.00671	0.4373
LANL-1	MRC-95	89-02-26	1591	8.07	1.632	0.4373	0.00671	0.2680
IAEA-4887/1	MRC-95	89-03-20	1566	7.82	1.684	0.4373	0.00671	0.2597
IAEA-4887/3	MRC-95	88-09-06	1567	7.70	1.710	0.4373	0.00671	0.2557
IAEA-4787/4	MRC-95	90-02-27	1513	6.97	1.889	0.4373	0.00671	0.2315
IAEA-4887/5	MRC-95	90-08-08	1587	7.80	1.688	0.4373	0.00671	0.2591
IAEA-4887/7	MRC-95	89-03-22	1554	7.68	1.715	0.4373	0.00671	0.2550
IAEA-4887/8	MRC-95	90-01-10	1598	7.82	1.684	0.4373	0.00671	0.2597
IAEA-4887/Spare	MRC-95	89-03-28	1583	7.83	1.682	0.4373	0.00671	0.2600
IAEA-88-049-08	MRC-95	90-01-12	1598	7.82	1.684	0.4373	0.00671	0.2597
IAEA-88-049-09	MRC-95	90-02-20	1564	7.09	1.858	0.4373	0.00671	0.2354
IAEA-PWR/3 (UNCL-II)	MRC-95	90-02-28	2314	13.46	0.978	0.4373	0.00671	0.4471
IAEA-PWR/4 (UNCL-II)	MRC-95	90-03-06	2303	13.78	0.956	0.4373	0.00671	0.4574
EUR (PWR-5)	MRC-95	89-10-30	1565	9.37	1.406	0.4373	0.00671	0.311

[a]The measured totals rate corresponds to no Cd liners.

1. PWR Gd_2O_3 Correction—No Cd. A series of measurements were performed where different numbers of poison rods (see Table V) were added to the LANL PWR assembly. The positions of the poison rods represented typical PWR assemblies.[4]

Figure 9 shows the measured response as a function of the number of BP rods. The top curve in Fig. 9 shows the corrected response using the empirical correction formula

$$k_3 = \frac{\text{Response change in assay assembly from BP rods}}{\text{Response change in standard assembly from BP rods}} .$$

However, the standard assembly used for calibration has no BP rods so the denominator is unity.

In previous reports,[3,4] we used a correction algorithm of the form

$$k_3 = \frac{1 + n\left(\frac{204}{N}\right)(corr./rod)}{1.00} ,$$

Table XV. **BWR Calibration Cross-Reference Data for UNCL (AMPTEK Upgrades) and UNCL-II—Cd Mode**

Collar Unit	AmLi Source	T_0 Date (y/m/d)	T_0 (empty)[a] MRC-XX (s^{-1})	R_0 (XX)[b] (s^{-1})	k_2 $\frac{R_0\,(LANL\text{-}4)}{R_0\,(XX)}$	[453 g U/cm] a	b	A (a/k_2)
LANL-4 (ref.)	MRC-95	89-10-17	2717	9.85	1.000	0.7582	0.00705	0.7582
IAEA-4887/1	MRC-95	89-03-28	1900	5.70	1.728	0.7582	0.00705	0.4388
IAEA-4887/3	MRC-95	88-09-10	1880	TBD	TBD	0.7582	0.00705	TBD
IAEA-4887/4	MRC-95	90-02-27	1844	5.09	1.935	0.7582	0.00705	0.3918
IAEA-4887/5	MRC-95	90-08-08	1937	5.38	1.831	0.7582	0.00705	0.4141
IAEA-4887/7	MRC-95	89-03-27	1871	5.75	1.713	0.7582	0.00705	0.4426
IAEA-4887/8	MRC-95	90-01-10	1941	5.57	1.768	0.7582	0.00705	0.4288
IAEA-4887/Spare	MRC-95	89-03-28	1913	5.69	1.731	0.7582	0.00705	0.4380
IAEA-88-049-08	MRC-95	90-01-12	1940	5.57	1.768	0.7582	0.00705	0.4288
IAEA-88-049-09	MRC-95	90-02-20	1939	5.00	1.970	0.7582	0.00705	0.3849
IAEA-BWR/1 (UNCL-II)	MRC-95	90-02-21	2693	9.96	0.989	0.7582	0.00705	0.7667
IAEA-BWR/2 (UNCL-II)	MRC-95	90-02-22	2684	9.88	0.997	0.7582	0.00705	0.7605
EUR (BWR-3)	MRC-95	89-10-30	1959	6.39	1.541	0.7582	0.00705	0.492

[a]The totals rate corresponds to no Cd liners.
[b]The net reals rate corresponds to the 9 x 9 BWR assembly at LANL with 76 rods and 14.4 g ^{235}U/cm.

where n is the number of BP rods and N is the total number of fuel rods (including the gadolinium rods) in the assembly. Our standard assembly for calibration contained 204 fuel rods and no BP rods.

This equation is based on the assumption that the BP rods do not interact with each other (shadow shielding) and that the fractional neutron absorption in the BP rods is independent of the average uranium enrichment. The first assumption is valid for $n \leq 12$ for BWR assemblies (76 rods) and $n \leq 20$ for PWR assemblies; however, the second assumption is not true for a wide range of enrichments.

Careful measurements[11] with our BP rods and our standard assemblies have demonstrated that the correction for BP rods is a function of the average enrichment in the assembly. As the enrichment increases, there are fewer thermal neutrons in the interrogation flux and the effect of the BP rods is decreased. We measured the BP correction at three different enrichments (3.19%, 2.26%, and 1.36%) and derived a linear empirical correction of the form,

$$\delta = (2.27 - 0.40\, E_n) \quad ,$$

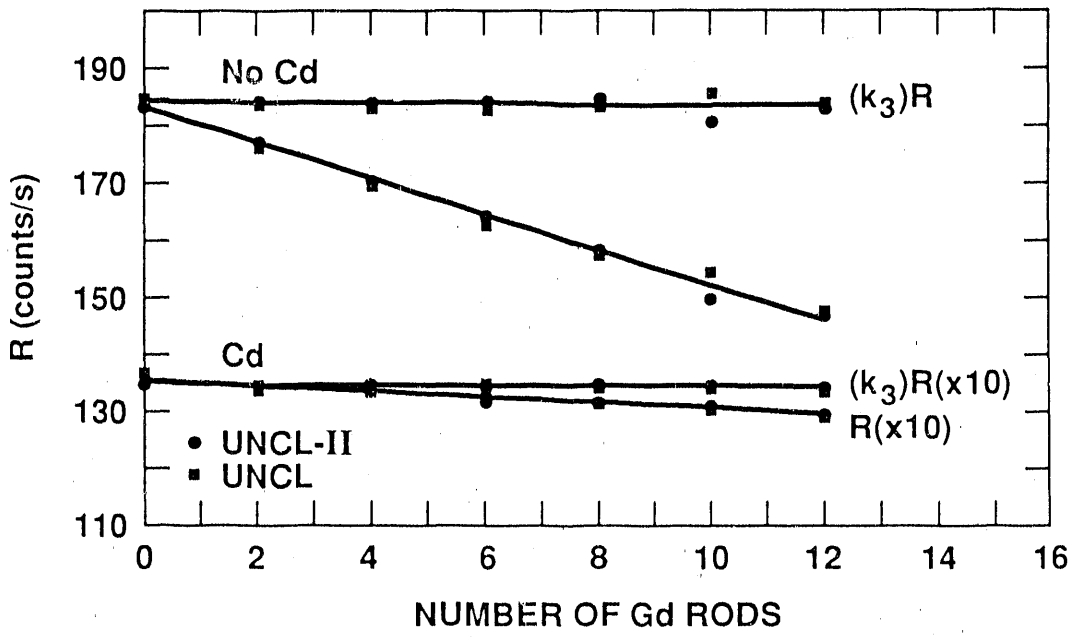

Fig. 9. Reals rate (PWR) as a function of the number of poison rods before correction and after the k_3 correction. The Cd-mode data have been multiplied by 10 to show the data on the same scale as the no-Cd-mode data.

where E_n is the average ^{235}U enrichment (percent) in the fuel assembly. The declared value of E_n can be used for the correction. If the measured fuel loading differs significantly from the declared enrichment, then we can repeat the enrichment correction based on the measured E_n in an iterative procedure.

Our full BP rod correction is

$$k_3 = 1 + n\left(\frac{204}{N}\right)(corr./rod)\delta \ .$$

Our correction per rod is based on previous measurements[4] and MCNP computer calculations.[10] For PWR assemblies (no Cd), we estimate

$$(corr./rod) = (1 - e^{-0.647\ Gd})\ 0.0213 \ ,$$

where Gd is the weight percent of gadolinium in the poison rods.

Thus the PWR (no Cd) correction is

$$k_3 = 1 + n\left(\frac{204}{N}\right)(0.0213)\left(1 - e^{-0.647\ Gd}\right)\delta \ .$$

or

$$k_3 = 1 + \frac{n\,(9.86)}{N}\,(1 - e^{-0.647\,Gd})\ (1 - 0.176\,E_n)\ .$$

The declared value of n (number of gadolinium rods) can be verified by the Cd-ratio measurement (see Section X).

The top curves in Fig. 9 show the measured values of R vs BP rods before and after the $k_3 R$ correction.

2. PWR Gd_2O_3 Correction—Cd. If the Cd liners are in place, the perturbation from the BP rods is much smaller. MCNP calculations[10] and measurements[11] have shown that R decreases by ~0.3% per Gd_2O_3 rod for our 15 x 15 reference assembly.

The correction term is given again by

$$k_3\,(Cd) = 1 + n\left(\frac{204}{N}\right)(corr./rod)$$

where the

$$(corr./rod) = 0.00295\,(1 - e^{-0.647\,Gd})\ .$$

Thus,

$$k_3\,(Cd) = 1 + \frac{n}{N}\,(0.602)\,(1 - e^{-0.647\,Gd})\ .$$

The correction coefficient of 0.00295 for the Cd mode is about an order of magnitude smaller than the value of 0.0213 corresponding to the no-Cd case (see Section IX.D.1).

There is no enrichment effect (δ = 1.00) for the Cd-mode case because the Cd removes the thermal neutrons from the interrogation, and thus the ^{235}U enrichment has a negligible effect on the poison rod perturbation.

The bottom curves in Fig. 9 show the measured values of R vs BP rods before and after the $k_3 R$ correction. The R values have been increased by 10 to place them on the same graphical scale as the no-Cd data.

3. BWR Gd_2O_3 Correction—No Cd. The correction per BP rod for BWR assemblies is higher than the corresponding correction for PWR assemblies because a higher fraction of the induced fissions are from thermal neutrons for the BWR case. The correction factor is

$$k_3\,(\text{no Cd}) = 1 + n\left(\frac{76}{N}\right)(corr./rod)\,\delta\ ,$$

where

$$\delta = (1.92 - 0.29\,E_n)$$

$$(corr./rod) = 0.0572\,(1 - e^{-0.647\,Gd})\ .$$

Thus,

$$k_3 = 1 + \frac{n}{N}(8.35)(1 - e^{-0.647\,Gd})(1 - 0.151\,E_n) \ .$$

Figure 10 (top curves) shows the reals as a function of gadolinium loading before and after the BP rod correction (k_3).

4. BWR Gd_2O_3 Correction—Cd. The BWR correction with Cd liners is about an order of magnitude smaller than the no-Cd case. The correction is

$$k_3\,(\mathrm{Cd}) = 1 + n\left(\frac{76}{N}\right)(corr./rod) \ ,$$

where

$$(corr./rod) = 0.00661\,(1 - e^{-0.647\,Gd}) \text{ and}$$

$$k_3\,(\mathrm{Cd}) = 1 + \frac{n}{N}(0.502)(1 - e^{-0.647\,Gd}) \ .$$

As in the PWR case, there is a negligible enrichment effect (δ = 1.00) for the BWR Cd-mode interrogation.

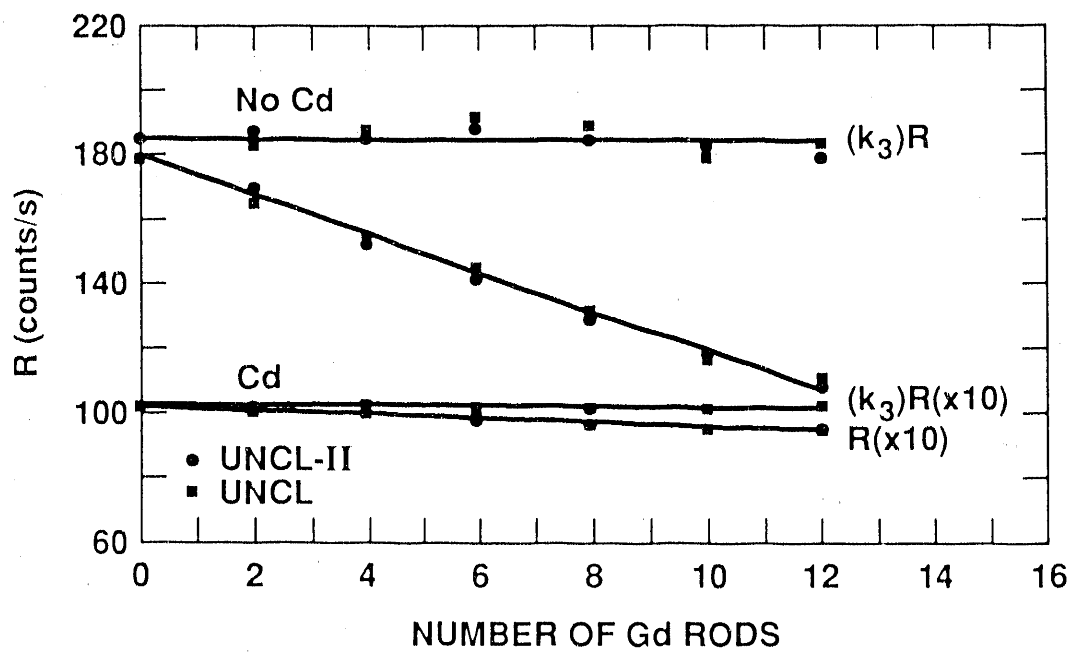

Fig. 10. Reals rate (BWR) as a function of the number of poison rods before correction and after the k_3 correction. The scale for the Cd-mode data has been changed by a factor of 10 so that the Cd and no-Cd data can be presented on the same scale.

The bottom curves in Fig. 10 show the measured values of R (x 10) vs BP rods before and after the $k_3 R$ correction.

E. k_4—Uranium Mass Correction

1. PWR Assemblies. For some PWR assemblies the uranium mass per unit length is very different from the calibration condition of 1215 g U/cm. In particular, smaller PWR assemblies have loadings as small as ~900 g U/cm, thus lessening fast-neutron multiplication, neutron scattering, and end reflection from the extended fuel column. These reductions decrease the observed response.

MCNP calculations[10] and experiments[11] were performed to establish a correction for the differences in the uranium loading between the standard and the unknowns.

The correction for PWR assemblies is

$$k_4 = 1 + 3.89 \times 10^{-4} (1215 - U) \ ,$$

where 1215 g U/cm is the loading of our calibration assembly and U is the g U/cm of the unknown assembly.

This k_4 correction is the same for both the no-Cd mode and the Cd-mode interrogations.

2. BWR Assemblies. Our experience has shown that usually the k_4 mass correction is not needed for BWR assemblies because the content of the current production loadings is similar (450-485 g U/cm).

Our calibration reference assembly was 453 g U/cm, and if the unknown assemblies are significantly different, the correction for BWR is

$$k_4 = 1 + 7.24 \times 10^{-4} (453 - U) \ .$$

For the normal range of BWR fuel loadings (450-485 g U/cm), this correction is only 1%-2%.

The same k_4 correction is used for both the no-Cd and Cd cases.

F. k_5—Other Sample Corrections

In some cases, there might be other sample factors that perturb the response, and when these are known, they can be included in the k_5 term. Examples of these factors are cardboard liners and plastic protective bags covering the assembly and stainless steel structural tubes in the assembly.

Many fuel assemblies are covered by plastic bags or cardboard for protection. Measurements both with and without the plastic bags have shown R is changed only a small amount in the no-Cd mode and R is increased by a few percent in the Cd mode.

Measurements were performed to establish the k_5 factors for PWR assemblies both with and without Cd liners. The results are summarized in Table XVI for typical protective covers.

If a plant fuel assembly is certified as a reference assembly by pellet sampling at the time of fabrication, then the k factor can be used to adjust the measured R to fit the calibration curve exactly.

Table XVI. Coincidence Count Perturbations from Fuel Assembly Protective Bagging and Cardboard

	k_5 Factor	
UNCL Configuration	Plastic Bag	Cardboard Liner
PWR—no Cd	0.997	0.990
PWR—Cd	0.985	0.921
BWR—no Cd	0.996	0.986
BWR—Cd	0.971	0.877

That is,

$$kR = \frac{aM}{1 + bM}$$

defines k when a, b, R, and M are known. This assumes that all of the unknown assemblies are similar to the certified reference assembly. If at a later time the operator changes the number of BP rods, then the k_3 correction can be applied to the k obtained from the plant's reference assembly. Under these ideal calibration conditions, the assay accuracy is improved by a factor of ~2.

X. CADMIUM RATIO METHOD

There are two ways to use the Cd liners. One is to obtain a Cd-calibration curve that is almost independent of the Gd_2O_3 loadings. This approach does not require the no-Cd measurement if a small correction (~3%) is made based on the operator's declared poison loading.

The second approach is to measure the **Cd ratio** and use it to check the declared Gd_2O_3 loading. This approach has the advantage that the detector efficiency and AmLi source strength cancel out in the Cd-ratio measurement.

Both approaches require long measurement times for the Cd cases.

Because of thermal-neutron absorption in the Gd_2O_3 rods, the ratio $R_{Cd}/R_{no\ Cd}$ will increase as the number of BP rods increases. Similarly, the ratio $T_{Cd}/T_{no\ Cd}$ where T is the net totals rate will increase with an increase in the number of BP rods. The fractional perturbation in R (or T) from the addition of a poison rod will depend on the number of rods in an assembly (N).

A. Experimental Procedure

The poison rod Cd-ratio measurements were performed using the LANL-prototype UNCL and the UNCL-II with source MRC-95.

The Gd_2O_3 rods (see Table V) were inserted into the PWR and BWR fuel assembly arrays. The BP rod locations were typically two rows in from the perimeter to be similar to commercial fuel assemblies.[4]

For each BP rod loading configuration,[11] measurements were made both with and without the Cd liners. Long measurement intervals (many hours) were used to obtain good counting precision.

B. Poison Rod Results

The BP rod measurements can be analyzed using the net reals or net totals. The totals give better counting precision but the accuracy is degraded by background uncertainties and a smaller net signature. Table XVII gives the net T and R results as a function of BP rods for the PWR assembly. The totals background rate was determined by measuring an assembly with all DU rods and subtracting the small induced fission component based on the residual ^{235}U.

Figure 11 shows the normalized Cd ratios for both the reals (R_{Cd}/R_{noCd}) and totals (T_{Cd}/T_{noCd}) for BWR and PWR fuel assemblies. The ratios are normalized to the no-BP case so that the slopes can be compared. We see that R ratios have a greater slope than the T ratios. The scatter in the data for the T ratios is higher than the R ratios in spite of the better precision on the T ratios.

Similar BP rod results for BWR assemblies are given in Table XVIII. Figure 12 shows the interesting result that the normalized R ratios have about the same slope for both PWR and BWR assemblies for this special case of a constant gadolinium loading (5.2%) in each rod for which the gadolinium content is expressed as weight percent.

Table XVII. PWR Cd Ratio for Reals and Totals

BP Rods	T_{net}[a] no Cd	T_{net}[a] Cd	$T_{Cd}/T_{no\ Cd}$	R_{net} no Cd	R_{net} Cd	$R_{Cd}/R_{no\ Cd}$
0	1819	671.1	0.369	112.0	8.31	0.0742
2	1777	681.9	0.384	106.5	8.14	0.0764
4	1745	676.4	0.388	102.3	8.10	0.0792
6	1704	696.6	0.409	98.3	8.06	0.0820
8	1679	670.0	0.399	95.2	7.98	0.0838
10	1666	673.7	0.404	93.3	7.93	0.0850
12	1627	672.2	0.413	89.2	7.86	0.0881

[a]Data obtained using LANL-Prototype UNCL and MRC-95.

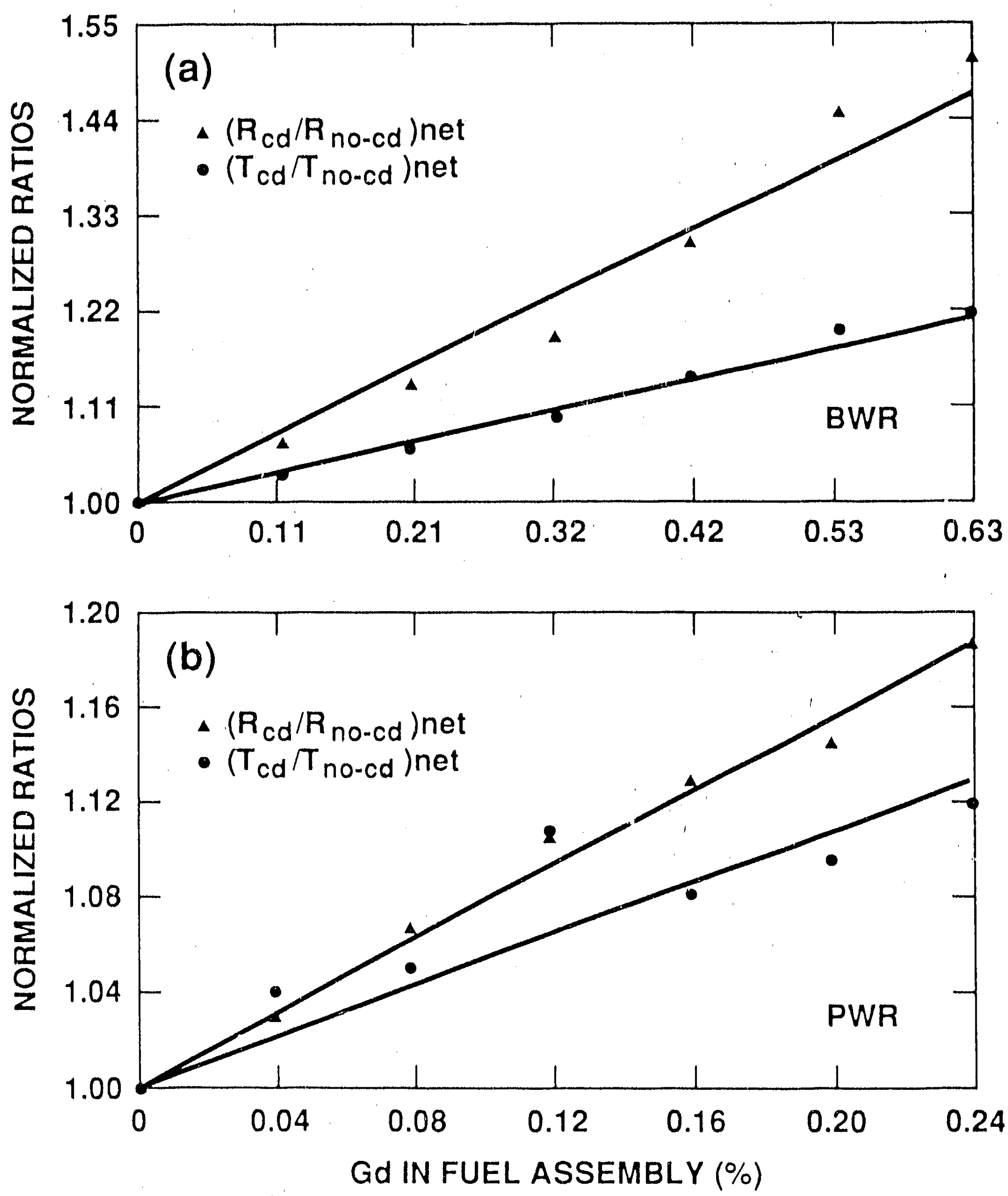

Fig. 11. Normalized Cd ratios for both R and T as a function of the gadolinium loading. The top curve corresponds to BWR assemblies and the bottom curve is for PWR assemblies.

Table XVIII. BWR Cd Ratio for Reals and Totals

BP Rods	T_{net}[a] no Cd	T_{net}[a] Cd	$\frac{T_{Cd}}{T_{no\ Cd}}$	R_{net} no Cd	R_{net} Cd	$\frac{R_{Cd}}{R_{no\ Cd}}$
0	2180	929	0.426	97.6	5.79	0.0593
2	2105	928	0.440	90.4	5.73	0.0634
4	2036	927	0.453	84.4	5.69	0.0674
6	1981	917	0.468	79.3	5.60	0.0706
8	1898	925	0.488	71.9	5.53	0.0769
10	1807	924	0.511	63.5	5.46	0.0860
12	1771	920	0.519	60.5	5.40	0.0893

[a]Data obtained using LANL-Prototype UNCL and MRC-95.

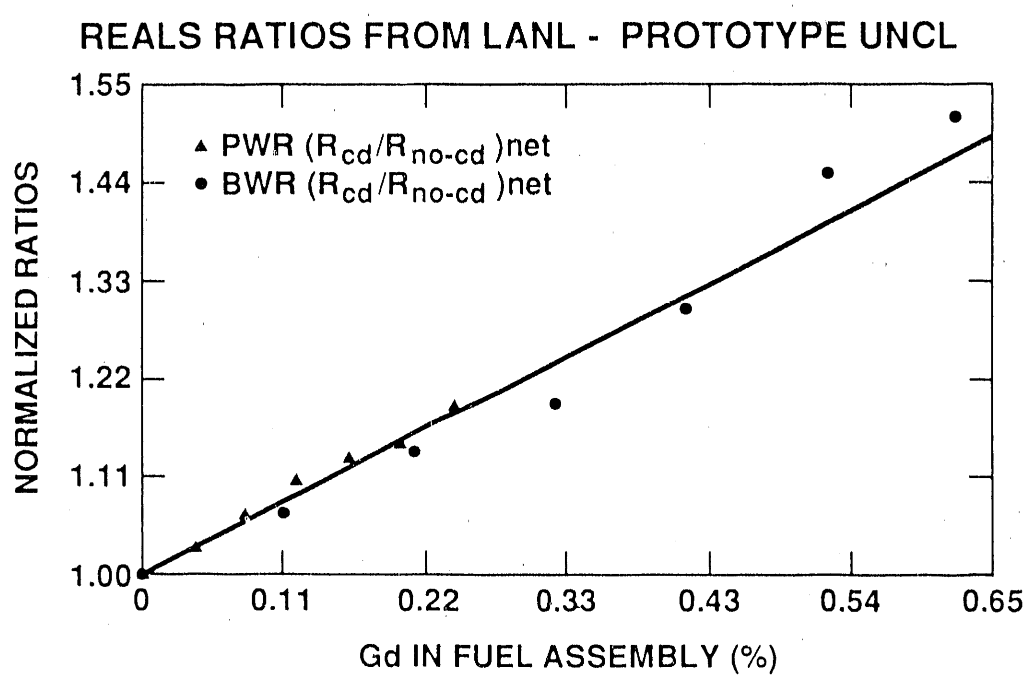

Fig. 12. Superposition of the normalized reals Cd ratio for both BWR and PWR as a function of percent gadolinium in fuel for the special case of 5.2% gadolinium rods

Because of the background uncertainties in measuring the *T* ratios, we will base our future work on the *R* ratios.

The results presented in Figs. 9-12 are based on 204-rod (PWR) and 76-rod (BWR) fuel assemblies in which each BP rod contained 5.2% gadolinium by weight. If the individual BP rods contain a different gadolinium weight percent, then the horizontal axis in Figs. 9-12 must be adjusted by the ratio

$$\frac{\left[1 - e^{-(0.647)(Gd)}\right]}{\left[1 - e^{-(0.647)\,(5.2)}\right]} ;$$

Gd is the average weight percent of gadolinium in the BP rods.

The reason for the above self-shielding ratio correction is that the gadolinium in a single rod is loaded to near the saturation level for thermal-neutron absorption. Thus, rods loaded with, for example, 5.2% gadolinium will have almost the same effect on the measurement as rods loaded with 6.2% gadolinium. However, a gram of gadolinium in a lightly loaded BP rod will have more effect than a gram in our 5.2% gadolinium calibration rods.

For example, if the rods contain only 2% gadolinium by weight, then

$$\frac{\left[1 - e^{-0.647\,(2.0)}\right]}{\left[1 - e^{-0.647\,(5.2)}\right]} = \frac{0.726}{0.965} = 0.752 .$$

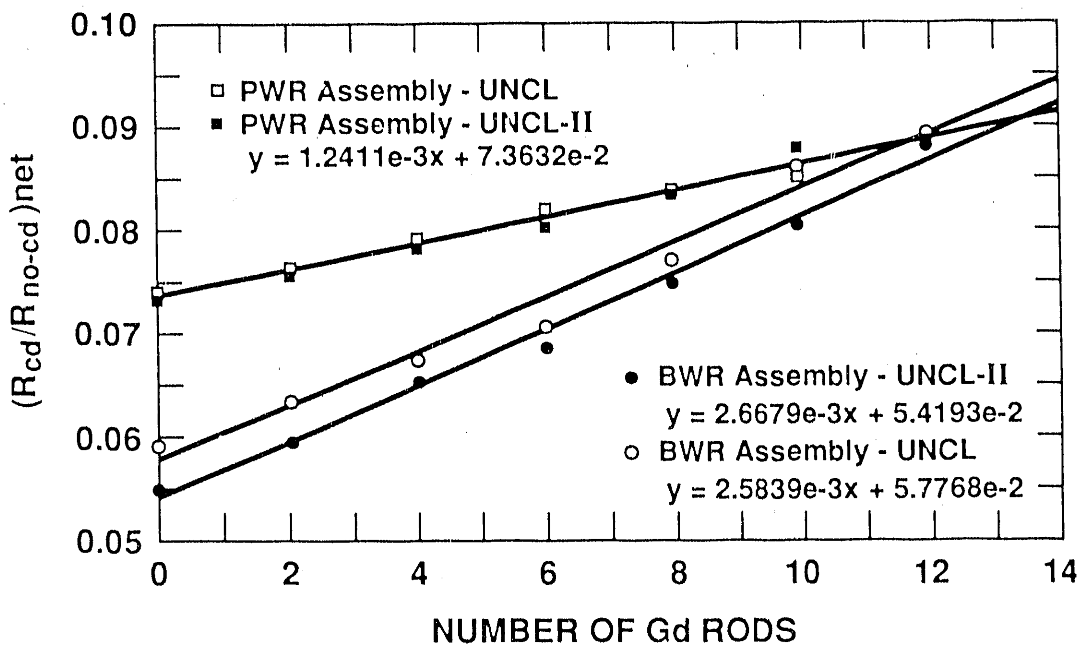

Fig. 13. The Cd ratios as a function of the number of poison rods for both UNCL and UNCL-II (PWR top and BWR bottom).

Thus, if our measured $R_{Cd}/R_{no\ Cd}$ was used to get the gadolinium weight percent from Figs. 11 and 12 or the number of BP rods from Fig. 13, we would have to divide the value from our calibration curves by 0.752 to obtain the true number of BP rods for the unknown assembly.

Figure 13 shows the measured Cd ratios for both the UNCL and UNCL-II model collars. We see that the old and new collars give the same Cd-ratio calibration for PWR assemblies; however, for BWR assemblies the old and new Cd-ratio curves are offset by ~6%. This offset is caused by differences in the sample cavities of the old (Mod-I) and new (Mod-II) BWR units that affect the average interrogation flux spectra. The Mod-II BWR collars have the CH_2 back walls more closely coupled to the fuel assembly. This results in a higher thermal-neutron albedo for the Mod-II units, and thus the thermal/fast neutron ratio is increased for the Mod-II units. The measured $R_{Cd}/R_{no\ Cd}$ ratio is decreased as the thermal/fast neutron ratio increases resulting in the curve offset shown in Fig. 13.

C. Poison Rod Example Calculation

As an example of the use of Fig. 13 to verify the declared number of BP rods, we will assume the following BWR data:

$$y = \frac{R_{Cd}}{R_{no\ Cd}} \text{ (measured)} = 0.075, \quad \text{(Mod-II UNCL)}$$

$$n \text{ (Ref. condition)} = (y - 0.0542)/2.668 \times 10^{-3} = 7.79 \text{ rods} \quad \text{(from Fig. 13)}$$

$$n \text{ (new assembly)} = 7.79 \left(\frac{N}{76}\right) \left[\frac{1-e^{-0.647(5.2)}}{1-e^{-0.647(Gd)}}\right] ,$$

where,

N = 64 rod BWR new assembly,
Gd = 4.5 wt.% (new assembly), and
E_n = 3.4% ^{235}U .

The number of BP rods is

$$n = 7.79 \left(\frac{64}{76}\right)\left(\frac{0.965}{0.945}\right) = 6.7 .$$

For the general case

$$n = \left[(y - 0.0542)/2.668 \times 10^{-3}\right]\left(\frac{N}{76}\right) \left[\frac{1 - e^{-0.647\ (5.2)}}{1 - e^{-0.647\ (Gd)}}\right] .$$

The BP correction factor for the no Cd mode is

$$k_3 = 1 + n\left(\frac{76}{N}\right) 0.0572 \left(1 - e^{-0.647\ Gd}\right) \delta ,$$

$$\delta = 1.92 - 0.29\ E_n = 0.934 ,$$

$$k_3 = 1 + 6.7\left(\frac{76}{64}\right)(0.0572)\ (0.934)\ \text{, and}$$

$$k_3 = 1.402\ .$$

The Cd-ratio measurement gives us the effective number of 4.5 wt% gadolinium rods that is the appropriate value to use for n in the k_3 equation. This measured effective n does not have to be an integer.

D. Direct Measurement of k_3 from the Cd Ratio—BWR

As an alternative to the above example in which we determined an effective n to use in the k_3 equation, we can use the Cd ratio ($y = R_{Cd}/R_{no\ Cd}$) to directly solve for k_3 using a linear fit to our BP rods vs Cd-ratio data shown in Fig. 13.

The linear fits in Fig. 13 give

$y = 0.00124\ n + 0.0736$ (PWR Mod I and Mod II),
$y = 0.00258\ n + 0.0578$ (BWR Mod I), and
$y = 0.00267\ n + 0.0542$ (BWR Mod II),

where y is the measured Cd ratio and n is the number of BP rods for the LANL reference specifications (76 rods and 5.2% Gd).

1. **PWR Case.** Our k_3 correction equation (PWR) is

$$k_3 = 1 + n\left(\frac{204}{N}\right)(0.0213)\left(1 - e^{-0.647\ Gd}\right)\delta\ ,$$

however,

$$n = [(y - 0.0736)/0.00124)]\ \ \text{(ref. rods)}\ ,$$

and

$$n = [(y - 0.0736)/0.00124]\left(\frac{N}{204}\right)\left[\frac{1 - e^{-0.647\ (5.2)}}{1 - e^{-0.647\ (Gd)}}\right]$$

for the general case.

After substituting n into the k_3 equation, the terms involving N and Gd cancel and we are left with

$$k_3 = 1 + C\ (y - 0.0736)\ \delta\ ,$$

where

$$C = \frac{0.0213\left[1 - e^{-0.647\ (5.2)}\right]}{0.00124}\ ,$$

$$C = 16.58 \text{ and}$$

$$\delta = 2.27 - 0.40\, E_n \; .$$

Thus, $k_3 = 1 + 16.58\,(y - 0.0736)\,(2.27 - 0.40\, E_n) = 1 + 37.64\,(y - 0.0736)\,(1 - 0.176\, E_n)$.

This gives the favorable result that if the Cd-ratio measurement is made, the k_3 correction for poison rods can be made without any information about the number of rods in the assembly, the number of BP rods, or their gadolinium loadings.

2. **BWR Case.** Similar to the PWR case, we can simplify the k_3 equation; however, the older Mod I UNCLs and the new UNCL-IIs have separate Cd-ratio calibrations as shown in Fig. 13.

For **Mod-I** BWRs,

$$k_3 = 1 + C_1(y - 0.0578)\,\delta \; ,$$

$$C_1 = \frac{0.0572\left[1 - e^{-0.647\,(5.2)}\right]}{0.00258} = 21.40, \text{ and}$$

$$\delta = 1.92 - 0.29\, E_n \; .$$

Thus,

$$k_3 = 1 + 21.40\,(y - 0.0578)\,(1.92 - 0.29\, E_n) = 1 + 41.09\,(y - 0.0578)\,(1 - 0.151\, E_n) \; .$$

For **Mod-II** BWRs,

$$k_3 = 1 + C_2\,(y - 0.0542)\,\delta \; ,$$

$$C_2 = \frac{0.0572\left[1 - e^{0.647\,(5.2)}\right]}{0.00267} = 20.68, \text{ and}$$

$$\delta = 1.92 - 0.29\, E_n \; .$$

Thus,

$$k_3 = 1 + 20.68\,(y - 0.0542)\,(1.92 - 0.29\, E_n) = 1 + 39.71\,(y - 0.0542)\,(1 - 0.151\, E_n) \; .$$

3. **Poison Rod Example Calculation.** For the same BWR (Mod-II UNCL) example given in Section X.C, we have $N = 64$, $E_n = 3.4\%$, $Gd = 4.5\%$, and $y = 0.075$. Using only the measured y value, we can calculate

$$k_3 = 1 + C_2\,(y - 0.0542)\,\delta \; ,$$

$$C_2 = 20.68 \; , \text{ and}$$

$$\delta = 1.92 - 0.29\, E_n = 0.934 \; .$$

Thus,

$$k_3 = 1 + 20.68\ (0.075 - 0.0542)\ (0.934) = 1.402\ .$$

This is the same as the result from the k_3 equation, but we did not have to input the values of N and Gd because these parameters cancel in the Cd-ratio method.

XI. URANIUM-238 CALIBRATION—PASSIVE MODE

The passive fuel assembly background measurement can be used to calculate the g ^{238}U/cm, independent of the operator's declaration. Also, the passive reals rate, after background corrections, gives a check on the consistency of the ^{238}U/cm for a group of fuel assemblies.

After correcting for multiplication in the ^{235}U, the net passive reals rate can give a quantitative value for the g ^{238}U/cm or the total mass after multiplication by the length.

Table XIX presents the passive reals rates for the various collars that were included in the cross-reference measurements.

A. Correction for Room-Background-Induced Fissions

The net coincidence rate, R(net), corresponds to the measured value corrected for induced fissions from the room-background neutrons. This correction is obtained from an empirical relationship as follows:

$$R(corr.) = R(meas.) - 0.014(T - 120), \quad \text{(for PWR)}\ ,$$

where T is the measured totals rate, 120 s^{-1} is the background rate (UNCL LANL-1) from a typical PWR fuel assembly, and 0.014 is an empirical constant.

A similar relationship for BWR assemblies is

$$R(corr.) = R(meas.) - 0.014(T - 45), \quad \text{(for BWR)}\ .$$

The passive totals rate from spontaneous fission is proportional to the g ^{238}U/cm, and a more accurate value than the above approximations can be obtained from

$$T(PWR\ assembly\ bkg) = 0.107 \times (g\ ^{238}U/cm)\ ,$$

and

$$T(BWR\ assembly\ bkg) = 0.101 \times (g\ ^{238}U/cm)\ ,$$

for a Mod-I type collar.

These totals background rates (UNCL) are 120 counts/s and 45 counts/s for typical PWR and BWR loadings of 1120 and 446 g ^{238}U/cm, respectively. Because this correction is small, we will use the nominal values of T.

Table XIX. Passive Reals Rates for LANL PWR and BWR Reference Assemblies (no Cd liners)

Collar	Mod	PWR R(pass.) (s^{-1})	BWR R(pass.) (s^{-1})	PWR[a] r	BWR[a] r
LANL-1	I	10.02	3.12	1.000	1.00
LANL-3	II	14.83	NA	0.676	NA
LANL-4	II	NA	4.99	NA	0.625
IAEA-BWR/1	II	NA	4.98	NA	0.627
IAEA-BWR/2	II	NA	4.95	NA	0.630
IAEA-PWR/3	II	14.66	NA	0.684	NA
IAEA-PWR/4	II	14.56	NA	0.688	NA
IAEA-4887/1	I	9.80	2.97	1.022	1.050
IAEA-4887/4	I	9.07	2.89	1.105	1.080
IAEA-4887/5	I	9.67	3.09	1.036	1.010
IAEA-4887/7	I	10.00	3.14	1.002	0.994
IAEA-4887/8	I	9.79	3.12	1.024	1.000
IAEA-4887/Spare	I	10.03	3.11	0.999	1.003
IAEA-88-049-08	I	9.79	3.12	1.020	1.000
IAEA-88-049-09	I	9.07	2.97	1.105	1.057
EUR (BWR/PWR-5)	I	10.44	3.20	0.960	0.975
EUR (BWR/PWR-5)	I	10.26	3.20	0.977	0.975
EUR (JOMAR 1988)	I	10.10	--	0.992	--

[a] r is the ratio of R (LANL-1)/R (XX).

B. Correction for ^{235}U Fissions—Passive Mode

The passive coincidence rate increases as the enrichment increases because of neutron multiplication in the ^{235}U. An example of the enrichment effect on the passive reals rate is shown in Fig. 14 where the top curve corresponds to the LANL BWR assembly and the bottom curve corresponds to the LANL PWR assembly. The UNCL-IIs (LANL-3 and LANL-4) were used to collect the data, and the heavy metal loadings were fixed at 453 g U/cm for the BWR assembly and 1215 g U/cm for the PWR assembly.

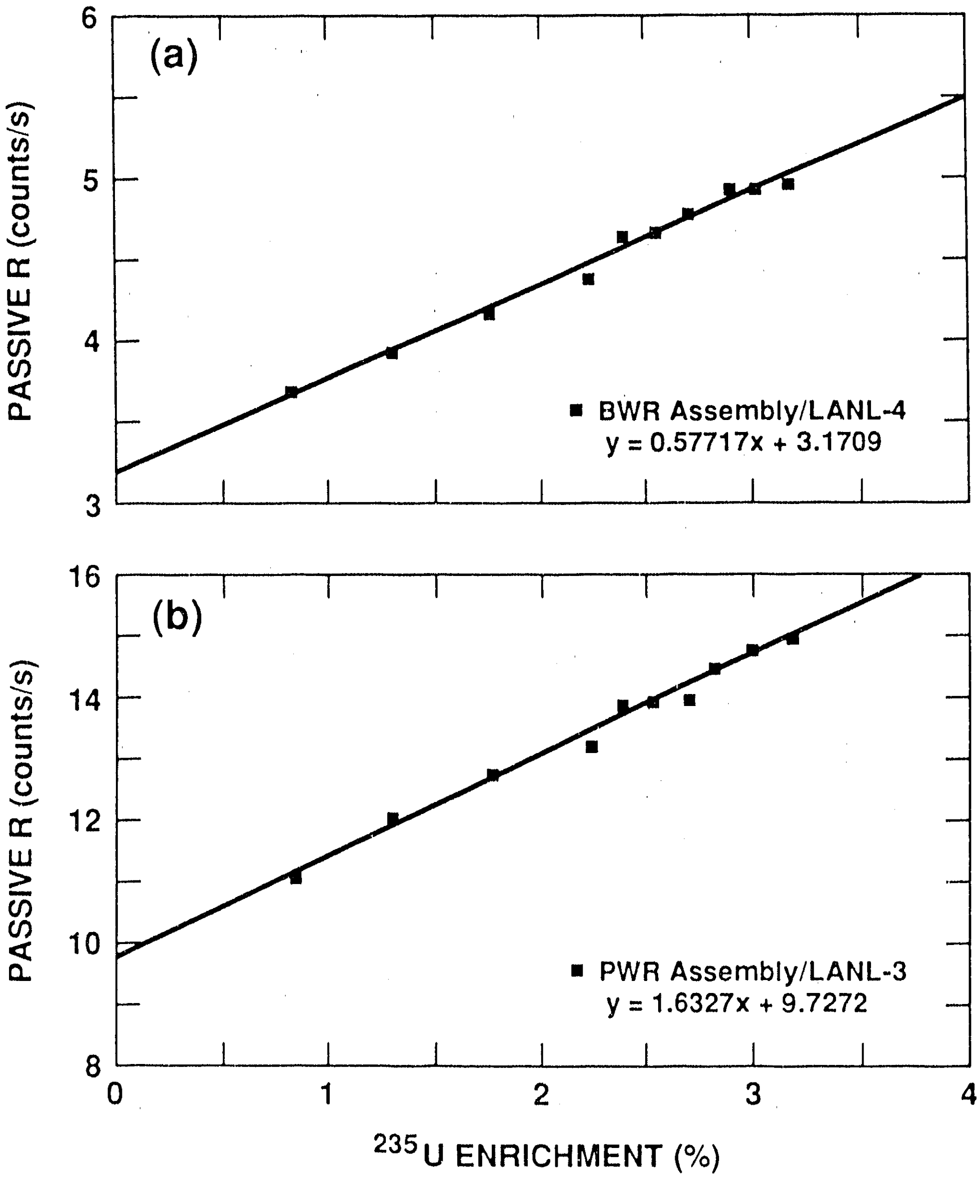

Fig. 14. The passive rates from BWR (top) and PWR (bottom) assemblies as a function of the ^{235}U enrichment for constant heavy metal loading.

The linear dependence of the passive reals rate on the ^{235}U enrichment is given in Fig. 14 as

$$R\ (passive) = 3.17 + 0.577\ E_n \quad \text{(BWR, UNCL-II)}\ ,$$

and

$$R\ (passive) = 9.73 + 1.63\ E_n \quad \text{(PWR, UNCL-II)}\ .$$

If we normalize the R values by the zero enrichment value of R_0, we get

$$R/R_0 = 1 + 0.182\ E_n \quad \text{(BWR, UNCL-II)}\ ,$$

and

$$R/R_0 = 1 + 0.168\ E_n \quad \text{(PWR, UNCL-II)}\ ,$$

and these normalized functions give the enrichment dependence of the passive R rate for any collar.

Because we have measured the passive mode calibration by removing rods and keeping the enrichment fixed at 3.19%, the passive R enrichment correction factor for other enrichments (E_n) is

$$\frac{Reference\ E_n\ corr.}{General\ E_n\ corr.} = \frac{1 + 0.182\ (3.19)}{1 + 0.182\ E_n} = \frac{1.581}{(1 + 0.182\ E_n)} \quad \text{(BWR, UNCL-II)}\ .$$

C. Passive Reals Correction

When we combine the room-background neutron correction with the enrichment correction, we get for BWR assemblies

$$R(corr.) = [R(meas.) - 0.014\ (T\text{-}45)]\frac{1.581}{(1 + 0.182\ E_n)}\ ,$$

and for PWR assemblies

$$R(corr.) = [R(meas.) - 0.014\ (T\text{-}120)]\frac{1.536}{(1 + 0.168\ E_n)}\ .$$

These two equations have room-background corrections that correspond to the UNCL (Mod-I) units. For the new UNCL-II units, the passive efficiencies are higher and the measured R and T rates must be reduced to use the UNCL (LANL-1) passive calibration curves shown in Fig. 15.

Table XIX lists the passive coincidence rates for all of the collar units that were calibrated with the LANL BWR and PWR fuel assemblies. The normalized ratios of

$$\frac{R(LANL\text{-}1)}{R(XX)} = r$$

are used to correct the measured reals rate, $R(meas)$, to the calibration curves given in Fig. 15, and the r values given in Table XIX. The passive correction for any collar is

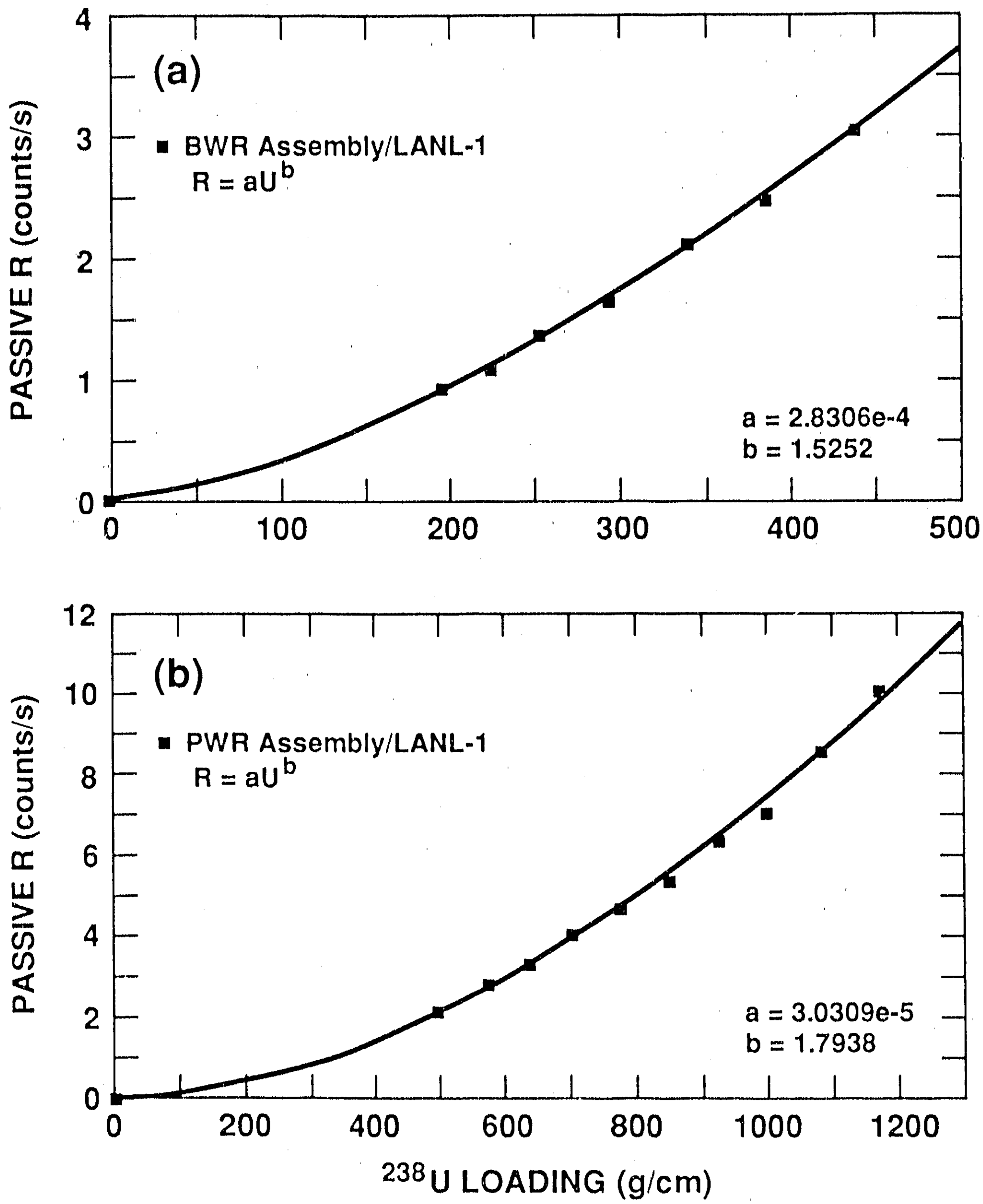

Fig. 15. Reference passive calibration curves for quantitative measurement of ^{238}U g/cm. The reference data correspond to the UNCL (LANL-1).

$$R(corr.) = [r\, R(meas.) - 0.014\, (\sqrt{r}\, T - 45)] \frac{1.581}{(1 + 0.182\, E_n)} ,$$

$$R(corr.) = [r\, R(meas.) - 0.014\, (\sqrt{r}\, T - 120)] \frac{1.536}{(1 + 0.168\, E_n)} ,$$

for BWR and PWR assemblies, respectively. For the reference case of LANL-1 and $E_n = 3.19\%$, $R(corr.) = R(meas.)$.

D. BWR Calibration Curve (Passive)

The calibration curve for BWR assemblies is given in Fig. 15. The g ^{238}U/cm can be obtained directly from the curve.

The data were fit by the power function

$$R(corr.) = aU^{b} ,$$

where

$$a = (2.83 \pm 0.49) \times 10^{-4} , \text{ and}$$

$$b = 1.525 \pm 0.0295 .$$

The covariances are

a: a 2.413×10^{-9}
a: b -1.448×10^{-6}
b: b 8.705×10^{-4} .

Inverting the equation gives

$$U = 212\, R^{0.656} ,$$

where U is the g ^{238}U/cm and R is the corrected passive rate.

E. PWR Calibration Curve (Passive)

The passive calibration curve for PWR assemblies is given in Fig. 15. The power function fit was

$$R\,(corr.) = aU^{b} ,$$

where

$$a = (3.03 \pm 0.10) \times 10^{-5} ,$$
$$b = 1.794 \pm 0.048 ,$$

and

$a{:}a$ 1.020 x 10^{-10}
$a{:}a$ -4.887 x 10^{-7}
$b{:}b$ 2.343 x 10^{-3} .

Inverting the equation gives

$$U = 330\, R^{0.557} \ .$$

F. Enrichment Calculation

The ^{235}U enrichment is calculated from

$$^{235}U(enrichment) = \frac{g\ ^{235}U/cm}{g\ ^{235}U/cm + g\ ^{238}U/cm} \ .$$

This value is used only to check the operator's declaration of enrichment because the passive measurement of the g ^{238}U/cm has a relatively large uncertainty.

G. Moderator Substitution

An additional benefit of the passive measurement is that it prevents the undetected substitution of moderator rods for UO_2 rods. Such a substitution would cause a drop in the passive coincidence rate.

SUMMARY

The calibration curves and cross-reference tables are presented for BWR and PWR fuel assemblies, both with and without Cd liners. The curves are presented for the reference UNCL-II units and reference PWR and BWR fuel assemblies. For field conditions using different UNCL units for a wide variety of fuel assemblies, signal conditioning factors $(k_0 \cdot k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5 = k)$ are presented to correct the measured response to the calibration conditions.

Cd-ratio measurements can be performed to make the measurement independent of the declared poison rod loading in the fuel assembly.

For future applications of the UNCL to verify the ^{238}U content as well as the ^{235}U content, we have presented the passive mode calibration functions and cross-reference parameters. The active mode (^{235}U) calibration can be used without the quantitative ^{238}U calibration that is presented in Section XI.

Appendix A presents data showing the position sensitivity for the substitution or removal of fuel rods.

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APPENDIX A
ROD SUBSTITUTION SENSITIVITY

Measurements were performed using the LANL prototype UNCL to establish the position sensitivity for rod removal or rod substitution.

Three cases were examined:

1. empty rod substitution,
2. iron rod substitution, and
3. DU rod substitution.

The rod removals were performed with groups of 8 to 14 rods as shown in Fig. A-1 where one group of rods was removed at a time. The fuel assembly is described in Table IV. The results in Table A-1 are presented in terms of the percent change in R per rod removed. Long measurement times (~24 h) were needed for each configuration to obtain the statistical precision given in Table A-1.

The results show that the iron rod substitution gives the largest perturbation per rod because of thermal-neutron absorption. The DU rod substitution can still be detected in the center of the assembly with roughly half the sensitivity level at the perimeter. Fast neutron multiplication in the ^{238}U is the reason for the reduced perturbation from DU rod substitution.

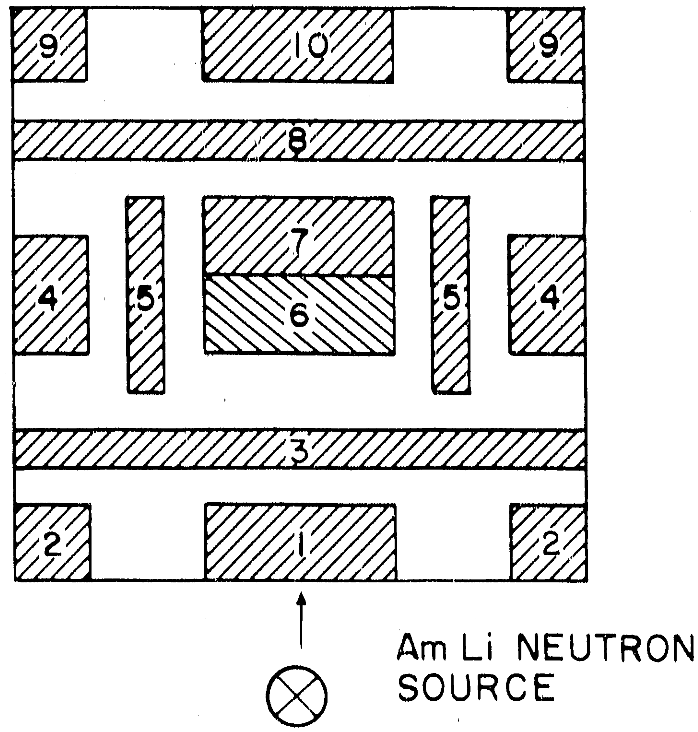

Fig. A-1. Diagram of mockup PWR fuel assembly (15 x 15 rod array) showing the fuel rod zones where the EU rods were replaced by DU rods or iron rods or empty rods. The substitutions were made one zone at a time.

TABLE A-1. Rod Substitution Sensitivity

Substitution Location	Empty Rod (%/rod)	Iron Rod (%/rod)	DU Rod (%/rod)
1	0.35	1.68	0.40
2	0.64	1.25	0.46
3	0.41	0.71	0.34
4	0.41	0.62	0.32
5	0.54	0.53	0.21
6	0.57	0.51	0.20
7	0.53	0.44	0.20
8	0.36	0.32	0.21
9	0.48	0.60	0.25
10	0.46	0.47	0.36
Av	0.48	0.71	0.30

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