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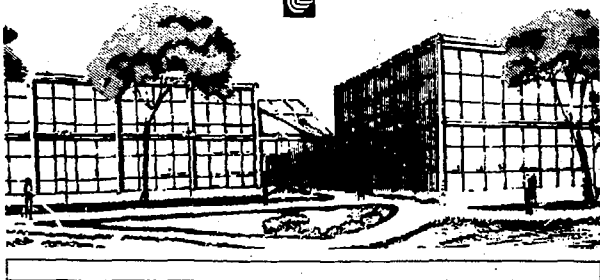
AN INTRODUCTION TO ALBEDO NEUTRON DOSIMETERS

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AN INTRODUCTION TO
ALBEDO NEUTRON DOSIMETERS*

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The concept of albedo neutron dosimeters is not a new development and these studies date back to the earliest days of the atomic energy programs. The development of lithium-fluoride thermoluminescence dosimeters provided a sensitive thermal neutron detector and created a new interest in albedo neutron dosimeters. This interest, however, was discouraged by the energy dependence studies which indicated the dosimeters had responses that were not proportional to the dose. Recently, field methods for determining the calibration factors required to interpret the badges properly have been developed and there has been a significant increase in their use. The dosimeters have one major advantage over other types of personnel neutron dosimeters, that being they always provide a reading when the person is exposed to significant neutron dose. The main disadvantage is the determination of the proper calibration factor.

An albedo neutron dosimeter is designed to measure the flux of thermal neutrons which leave the body when a person is exposed to fast energy neutrons. The fast neutrons are scattered and moderated in the body, and many have lost most of their initial energy and emerge as thermal neutrons. The albedo neutron dosimeter is designed to detect this flux of thermal neutrons by using a thermal neutron detector. This could be any type of thermal neutron detector but in practical applications lithium fluoride (LiF) thermoluminescent dosimeters (TLDs) are most frequently used.

Natural lithium TLDs are sensitive to thermal neutrons and this sensitivity can be increased by making the TLD of lithium enriched in the isotope ⁶Li. TLDs are also made from lithium where the ⁶Li isotope has been removed (leaving only the ⁷Li isotope). These TLDs have essentially no response to thermal neutrons. Both types of TLDs, enriched in the lithium-6 isotope (Li-6) or with only the lithium-7 isotope (Li-7), have the same sensitivity to gamma rays. (There may be a small difference with the Li-6 TLDs normally being less sensitive. This is corrected by reading the TLDs separately and applying the appropriate calibration factor to each type TLD. This requires that the TLDs be marked in some manner to permit identification as a Li-6 or Li-7). These Li-6 and Li-7 TLDs are used in pairs with the reading of the Li-7 TLD (gamma response only) being subtracted from the Li-6 reading (gamma and neutron response) to obtain the neutron response of the Li-6 TLD.

When a pair of Li-6 and Li-7 TLDs are placed on a person, the neutron response of the Li-6 TLDs will be primarily from thermal neutrons entering the body (incident thermal neutrons) with only a small part of the response coming from fast neutrons returning from the body (albedo neutrons). To make a dosimeter which will have a useful reading from albedo neutrons, the incident thermal neutrons must be removed or at least greatly reduced. This is done by placing a material which captures thermal neutrons such as cadmium (or boron-loaded plastics) over the TLDs. This TLD and cadmium combination is called an albedo neutron dosimeter.

Figure 1 shows schematics of 6 types of albedo neutron dosimeters that are in use or have been studied. The schematics have been drawn so that the bottom of the figure represents the side of the dosimeter that

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would be against the body. The first dosimeter (a) is the basic or simple albedo neutron dosimeter. It consists of a pair of Li-6 and ⁷Li TLDs on either side of a cadmium disk (Fa 71, Un 71). The TLD pair on the bottom is used to measure the albedo neutrons, and the top pair of TLDs is used to measure the incident thermal neutron fluence or dose.

The thickness of the cadmium in an albedo neutron dosimeter can be from 15 mils, shown in Fig. 1(a), to 60 mils, although 30 mils is most frequently used. Cadmium thinner than 15 mils allows too many of the incident and albedo thermal neutrons to leak through the cadmium which complicates the interpretation of the dosimeter (Ba 72a, Ha 72b).

The size of the cadmium disk should be as large as possible to keep incident thermal neutrons from entering the body near the TLDs where they have a good chance of scattering and being detected. Since thermal neutrons migrate in the body large distances before being captured, the cadmium size should be about 4 inches in diameter. A dosimeter of this type was designed in England (Br 67), but proved to be impractical because of its size. A smaller disk can be used if the response of the bottom TLD is corrected for the incident thermal neutrons. This can be done by subtracting a portion of the incident thermal neutron reading of the top TLDs from the reading of the bottom TLD. This correction depends on the relative response of the top and bottom TLDs when exposed to thermal neutrons and is determined by exposing the dosimeters in thermal neutron beams from reactors. The correction factor includes the leakage of thermal neutrons through the cadmium and the response to incident thermal neutrons entering the body beyond the edges of the cadmium.

The cadmium size cannot be reduced indefinitely, however, and a diameter of $\sim 3/8$ -in. is considered to be about the smallest useful size (Ha 72a, Ha 72b). For smaller diameters, the incident thermal neutron response of the TLDs below the cadmium is as great or greater than their response to albedo neutrons, even when the thermal neutrons contribute only a small part of the total neutron dose.

The two Li-7 TLDs shown in part (a) of Fig. 1 are the same, but their readings will, in many cases, be different. The cadmium is a very good shielding material for x- and gamma-rays energies less than 100 keV. This causes gamma readings of the bottom TLDs (both Li-6 and Li-7) to be lower than the top TLD readings when the exposure includes a component of low energy photons. Since this frequently occurs, two Li-7 TLDs are required in an albedo neutron dosimeter for proper evaluation of the results. If the cadmium is replaced by boron-loaded plastic, the shielding effect for low energy x or gamma rays is much smaller and only one Li-7 TLD is required. The disadvantages of boron-loaded plastics are: (1) the thickness required to stop all thermal neutrons is large compared to cadmium, and (2) to reduce this thickness, the boron-10 isotope must be used and B-10 is very expensive (Gr 72). In spite of these disadvantages, the English albedo neutron dosimeter (Har 69, Har 72), Fig. 1(d), and the German dosimeter (Pi 74, Do 77), Fig. 2(b), are made of a boron-loaded plastic.

If the albedo neutron dosimeter consists of cadmium and the neutron spectrum contains significant thermal neutrons, the Li-7 TLD readings can not be used to determine the wearers gamma exposure. The capture of the

thermal neutrons by cadmium results in capture of gamma rays which increases the readings of all TLDs near the cadmium. For example, at a power reactor the observed reading of a Li-7 TLD located on an albedo neutron dosimeter was twice as large as a Li-7 TLD located away from the cadmium. The measurement of the gamma exposure the individual receives must be made with a TLD separate from the albedo neutron dosimeter if the dosimeter is made of cadmium.

To evaluate the basic albedo neutron dosimeter, Fig. 1(a) (Fa 71), both sets of TLDs are read on a TLD reader. (If necessary, the TLD readings are corrected for differences in sensitivity between the Li-6 and Li-7 TLDs.) For each pair of TLDs the Li-7 (gamma exposure reading) is subtracted from the Li-6 reading (gamma plus neutron reading) to obtain the neutron response of the TLD. The Li-6 TLD located above the cadmium represents the incident thermal neutron response. (This also includes a small contribution from incident fast neutrons which is ignored.) The albedo neutron response is found by subtracting from the bottom Li-6 TLD reading a fraction of the reading obtained from the Li-6 TLD located above the cadmium (this fraction having been determined experimentally as discussed previously). To determine the fast neutron dose an albedo neutron calibration factor is applied to the remainder of the Li-6 TLD reading.

The albedo neutron calibration factor is a function of the neutron energy and its value can vary by > 2 orders of magnitude (Ha 75, Ha 77). This variation is the prime disadvantage of albedo neutron dosimeters; they are highly energy dependent. The energy dependence of albedo neutron

dosimeters is shown in Fig. 3. Here we have plotted the relative response of a Mankins-type albedo neutron dosimeter (determined by calculations (A1 72) and experimentally) as a function of neutron energy. A dosimeter with no energy dependence would give a straight horizontal line, but the albedo neutron dosimeters response changes rapidly with neutron energy. To evaluate the reading from an albedo neutron dosimeter properly, the appropriate calibration factor for the exposure must be determined.

Two techniques are commonly used to determine the albedo calibration factor. One is to place the albedo neutron dosimeter on an appropriate phantom (usually a gallon jug of water) at a location where the dose rate has been determined. The dosimeters are left for a known time and the total dose is calculated. The calibration factor is determined by dividing the albedo neutron TLD reading by the dose. This procedure, although accurate, is time-consuming and the preferred technique is to use the ratio of two types of neutron detectors; one a remmeter and the other an instrument that responds primarily to low energy neutrons. An example is the use of the 9-in. sphere remmeter and 3-in. sphere covered with 10-mil thick cadmium (Ha 75). A measurement (usually in counts per minute using a portable scaler) is made with both spheres and the ratio of the 9/3-inch sphere is determined. By using a curve similar to the one shown in Fig. 4, the calibration factor for that point is obtained. The location of the curve on Fig. 4 will vary slightly depending on the sensitivity of the Li-6 TLDs that are used and the type of albedo neutron dosimeter, but the curve will always be a straight line and have the same slope.

The ratio of the 9/3-in. sphere and corresponding calibration factor is determined at each location where neutron exposure may occur. By comparing these calibration factors, the accuracy that could be obtained from albedo neutron dosimeters is determined. In most field situations the calibration factors will not vary more than ± 20 to 30% (Ha 75). This variation is the size of error one could expect in the dosimetry results. If larger variations are obtained, a separate calibration factor for each location or building may be required or another type of personnel dosimeter may have to be used.

An error in the interpretation of the results of albedo neutron dosimeters can occur if the gamma-ray exposure is high compared to the neutron dose. The reading of the Li-7 TLD (gamma-ray exposure) is subtracted from the reading of the Li-6 TLD (gamma-ray plus neutron exposures); consequently, if there is a large gamma-ray component the difference between the readings of the two TLDs will be small. The TLDs used in personnel dosimeters usually have an accuracy of about ± 5 to 10%. Small differences in reading could go undetected because of these variations, or a difference in readings could be obtained although none actually exists. If the ratio of gamma-ray to neutron doses are expected to be high, an albedo neutron dosimeter with high neutron sensitivity should be used. These dosimeters contain significant amounts of polyethylene (see discussion below) and are consequently heavy and bulky.

Many different types of albedo neutron dosimeters have been designed, (see Figs. 1 and 2). Studies have been made to see if changes in size, material, or location of the TLD in or on the dosimeter would give a different energy dependence. With the exception of small variations at the lower intermediate energy region, all albedo neutron dosimeters have the same energy dependence (Ha 72a, Ho 72b).

The studies above indicated that the sensitivity of the dosimeters can be changed by the addition of polyethylene in the dosimeter, and some dosimeter designs have used this feature. This study also pointed out the necessity of keeping the dosimeter worn against the body and that the dosimeter must be oriented properly; that is, not worn backwards.

The different types of albedo neutron dosimeters shown in Figs. 1 and 2 were designed for specific purposes. Dosimeter Fig. 1(b) is used at the Hanford facilities and was designed to permit an automatic TLD reader to be used with 5 TLDs mounted on a card (Un 69, Un 71). Only three TLDs are used in the albedo neutron portion of the badge. The two TLDs that are not under the cadmium are shielded to give the same response to low energy gamma rays as the TLD under cadmium. The dosimeter badge is similar in size to a film badge dosimeter and is worn loosely on the clothing.

The dosimeter in Fig. 1(c) is the Hankins-type dosimeter (Ha 73a) and uses only two TLDs. The dosimeter was designed to have a thermal neutron response equal to the response of the dosimeter to 1.0 MeV neutrons, making a separate measurement of the thermal dose unnecessary. The dosimeter's design permits it to be worn backwards or at varying distances from the

body. The cadmium completely surrounds the dosimeter and its sensitivity to neutrons is lower by about a factor of 3 (see Fig. 3) than a dosimeter with cadmium on only one side. This dosimeter responds primarily to intermediate energy neutrons since the cadmium removes most of the thermal energy albedo neutrons. The dosimeter is available commercially for about \$6 without TLDs.

The dosimeter shown in Fig. 1(d) was developed in England and was designed for use at reactors (Har 69, Har 72). The TLDs are "hidden" in a recess to reduce the incident thermal neutron response to be equal to the dosimeter's response from the low energy reactor leakage neutrons. The dosimeter is held to the clothing by a safety pin.

The boron and cadmium shielded TLDs in the dosimeter studied at the Lawrence Livermore Laboratory (Un 71, Gr 72) and shown in Fig. 1(e), give different readings when exposed to intermediate energy neutrons. This is caused by the different cross sections of B and Cd near the thermal region, and by observing these differences, information on the neutron energy spectrum could be obtained. Unfortunately, the differences in readings are small, and, in field application, the small differences cannot be accurately evaluated and the dosimeter study was discontinued.

The dosimeter shown in Fig. 1(f) is the largest dosimeter and is ~ 2 in. in diameter (Ho 72). It contains considerable polyethylene and therefore is the most sensitive of the dosimeters. Because of its weight, it is worn on a belt. It is commercially available, without TLDs or belt, for about \$16.

The dosimeters in Fig. 2 were recently designed in Europe. The dosimeter shown in Fig. 2(g) was designed by Piesch (Pi 74, Do 77) in Germany. The dosimeter is somewhat similar to the English dosimeter shown in Fig. 1(d) but uses 3 sets of TLDs. The top set measures incident thermal neutrons, the middle set measures incident as well as backscattered intermediate energy neutrons, and the bottom set measures albedo neutrons. By subtracting a part of the intermediate neutron reading (middle set of TLDs) from the albedo neutron reading (bottom set of TLDs), the energy dependence can be partially corrected for spectra containing a large component of intermediate energy neutrons. This dosimeter is commercially available in Germany.

The dosimeter shown in Fig. 2(h) was designed by Burger in Germany (Do 77, Br 77). It consists of polyethylene 32-mm in diameter which gives the dosimeter high sensitivity. Recently, this dosimeter has been modified to include a 1-mm thick layer of a polymere resin containing natural boron placed over the polyethylene. This was added to decrease its sensitivity to incident thermal neutrons.

The dosimeter shown in Fig. 2(i) is a dosimeter designed in England (Do 77) which is similar in principle to the Hankins dosimeter shown in Fig. 1(c). Both dosimeters can be worn on an individual without having to keep the dosimeter oriented properly or held closely to the wearer. There is some sacrifice in sensitivity.

There are several other albedo neutron dosimeter designs in use but they are generally similar to one of the dosimeters shown in Figs. 1 or 2. In the selection of an albedo neutron dosimeter, several factors must be considered. If the gamma-ray component of the dose is high or the neutron dose is from high-energy neutrons, where the sensitivity of an albedo dosimeter is low, an albedo dosimeter with high neutron sensitivity must be used. The sensitivity of the various dosimeters vary by as great as a factor of 10. Some albedo dosimeters are small and convenient to wear, while others are large and must be worn on a belt. Orientation on the person is important for some albedo dosimeters with large errors in evaluation of the dose being possible if the dosimeter is worn improperly. Allowing the dosimeter to pull away from the body can decrease or increase its reading depending on whether the neutron energy is fast or thermal, respectively. Some dosimeters can be used with automated readout.

The advantage of albedo neutron dosimeters over other types of personnel neutron dosimeters is sensitivity. If an individual receives an exposure ~ 20 mrem or more, a positive reading will be obtained. Other types of dosimeters may have thresholds which make them insensitive to low energy neutrons, fade when the temperature or humidity is high, or do not have adequate sensitivity to be useful at the lower neutron doses. The primary problem in using albedo neutron dosimeters is the determination of the proper calibration factor. In spite of this, albedo neutron dosimeters will be used extensively because they do provide a reading which other dosimeters, in many cases, do not.

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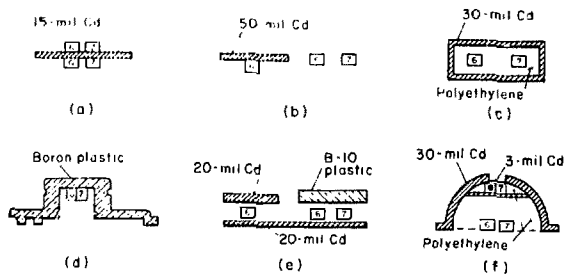
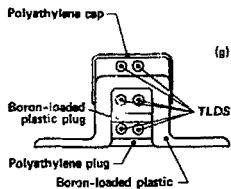
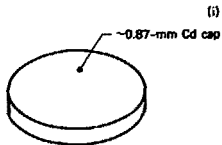


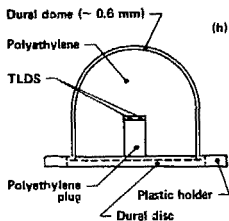
Fig 1 Typical albedo dosimeter designs



(g)



(i)



(h)

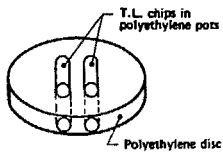


Fig 2 Typical albedo dosimeter designs

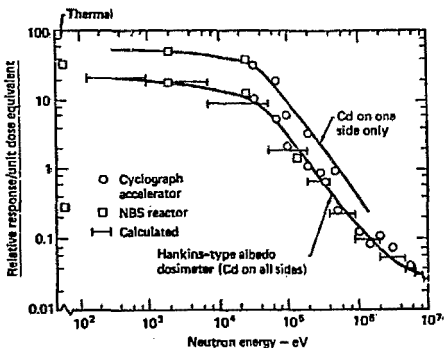


Fig. 3. Curves showing the energy dependence of the Hankins-type albedo neutron dosimeter and of TLDs taped to the bottom of the dosimeters. Also shown is calculated response by Alsmiller and Barish.

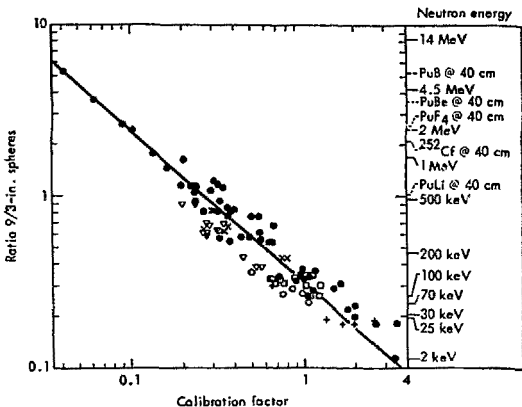


Fig. 4. Calibration factors for the Hankins-type albedo dosimeter as a function of the ratio of 9- and 3-in. spheres.