LA-UR-80-1797

CONF-800655--7

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SUBMITTED TO: The Institute of Nuclear Materials Management
21st Annual Meeting, Palm Beach, Florida
June 30 to July 1-2, 1980

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SCINTILLATOR SPENT FUEL MONITOR

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ABSTRACT

A monitor for rapidly measuring the gross gamma-ray flux immediately above spent fuel assemblies in underwater storage racks has been developed. It consists of a plastic scintillator, photomultiplier, collimator, and a small battery-powered electronics package. The crosstalk from an isolated fuel assembly to an adjacent void is only about 2%. The mean difference between the measured gamma-ray flux and the flux estimated from the declared burnup and cooling time with a simple formula is 22%.

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,[1,2,3] it is essential that techniques be developed for this task. The techniques must be nondestructive and must impact the facility operator as little as practicable. In particular, fuel movement or the need for a special geometric arrangement of the fuel should be avoided. Only simple, portable instruments that can be used to sample significant fraction of the entire pool inventory at a rate of about one assembly per minute will be considered in this report. More 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] The Cerenkov glow technique, which measures a secondary radiation effect, does not require this.[7,8,9] Because adjacent assemblies are packed close together and may differ greatly in activity, good collimation is necessary to reduce interference from adjacent fuel assemblies (crosstalk) and avoid the need for unfolding techniques. The instrument should be lightweignt so that it can be quickly positioned by hand; it should give an immediate result; it must not be damaged by the high radiation levels; it must give results that are quantitatively precise enough to give a meaningful measurement of the fuel inventory. Several techniques are being actively investigated.[6] Recent reports have described instruments based on the Cerenkov glow[7,8,9] and the ion chamber.[10] In the present report, the scintillator monitor is described.

DESCRIPTION OF EQUIPMENT

Figure 1 shows the scintillator detector assembly. The collimator is an air-filled thin-walled stainless steel tube approximately 1.5-m long with a 24-mm inner diameter. The scintillator is a cylinder of Pilot F* plastic (1.6-mm diameter x 1.6-mm length). An organic scintillator is used because the decay time is short and therefore high counting rates can be tolerated.

The RCA-8053+ photomultiplier is a 50.8-mm diameter tube† with a venetian blind structure and BeO dynode emitting surfaces. At high counting rates photomultipliers suffer fatigue that reduces their gain as a function of time.[11,12] However, this tube suffers little fatigue because the venetian blind structure does not produce a high current density on the dynodes and the BeO dynodes are relatively stable. A smaller diameter tube was not used because it would have had higher current density and therefore more fatigue.

The lead shield (Fig. 1) is necessary because the water 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 manually positioned with a nylon rope. The fins at the bottom allow it to rest on the top of the fuel storage racks.

The high voltage and signal cables were placed inside a tygon tube and connected the underwater detector assembly to an electronics package on the bridge over the pool. The tygon tube also serves as a safety line.

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

EXPERIMENTAL RESULTS

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

In early designs various scintillators and photomultipliers were tested. The liquid scintillators NE-224 and NE-226,++ which are more resistant to radiation damage,[13] were tried but because no damage has been observed with the Pilot F, we chose to use the solid scintillator. Scintillators larger than the present one gave too high a counting rate for the electronics.

Interference between adjacent fuel assemblies is an important effect for a spent fuel monitor. An easily measured parameter that gives some indication of this effect is percent crosstalk, which is defined here as

$$\text{Percent crosstalk} = \frac{\text{(signal in adjacent void)-(background)}}{\text{(signal over isolated assembly)-(background)}} \times 100 \qquad (1)$$

A significant effort was made to reduce the crosstalk by optimizing the collimation. The present collimator is 152.4-cm long and is made of 0.89-mm wall stainless steel tubing. 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 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 high Z material, such as lead, gave approximately 30% less crosstalk but the monitor was too heavy to manipulate by hand. Low Z material, such as PVC plastic, was no better than stainless steel. The effect on the crosstalk of varying the photomultiplier voltage with the threshold discriminator fixed is shown in Fig. 2. This is equivalent to varying the threshold discriminator with the high voltage fixed. Although there is considerable scatter in the data points, it is clear that the minimum crosstalk is achieved at either a very low voltage corresponding to looking at just high energy gamma rays or at a very high voltage corresponding to looking at most of the spectrum reaching the detector, which is dominated by low energy gamma rays. We have chosen to operate at the high voltage end because the counting rate is higher and therefore the counting times can be shorter.

Figure 3 shows a typical map of counting rates with background subtracted for an isolated assembly. Background readings for all scintillator measurements were determined by moving the detector assembly to a section of the pool several meters from any fuel assemblies. Typical background readings were about 342 cps. Statistical uncertainties were typically less than one percent. Uncertainties due to positioning of detector assembly relative to the fuel assembly and electronic drifts contributed an additional five per cent.

Figures 4 and 5 show maps of counting rates for two arrays of two assemblies. The measurements on [illegible]9P are higher than expected on the basis of the isolated measurements. Some of the discrepancy may be due to electronic drifts.

Figure 6 shows a map of counting rates for a 4x4 array of assemblies. Again, the interference is higher than expected. Due to time limitations not all of the assemblies were measured isolated.

The counting rate observed in the scintillator is mainly a function of the irradiation time and the cooling time. Using the approximation of Ref. 14 for the decay heat, we have fitted the following formula for the counting rate divided by the burnup to the scintillator data.

$$R = 0.459 \left[T_C^{-0.2} - (T_R + T_C)^{-0.2} \right] \quad (2)$$

where R = detected gamma-ray counts per second per megawatt days/metric ton uranium burnup

T_C = cooling time in months

T_R = time in the reactor in months

Figure 7 shows the agreement with the data. The mean difference is 22%. Of course, the counting rate really depends on the details of the power history and neutronics in the reactor, and the gamma-ray transport from the fuel to the scintillator. More complicated approximation with more parameters can reduce the mean difference.

CONCLUSION

The scintillator detector system can be used to rapidly (one per minute) measure the gamma-ray signatures of irradiated fuel assemblies in vertical underwater storage racks. The relative gross gamma-ray measurements have been correlated with the declared irradiation histories and cooling times of selected fuel assemblies. If this information is provided by the operator or is measured independently, then Eq. (2) can be used to calculate an expected counting rate in the scintillator. This relationship has been demonstrated on irradiated PWR fuel assemblies with a precision of 22%.

The scintillator detector is simple and easy to operate. It requires only a small electronic package and is highly portable. It can be easily adapted to various underwater handling devices; for example, it could be incorporated in an underwater telescope used for reading serial numbers of fuel assemblies. This would permit the measurement of an assembly while performing an item counting inventory.

ACKNOWLEDGMENTS

J. K. Halbig, D. M. Lee, J. R. Phillips, and L. A. Stovall assisted us in this work. We are indebted to Commonwealth Edison Corporation for assistance in performing many of the measurements. The work was supported by the Office of Safeguards and Security of the Department of Energy and by the International Safeguards Program Office under the direction of the State Department.

FOOTNOTES

* Nuclear Enterprises, Inc., San Carlos, California.

+ RCA Inc., Solid State Division, Electro Optics and Devices, Lancaster, Pennsylvania.

† Norton Corporation, Plastics and Synthetics Division, Akron, Ohio.

** Operated by Commonwealth Edison, Chicago, Illinois.

++ Nuclear Enterprises, Inc., San Carlos, California.

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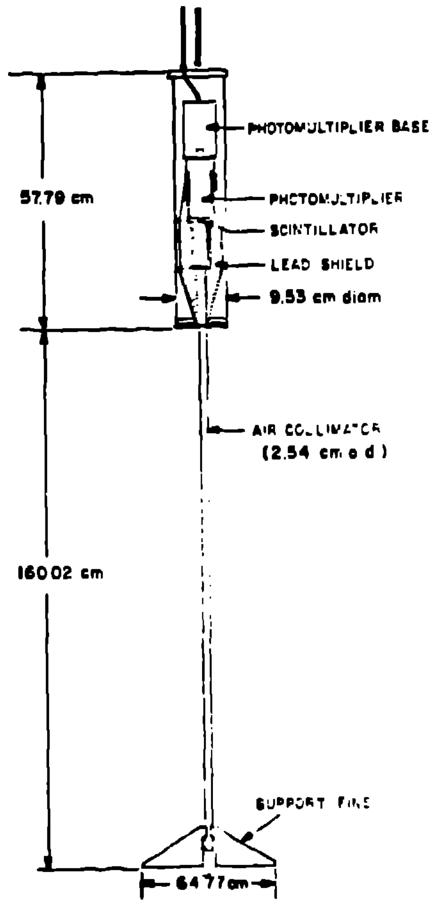

Fig. 1. Detector assembly containing the scintillator.

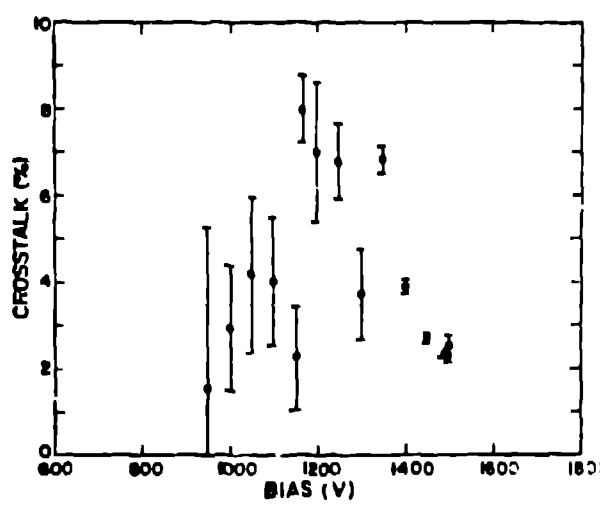

Fig. 2. Scintillator crosstalk from an isolated fuel assembly to an adjacent void as a function of the high voltage on the photomultiplier.

Fig. 3. A typical map of scintillator counting rate after background subtraction for an isolated assembly. The boxes represent storage positions in the spent fuel storage pool.

	P	N	
cps	VOID	VOID -7	18
MWd/MTU Months cooling cps	32185 22 1868	VOID 24	19

Fig. 4. A typical map of scintillator counting rate after background subtraction for a moderately radioactive assembly next to a weakly radioactive one.

	P	N	
cps in array	VOID	VOID 10	18
MWd/MTU Months cooling cps isolated cps in array	32185 22 1868 2037	19826 30 695 718	19

Fig. 5. A typical map of scintillator counting rate after background subtraction for a moderately radioactive assembly next to a strongly radioactive one.

	P	N	
cps in array	VOID	VOID 57	18
MWd/MTU Months cooling cps isolated cps in array	32185 22 1868 2158	35764 9 3028 3072	19

	G	F	E	D	
MWd/MTU	17404	39167	VOID	39536	17
Months cooling	30	4		4	
cps in array	682	6124	231	8036	
MWd/MTU	30552	31087	38309	18666	18
Months cooling	17	17	9	40	
cps in array	1849	2599	2704	806	
MWd/MTU	32185	19826	35764	31851	19
Months cooling	22	30	9	22	
cps isolated	1909	695	3628	1862	
cps in array	2056	879	3169	1610	
MWd/MTU	38588	36405	36581	VOID	20
Months cooling	9	9	9		
cps isolated	2895	2894	2372		
cps in array	3101	3219	2690	107	

Fig. 6. A map of scintillator counting rate after background subtraction for a 4x4 array of assemblies.

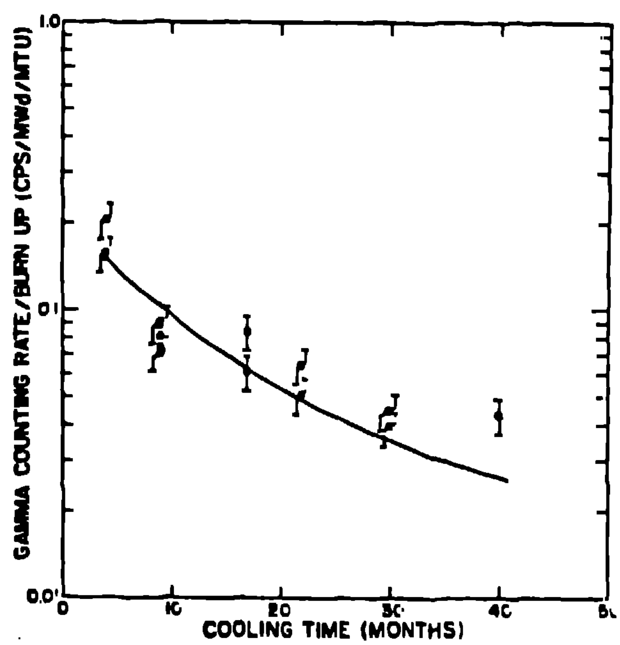

Fig. 7. Scintillator count rates divided by burnup versus cooling time. The curve was calculated with Eq. (2). The experimental data are for the 4x4 array shown in Fig. 6.