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Neutron Detector Counting Capabilities for ^{10}B -Lined and ^{235}U Fission Chambers in High Gamma-Ray Fluxes

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NEUTRON DETECTOR COUNTING CAPABILITIES FOR ^{10}B -LINED AND ^{235}U FISSION CHAMBERS IN HIGH GAMMA-RAY FLUXES

by

L. Oscar Lindquist and E. J. Dowdy

ABSTRACT

This report compares the performance characteristics of ^{10}B -lined and fission-neutron detectors in gamma-ray fluxes typical of the fields to be encountered during nondestructive testing of irradiated light-water fuel assemblies stored in water. Using the optimum time constants for each of the ^{10}B -lined detectors, the 0.25-in.-diam detector had a 5% loss in neutron count sensitivity at 7000 rad/h. Similarly, the 0.5-in.-diam detector had a 7% loss at 13,000 rad/h and the 1-in.-diam detector had a 5% loss in sensitivity at 1000 rad/h. Uranium-235 fission chambers were operated successfully in fields above 100,000 rad/h with no loss in neutron counting sensitivity. Shielding calculations were done to determine the appropriate shield thickness needed for a ^{10}B -lined neutron detector to operate in a 50,000 rad/h field, typical of light-water-reactor spent-fuel assemblies stored in water.

I. INTRODUCTION

Safeguards inspectors from the International Atomic Energy Agency (IAEA) use ^{235}U fission detectors to detect neutrons emitted by light-water-reactor (LWR) spent-fuel assemblies. However, fission detectors create three problems for the inspector. First, the ^{235}U in the detector subjects the detector to stringent controls that affect its movement across national boundaries. Second, the fission detector is radioactive because of fission fragments and ^{235}U gamma-ray decay. The inspector has a difficult time transporting radioactive, fissile sources into and out of facilities. Third, the counting efficiency of the fission detector is less than the efficiencies of other types of neutron detectors.

Several types of gas detectors are also available for possible safeguards applications: $^{10}\text{BF}_3$ gaseous detectors, ^{10}B -lined detectors, ^3He -filled detectors, and ^4He -filled detectors. The efficiency of these detectors can be a factor of 100 greater than that of fission detectors. Furthermore, gas

detectors contain no fissile material, which means that they are not radioactive after use and thus can be easily transported across national boundaries.

Our study found fission detectors to be insensitive to high gamma-ray fluxes typically found near LWR spent-fuel assemblies, which makes them ideal for detecting neutrons. A ^{235}U fission will give approximately 180 MeV of kinetic energy to two or more fission fragments. These large-amplitude pulses from fission fragments are easy to identify in the detector output. If the detector is placed in a high-flux gamma-ray field, the 90-MeV pulses due to fission fragments are still identifiable over the gamma-ray-flux-induced pulses in the detector output.

Boron-10-lined or $^{10}\text{BF}_3$ detectors are more sensitive to background gamma-ray fluxes than are fission detectors. In spite of this limitation, boron detectors are more desirable to use than fission detectors because of their higher neutron counting efficiency. For a $^{10}\text{BF}_3$ detector or a ^{10}B -lined detector, the energy released in the $^{10}\text{B}(\text{n},\alpha)$ reaction is 2.78 MeV per reaction.¹ The energy release of a $^{10}\text{B}(\text{n},\alpha)$ reaction in the ^{10}B -based detector is approximately 1.5% the energy of a fission-based detector per event. If a ^{10}B -lined detector is placed in a high gamma-ray flux while it is detecting neutrons, the neutron count information will not be available if the secondary electron pileup induced by the gamma-ray flux is greater than or equal in amplitude to the neutron pulse amplitude.

Helium-3 detectors are more sensitive to background gamma-ray fluxes than are ^{10}B lined or $^{10}\text{BF}_3$ detectors, thus they are even less desirable than the boron detectors for safeguards neutron-detection applications that have medium- to high-background gamma-ray fluxes. However, in low gamma-ray fluxes, helium detectors have the highest neutron-counting efficiency of all the detectors mentioned. For a ^3He detector, the $^3\text{He}(\text{n},\text{p})^3\text{H}$ reaction energy release is 765 keV. The pulse height is less than the ^{10}B reaction pulse height. The secondary electron pileup argument makes the ^3He -filled detector more sensitive to gamma rays than ^{10}B -lined detectors. We did not include ^3He or ^4He detectors in our study because of their high sensitivity to gamma rays in the radiation fields near spent fuel.

This report describes the results of neutron sensitivity measurements compared to gamma-ray dose rates for ^{235}U fission detectors and ^{10}B -lined neutron detectors of several different diameters. We chose ^{10}B -lined detectors for this study because they appeared to have the most gamma-ray flux resistance after the fission detector. This study also recommends shielding materials and thicknesses needed to enable operation, with minimum loss in neutron counting sensitivity, of ^{10}B -lined detectors in 50,000 rad/h fields encountered in spent-fuel storage pools.

Three appendixes in this report completely develop and describe areas that are mentioned in the main text. Appendix A reports the analysis of gamma-ray pileup and pulse-height reduction. Appendix B describes three techniques to reject gamma-ray pileup. Appendix C provides calculation techniques for determining material thickness for detector shields.

II. PHYSICAL DESCRIPTIONS

A. Experimental Facility

The experiments to determine the gamma-ray-flux sensitivity of the neutron detectors were conducted in the laboratory of the Nuclear Engineering Department at the University of New Mexico. This laboratory has a variable flux ^{60}Co gamma-ray facility with a maximum flux producing an exposure rate of 660,000 rad/h. Neutron sources of ^{238}Pu -Be moderated with polyethylene and paraffin were also available for the experiments. The gamma-ray flux and neutron flux were varied independently to determine sensitivities. This combination of radiation sources simulates the radiation environment for neutron detectors near an LWR spent-fuel assembly stored in water. The gamma-ray flux near a spent-fuel assembly stored in water has been reported as high as 36,000 rad/h.*

B. Detectors

Descriptions of the detectors used for this study appear in Table I. The counting gas in all four detectors was Ar-CO_2 at 1-atm pressure. The gamma-ray flux was directly measured with a 0.5-in.-diam, 5-in.-long ion chamber, which was previously calibrated using LiF crystals as the radiation dose standard. This permitted us to make a real-time gamma-ray-flux measurement during the experiment. All four detectors are standard commercial products manufactured by the Reuter-Stokes Company.

To collect pulse-height spectra data we used a Nuclear Data ND-60 Multichannel Analyzer. A Texas Instrument ASR-733 terminal recorded data on cassette and produced a printed copy. The terminal also transmitted the cassette data to the Central Computing Facility (CCF) at the Los Alamos National Laboratory for data analysis. Standard single-channel analyzers and counter-scalers were also used to acquire neutron counts.

TABLE I
PHYSICAL CHARACTERISTICS OF NEUTRON DETECTORS

Detector Type	Diameter (in.)	Length (in.)	Fill Gas
^{10}B -lined	0.25	12	Ar-CO_2
^{10}B -lined	0.5	12	Ar-CO_2
^{10}B -lined	1.0	5	Ar-CO_2
^{235}U (150-mg loading) ^a	1.0	5	Ar-CO_2
^a Fission detector.			

*This information was supplied by J. Halbig, D. Lee, and J. Phillips, Los Alamos National Laboratory, September 1979.

C. Detector Electronics

The preamplifiers used for the detectors were Ortec 142PC charge-sensitive preamps. The circuit was a standard nuclear electronics circuit used for gas proportional and ionization counters. It had a risetime of approximately 25 ns with a decay time of 50 μ s. Several amplifiers, manufactured by the Ortec and Tennelec companies, were used in the course of our experiment.

III. FISSION DETECTOR RESULTS

A. Setup

The detector electronics setup appears in Fig. 1. The amplifier had a 2- μ s risetime and bipolar output. The amplifier gain was adjusted so that, with a 300-V bias on the fission chamber, the maximum pulse height resulting from a neutron-related fission event was 5 to 6 V. The output of the amplifier was connected to a single-channel analyzer operating in the integral mode with a discriminator circuit setting of 1 V. All counts taken were for 100 s.

B. Neutron Response versus Gamma-Ray Dose Rate

The fission chamber was exposed to a 100,000 rad/h gamma-ray flux with no counts recorded in 100 s. Then the fission detector was placed near a moderated neutron (plutonium-beryllium) source and the gamma-ray flux was varied. Table II shows the results. The experiment was repeated several times to evaluate neutron-source repositioning errors. The fission detector had no gamma-ray sensitivity at fields up to 100,000 rad/h and also displayed no loss

Fig. 1.
Fission detector electronics and data acquisition.

TABLE II
FISSION DETECTOR COUNT RATE IN VARIOUS
NEUTRON AND GAMMA-RAY FLUXES

Gamma-Ray Field (rad/h)	With Constant Thermal-Neutron Flux	Without Thermal Neutrons
0	16,263 $\pm$ 127	0
20,000	- -	0
50,000	16,148 $\pm$ 127	0
100,000	16,354 $\pm$ 127	0

Note: All counts in 100 s. Discriminator set at 1 V. No error greater than counting statistics was found in repositioning the ^{238}Pu -Be source.

in neutron detection sensitivity in these gamma-ray fields. This is an important result because the unshielded detector can be used for neutron verification work at LWR spent-fuel pools with no loss in sensitivity. Jackson and Hoitink² have reported a 5 to 20% loss in neutron counting sensitivity for fission detectors operating in an 80,000-rad/h gamma-ray flux. Our experiments show no loss in sensitivity at that gamma-ray flux level.

The gamma-ray pileup "noise" in the amplifier output was observed on an oscilloscope. The oscilloscope trace associated with this noise was the equivalent of 0.6 V at 100,000 rad/h. The alpha activity pulse height, intrinsic in a fission detector, was observed to be 0.2 V with no neutrons or gamma rays. The discriminator threshold was set significantly above this "noise level," at 1 V.

IV. BORON-10-LINED NEUTRON DETECTOR RESULTS

The primary purpose of this study was to evaluate the operating range of gamma-ray flux that ^{10}B -lined neutron detectors can operate in with no loss in sensitivity. Seven primary controlling factors determine the operating range:

- diameter of detector,
- length of detector,
- bias on the detector,
- risetime of preamplifier,
- risetime of the amplifier circuit,
- discriminator level setting, and
- detector gas pressure.

The $^{10}\text{B}(n,\alpha)^7\text{Li}$ reaction originates on the inside radius of the detector cathode annulus. The counting gas inside the annulus stops the reaction particles (alpha and lithium) and the resulting ion pairs generated by the particles slowing down in the detector gas are amplified by the electronics. Gamma rays also interact with the counting gas. Ion pairs result from this interaction. Several detector diameters were tested to evaluate reduction of counting gas volume versus reduced sensitivity to the gamma-ray flux. The cathode wall thickness was the same in all detectors.

The ^{10}B -lined detectors were tested at the recommended operating voltage of 725 V; that is, in the proportional region.

A. Setup

The typical counting arrangement for the experiments is shown in Fig. 2. Standard nuclear electronics were used.

B. Experimental Approach

In the initial set of experiments, the amplifier differentiating and integrating time constants were 2 μs for all detectors. This time constant is adequate for good charge collection and pulse-height resolution from a gas-filled proportional detector. As the detectors were exposed to increasing

Fig. 2.
Boron-10-lined detector electronics and data acquisition.

levels of gamma-ray dose rate, we observed that the gamma-ray pileup pulses in the amplifier output increased in amplitude. This observation was made using the multichannel analyzer display. It was an expected result that occurs because of the very high rate of low-energy gamma-ray pulses from the detector.

We also observed that the pulse height of neutron-related events (that is, alpha and lithium particles) decreased as the intensity of the gamma-ray flux increased. The system was investigated for possible electronics problems such as low bias voltage and saturated amplifier pulses. Nothing was found to account for the gain reduction, which apparently occurs within the detector gas volume. Neutron-related counts were lost because the discriminator had to be set above the gamma-ray pileup during which time the gain of the neutron-related pulses was reduced. The gain reduction occurs on all pulses regardless of pulse height and thus the neutron pulse-height spectrum is shifted to lower voltages. Because neutron counts were being lost, we conducted a final set of experiments to minimize the gamma-ray pulse pileup and, hence, to maximize the number of neutron pulses counted. If the pileup is reduced, then the discriminator can be set lower.

For this final set of experiments, the differentiating and integrating amplifier time constants were varied from 50 to 250 ns in a systematic way to evaluate the possible reduction of gamma-ray pulse pileup versus differentiation time. We also evaluated the increased (or decreased) detector neutron sensitivity. The procedure was implemented in the following way. For each selected gamma-ray flux, each detector, and each chosen differentiation time (with a corresponding equal integration time), we selected a discriminator setting in the single-channel analyzer by determining the minimum setting in which the counter scaler recorded no counts in 10 s. We followed this procedure to count the maximum number of neutron-related pulses above the gamma-ray pileup by determining the minimum threshold.

After all discriminator settings were determined for the time constants and detectors, a polyethylene-moderated ^{238}Pu -Be source was introduced to the experiment. Counts of 100 s were then recorded for all discriminator settings with the neutron source and selected gamma-ray fluxes present simultaneously. After those measurements were completed, we repeated the same experiment except that we set the gamma-ray flux to zero.

C. Experimental Results

1. Differentiation Times of 2 μs . Figure 3 shows the 1-in.-diam detector response to increasing gamma-ray flux with a constant neutron flux strength at three different lower-level discriminator (LLD) settings. This figure shows that 1-in.-diam detectors have a high sensitivity to gamma-ray fluxes in the krad/h range. The neutron sensitivity begins to deteriorate at 300 to 500 rad/h, irrespective of LLD setting on the single-channel analyzer.

Figure 4 shows the 0.25-in.-diam ^{10}B -lined detector response to increasing gamma-ray flux with a constant neutron flux strength at three different LLD settings. The figure shows that this detector has a low sensitivity to gamma-ray fluxes, depending on the LLD setting. The response to

Fig. 3.
Neutron counts versus gamma-ray dose rate for 1-in.-diam ^{10}B -lined detector.

Fig. 4.
Neutron counts versus gamma-ray dose rate for 0.25-in.-diam ^{10}B -lined detector.

neutrons for the detector is unaffected at a gamma-ray flux intensity of 6350 rad/h. There is no background count associated with the gamma-ray flux at 2 V LLD. The data at 12,000 rad/h indicate a neutron sensitivity loss of approximately 2 to 10%, depending on discriminator setting. Jackson and Hoitink² report no loss in neutron count sensitivity for 30,000 rad/h in a 0.25-in.-diam ^{10}B -lined detector.

A 0.5-in.-diam, 12-in.-long cylindrical ^{10}B -lined detector was also tested at 6800 rad/h. It showed a 10% reduction in neutron count rate at 6800 rad/h as compared with the neutron count rate with no gamma-ray field. This detector is less sensitive to gamma radiation than the 1-in.-diam detector. Stooksberry³ found that four 0.5-in.-diam, 24-in.-long, ^{10}B -lined detectors in parallel operated satisfactorily in 2400 rad/h. Our experiments with one detector confirm satisfactory operation with no loss in neutron count sensitivity at 2400 rad/h for 2- μs differentiating times.

2. Short-Time Constant Experiments to Reduce Gamma-Ray Pileup.

The reduction of gamma-ray pulse pileup was the motivating factor for using short time constants for differentiating and integrating. The first parameter determined was the minimum LLD setting that yielded no counts with a gamma-ray flux environment only. Table III shows the minimum LLD setting for the 1-in. detector as a function of gamma-ray flux intensity and differentiating time constants. Table IV lists the minimum LLD setting for the 0.5-in. detector as a function of gamma-ray flux intensity and differentiating time constants. Similarly, Table V is given for the 0.25-in. detector. These minimum thresholds were used for the remainder of the experiments with the corresponding three detectors.

TABLE III

MINIMUM THRESHOLD FOR GAMMA-RAY-RELATED PULSE REJECTION
IN 1-in. ^{10}B -LINED DETECTOR AS A FUNCTION OF AMPLIFIER
DIFFERENTIATING TIME CONSTANTS AND GAMMA-RAY FLUX

Gamma-Ray Flux (rad/h)	Minimum Threshold (V) at Five Amplifier Time Constants				
	50 ns	100 ns	200 ns	400 ns	800 ns
250	0.3	0.3	0.2	0.3	0.45
400	0.3	0.3	0.25	0.35	0.5
700	0.5	0.7	0.3	0.4	0.55
1,000	1.1	0.6	0.3	0.45	0.7
1,500	1.0	0.6	0.3	0.5	0.6
2,900	1.3	0.7	0.35	0.5	0.8
5,200	1.7	0.5	0.3	0.5	0.8
10,000	2.0	0.7	0.3	0.5	0.7
15,000	2.0	0.5	0.3	0.5	0.7

TABLE IV

MINIMUM THRESHOLD FOR GAMMA-RAY-RELATED PULSE REJECTION
IN 1-in. ^{10}B -LINED DETECTOR AS A FUNCTION OF AMPLIFIER
DIFFERENTIATING TIME CONSTANTS AND GAMMA-RAY FLUX

Gamma-Ray Flux (rad/h)	Minimum Threshold (V) at Two Amplifier Time Constants	
	100 ns	250 ns
600	0.7	0.9
1,300	0.5	0.8
2,300	0.6	1.1
3,400	0.6	1.2
5,800	0.8	1.5
8,600	1.0	1.7
13,000	1.0	1.7
20,000	1.4	2.2
50,000	1.9	2.2

TABLE V

MINIMUM THRESHOLD FOR GAMMA-RAY-RELATED PULSE REJECTION
IN 0.25-in. ^{10}B -LINED DETECTOR AS A FUNCTION OF AMPLIFIER
DIFFERENTIATING TIME CONSTANTS AND GAMMA-RAY FLUX

Gamma-Ray Flux (rad/h)	Minimum Threshold (V) at Five Amplifier Time Constants				
	50 ns	100 ns	200 ns	400 ns	800 ns
1,000	0.7	0.5	0.5	0.7	0.8
2,000	0.4	0.4	0.8	0.7	1.0
4,000	0.4	0.4	0.7	0.8	1.2
7,000	1.2	0.5	0.7	0.8	1.3
10,000	0.9	0.4	0.7	1.1	1.6
19,000	0.9	0.5	0.8	1.0	1.4
32,000	0.7	0.5	0.8	1.1	1.5
45,000	0.5	0.5	0.6	1.0	1.5
100,000	1.0	0.6	0.7	1.0	1.5

Table VI describes the 1-in.-diam neutron detector response to increasing intensities of gamma-ray flux. The 50-ns time constant measurements discriminated against high-amplitude gamma-ray-related oscillatory pulses during the experiment. Many neutron-related pulses were also discriminated against because of the short time constant. The 50-ns data indicate that loss of neutron sensitivity occurs at lower gamma-ray flux levels than it does for the longer rise time (above 50 ns) electronic systems. The data in the table for 100-, 200-, 400-, and 800-ns differentiating time constants show that the 1-in. ^{10}B -lined detector has 90% or more neutron-counting sensitivity in gamma-ray fields of 1500 rad/h or less.

Table VII describes the 0.25-in.-diam detector response to increasing levels of gamma-ray flux. The response is the neutron sensitivity of the detector in a particular gamma-ray flux. For example, 1.0 indicates no loss in neutron counting sensitivity compared to 0.5, which indicates a 50% loss in counting sensitivity. Note that for the 200- and 400-ns data, the neutron sensitivity is no less than 90%, up to 10,000 rad/h. During the experiment, the gamma-ray flux added oscillatory "noise" to the 50- and 100-ns time-constant measurements.

Table VIII describes the 0.5-in.-diam detector response to increasing levels of gamma-ray flux. The data show better than 90% neutron counting sensitivity in gamma-ray fields as high as 13,000 rad/h. This 0.5-in. detector is more gamma-ray resistant than the 0.25-in. detector tested. It can operate in a 30% higher gamma-ray flux with more than 90% neutron counting sensitivity.

TABLE VI

NEUTRON COUNTING SENSITIVITY OF 1-in.-diam
¹⁰B-LINED DETECTOR AS A FUNCTION OF
 GAMMA-RAY FLUX AND DIFFERENTIATING TIME CONSTANTS

Gamma-Ray Flux (rad/h)	Neutron Counting Sensitivity at Five Amplifier Time Constants				
	50 ns	100 ns	200 ns	400 ns	800 ns
0	1.0	1.0	1.0	1.0	1.0
250	0.95	0.99	0.99	0.99	0.99
400	0.94	0.98	---	0.97	0.98
700	0.93	0.94	0.96	0.96	0.95
1,000	0.65	0.91	0.95	0.91	0.91
1,500	0.60	0.90	0.93	0.90	0.92
2,900	0.36	0.77	0.85	0.82	0.74
5,200	0.06	0.78	0.81	0.74	0.60
10,000	0.02	0.81	1.37	0.54	0.46
15,000	0	0.91	1.08	0.79	0.53

TABLE VII

NEUTRON COUNTING SENSITIVITY OF 0.25-in.-diam
¹⁰B-LINED DETECTOR AS A FUNCTION OF
 GAMMA-RAY FLUX AND DIFFERENTIATING TIME CONSTANTS

Gamma-Ray Flux (rad/h)	Neutron Counting Sensitivity at Five Amplifier Time Constant (ns)				
	50 ns	100 ns	200 ns	400 ns	800 ns
0	1.0	1.0	1.0	1.0	1.0
1,000	1.01	0.89	0.94	1.00	1.01
2,000	0.99	1.01	0.99	0.99	0.98
4,000	---	0.97	0.96	0.97	0.96
7,000	0.83	0.95	0.92	0.95	0.91
10,000	0.87	0.94	0.90	0.90	0.85
19,000	0.77	0.87	0.83	0.82	---
32,000	0.76	0.81	0.74	0.72	0.62
45,000	0.81	0.74	0.79	0.66	0.50
100,000	0.04	0.12	0.22	0.17	0.09

TABLE VIII

NEUTRON COUNTING SENSITIVITY OF 0.5-in.-diam
 ^{10}B -LINED DETECTOR AS A FUNCTION OF
 GAMMA-RAY FLUX AND DIFFERENTIATING TIME CONSTANTS

Gamma-Ray Flux (rad/h)	Neutron Counting Sensitivity at Three Amplifier Time Constants		
	40 ns	100 ns	250 ns
0	1.0	1.0	1.0
600	1.03	1.00	1.00
1,300	0.96	0.99	1.01
2,300	---	1.00	0.99
3,400	0.93	1.01	0.99
5,800	0.86	0.98	0.97
8,600	0.79	0.95	---
13,000	0.84	0.93	0.92
20,000	0.65	0.81	0.81
50,000	0.42	0.24	0.60

V. COMPARISON OF NEUTRON COUNTING EFFICIENCIES

The counting efficiencies of the fission chamber and the ^{10}B -lined detectors are compared in this section. Each of the detectors was placed in the same neutron flux environment for up to 20 cm of its active length. The fission chamber and 1-in.-diam ^{10}B -lined detector are 5 in. long (active length). The 0.5-in.- and 0.25-in.-diam ^{10}B -lined detectors are 12 in. long.

In Table IX, we list relative counts/cm normalized to the 1-in.-diam fission chamber. The table describes the counting efficiency of each detector for a relatively low gamma-ray flux. At higher gamma-ray intensities, the discriminator setting must be increased for ^{10}B -lined detectors because of pulse pileup considerations. The fission chamber discriminator is not changed at higher gamma-ray fluxes. For optimum preamp and amplifier risetimes (200 ns) the 1-in.-diam ^{10}B -lined detector loses 7% of its efficiency at 1000 rad/h. Similarly, the 0.5-in.-diam ^{10}B -lined detector loses 14% at 13,000 rad/h, and the 0.25-in.-diam ^{10}B detector loses 4% at 7000 rad/h.

TABLE IX
RELATIVE COUNTING EFFICIENCIES PER UNIT LENGTH
FOR FISSION AND ^{10}B -LINED DETECTORS

Detector Type	Detector Diameter (in.)	Relative counts/in.
Fission chamber	1.00	1
^{10}B -lined	1.00	6.5
^{10}B -lined	0.5	11
^{10}B -lined	0.25	1.45

VI. CONCLUSIONS

Five conclusions can be drawn as a result of this study. The first is that 1-in.-diam, 5-in.-long ^{235}U fission chambers can be used with no loss in neutron-detection sensitivity in gamma-ray fields above 100,000 rad/h.

Second, ^{10}B -lined gas detectors operating in the proportional region have a significantly higher neutron-detection efficiency than ^{235}U fission chambers have. The efficiency of the 0.5-in.-diam ^{10}B -lined detector was 11 times larger than the efficiency of the ^{235}U fission chamber in the same neutron environment.

Third, ^{10}B -lined detectors can be used in relatively high gamma-ray fields. The 1-in.-diam detector was operated in our experiments at 1000 rad/h with a 5% loss in neutron sensitivity. Similarly, the 0.5-in.-diam detector suffered 7% loss at 13,000 rad/h. The 0.25-in.-diam ^{10}B -lined detector at 10,000 rad/h experienced a 5% loss in neutron sensitivity.

Fourth, fast differentiating times are needed in the detector electronics to establish good neutron sensitivity in high-intensity gamma-ray fields. The fast differentiating times reduce gamma-ray pileup effects. An optimum differentiating time constant for the ^{10}B -lined detectors was determined to be 200 ns. The fission chamber data were acquired with a 2- μs time constant.

The fifth and final conclusion is that lightweight (10 kg for a 12-in.-long detector) and thin (about 1 in. of lead) shielding can be implemented to attenuate the gamma rays from LWR spent fuel in water to a radiation level low enough that will enable operation of ^{10}B -lined neutron detectors with a negligible loss in neutron sensitivity. This conclusion is supported by calculations using the best available data.

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APPENDIX A

ANALYSIS

I. GAMMA-RAY PILEUP RESULTS

Gamma-ray pileup occurs in the detector system when the pulse rate caused by the gamma rays is so high that one pulse piles up on another and causes the two pulses to be combined into a larger pulse. This pulse pileup becomes increasingly significant as the background gamma-ray flux for the neutron detector is increased. The LLD must be set higher than the pileup pulses to avoid spurious counts. However, as the LLD setting is increased, the counts per unit neutron flux are decreased because a smaller part of the alpha and lithium energy spectrum is being integrated. This is seen in Fig. A-1 where a typical pulse-height spectrum is shown for a ^{10}B -lined detector. As the discriminator level is increased, the net area available for neutron-count integration is reduced.

II. PULSE-HEIGHT REDUCTION

Figure A-1 is a spectrum of the alpha and lithium pulse heights in a ^{10}B -lined detector with no gamma-ray field. Figure A-2 is a spectrum of the same detector in the same neutron environment but with a 3500 rad/h gamma-ray field present. The spectrum has been shifted to the left; that is, the average pulse height has been reduced. If the electric field in the tube is reduced by a large rate of gamma-ray ionizing events, the gain will also be reduced. For a simple system that counts above a fixed discriminator level, the count rate will decrease as a function of the intensity of the background gamma-ray flux. Halbig* observed this same reduction in pulse-height phenomena while using ^{10}B -lined detectors adjacent to spent-fuel assemblies.

Gain reduction resulting from high-background gamma-ray fields caused these experiments with ^{10}B -lined detectors to show a decrease in count rate as the gamma-ray flux intensity increased. We observed pulse-height reduction of the neutron-related spectrum (that is, alpha and lithium particles) as a function of gamma-ray flux with all differentiating time constants and all detectors. The large number of gamma-ray-related ion pairs at high gamma-ray backgrounds reduced the electric field intensity in the detector near the anode where the multiplication occurs and hence reduced the gain, or multiplication, of the proportional counter. The entire pulse-height spectrum is therefore shifted to the left, that is, lower pulse height, and consequently the net integrated count area above the LLD setting decreases.

*This information was supplied by J. Halbig, Los Alamos National Laboratory, October 1979.

Wilkinson⁴ has a good treatment of the count rate attainable with a proportional mode detector. In the ^{10}B -lined detectors, the gas is at standard temperature and pressure. If we assume 34 eV/ion pair, then 5.79×10^5 ion pairs/cm³-s will be produced in a 1-rad/h field. Therefore, at 10,000 rad/h, the ion-pair rate will be 5.8×10^9 /cm³-s. Assuming 10^3 ion pairs per gamma-ray interaction in this 10^4 -rad/h field, we have 5.8×10^6 pulses/cm³-s. These calculations do not include wall ion-pair contributions.

Wilkinson finds in his analysis that the maximum counting rate without substantial gain reduction is 10^7 /s if the risetime is sufficiently short in the electronics. The maximum pulse rate is determined by the minimum number of electrons required for detection. Our experiments have shown that the neutron-related pulse heights have deteriorated at lower gamma-ray fluxes as the diameter of the gas detector increases. A larger diameter produces a larger gamma-ray-pulse ion-pair rate per unit-length detector. The experiments are consistent with Wilkinson's analysis.

Fig. A-1
Pulse-height spectrum for
 ^{10}B -lined detector in neutron
radiation environment.

Fig. A-2.
Pulse-height spectrum for
 ^{10}B -lined detector in
gamma-ray and neutron
environment (same detector
and neutron flux as in Fig.
A-1).

APPENDIX E

GAMMA-RAY PILEUP REJECTION TECHNIQUES

I. REDUCE GAMMA-RAY FLUX

The gamma-ray flux can be reduced by shielding and distance considerations. In Appendix C, we estimate the shielding thickness needed to attenuate the gamma-ray flux to reduce pileup effects.

II. REDUCE COUNTING GAS VOLUME

We have effectively reduced the volume of counting gas from relative volumes of 5, 3, and 0.75 with the 1-in., 0.5-in., and 0.25-in.-diam detectors, respectively. The gamma-ray pileup was reduced as the diameter of the detector decreased. Menlove* also suggested shortening the length of the detector to reduce the gamma-ray pileup in the counting electronics. This may be a reasonable approach because the detector could be visualized as a pulse generator for the electronics with the maximum rate determined by the length of the detector in a constant radiation environment. We connected two 1-in.-diam, 5-in.-long ^{10}B -lined detectors in parallel to simulate a single tube twice as long.

We then determined the threshold for no counts from gamma rays at 15,000 rad/h. This was done for 200- and 400-ns differentiating time constants. In the same manner as the previous experiments, we counted a neutron source with and without a 15,000 rad/h gamma-ray field for 100 s for each measurement. The ratio of the counts with the neutron and gamma-ray source both present divided by the neutron source only is the reduced sensitivity. For the 200-ns data, the ratio for two electrically parallel tubes is 0.45 versus 1.08 for one detector. For the 400-ns data, the ratio is 0.27 for two tubes versus 0.79 for one detector. These measurements indicate that there are ratio differences between one- and two-detector arrangements (that is, the length may affect the system neutron sensitivity loss of a given detector diameter).

III. OPTIMIZE THE DIFFERENTIATING RC TIME CONSTANT OF THE ELECTRONICS

The RC time constant for these series of experiments was typically 25 ns in the preamplifier circuit. The amplifier time constants were varied from 50 ns to 2 μs . The time constants were varied to determine the optimum differentiating time constant for each detector. We found that 200 and 400 ns were near optimum for all three detectors. The optimized time constant is related to the average electron collection time for the detector diameter.

*This information was supplied by H. Menlove, Los Alamos National Laboratory, June 1980.

APPENDIX C

CALCULATIONS FOR DETECTOR SHIELDING REQUIREMENTS

Our experiments did not demonstrate that ^{10}B -lined detectors can operate in LWR spent-fuel assembly environments of 50,000 rad/h without appropriate shielding. This appendix gives the calculational recommendations for the minimum-thickness shielding required to operate these detectors in that radiation environment. We shall begin by describing the nine most intense gamma-ray emissions in spent LWR fuel inventories.

I. GAMMA-RAY EMITTERS PRESENT IN SPENT LWR FUEL

Phillips et al.⁵ used an intrinsic, high-purity germanium (HPGe) detector to measure specific gamma rays from spent LWR fuel in water to establish a relationship between relative burnup values and gamma-ray emission rate to characterize the total plutonium content of the fuel assembly. They established the nine most intense gamma rays experimentally with the HPGe detector. Rinard⁶ used this data to establish calculational each gamma-ray-related dose rate at a detector placed at various distances from the fuel assembly stored in water.

The percentage dose rate due to each gamma ray depends on the burnup and cooling time of the LWR fuel assembly. The gamma-ray-emitting isotopes and their half-lives are listed in Table C-I. The maximum gamma-ray energy produced by these isotopes is 2186 keV. This is from ^{144}Pr , which is in secular equilibrium with the fission product ^{144}Ce .

TABLE C-I

ISOTOPES PRODUCING NINE MOST INTENSE GAMMA RAYS
IN LWR SPENT-FUEL ASSEMBLIES

Isotopes	Half-Life	Gamma-Ray Energies (keV)
^{144}Pr - ^{144}Ce	284.4 days	696, 1489, 2186
^{154}Eu	8.6 years	1274
^{134}Cs	2.062 years	605, 796
^{95}Nb	35 days	765
^{95}Zr	64 days	724, 756
^{137}Cs	30.17 years	662

Figure C-1, repeated here with the permission of Rinard, shows the percent of the total gamma-ray dose rate presented to an air ion chamber from each of the nine gamma-ray energies found in the previously mentioned HPGe detector experiments. The percentages are determined by finding the ordinate distance between successive lines. As the detector is moved farther away from the fuel assembly in the water, the higher energy gamma rays from ^{144}Pr - ^{144}Ce become a more dominant contributor to the dose rate. Figure C-2, similar to Fig. C1, shows a pressurized water reactor (PWR) fuel assembly with moderate burnup of 32,000 MW days/tonne of uranium and moderate cooling time after irradiation of 279 days.

The dose-rate percentages change as a function of cooling time. Figure C-3, again taken from Rinard, shows that the dominance of ^{144}Pr - ^{144}Ce begins to fade after 3 yr of cooling time. This change is due to the different half-lives of the isotopes. The highest energy gamma rays from ^{144}Pr have their maximum percentages when the cooling times are between 1 and 2.5 yr.

Fig. C-1.
Dose contribution from eight different gamma-ray emitters as a function of distance from a BWR fuel assembly in water.

Fig. C-2.
Dose contribution from eight different gamma-ray emitters as a function of distance from a PWR fuel assembly in water.

Fig. C-3.
Dose contributions from eight different gamma-ray emitters as a function of cooling time (a) for a BWR fuel assembly and (b) for a PWR fuel assembly.

In the next section, we evaluate the shielding needed for a ^{10}B -lined detector for the dose contributions given by the nine most intense gamma rays.

II. SHIELDING FOR MULTIENERGY GAMMA-RAY FLUX

The two facets for radiation attenuation are distance and shielding. For the case of a gamma-ray source in water, an increase in distance from the source also implies an increase in shielding thickness of the water. This shield does not add any weight to the neutron detector assembly that the IAEA inspector is using. It does, however, reduce the neutron count rate because of distance and neutron absorption considerations.

The pragmatic approach to this shielding problem is to define the maximum mass that will allow the detector assembly to be truly portable. An upper limit is approximately 10 kg.* The shield material should not absorb neutrons significantly; it should have a high gamma-ray attenuation coefficient, $\mu(\text{cm}^2/\text{g})$, and should not produce neutrons as a result of (γ, n) reactions. Lead is an appropriate choice for this application.

In a previous memo,⁷ we selected three gamma-ray energies representative of the nine most intense gamma rays in LWR spent-fuel assemblies. They are 2, 1.3, and 0.5 MeV. We then used the gamma-ray attenuation formula

$$\frac{\phi}{\phi_o} = B_m (\mu a) e^{-\mu a},$$

where ϕ is the emerging flux, ϕ_o is the incident flux, B_m is the buildup factor, μ is the mass attenuation coefficient of the shield, and a is the thickness of the shield. Table C-II is a tabulation of attenuation for 0.5-, 1.3-, and 2-MeV gamma rays for different thicknesses of lead of density 11.34 g/cm³. A graphical representation of the table is found in Fig. C-4. If we use a 1-in.-thick lead shield around the 0.25-in.-diam, 12-in.-long detector, the shield will weigh 20 lbs, which is a satisfactory weight for the portability criterion.

Using Table C-II and the figures obtained from Rinard's work, we can find a reasonable multienergy dose-rate attenuation factor for an LWR spent-fuel gamma-ray spectrum. The calculational estimate should be conservative because Compton scattering in the fuel assembly and water will soften the gamma-ray spectrum and increase the attenuation predicted in this section. In Table C-III, we list the proportion of dose rate and the energy of each of the nine most intense gamma rays for the LWR spent-fuel assembly described in Rinard's work.

For the case of 1-in.-thick lead shielding around a ¹⁰B-lined neutron detector, we use the gamma-ray attenuation factor for each energy to determine dose-rate reduction for the detector from all energies. The following equation shows the form

$$\text{dose rate}_{\text{shielded}} = \sum_{i=1}^N A_i \cdot P_i \cdot \text{dose rate}_{\text{unshielded}},$$

where N = number of gamma-ray energies, A_i = attenuation factor for energy i , and P_i = fraction of total dose rate due to i .

*This information was supplied by J. Foley, Los Alamos National Laboratory, July 1980.

TABLE C-II
LEAD SHIELDING ATTENUATION FACTOR
VERSUS THICKNESS AND GAMMA-RAY ENERGY

Lead Thickness (cm)	Attenuation Factor		
	0.5 MeV	1.3 MeV	2 MeV
1	2.6×10^{-1}	6.5×10^{-1}	7.2×10^{-1}
2	5.8×10^{-2}	4.0×10^{-1}	5.0×10^{-1}
3	1.2×10^{-2}	2.4×10^{-1}	3.4×10^{-1}
4	2.6×10^{-3}	1.4×10^{-1}	2.2×10^{-1}
5	5.3×10^{-4}	7.9×10^{-2}	1.5×10^{-1}
6	1.1×10^{-4}	4.5×10^{-2}	9.0×10^{-2}
7	2.1×10^{-5}	2.5×10^{-2}	6.0×10^{-2}
8	4.0×10^{-6}	1.4×10^{-2}	4.0×10^{-2}
9	7.8×10^{-7}	7.7×10^{-3}	2.5×10^{-2}
10	4.2×10^{-3}	1.6×10^{-2}	---
12	1.3×10^{-3}	6.2×10^{-3}	---
14	3.8×10^{-4}	2.4×10^{-3}	---
16	1.1×10^{-4}	9.5×10^{-4}	---
18	3.3×10^{-5}	3.7×10^{-4}	---
20	9.6×10^{-5}	1.3×10^{-4}	---

We computed a dose rate that is 17% of the unshielded dose rate for 1-in.-lead shielding using the spent-fuel gamma-ray spectrum. This calculated shield attenuation is sufficient for proper operation of a 0.5-in.-diam ^{10}B -lined shielded neutron detector with minimal (approximately 7%) loss in neutron counting sensitivity. Thus, it is reasonable to consider using a lead-shielded 0.5-in.-diam ^{10}B -lined detector in a spent-fuel measurement application to enhance the neutron counting efficiency.

Fig. C-4.
Calculated lead shielding attenuation factor versus thickness for several gamma-ray energies. Buildup is incorporated in the calculations for these curves.

TABLE C-III
PROPORTION OF DOSE RATE AND ENERGIES
OF NINE LWR GAMMA RAYS

Dose Rate (%)	Energy of Gamma Ray (keV)
25	2186
5	1230
25	800
28	750
8	700
6	660
3	605

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