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GROSS GAMMA-RAY MEASUREMENTS OF LIGHT WATER REACTOR SPENT-FUEL ASSEMBLIES IN UNDERWATER STORAGE ARRAYS

by

C. E. Moss and D. M. Lee

ABSTRACT

Two gross gamma-ray detection systems have been developed for rapid measurement of spent-fuel assemblies in underwater storage racks. One system uses a scintillator as the detector and has a 2% crosstalk between a fuel assembly and an adjacent void. The other system uses an ion chamber as the detector. The measurements with both detectors correlate well with operator-declared burnup and cooling-time values.

I. INTRODUCTION

Spent fuel from light water power reactors contains significant quantities of ^{235}U and ^{239}Pu and a very large inventory of highly radioactive fission products and actinides. Measurement of the inventory in spent-fuel storage pools is the responsibility of both domestic and international safeguards inspectors. Because the number of spent-fuel assemblies is growing rapidly worldwide,¹⁻³ it is essential that accurate measurement techniques be developed that are nondestructive and require a minimum effort by the operator. In particular, fuel movement or special geometric arrangement of the fuel should be avoided. Only simple, portable instruments that can sample a significant fraction of the entire pool inventory at a rate of about one assembly per minute are considered in this report. Elaborate equipment for detailed assay has been reported elsewhere.^{4,5}

All technical approaches for simple instruments that involve direct measurement of gamma-ray or neutron fluxes require placing an instrument in the water;⁶ however, such placement is not required with the Cerenkov glow technique, which measures a secondary radiation effect.^{7,8} Because adjacent fuel assemblies are close together, as shown in Fig. 1, and may differ greatly

in activity, good collimation is necessary to reduce interference from adjacent assemblies and to avoid using unfolding techniques. The instrument should (1) be lightweight so that it can be positioned quickly by hand, (2) give an immediate result, (3) not be damaged by the high radiation levels, and (4) have an accuracy ensuring a meaningful measurement of the fuel inventory. Two promising instruments that satisfy these conditions, the scintillator and the ion chamber, are discussed in this report. Both detectors measure the gross gamma-ray flux immediately above a fuel assembly.

II. EQUIPMENT

A. Scintillator

Figures 2 and 3 show the scintillator detector assembly. The collimator is an air-filled, thin-walled, stainless-steel tube ~ 1.5 m long with inside diameter of 24 mm. The scintillator is a cylinder of Pilot F* plastic 1.6 mm long with a diameter of 1.6 mm. An organic scintillator is used because the decay time is short and, therefore, high counting rates can be tolerated.

*Nuclear Enterprises, Inc., San Carlos, CA 94070.

Fig. 1.

An underwater, PWR spent-fuel storage rack at the Zion Nuclear Power Station, Zion, Illinois. The units are centimeters.

The RCA-8053* photomultiplier is a 50.8-mm-diam tube with a venetian-blind structure and BeO dynode emitting surfaces. At high counting rates photomultipliers suffer fatigue, which reduces their gain as a function of time.^{9,10} The RCA tube, however, suffers little fatigue because the venetian-blind structure does not produce a high current density on the BeO dynodes, which are relatively stable. A smaller diameter tube would have had higher current density and, therefore, more fatigue.

The lead shield, shown in Fig. 2, is necessary because the water in storage pools is often contaminated with gamma emitters that cause a significant background. The lead shield is a preliminary design and size reductions are expected. The detector assembly is positioned manually with a nylon rope, and the support fins at the

bottom of the assembly rest on top of the fuel storage racks.

The high-voltage and signal cables are inside a tygon tube* that connects the underwater detector assembly to an electronics package on the bridge over the storage pool. The tube is also a safety line.

The battery-powered electronics package contains a high-voltage power supply, a fast amplifier, a discriminator, and a scaler/timer. The counting time is chosen automatically from 0.1, 1.0, and 10.0 s to give 1% statistics or to terminate after 10 s, and the decimal point on the display is positioned automatically so that the reading is in kilohertz. The rechargeable batteries have an estimated lifetime of 30 h. The package has a 16-cm width, a 22-cm height, and a 21-cm length; it weighs 2.7 kg, including the batteries.

*RCA Electro-Optics and Devices, Lancaster, PA 17604.

*Norton Co., Plastics and Synthetics Division, Akron, OH 44309.

Fig. 2.

Detector assembly containing the scintillator.

B. Ion Chamber

Figure 4 shows the ion chamber and its tungsten shield. Fig. 5 presents the experimental setup, and Fig. 6 shows the ion-chamber electronics. The chamber is a commercially available (Model 52105

Fig. 3.

Detector assembly containing the scintillator.

LND*) xenon-filled cylindrical chamber. The sensitive volume is 20 cm^3 and the diameter is 1.9 cm. A tungsten annular shield 21.6 cm long with a 2.05-cm i.d. and a 4.75-cm o.d. surrounds the ion chamber. The ion-chamber and tungsten-shield assembly is inserted into a 5-cm-i.d. aluminum tube with a 6-mm-thick wall.

*LND, Inc., Oceanside, NY 11572.

Fig. 4.
Ion-chamber and tungsten-shield assembly.

Fig. 5.
Experimental setup for the ion chamber.

Fig. 6.
Diagram of the ion-chamber electronics.

Fig. 7.
Ion-chamber electronics package.

which provides both the air collimation between the top of the fuel assembly and the ion chamber and the routing for the signal cable to the surface of the storage pool.

The portable, battery-operated electronics package, shown in Fig. 7, measures both gamma-ray and neutron activities; only the gamma-ray section of the instrument was used. Eight D-cell batteries (which last 30 h) provide power. Figure 7 shows a liquid-crystal display that indicates the relative gamma dose sensed by the ion chamber. The knob below the display provides the gain control and decimal positioning. The range of the instrument is from 0.01 to 19.99 units, where one unit is nominally 5×10^{-12} A.

As shown in Fig. 6, the first stage consists of a standard current-to-voltage converter with a transfer gain of 10^{-8} A/V. Gain stages that follow provide gains of 10, 100, and 1000. The electronics package provides the high-voltage bias for the ion chamber. The specially fabricated signal cable uses the center conductor of two RG-174 coaxial cables as the bias conductor and the current return. The two shields from the coaxial cables are connected to the instrument-case ground. A third shield encloses both cables for protection and noise reduction. By doubly shielding the current return from leakage currents, the integrity of the cable is enhanced.

The electronics were very stable and there were no serious problems. Setup and check-out were completed quickly. Battery power allowed noise-free operation—which might have been a problem with ac power.

III. EXPERIMENTAL RESULTS

A. Scintillator

Measurements were made on materials testing reactor (MTR) fuel and a 75-Ci ^{60}Co source during the initial instrument development. Later, two series of measurements were made on the pressurized water reactor (PWR) fuel in the spent-fuel storage pool at the Zion Nuclear Power Station, Zion, Illinois.*

In early designs of the system described here, different scintillators and photomultipliers were tested. The liquid scintillators NE224 and NE226,** which are resistant to radiation damage,¹¹ were tried, but we chose the solid scintillator because no damage has been observed with

*Operated by Commonwealth Edison Company, Chicago, IL 60690.

**Nuclear Enterprises, Inc.

the Pilot F plastic. When scintillators larger than that described in this report were tested, counting rates for the electronics were too high.

Interference between adjacent fuel assemblies has an important effect on a spent-fuel monitor. An easily measured parameter indicating this effect is percent crosstalk, defined here as

$$\frac{(\text{signal in adjacent void}) - (\text{background})}{(\text{signal over isolated assembly}) - (\text{background})} \times 100.$$

A significant effort was made to reduce the crosstalk by improving the collimation. The present collimator is stainless-steel tubing 152.4 cm long with an 0.89-mm wall. A collimator 91.44 cm long gave too high a counting rate, whereas one 213.6 cm long gave too low a counting rate relative to the gamma-ray background from the radioactive isotopes present in the storage-pool water. Smaller diameter collimators reduced the crosstalk, but the reading became very sensitive to the horizontal position of the collimator relative to the fuel assembly. A 3-mm-wall collimator of the high-Z material lead gave ~30% less crosstalk, but the monitor was too heavy to manipulate. A low-Z material, polyvinyl chloride (PVC) plastic, was no better for reducing crosstalk than stainless steel. The effect on the crosstalk of varying the photomultiplier voltage with a fixed threshold discriminator is shown in Fig. 8. (This is equivalent to varying the threshold discriminator with a

Fig. 8.

Scintillator crosstalk from an isolated fuel assembly to an adjacent void as a function of the high voltage on the photomultiplier.

fixed high voltage.) Although there is considerable scatter in the data points, the minimum crosstalk is at either a very low voltage, corresponding to looking at high-energy gamma rays only, or a very high voltage, corresponding to looking at most of the spectrum reaching the detector, which is dominated by low-energy gamma rays. We operate at the high-voltage end because the counting rate is higher and, therefore, the counting times can be shorter than for operation at the low-voltage end.

Figure 9 is a map of counting rates with background subtracted for an isolated assembly. Background readings for all scintillator measurements were determined by moving the detector assembly several meters from any fuel assemblies. Typical background readings were ~342 counts/s. Statistical uncertainties were usually less than 1%. Uncertainties attributed to the position of the detector assembly relative to the fuel assembly and to electronic drifts contributed an additional 5%.

Figures 10 and 11 present counting rates for two arrays of two fuel assemblies each. Assembly 19P measurements are higher than expected from the isolated measurements. Some of the discrepancy may be due to electronic drifts.

Figure 12 is a map of counting rates for a 4 by 4 fuel-assembly array. Again, the interference is higher than expected. Because of limited time, not all of the fuel assemblies were measured isolated.

The counting rate observed in the scintillator is mainly a function of the irradiation and the cooling times. Using the approximation given in Ref. 12 for the decay heat, we have fitted the following formula for the counting rate divided by the burnup to the scintillator data.

counts/s	Void	Void -7	18
MWd/tU Months cooling	32185 22	Void	19
counts/s	1868	24	
	P	N	

Fig. 9

Map of scintillator counting rates after background subtraction for an isolated fuel assembly. The boxes represent storage positions in the spent-fuel storage pool.

	Void	Void	18
counts s in array		10	
MWd tU	32185	19826	
Months cooling	22	30	
counts s isolated	1868	695	19
counts s in array	2037	718	
	P	N	

Fig. 10.

Map of scintillator counting rates after background subtraction for a moderately radioactive fuel assembly next to a weakly radioactive one.

	Void	Void	18
counts s in array		57	
MWd tU	32185	35764	
Months cooling	22	9	
counts s isolated	1868	3028	19
counts s in array	2158	3072	
	P	N	

Fig. 11.

Map of scintillator counting rates after background subtraction for a moderately radioactive fuel assembly next to a strongly radioactive one.

MWd/tU	17404	39167	Void	39536	
Months cooling	30	4		4	17
counts s in array	682	6124	231	8036	
MWd/tU	30552	31087	38309	18666	
Months cooling	17	17	9	40	18
counts s in array	1849	2599	2704	806	
MWd/tU	32185	19326	35764	31851	
Months cooling	22	30	9	22	19
counts s isolated	1909	695	3028	1862	
counts s in array	2056	879	3169	1610	
MWd/tU	38588	36405	36581	Void	
Months cooling	9	9	9		20
counts s isolated	2895	2894	2372		
counts s in array	3101	3219	2690	107	
	G	F	E	D	

Fig. 12.

Map of scintillator counting rates after background subtraction for a 4 by 4 array of fuel assemblies.

$$R = 0.459 [T_c^{-0.2} - (T_R + T_c)^{-0.2}]$$

(1)

T_c = cooling time in months

T_R = time in the reactor in months.

where

R = detected gamma-ray counts/second/megawatt days/metric ton uranium (MWd/tU) burnup

Figure 13 shows a mean difference of 22% with the data. The counting rate depends on the details of the

Fig. 13.

Scintillator count rates divided by burnup vs cooling time. The curve was calculated with Eq. (1). The experimental data are for the 4 by 4 array shown in Fig. 12.

power history and the neutronics in the reactor and the gamma-ray transport from the fuel to the scintillator.

B. Ion Chamber

The first series of measurements was for the ion chamber over isolated fuel assemblies and the adjacent voids to determine the collimation geometry producing the minimum signal over an adjacent void. The second series measured the gamma dose at the top of a fuel assembly when additional assemblies were moved into proximity.

1. Isolated Assemblies. For measurements of isolated fuel assemblies, the chamber and tungsten shield were placed at different vertical positions inside the collimator pipe above the fuel assemblies. In addition, various thicknesses of lead absorbers were placed on the bottom of the chamber to determine whether crosstalk could be reduced by removing lower energy gamma rays. Figures 14 through 16 show crosstalk vs ion-chamber height for various absorbers. The crosstalk percentage is used as figure of merit for evaluating the various collimation

Fig. 14.

Ion chamber crosstalk vs ion chamber elevation without a lead absorber. For the points without a collimator, the collimator pipe, ion chamber, and tungsten shield are raised as a unit. For the other points, the collimator pipe remains fixed and the ion chamber and tungsten shield are positioned in the pipe.

geometries. The separation of the two rack locations (PWR-1 and PWR-2) is 35.5 cm and the positioning accuracy is estimated to be ± 2.5 cm. The burnups for PWR-1 and PWR-2 are 35 764 and 31 851 MWd/tU and the cooling times are 11 and 23 months, respectively.

Without a lead absorber (Fig. 14), there is no significant reduction in crosstalk for increasing elevations of the ion chamber. When the collimator pipe, ion chamber, and tungsten shield are raised as a unit, in which case there is no longer any air collimation (Fig. 14), the crosstalk increases with height because the percentage

Fig. 15.
Ion chamber crosstalk vs ion-chamber elevation.

Fig. 16.
Ion-chamber crosstalk vs ion-chamber elevation in the collimator pipe with a 6-mm-thick lead absorber.

path-length difference through water from detector to fuel assembly and from detector to void decreases with height. The error bars shown in Figs. 14 through 16 are determined from variations in the readings on different scales of the electronics or by the observed fluctuations of the most sensitive scale. When a 1.5-mm lead absorber is placed on the bottom of the ion chamber (Fig. 15), the crosstalk is reduced as the detector assembly is raised. Crosstalk less than 5% is achieved at heights above 90 cm. A 6-mm lead absorber reduced the crosstalk at 90 cm to ~3% (Fig. 16).

A possible explanation for crosstalk reduction with the lead absorbers is that the chamber response comes from two sources: (1) unscattered or single scattered gamma rays entering the collimator and being detected by the ion chamber and (2) gamma rays multiple scattering in the water and the collimator wall. The multiple scattered gamma rays will, by virtue of the scattering process, lose energy and, therefore, their energy distribution will be lower than unscattered or single scattered gamma rays. By using the lead absorber to remove the lower energy gamma rays, the chamber preferentially detects the gamma rays that enter the collimator from the top of the fuel assembly (or rack location) rather than those that scatter in from adjacent locations.

Because of the measurements over the isolated assemblies, a collimator height of 90 cm and a 1.5-mm lead absorber were used for the remaining measurements. Although Fig. 15 indicates that a greater elevation might produce a smaller crosstalk, 90 cm was a compromise based on signal levels and statistical precision.

2. Interference from Adjacent Assemblies. Our crosstalk measurements do not include the signal change over one fuel assembly when another assembly is moved into an adjacent position. The signal change was measured by isolating assembly PWR-2 and then moving a similar assembly, PWR-3, into the adjacent (non-diagonal) location (35.5-cm center-to-center separation). The results of these measurements are given in Table I. No change in the signals was observed; that is, the interference was less than the measurement uncertainty ($\pm 8\%$) as determined by repeat measurements. This effect is expected because the top of the fuel assembly will shield, to some extent, the gamma rays from an adjacent assembly. For an isolated assembly the only shielding over the void will be the water between the end of the collimator and the side of the fuel assembly.

TABLE I

ION-CHAMBER SIGNALS FOR ISOLATED AND NONISOLATED ASSEMBLIES

Assembly	Isolated (V)	Adjacent (V)
PWR-2	0.74 ± 0.06	0.72 ± 0.06
PWR-3	0.76 ± 0.06	0.74 ± 0.06

Figure 17 presents data for a 3 by 3 array of fuel assemblies with a void at the center (array element 2,2). Table II shows results of measurements taken for this configuration with the void and then with a fuel assembly placed in the void.

Except for the fuel assembly in location (2,2), the results agree with those from Table I; that is, no increase in the signals was observed when the void was filled. For the void (2,2) the signal is due to the sum of the signals detected from the adjacent assemblies. Comparison of the isolated readings for the assemblies in location (2,1), (2,2), and (2,3) shows that the differences, shown in Table III, are approximately the same.

Unlike the situation for two adjacent fuel assemblies, where the differences are small (Table I), a noticeable background is added to the isolated signal for the larger 3 by 3 array, so that the measured response is 20 to 30% higher than the isolated response. However, the uniformity of the ion-chamber measurements for assemblies with similar burnups is quite good (Table II).

IV. CONCLUSION

Both scintillator and ion-chamber detector systems can be used to measure rapidly (1/min) the gamma-ray signatures of irradiated fuel assemblies in vertical storage racks. The relative gross gamma-ray measurements have been correlated with the declared irradiation histories and the cooling times of selected fuel assemblies. If the histories and the cooling times are provided by the operator or are measured independently, an expected counting rate in the scintillator can be calculated with Eq. (1). The difference between the measured counting rate and that predicted by Eq. (1) has been demonstrated on irradiated PWR fuel assemblies to be $\leq 22\%$.

Ion-chamber measurements show that assemblies with similar irradiation histories have similar gross gamma-ray signals. The measurements can be used to verify rapidly the consistency of a set of fuel assemblies; that is, to identify from which fuel cycle the assemblies were discharged.

Accurate measurement of an array of fuel assemblies depends on the interference from adjacent assemblies, or crosstalk. The amount of crosstalk for both detectors appears to be determined by the collimator geometry and material. The system containing the scintillator has only 2% crosstalk, and a similar value should be possible with the system containing an ion chamber.

Scintillator and ion-chamber detectors are simple, easy to operate, portable, and require only small electronic packages. A scintillator or an ion chamber can be adapted easily to various underwater handling devices; for example, either detector could be incorporated in an underwater telescope for reading fuel-assembly serial

MWd/tU Months cooling	30552 17	31087 17	38309 9	18
MWd/tU Months cooling	32185 22	31851 23 or Void	35764 9	19
MWd/tU Months cooling	38588 9	36405 9	36581 9	20
	G	F	E	

Fig. 17.

Map of the 3 by 3 array of fuel assemblies used with the ion chamber to investigate interference.

TABLE II
ION-CHAMBER SIGNALS AT THE TOP
OF A 3 BY 3 FUEL-ASSEMBLY ARRAY

Assembly Location	Burnup (MWd/tU)	Cooling Time (months)	Signals (V)	
			(2,2) Void	(2,2) Full
(1,1)	30 552	18	0.98 ± 0.08	0.98 ± 0.08
(1,2)	31 087	18	1.26 ± 0.10	1.29 ± 0.10
(1,3)	38 309	18	1.59 ± 0.13	1.62 ± 0.13
(2,1)	32 185	23	0.95 ± 0.08	0.97 ± 0.08
(2,2)	31 851	23	0.39 ± 0.03	0.98 ± 0.08
(2,3)	35 764	11	1.53 ± 0.12	1.54 ± 0.12
(3,1)	38 588	11	1.36 ± 0.11	1.35 ± 0.11
(3,2)	36 405	11	1.38 ± 0.11	1.40 ± 0.11
(3,3)	36 581	11	1.34 ± 0.11	1.36 ± 0.11

TABLE III
COMPARISON OF ION-CHAMBER SIGNALS
FROM FUEL ASSEMBLIES IN THE
3 BY 3 ARRAY AND ISOLATED

Location	Difference (V)
(2,1)	0.23 ± 0.09
(2,2)	0.25 ± 0.09
(2,2)	0.22 ± 0.09

numbers. This would permit the measurement of an assembly while performing an item inventory.

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