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A NONINTRUSIVE IRRADIATED FUEL INVENTORY CONFIRMATION TECHNIQUE

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Abstract

Successful tests showing correlation between the intensity of the Cerenkov glow surrounding irradiated fuel assemblies in water-filled spent fuel storage ponds and the exposure and cooling times of assemblies have been concluded. Fieldable instruments used in subsequent tests confirmed that such measurements can be made easily and rapidly, without fuel assembly movement or the introduction of apparatus into the storage ponds.

1. Introduction

A signficant fraction of the special nuclear material in the fuel cycle is represented by the plutonium and unburned ^{235}U in irradiated fuel assemblies. Almost all of these assemblies are in water-filled storage ponds at reactor sites. Consequently, confirmation of declared inventories of fissile material in irradiated fuel in these storage ponds is one of the responsibilities of safeguards inspectors. Such confirmations can be attempted by a staged approach: beginning with item counting and proceeding through obtaining evidence of irradiation exposure, identifying fission product signatures, correlating measured neutron and gamma ray signals and signatures with fissile loadings, and perhaps concluding with a "direct" determination of fissile content by neutron interrogation. Progressing beyond item counting and evidence of irradiation exposure requires a commitment of signficiant resources and is consequently limited to quite small sample sizes in cases of large inventories. Thus, the IAEA (International Atomic Energy Agency) relies on containment and surveillance for irradiated fuel safeguards, resorting to NDA measurements only for establishing inventories or for reverificaton following the failure of the containment and surveillance system. Because most NDA measurements are limited to small samples of the inventory, it seems desirable that relative attribute measurements, normalized to the NDA results, be made on the majority of the fuel assemblies or bundles, or even on the entire inventory. Such measurements would allow also for consistency checks among repeated inspections.

Under the US program of technical assistence to international safeguards, we began investigating possible approaches to irradiated fuel attribute measurement and monitoring techniques.[1] We sought to satisfy several criteria we deemed important for routine inspection purposes, viz., ease of implementation, simple interpretation of any measurement data, and minimal impact on the facility operator's schedule. The technique[2] most suitably satisfying these criteria is that of imaging and possibly measuring the intensity of the Cerenkov glow that results from the interactions of the radiation from fission products in the assemblies or bundles with the water in the storage ponds. Currently, IAEA inspectors visually confirm the movement and storage of freshly discharged fuel assemblies during refueling operations, when the Cerenkov glow from such intensely radioactive assemblies is visible. Although shortly thereafter the glow is not visible to the unaided eye, electronic light amplification renders the low light levels measurable. Because water has a very small attenuation coefficient for visible and near-ultraviolet (uv) light, the measurements can be made from above the storage pond surface, obviating the introduction of equipment into the pond. For the standard vertical LWR assembly storage, the penetrations in the upper mechanical structure of the assembly serve as Cerenkov light channels, allowing sampling of the nuclear radiation intensity to be deeper than the top of the fuel assembly. The Cerenkov light intensity measurement is thus considered less susceptible to crosstalk among adjacent assemblies than are nuclear radiation intensity measurements made at the tops of the assemblies.

The theoretical basis for the technique is described in some detail in one of our earlier papers[3] and will not be repeated here. Suffice it to say that the major portion of the Cerenkov emissions is believed to be caused by the fission product decay gamma rays. Secondary electrons of energy greater than 0.6 MeV in the water directly generate the Cerenkov photons, and these electrons are produced both in the water and in the cladding. The number of Cerenkov photons per primary gamma ray photon is strongly dependent on the gamma ray energy. Because both the intensity and the spectrum of the fission product gamma rays is dependent on burnup and cooling time, it is expected that the Cerenkov glow intensity will carry the burnup and cooling time information. Our results have given us confidence that this is the case.

The Cerenkov glow can be imaged and intensities measured in several ways. We have concluded preliminary tests of the technique using imaging instruments that included a silicon-intensified target (SIT) video camera, an itensified silicon-intensified target (ISIT) video camera, a prototype hard-film camera that incorporates a microchannel plate image intensifier, and a standard hard-film camera with uv-transmitting lenses. Images of both MTR (Materials Testing Reactor) plate-type fuel elements from the Los Alamos Scientific Laboratory OWR (Omega West Reactor) and commercial PWR (Pressurized Water Reactor) pin-type assemblies from the Zion Nuclear Station have been made. The Cerenkov intensity was quantified by photometric measurements of selected bright spots on the recorded images corresponding to the water-filled interstices of the assemblies. Results of these earlier measurements are contained in separate reports.[3,4]

In this report, we describe exercises at the Morris, Illinois irradiated fuel storage facility, owned and operated by the General Electric Company, and at the NRX irradiated fuel storage bay at the Chalk River National Laboratory, operated by Atomic Energy of Canada, Limited. Both PWR and BWR (Boiling Water Reactor) assemblies were imaged at the Morris facility, and measurements were made of the Cerenkov glow from a number of the PWR assemblies. Thirteen CANDU bundles, of the 19-pin type, were imaged at CRNL, and coarse estimates were made of the Cerenkov glow intensity of each.

2. Experimental Method

Morris

Our earliest quantitative data from PWR assemblies at the Zion Station had been obtained by off-line analysis of video-taped images of the glow from the assemblies.[3] These data confirmed our predictions, but the intensities we measured were amplified intensities because the output of an ISIT video camera was used to record the images. In the Morris exercise, we desired to measure the emitted Cerenkov radiation directly and chose to use a high-gain spot photometer with digial readout* and an ISIT TV camera attached to the viewing lens to assist with alignment in the darkened storage bay. The majority of ambient lighting had been extinguished to reduce the background. The requirement for a darkened storage bay is currently indispensible because the equipment we now use is sensitive to a broad spectrum of light. We foresee the possiblity of relaxing this requirement by a judicious choice of photosensitive response, tailored lighting spectrum, and low band pass filtering of the incoming spectrum. The photometer/ISIT camera combination (weighing approximately 20 kg) was attached to an articulating fixture, which was in turn clamped to the railing of the bridge that travels over the storage pond. The bridge and fixture were used to align the instrument over the selected fuel assembly and the photometer readings were recorded.

In addition to the photometer, another system was used to estimate the amplified Cerenkov glow intensity. This system consisted of a standard 135-mm telephoto lens, an electrostatically-focused night vision device (NVD)** with a gain estimated to be approximately $3x10^4$, and a SLR automatic camera back coupled to the output phosphor of the NVD. The total weight of this system is approximately 10 kg. Estimates of the glow intensities were made using the automatic exposure feature of the camera. Through-the-lens metering provides for an optimum exposure on the film plane. Thus, for a fixed aperture, the length of time the shutter remains open is a measure of the intensity of illumination of the film plane and hence of the brightness of the output phosphor, and of the Cerenkov glow, under the assumption of linearity of the NVD gain. We had the NVD modified to eliminate the automatic brightness control feature to provide for a linear response. This instrument was aligned over the assemblies and shutter speeds recorded for each assembly.

A third instrument was used in yet another way to estimate the glow intensity. This instrument consisted of a 75-mm telephoto lens, a proximity-focused NVD*** with a gain of approximately $1.5x10^4$, and a biocular viewer. The total weight of this instrument is approximately 2 kg. An "image-extinction" type of determination was made using the distinctive circular poison pin hole images in the PWR assemblies as targets. With these holes sharply defined for large lens aperture and full gain on the NVD, the aperture was stopped down until the image of the holes became "fuzzy". The aperture settings for the onset of "fuzziness" or the extinction of the images were recorded. It is assumed these settings are directly related to the Cerenkov intensity.

Chalk River

Only the electrostatically-focused NVD, 135-mm lens, and SLR camera back were used in the exercise with CANDU bundles. Images were made of the bundles in storage baskets with axes vertical, and lying in trays with axes horizontal. Shutter speed measurements were also made in the same way as for the Morris exercise. The major objective in this exercise was to obtain the visual information for CANDU bundles.

Results

Morris. The irradiated fuel assemblies are stored vertically in baskets, the PWR basket holding four assemblies and the BWR basket holding nine assemblies. The initial measurements were designed to test reproducibility of measurements with the photometer unit because alignment over the assemblies is deemed important. This test was conducted on one row of PWR baskets containing 52 assemblies. The results are shown in columns 4 and 5 of Table I. The burnup and cooling time values are those provided by the operator.

* Pritchard Model #190A

** Javelin Model #226

*** Javelin Model #222

TABLE I

RESULTS OF THE MEASUREMENTS ON PWR ASSEMBLIES AT THE MORRIS FACILITY.
THE DATES OF THE MEASUREMENTS ARE INDICATED IN THE COLUMN HEADINGS.
(06/14/79 and 06/18/79)

Assembly Location	Burnup, D GWD/MTU	Cooling Time, Tc days	Photometer Readings, I			$\bar{I}$	$\bar{I}/B$	Shutter Speed, Ts Secs.	BT_s	$\bar{I}T_s$
			I_1 (6/14)	I_2 (6/18)	I_1/I_2					
I 15 lu	26.17	1300	2.02×10^{-3}	2.26×10^{-3}	.89	2.14×10^{-3}	8.18×10^{-5}	76	1.99×10^{3}	1.63×10^{-1}
ll	26.40	1300	2.18	2.3	.95	2.24	8.48	75	1.98	1.68
I 14 lu	28.90	1000	2.0	2.17	.92	2.08	7.20	68	1.96	1.41
ll	18.47	1700	0.77	0.696	1.11	0.733	3.97	174	3.21	1.28
13 lu	31.79	1000	2.76	2.77	1.00	2.76	8.68	65	2.07	1.79
ll	32.72	1000	2.80	2.65	1.06	2.72	8.31	94	3.08	2.56
12 lu	30.57	1000	2.03	1.96	1.04	2.00	6.54	75	2.25	1.50
ll	33.09	1000	2.60	2.46	1.06	2.53	7.64	80	2.65	2.02
11 lu	20.79	1700	0.96	0.885	1.08	0.922	4.43	171	3.56	1.58
ll	20.81	1700	1.23	1.09	1.13	1.16	5.57	165	3.43	1.91
10 lu	31.64	1000	2.73	2.63	1.04	2.68	8.47	79	2.50	2.12
ll	33.05	1000	2.65	2.53	1.05	2.59	7.84	86	2.84	2.22
9 lu	20.93	1700	1.13	1.09	1.04	1.11	5.30	170	3.56	1.89
ll	20.38	1700	1.02	0.93	1.10	0.98	4.81	177	3.61	1.73
8 lu	10.84	3400	0.570	0.597	.95	0.584	5.39	166	1.80	0.97
ll	10.90	3400	0.620	0.567	1.09	0.594	5.45	165	1.80	0.98
7 lu	19.28	3400	1.12	1.16	.96	1.14	5.91	169	3.26	1.93
ll	19.12	3400	1.03	1.04	.99	1.04	5.44	165	3.15	1.72
6 lu	19.30	3400	1.03	1.08	.95	1.05	5.44	165	3.18	1.73
ll	19.01	3400	1.06	1.20	.88	1.13	5.94	165	3.14	1.86
5 lu	19.11	3400	1.00	0.99	1.01	1.00	5.27	165	3.15	1.65
ll	19.01	3400	0.95	0.97	.98	0.96	5.05	165	3.14	1.58
4 lu	18.95	3400	1.20	1.3	.92	1.25	6.60	165	3.13	2.06
ll	19.62	3400	0.98	1.02	.96	1.00	5.10	165	3.24	1.65
3 lu	19.11	3400	1.13	1.11	1.02	1.12	5.86			
ll	18.75	3400	0.75	0.690	1.09	0.72	3.84			
I 15 ru	26.45	1300	2.40	2.72	.88	2.56	9.68	64	1.69	1.64
rl	26.08	1300	3.22	3.20	1.01	3.21	12.31	69	1.80	2.21
14 ru	23.57	1900	0.98	1.00	.98	0.99	4.20	173	4.08	1.71
rl	31.71	1000	3.20	3.35	.96	3.28	10.34	42	1.33	1.38
13 ru	32.73	1000	3.20	2.85	1.12	3.02	9.23	71	2.32	2.14
rl	33.16	1000	4.0	3.74	1.07	3.87	11.67	52	1.72	2.01
12 ru	31.09	1000	3.4	3.20	1.06	3.30	10.61	55	1.71	1.82
rl	30.92	1000	3.5	3.24	1.08	3.37	10.90	96	2.97	3.24
11 ru	20.91	1700	1.44	1.41	1.01	1.43	6.84	173	3.62	2.47
rl	20.84	1700	1.42	1.24	1.14	1.33	6.38	134	2.79	1.78
10 ru	32.39	1000	3.90	3.68	1.06	3.79	11.70	44	1.42	1.67
rl	31.99	1000	3.56	3.30	1.08	3.43	10.72	69	2.21	2.37
9 ru	20.98	1700	1.58	1.52	1.04	1.55	7.39	114	2.39	1.77
rl	20.36	1700	1.52	1.44	1.06	1.48	7.27	115	2.34	1.70
8 ru	11.27	3400	0.78	0.730	1.07	0.755	6.70	169	1.90	1.28
rl	10.76	3400	0.79	0.70	1.13	0.745	6.92	165	1.78	1.23
7 ru	19.[illegible]5	3400	1.20	1.23	.98	1.22	6.30	168	3.25	2.05
rl	19.30	3400	1.34	1.29	1.05	1.32	6.84	123	2.37	1.62
6 ru	18.74	3400	0.92	0.90	1.02	0.91	4.86	167	3.13	1.52
rl	19.40	3400	1.18	1.18	1.00	1.18	6.08	148	2.87	1.75
5 ru	19.58	3400	1.34	1.27	1.06	1.30	6.64	160	3.13	2.0[illegible]
rl	19.61	3400	1.34	1.22	1.10	1.28	6.53	161	3.16	2.06
4 ru	19.59	3400	1.42	1.33	1.07	1.38	7.04	168	3.29	2.32
rl	19.54	3400	1.42	1.36	1.04	1.39	7.11	157	3.07	2.18
3 ru	19.62	3400	1.46	1.35	1.08	1.40	7.14	137	2.69	1.92
rl	19.42	3400	1.47	1.29	1.14	1.38	7.11	170	3.30	2.[illegible]5

The upper half of the table represents the left side of the baskets in row I of the pond and the lower half represents the right side of the row. The photometer was positioned over the left side and the photometer readings recorded for each assembly on the left side. The bridge was returned to the top of the row and the photometer positioned over the right side and the photometer readings recorded for each assembly on the right side. At the conclusion of this series, the entire photometer/ISIT camera and mounting fixture were removed from the bridge railing, and four days later the process repeated. Approximately 20 assemblies per hour were measured in this way. Column 4 represents the first series of readings and column 5 the second. Column 6 is the ratio of these readings, showing an average 3% bias and a 7% standard deviation about the biased mean.

The average measured intensities are given in column 7 of Table I. Only the assemblies with 3400 days cooling time have a reasonably varied burnup. There is a group of assemblies with an average of 19.27 GWD/MTU and another group with an average of 10.94 GWD/MTU. The ratio of these two burnup values is 1.76. The ratio of the corresponding average measured Cerenkov glow intensities is 1.73, in good agreement. Table II is a compilation of these averages for the various burnup/cooling time groupings. The last column of Table II is the normalized calculated value of the Cerenkov intensities. The average ratio of measured to calculated values is unity with a standard deviation of 18%.

TABLE II

RESULTS FROM GROUPING THE DATA FROM TABLE I. THE CALCULATED INTENSITIES ARE ALSO INCLUDED.

$\bar{B}$,GWD/MTU	T_C,days	$\bar{I}_{meas}$	I_{calc}
31.84	1000	2.96 ± 0.58	3.56
26.28	1300	2.54 ± 0.48	2.31
20.80	1700	1.22 ± 0.27	1.46
19.27	3400	1.16 ± 0.18	1.00
10.94	3400	0.67 ± 0.09	.56

Other correlations are suggested in the last two columns of Table I. The entries in the second to last column are the products of the burnup values and the recorded shutter speeds for the electrostatically-focused NVD. Such a correlation is expected because the through-the-lens metering system provides an optimum exposure, and the incoming light is integrated until this exposure level is reached. The product of the incoming light, presumed to be proportional to B, and the time the shutter remains open, T_s, should therefore be a constant. Two possible sources of error are known when using this instrument: the gain control potentiometer does not have detents, so gain variations can occur by inadvertent contact with the potentiometer, and, in order to limit the field-of-view to one assembly for the intensity estimates, a framing iris within the NVD case was used, and may not have been always returned to a standard position. A third difficulty that invalidates a large portion of the data was discovered at the conclusion of the exercise. The shutter on the automatic camera is limited to a maximum time in the neighborhood of 160 seconds. An improvement in the specular reflection of the film plane in the camera, e.g., with a mirror or flat white surface, has subsequently been shown to improve this condition markedly. Excluding those data for $T_s \geq 160$ seconds, the product BT_s is found to be constant within a standard deviation of 22%. A similar result is obtained for the product $\bar{I}\ T_s$, which has a standard deviation of 21% about a constant value.

An estimate of crosstalk among assemblies was made for the PWR assemblies in the storage basket. Two assemblies with comparable burnup and cooling time were isolated and the Cerenkov intensities measured for each using the photometer/ISIT camera instrument. The assemblies were then placed as close to each other as allowed by the storage pond basket indexing fixtures. The center-to-center separation was on the order of 36 cm. The intensities were again measured. There was no statistically significant differences between the average intensities for the isolated and adjacent assemblies.

The results of the image "extinction" method using the proximity-focused NVD are given in Table III. Because this method involves the subjective judgment of the observer, we refrain from comparing one observer with another. The aperture settings required for the range of assembly brightness represented in this set was from f/22 to f/5, a dynamic range of over 20, and yet the burnup values and aperture sizes track within 20% on average without taking cooling time into consideration. Approximately 40 assemblies per hour were examined using this method.

Chalk River. Thirteen NPD (Nuclear Power Demonstration) reactor irradiated bundles and one fresh fuel bundle of the 19-pin type were used to demonstrate the technique on CANDU fuel. The burnup and cooling time values for the irradiated bundles are given in Table IV, along with the values of camera shutter speeds recorded using the electrostatically-focused NVD on isolated bundles. The values in the second to last column are the calculated Cerenkov photon intensities. The calculations for these CANDU bundles and the PWR assemblies of Table I assume a uniform burnup rate, which is legitimate for PWR assemblies under good fuel management programs. However, CANDU bundles experience different burnup rates depending on the fuel channel they travel through, and the uniform rate model is expected to be faulty but not so much as to account for the three obvious outliers. With the exception of these three bundles (#5445, #GC020W, #5391), the product of T_s and I_{calc} is constant within 20%. We have no explanation for the discrepancies noted for the outliers.

The fresh fuel bundle was used to simulate a dummy bundle among irradiated bundles. The distinction between the images of the fresh fuel bundle and even the weakest of the irradiated bundles was striking, confirming the conviction that dummy bundles (unirradiated) can be spotted if an optical path is open.

Conclusions

We have continued to show the Cerenkov glow imaging and measuring technique to be promising for attribute measurements of irradiated fuel. Simple instruments have been used in exercises with both LWR assemblies and CANDU bundles. Direct measurements of the emitted radiation can be made using the photometer/ISIT camera combination, with reasonable precision (10%) for repeated trials, and fair accuracy (18%) with respect to calculations based on operator-supplied burnup and cooling time values. The NVD based instruments are not intended primarily for quantitative purposes, but the exercise reported here was to give assurance that the amplified Cerenkov glow tracked the emitted Cerenkov glow reasonably well. The ability to spot dummy assemblies or bundles was also demonstrated. A new instrument based on a direct quantification of the amplified light from the NVD is under construction.

TABLE III

RESULTS OF THE IMAGE "EXTINCTION" METHOD USED BY THREE DIFFERENT OBSERVERS.

Burnup/Aperture Size

T_c	Observer #1	Observer #2	Observer #3
1300	1.64×10^{-3}	1.64×10^{-3}	1.19×10^{-3}
1300	1.65	1.56	1.20
1300	1.65	1.23	1.20
1300	1.18	1.18	1.18
1000	1.61	1.31	1.31
1900	1.57	1.47	1.68
1700	1.68	1.15	1.03
1000	1.98	1.44	1.44
1000	1.99	1.44	1.67
1000	2.18	1.72	1.72
1000	2.52	1.72	1.49
1000	2.07	1.51	1.51
1000	2.18	1.91	1.53
1000	2.59	2.07	1.55
1000	1.49	0.95	1.04
1000	1.93	1.63	1.93
1700	1.89	2.08	1.16
1700	1.90	1.90	1.16
1700	2.08	1.89	1.49
1700	1.89	1.89	1.49
1000	1.98	1.44	1.98
1000	2.31	1.70	2.02
1000	2.06	1.50	1.50
1000	2.13	1.45	1.60
1700	1.90	1.49	1.50
1700	2.10	1.31	1.31
1700	1.85	1.27	1.46
1700	2.04	1.27	1.45
3400	1.55	1.55	1.55
3400	1.13	1.25	1.61
3400	1.95	1.21	1.56
3400	2.15	1.34	1.54
3400	1.48	1.75	1.48
3400	1.49	1.76	1.49
3400	1.91	1.91	1.36
3400	1.75	1.75	1.38
Averages			
1000	2.07 ± 0.30	1.56 ± 0.27	1.59 ± 0.26
1300	1.53 ± 0.23	1.41 ± 0.22	1.19 ± 0.01
1700	1.92 ± 0.13	1.57 ± 0.35	1.34 ± 0.18
3400	1.68 ± 0.33	1.56 ± 0.27	1.50 ± 0.09
Overall	1.87 ± 0.32	1.55 ± 0.28	1.46 ± 0.24

TABLE IV

RESULTS OF THE MEASUREMENTS MADE OF THE CANDU BUNDLES. CALCULATED INTENSITIES ARE ALSO INCLUDED.

Bundle Number	Burnup, B, GWD/MTU	Cooling Time, T_c months	Shutter Speed, T_s Seconds	I_{calc}	$T_s I_{calc}$
BF072C	8.2	10	6.06	6.49	39.33
BF071C	8.9	10	5.55	6.88	38.18
5759	4.4	10	16.04	3.97	63.68
5445	7.8	10	17.90	6.26	112.05
BF041	4.8	34	45.22	0.99	44.77
AF003C	10.0	22	14.90	3.47	51.70
DC003W	10.4	20	13.86	4.03	55.86
GC020W	6.8	18	39.03	3.32	129.58
5391	6.5	20	32.90	2.83	93.11
BF024C	8.5	18	11.75	3.94	46.29
LC011C	11.3	27	13.22	3.78	49.97
AF004C	10.0	22	14.65	3.47	50.84
BF022C	10.8	18	15.68	4.67	73.22

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