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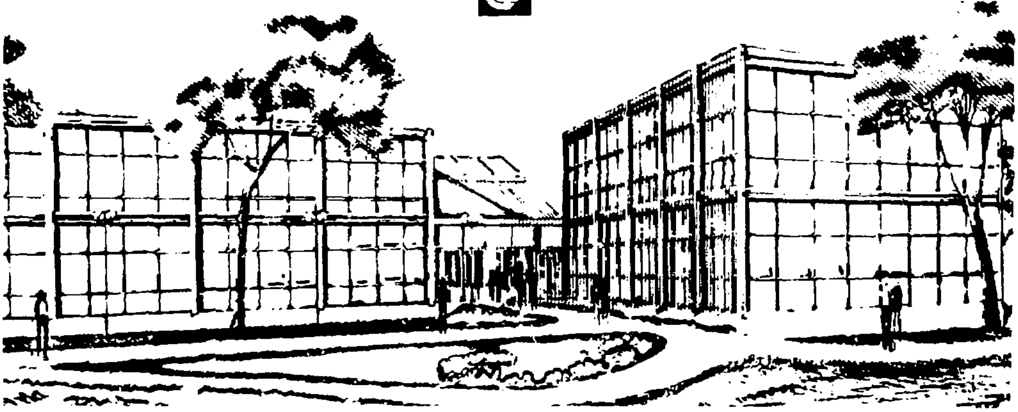

ALBEDO-NEUTRON DOSIMETRY STUDIES AT LAWRENCE LIVERMORE LABORATORY*

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This report summarizes studies performed since the last Workshop meeting. The studies have been divided into four sections:

1. The relative response of Hankins-type albedo-neutron dosimeters made of cadmium and boron.

2. The effect of distance from the body on the response of albedo-neutron dosimeters.

3. The use of the ratio of the top to bottom TLDs to determine the calibration factor for albedo-neutron dosimeters.

4. Neutron survey at a power reactor and at a neutron radiography facility.

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The Relative Response of Hankins-Type Albedo-Neutron Dosimeters Made of Cadmium and Boron

The Hankins-type albedo-neutron dosimeter consists of three small polyethylene sheets completely surrounded by 30-mil-thick cadmium. The sheet size and cadmium thickness were carefully selected to give a dosimeter having a thermal neutron sensitivity equal to the albedo-neutron sensitivity for neutrons having energies around 1.0 MeV. This type of dosimeter has an advantage in that it can be worn backwards and still have the same fast- or thermal-neutron response. Also, the dosimeter need not be held tightly against the body because it retains the same neutron response for body-to-dosimeter distances up to 3 cm. Therefore, the dosimeter can be clipped to the wearer's clothing like a film badge.

Several years ago, researchers at Lawrence Livermore Laboratory made a study of double albedo dosimeters of boron and cadmium. The capture cross section of cadmium drops rapidly for neutron energies above 0.4 eV (cadmium cutoff), but the cross section of boron has a constant 1/v dependence. When exposed to spectra having neutrons in the intermediate energy region, more intermediate-energy neutrons would pass through the cadmium than through the boron of dosimeters having the same thermal-neutron absorption. The difference in TLD readings would thus be a rough measure of the hardness or softness of the incident neutron spectrum. Although this effect was confirmed in the LLL study, the difference in TLD readings was small; for field application, the variations in individual TLD readings made the interpretation unreliable. In a recent review of this work, we found that the thickness and size of the cadmium filters being used were small and that neutron-capture gamma-rays in *the cadmium may have interfered with the readings.* Therefore, we decided to again study the relative response of albedo dosimeters made of boron or cadmium under cleaner experimental conditions.

We made two albedo-neutron dosimeters of boron-loaded plastic. For the first, we removed the cadmium from a Hankins-type dosimeter and replaced it with a plastic loaded with boron 10 (black boron), which completely removes all incident thermal neutrons. We made the other dosimeter by replacing the cadmium with plastic loaded with normal boron (grey boron), which has a thermal-neutron leakage equivalent to that of the 30-mil cadmium of the Hankins-type dosimeter. Then we exposed both dosimeters to neutrons from PuBe, ^{252}Cf, ^{252}Cf with polyethylene and D_2O moderators, and to reactor leakage neutrons at the LPTR.

The ratio of the boron-to-cadmium dosimeter readings are given in Table 2. These ratios show a lower sensitivity of boron dosimeters and a difference in observed ratio for different types of neutron sources. We had expected the boron dosimeters to have a lower sensitivity on the basis of the relative capture cross sections of boron and cadmium for neutron energies above 0.4 eV. The Hankins-type albedo dosimeter is most sensitive to neutron energies just above 0.4 eV. and a boron-covered (grey boron) dosimeter having the same thermal-neutron capture as 30-mil cadmium would remove more of the albedo as well as incident neutrons in this energy region. In Table 2, we see about a factor of two decrease in sensitivity for the grey boron dosimeter. The black boron removed all thermal neutrons and more of the intermediate-energy neutrons, which additionally decreased this dosimeter sensitivity.

The variation in the boron-to-cadmium ratios in Table 2 indicates that boron- and cadmium-covered dosimeters have different energy dependencies. Unfortunately, this difference in energy dependency is small, and the ratios of the boron and cadmium dosimeter readings change very little for grey boron and only slightly more for black boron. Observed calibration factors for the neutron sources and moderators are shown in table 2. They vary from 0.10 to 3.4, but the corresponding changes in ratio are much smaller.

We concluded from this study that the difference in sensitivities between cadmium and boron albedo-neutron dosimeters is small. For normal use, where only one TLD pair would be used for each type of dosimeter, the variation in TLD response (up to ±10) would make determination of this difference unreliable. Because we could not accurately determine this difference, we could obtain no reliable information on the incident neutron spectra for use in determining appropriate calibration factors for albedo-neutron dosimeters. There also appeared to be no reliable correlation between the observed calibration factors and the relative sensitivities of the boron and cadmium dosimeters.

The Effect of Distance From the Body on the Response of Albedo-Neutron Dosimeters

At the last Workshop meeting, we presented results showing the effect of distance from the body on the readings of albedo-neutron dosimeters exposed to thermal neutrons and to ^{252}Cf and PuBe neutron sources. When dosimeters 1 cm from the phantom were exposed to thermal neutrons, dosimeter readings increased by a factor of 1.8 to 2.5, and these readings increased to a factor of 4 when larger albedo-neutron dosimeters were exposed 3 cm from the phantom. Readings from dosimeters exposed to Cf and PuBe sources at a source-to-phantom distance of 500 cm decreased as the separation between the albedo and the phantom was increased. However, when the source-to-phantom distance was increased to 3 m, dosimeter readings 1, 2, and 4 cm from the phantom were higher than readings from dosimeters in contact with the phantom.

From the above, we concluded that thermal neutrons were responsible for the higher observed albedo-dosimeter readings when the source-to-phantom distance was 3 m and the dosimeters were 1 to 4 cm from the phantom. Because most field exposures are not in a scatter-free geometry, we assumed the significant thermal neutrons present probably result in higher dosimeter readings if the dosimeters are worn 1 to 3 cm away from the body. We based this assumption on measurements of field conditions in which the thermal component of the neutron dose rate was normally between 3 and 6% and seldom as low as the 0.6% that exists in our "low-scatter" facility.

Since the last meeting, we have tested this conclusion by making a number of exposures under field conditions with albedo-neutron dosimeters placed various distances from the phantom. Table I shows the readings obtained with dosimeters placed 1, 2, and 4 cm from the phantom relative to the contact reading from the same type of dosimeter. The percent thermal, determined with the bare probe of a PNR-4 instrument (described later), is given for each location.

We used the Hawkins-type dosimeter for two exposures. As expected it showed little variation as a function of dosimeter distance from the phantom even for high-percent (LPTR - 67%) thermal exposures. With one exception, the other dosimeters gave higher readings at 1 and 2 cm, the readings becoming larger as the percent thermal increased. The highest readings were obtained at the LPTR reactor, where boron-albedo readings at distances of 1, 2, and 3 cm were higher by a factor of ~2.0. The one exception was the HPRR (with no shield), where readings at 1 and 2 cm were less than the contact reading.

The above results indicate that holding a dosimeter tightly against the body is not as important as we once felt because higher than contact readings would be obtained in most field applications. While we normally accept readings slightly higher than the actual exposure, we do not like readings that may be low. The highest readings (~1.5 and 2.0) obtained at the LPTR with the two types of dosimeters are, however, larger than we would normally like.

From this study, we conclude that previous corrections for wearing a dosimeter away from the body are not necessary and in most cases would result in an over-estimate of exposure.

Use of the Ratio of Top to Bottom TLDs to Determine the Calibration Factor for Albedo-Neutron Dosimeters

At the last workshop meeting, we presented the results of a rather extensive study to evaluate the method for determining albedo-calibration factors based on the ratio of readings from TLDs located on the top and bottom of cadmium or boron dosimeters. This study involved measuring the thermal neutron-component of the dose by using the bare BF_3 probe from a PNR-4 remmeter. The total neutron dose rate was determined from readings made with the 9-in. sphere, and the thermal-neutron rate was determined by applying a calibration factor of 80 to the bare-probe reading. We used the ratio of these two dose rates to calculate the "percent thermal neutrons." The albedo calibration factors were determined using the 9- and 3-in. sphere technique.

The reading of the TLD on top of an albedo dosimeter is primarily (there is a <4% response to fast neutrons) from incident thermal neutrons and from albedo neutrons having intermediate energies above the cadmium cutoff. (For example, cadmium surrounds the TLDs in the Hankins-type albedo dosimeter and its response is primarily from these intermediate-energy neutrons.) If the percent of total neutron dose from thermal neutrons is high, most of the top TLD reading is from thermal neutrons, and the bottom TLD reading from thermal neutrons is ∿10 to 75% (depending on dosimeter design) of the top TLD reading.

If the percent thermal neutrons is negligible, the top TLD reading will be from albedo neutrons with energies above the cadmium cutoff that penetrate the cadmium of the dosimeter. Depending on the dosimeter design, (1) the top TLD reading will be about 10 to 35% of the bottom reading; (2) the top-to-bottom ratio will be constant for a specific dosimeter; and (3) the top-to-bottom ratio is independent of neutron energy. Therefore, the only variation in the ratio has to be from changes in the thermal-neutron component of the dose.

If the thermal-neutron component of the dose were a function of neutron energy, the ratio of TLD readings on the top and bottom of an albedo dosimeter could be used to determine the calibration factor of albedo-neutron dosimeters. However, we know from work in a low-scatter facility that the thermal-neutron component of the dose can be changed significantly without a measurable change in the fast-neutron energy spectrum. The calibration factor for albedo-neutron dosimeters would remain constant but the top-to-bottom ratio would change. In a low-scatter facility, we also find a higher top-to-bottom TLD ratio for ^{238}PuBe than for a ^{252}Cf neutron source. The average fast-neutron energy for the PuBe sources is significantly higher than for ^{252}Cf, and the albedo-neutron-dosimeter calibration for PuBe is ~27 lower than ^{252}Cf. If the top-to-bottom ratio were a true indicator of the calibration factor, the ratio for PuBe should be 27% lower than Cf instead of the higher value observed experimentally.

At the last Workshop meeting, we showed the results of our survey of the "percent thermal neutrons" plotted as a function of the albedo-calibration factor (see Fig. 6 in PNL-2449, page 80). There was little correlation of the percent thermal with the calibration factor, indicating the calibration factor is not a function of the thermal-neutron component of the dose. In Table 1 we show the percent of the neutron dose from thermal neutrons, the ratio of TLD readings on the top and bottom of several types of dosimeters, and the albedo calibration factor determined by using the 9- to 3-in. spheres. There is no correlation between the calibration factors and the percent thermal or between the calibration factor and the ratio of the top-to-bottom TLD readings.

Our conclusion (again) is that the ratio of the top-to-bottom TLD readings cannot be used to determine the calibration factors for albedo-neutron dosimeters.

Neutron Survey at a Power Reactor and a Neutron Radiography Facility

In November of 1977 we made a neutron survey inside the containment of the Alabama Power and Light Company, Farley Nuclear Plant, Dothan, Alabama to determine the spectra of leakage neutrons and to evaluate the accuracy of a 9-in.-diam sphere rem meter (PNR-4) and of albedo-neutron dosimeters. We also studied variations in the neutron spectra, the ratio of gamma-to-neutron dose rates, and the thermal-neutron component of the neutron dose.

The results of our study indicated the neutron spectrum at the reactor is very constant throughout the reactor and probably consists of a 25-keV component superimposed on a 1/E spectrum. Albedo-neutron dosimeters could be used very effectively at this reactor. They would have a high efficiency, and the constant neutron spectrum in the reactor would make their interpretation accurate to within $\sim \pm 25\%$.

A full report of this work is given in a paper entitled "A Survey of Neutrons Inside the Containment of a Pressurized Water Reactor" by Dale E. Hankins and Richard V. Griffith, which is being presented at the Washington D.C. ANS Meeting on November 13-17, 1978.

The neutron survey at the neutron radiography facility indicated albedo-neutron dosimeters could be used with an expected accuracy of $\sim \pm 33\%$.

Table 1. Albedo-neutron dosimeter readings at various distances from the phantom relative to the contact reading. Also given are the percent of the total neutron dose from thermal neutrons and the ratios of the 9- to 3-in. spheres and of the readings of TLDs placed on top an albedo to the reading of the albedo TLDs.

Neutron source	Albedo dosimeter	Distance from phantom (cm) 1.0	2.0	4	Percent thermal neutrons	Top TLD albedo	9/3 in. sphere	Albedo calibration factor
Godiva IV	Hankins type	1.00	0.92	0.87	1.1	1.45	0.65	0.44
	Bottom of Hankins type	1.04	0.97	0.83		0.42		
	1-1/4-in.-diam boron disk	1.09	1.03	0.82		0.50		
LPTR Reactor	Hankins type	0.95	1.06	0.98	67	7.00	0.19	1.8
	Bottom of Hankins type	1.46	1.57	1.40		1.75		
	1-1/4-in.-diam boron disk	1.90	2.16	1.92		2.62		
HPRR with steel and concrete shield	Hankins type				2.5	2.11	0.41	0.74
	1-in.-diam Cd	1.14	1.11	0.96		0.94		
	1-1/4-in.-diam boron disk	1.18	1.13	1.04		1.10		
HPRR with no shield	Hankins type				0.25	1.28	1.09	0.24
	1-in.-diam Cd	0.85	0.84	0.70		0.42		
	1-1/4-in.-diam boron disk	0.98	0.88	0.76		0.35		
HPRR with concrete shield	Hankins type				2.2	2.24	0.53	0.55
	1-in.-diam Cd	1.04	1.02	0.96		0.93		
	1-1/4-in.-diam boron disk	1.18	1.11	1.0		0.89		
Power Reactor								
Location 1	Hankins type				3.3	1.53	0.14	3.4
	Bottom of Hankins type	1.10	1.09	0.88		0.71		
Location 2	Hankins type				3.4	1.62	0.13	3.8
	Bottom of Hankins type	1.08	1.04	0.95		0.76		
Location 3	Hankins type	1.09	1.02	1.04	2.5	1.48	0.16	2.7
	Bottom of Hankins type	1.01	0.98	---		0.67		

Table 2. Ratio of readings from Hankins-type dosimeters of 30-mil Cd and boron-loaded plastics. Grey boron has the same thermal-neutron leakage as 30-mil Cd, and black boron has no measurable thermal-neutron leakage.

Neutron source	Distance from source (m)	Ratio of Readings $\frac{\text{boron}}{\text{cadmium}}$ Grey boron	Black boron	Observed calibration factor (Cd dosimeter)
^{252}Cf	0.5	0.69	0.33	.10
	1.0	0.57	0.29	.14
	3.0	0.57	0.23	.23
^{238}PuBe	0.5	0.61	0.33	.075
^{252}Cf + 10 cm polyethylene	1.0	0.54	0.27	.67
^{252}Cf + 25 cm D_2O	1.0	0.49	0.19	3.5
	1.17 (on back of phantom)	0.48	0.20	
LPTR (reactor)		0.45	0.10	2.5