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NEUTRON DOSIMETRY WITH THE ORNL BADGE

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C. D. Berger and B. H. Lane

INTRODUCTION

Personnel monitoring is an integral part of the Oak Ridge National Laboratory (ORNL) health physics program. The reasons for maintenance of an external dose monitoring program include the following: (1) the Department of Energy (DOE) Order 5480, "Standards for Radiation Protection," specifies that personnel monitoring must be performed if the expected whole body dose equivalent is greater than 10% of the quarterly standards for occupational workers; (2) ALARA goals can be more effectively evaluated; (3) integrated exposure records may be necessary in possible litigation involving radiation exposure; and (4) employees can be more easily reassured that they are not being unknowingly, unnecessarily, or accidentally exposed to radiation.

The ORNL personnel dosimeter (badge) must provide radiation dose information for personnel working in a wide range of radiation environments. Recent changes in monitoring requirements and performance criteria have necessitated changes in the basic badge components and in methods of data interpretation. Because of the many different exposure environments at ORNL, the badge must function as an identifier of the radiation type. Consequently, it must be a spectrometer as well as a dosimeter. This report describes the type of badge in use for neutron dosimetry, outlines current dose determination algorithms, and presents intercomparison results that demonstrate the effectiveness as well as the limitations of the badge.

BADGE COMPONENTS AND DESIGN

There are five types of ORNL badges, designated the red-, yellow-, green-, blue-, and white-dot badges. Table 1 shows the purpose of each type:

Table 1. ORNL Badges

Type	User	Purpose
Red-dot	ORNL radiation workers	β, γ, n dosimetry
Yellow-dot	ORNL radiation workers	β, γ dosimetry with an indication of neutron exposure
Green-dot	ORNL employees - special tasks	β, γ dosimetry with an indication of neutron exposure
Blue-dot	Non-employees, visitors	β, γ dosimetry with an indication of neutron exposure
White-dot	Employees, areas, facilities, etc.	Experimental (special design)

The ORNL red-dot badge contains the most comprehensive compliment of radiation dosimeters. Therefore, it will be the topic of this report.

The ORNL red-dot badge is composed of four basic parts: (1) a laminated identification insert, (2) a front frame, (3) a filter assembly (slide), and (4) the badge backing. Each of these parts, except for the laminated insert, are molded from high-impact styrene. The badge contents are secured with small metal latches, allowing entry with a magnetic opener only. The entire badge is approximately 4.6 cm wide, 7.6 cm long, and 0.8 cm deep.

The filter assembly holds four different absorbers: a window (60 mg/cm^2); a plastic filter (160 mg/cm^2); an aluminum filter (405 mg/cm^2); and a 1-mm-thick cadmium filter. Density thicknesses shown include the laminated identification insert as well as the respective filters.

Each badge contains a thermoluminescent dosimeter (TLD) card which holds six TLDs. A TLD-600/TLD-700 pair, 0.035-cm-thick, is located behind both the cadmium and aluminum filters. A TLD-700, 0.015-cm-thick, is positioned behind both the window and plastic filters. A sheet of beta/gamma photographic film (Eastman Type II) is positioned behind the TLD slide, and is used to supply supplementary information in the event of abnormal TLD readings.

Until recently, a vapor-sealed packet of Eastman NTA (Type A) film was positioned behind the beta/gamma film. Because of poor film quality, a high neutron energy detection threshold, and labor/time-intensive processing requirements, NTA is no longer used in the badge routinely. Special badges (white-dot) contain NTA when high-energy neutron measurements are needed.

THEORY

Neutron fields at ORNL range in energy from thermal to several million electron volts. To date, no neutron dosimetry system demonstrates linear response over this energy range. Thus, assessment of the field quality is a critical part of the ORNL neutron dosimetry program.

The ORNL red-dot badge uses a combination of direct TLD measurement and TLD albedo measurement. The direct measurement works on the principal that TLD-600 chips, enriched in ^{6}LiF, are responsive to thermal neutrons by the ^{6}Li(n,α)^{3}H interaction. The TLD-600 behind the aluminum filter responds to thermal neutrons (direct) as well as high-energy neutrons that are moderated and "reflected" by the body. The TLD-600 behind the cadmium filter responds only to reflected, or albedo neutrons. The TLD-700 chips, also behind the aluminum and cadmium filters, respond to gamma radiation, with little efficiency for neutrons. These chips are used to provide gamma dose (penetrating) as well as to account for gamma contribution and cadmium capture gamma response in the TLD-600. The ratio of gamma-corrected TLD-600 (cadmium) to TLD-600 (aluminum) is used as an indicator of neutron energy, and thus the quality of the neutron field.

The red-dot badge also contains two thin (0.015-cm) TLD-700 chips (behind a window and a plastic filter) used for shallow dose estimation. The theory behind this procedure is discussed in Dosimetry with the ORNL Badge, 1978.[1]

CALIBRATION

Each TLD-600 and TLD-700 chip in the ORNL inventory is irradiated to 100 mRad with a 98.5 mCi ^{222}Ra source. The chips are read with an Eberline TLD reader, and paired, based on relative response. Chips with read variation greater than ± 5% of the average response are discarded. The chips are then loaded into red-dot badges.

To determine the gamma-equivalent response vs total dose for each TLD-600/TLD-700 pair, ten red-dot badges containing matched TLDs were irradiated to 20, 50, 100, 250, 500, 1000, and 2000 mRem. Average response was determined after each irradiation. Linear curves were fit to the data. Table 2 shows the equations that describe each curve.

Table 2. Gamma-equivalent response vs total dose (millirem)

TLD type	Filter	Equation[a]	Regression coefficient[b]
700	Aluminum	y = 1.068x - 4.593	0.998
700	Cadmium	y = 1.135x - 4.663	0.998
600	Aluminum	y = 1.171x - 6.785	0.998
600	Cadmium	y = 1.267x - 8.592	0.998

[a]y = dose (millirem), x = response.

[b]Regression coefficients of 1.0 indicate a perfect fit of data to the curve.

The TLD-700 (aluminum) equation in Table 2 provides an estimate of the penetrating radiation dose (DC).

Neutron response of the TLD in the ORNL badge was determined by irradiation of badges at the Oak Ridge National Laboratory Health Physics Research Reactor (HPRR), operated by the Dosimetry Applications Research Facility staff. The HPRR is a small (20 cm diam x 23 cm high), unmoderated fast reactor, capable of 10^{17} fissions in a 60-μs pulse. The fuel is enriched uranium alloyed with nickel-coated molybdenum. Table 3 denotes the neutron energies which are obtainable by changing the shielding around the reactor.

Table 3. Median and mean neutron energies at the HPRR vs shield type

Shield type	Median energy (keV)	Mean energy (keV)
None (bare)	780.0	1280
Steel	340.0	580
Concrete	3.3	560
Lucite	0.07	640

Five red-dot badges were irradiated with varying shield types in order to determine a neutron dose-to-response calibration factor as well as relative energy response. The best method of deriving dose-equivalence from the data acquired is by employing the following calculation method:

1. Gamma-equivalent response for each TLD-600 and TLD-700 in the badge is determined as shown in Table 2.

2. T_1 is calculated by subtracting the corrected response of the TLD-700 (cadmium) chip from the TLD-600 (cadmium) chip. (T_1 is the albedo response under the cadmium filter.)

3. T_2 is calculated by subtracting the response of the TLD-700 (aluminum) chip from the TLD-600 (aluminum) chip. (T_2 is the incident and albedo response under the aluminum filter.)

4. $A = (T_2 - T_1)/T_2$, which indicates the response for incident thermal neutrons.

5. $R = T_1/T_2$, which indicates the quality of the neutron spectrum.

6. The calibration factor, determined empirically, is:

$$CAL = 1.46e^{-7.64(AR)} \quad .$$

7. Neutron dose (millirem) is determined by multiplying T_1 by CAL.

INTERCOMPARISON RESULTS

Twenty-eight ORNL red-dot badges were sent to the Tenth Personnel Dosimetry Intercomparison Study (PDIS), run by the Health and Safety Research Division at ORNL on April 9, 1984. The badges were mounted on the front, side, and back surfaces of lucite slab phantoms (40 cm x 40 cm x 15 cm), whose front edges were three meters from the HPRR vertical centerline. Three badges were irradiated in this fashion for each of eight exposure conditions (shield configurations). Table 4 is a summary of results.

Table 4. Tenth PDIS results

Shield type	Dose given[a] (millirem)		Dose measured[a,b] (millirem)	
	Neutron	Gamma	Neutron	Gamma
Bare	59	3	51	3
Bare	976	23	1059	21
Concrete	45	3	29	3
Concrete	881	41	845	42
Lucite	53	8	53	8
Lucite	1019	132	1127	138
Lucite[c]	51	570	50	549
Concrete[c]	43	842	59	853

[a]The number of observations made was not sufficient to calculate dose uncertainty values.

[b]Measured only by dosimeter positioned on the front of the slab phantom.

[c]Exposures enhanced with a ^{137}Cs source.

DISCUSSION

Table 5 shows the relative error for the ORNL red-dot badge in the Tenth PDIS:

Table 5. Measured-to-true dose ratios for the Tenth PDIS

Run	Shield type	Neutron[a]	Gamma[a]
1	Bare	0.86	1.00
2	Bare	1.09	0.91
3	Concrete	0.64	1.00
4	Concrete	0.96	1.02
5	Lucite	1.00	1.00
6	Lucite	1.11	1.05
7	Lucite[b]	0.98	0.96
8	Concrete[b]	1.37	1.01

[a]The number of observations made was not sufficient to calculate dose uncertainty values.

[b]Exposures enhanced with a ^{137}Cs source.

All gamma "measured-to-true" dose ratios and all neutron ratios, except runs 3 and 8 fall within ± 20%; an error range deemed acceptable by ORNL Radiation Dosimetry staff. The 36% and 37% error noted in runs 3 and 8, respectively, may be due to the low total neutron exposure to each badge. Since only one badge was used in each case, it is not possible to determine the statistical significance of the difference between the true and measured dose.

Although these results look encouraging, it is important to note that the ORNL red-dot badge was calibrated originally by exposures from the HPRR, the same source of neutrons used in the Tenth PDIS. Therefore, acceptable results were expected. The real test of the capabilities of the ORNL red-dot badge will come when other sources of neutrons are available for test and intercomparison.

Recent documents such as the Department of Energy (DOE) Laboraory Accreditation Program for Personnel Dosimetry Systems[2] and American National Standard for Dosimetry - Personnel Dosimetry Performance Criteria for Testing[3] recommend the use of ^{137}Cs for high-energy gamma-ray photon calibration and D_2O-moderated ^{252}Cf for fission neutron (as well as high-energy photon) calibration, with test categories in the range of 0.03-10 and 0.15-5 rem, respectively. Since these sources were not available at the time of dosimeter calibration, it is not known whether the ORNL red-dot badge would meet the recommended tolerance levels. When these sources become available for use, it may be necessary to adjust the analytical methods described within this report.

Finally, it is important to note that the red-dot badge is being used in this report as a "neutron spectrometer" as well as a neutron dosimeter. Because of the non-linear energy response of TLD, this technique should be used only as an approximation of true neutron dose when knowledge of the neutron spectrum does not exist. When possible, spectral quality should be determined in all work areas where there is a potential for personnel exposures to neutrons, and the proper calibration factor used when interpreting gross TLD data.

CONCLUSIONS

The ORNL red-dot badge was designed to provide radiation dose estimation for personnel working in neutron, gamma, and mixed-field environments. The primary quantitative radiation-sensing components in the red-dot badge are TLDs, used to measure direct neutron, gamma, and albedo neutron response. The TLDs were calibrated with radium gammas and HPRR-generated neutrons. In this study, the badge is used as a crude spectrometer as well as a dosimeter. Intercomparison results from the Tenth PDIS are favorable, as would be expected since the exposures in the intercomparison were from the same source as the original calibrations. Other neutron- and gamma-emitting sources are being sought in order to confirm the sensitivity of the red-dot badge in a wide range of radiation environments. Whenever possible, dosimeter calibration factors should be determined from independent measurements of neutron spectral quality.

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