5-73
LA-5261

A Small, Inexpensive Albedo-Neutron Dosimeter

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

↓ ↓

UNITED STATES
ATOMIC ENERGY COMMISSION
CONTRACT W-7405-ENG. 36

MASTER

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America. Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$4.00; Microfiche \$0.95

LA-5261

UC-41

ISSUED: July 1973

The logo features a vertical line with a wavy section at the top, passing through a circular emblem. The emblem contains a stylized atomic symbol with a central cross and three dots. Below the emblem, the text "los alamos" is written in a bold, sans-serif font, followed by "scientific laboratory" in a smaller font, and "of the University of California" in an even smaller font. At the bottom, "LOS ALAMOS, NEW MEXICO 87544" is printed in a small, all-caps font. Two arrows point downwards from the bottom of the emblem.

los alamos
scientific laboratory
of the University of California
LOS ALAMOS, NEW MEXICO 87544

A Small, Inexpensive Albedo-Neutron Dosimeter

by

Dale E. Hankins

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

A handwritten signature or initials are visible in the bottom right corner of the page.

A SMALL, INEXPENSIVE ALBEDO-NEUTRON DOSIMETER

by

Dale E. Hankins

ABSTRACT

A small (1-1/4 by 3/4 by 3/8 in.) albedo-neutron dosimeter that can be worn by taping it to the bottom of the existing film badge is described. It can be made in a workshop without special equipment or training in about one hour, from cadmium and polyethylene sheets at a materials cost of about 25 cents, excluding the thermoluminescent dosimeters (TLD's). It was designed to use ^6Li - and ^7Li -TLD chips, although other types of ^6Li and ^7Li TLD's could be used. The neutron dose is determined by subtracting the ^7Li reading from the ^6Li reading and applying the appropriate calibration factor. The dosimeter's thermal-neutron sensitivity (in rems) is equal to its sensitivity to fast neutrons of about 1-MeV energy.

The dosimeter is very energy dependent, having the same energy dependence for fast neutrons as other albedo-neutron dosimeters. Two calibration procedures for field use are described, one using a gallon jug and the other a 9-in. cadmium-loaded remmeter and a 12-mil cadmium-covered 3-in. sphere. Any type of TLD reader can be used because the TLD readout is not automated. For low-neutron doses, or if a high accuracy is desired, the dosimeter can be used with up to eight TLD's (four ^6Li and four ^7Li chips).

INTRODUCTION

The neutron film packet used in film badges has often proved unsatisfactory for measurement of the fast-neutron dose. Two of the major reasons are that the latent-image track fades rapidly where the humidity is high, and the lowest energy neutrons detectable in routine evaluations are ~ 0.8 to 1.0 MeV. These undesirable features have led many organizations to stop using the neutron film. Albedo-neutron dosimeters have been considered as a replacement for the neutron film to alleviate these problems.

When the human body is exposed to neutrons, some of the incident neutrons are backscattered to create a flux of neutrons of various energies leaving the body. These neutrons are called albedo neutrons. A dosimeter placed on the body to measure this flux of backscattered neutrons is called an albedo-neutron dosimeter. Such

dosimeters are usually designed to detect thermal neutrons. When cadmium is used to eliminate incident thermal neutrons, the dosimeter response is largely caused by the thermal neutrons backscattered from the body.

Several albedo-neutron dosimetry systems have been developed and studied,¹⁻⁹ with differing conclusions about their accuracy, sensitivity, and usefulness. At Los Alamos Scientific Laboratory (LASL), we made an extensive study including as many different albedo-neutron dosimeter designs as possible.¹⁰ This included variations in dosimeter size and thickness, and in thermoluminescent dosimeter (TLD) location in or on the dosimeter.

This study showed that albedo-neutron dosimeters are very energy dependent for fast-neutron (100-keV to 10-MeV) energies, and all the dosimeters studied had the same energy dependence. We could find no method to

determine the fast-neutron energy from the results obtained from a wide variety of dosimeters or from a combination of dosimeters. If this could be done, one could correct for the dosimeter energy dependence.

The study indicated that a major problem is the dosimeter's thermal-neutron response. Thermal-neutron leakage around the dosimeter cannot be eliminated using reasonable-size dosimeters, and moving the dosimeter away from the body or wearing it backwards can cause large errors in dosimeter response, even for thermal-neutron dose rates as small as 1 to 2% of the fast-neutron dose (measured in rem).

DOSIMETER DESIGN

The study indicated that dosimeter design must be directed toward eliminating or reducing the thermal-neutron sensitivity. We did this by completely surrounding the dosimeter with cadmium. The dosimeter size, the cadmium thickness, and the amount of polyethylene in the dosimeter were selected to produce a dosimeter with equal thermal- and fast-neutron sensitivity (in rem). Because the fast-neutron sensitivity varies rapidly with energy, we had to select a specific fast-neutron energy. Much of our personnel neutron dose is from ~1-MeV neutrons, so we selected 1 MeV as the fast-neutron energy for equating to the thermal-neutron response.

When the dosimeter is completely surrounded with cadmium, it can be worn backwards and still have the same fast- or thermal-neutron response. Another advantage is that 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 worn by clipping it to the clothing like a film badge.

On the basis of the above study, we designed three dosimeters (Fig. 1) and performed additional studies. The rectangular dosimeter (Fig. 2) immediately proved superior. It consists of two pieces of 1/8-in. polyethylene and one piece of 1/16-in. polyethylene with two 3/8-in.-diam holes drilled in it to receive the TLD's. A 30-mil-cadmium cover completely surrounds the polyethylene. The dosimeter is 1-1/4 in. long, 3/4 in. wide, and ~3/8 in. thick, and weighs ~17 g. A working drawing is shown as Fig. 3.

The dosimeters are worn by taping them to the bottom of the film badge, but they could be worn in any manner, including slipping them into a shirt pocket.

Fig. 1.
Three prototype dosimeters and the present LASL film-badge packet.

Fig. 2.
The rectangular albedo-neutron dosimeter.

DOSIMETER FABRICATION

To date, these dosimeters have been individually produced in a standard laboratory shop. The cadmium and polyethylene were rough cut on a band saw, and a belt sander was used to obtain the final dimensions. A bench

Fig. 3.
Working drawing of the dosimeter.

vise and hammer were used in forming the cadmium around the polyethylene pieces. A solder gun was used to solder the pieces together (NOTE: Avoid breathing cadmium fumes, because the material is toxic). The soldered joints were smoothed with the belt sander, and the cadmium was cleaned with trichloroethylene and spray-painted on the outside. The 3/8-in. holes were positioned using a polyethylene or metal jig and drilled with a standard drill press. The top piece of cadmium is held in place with Scotch tape. The time required to make each dosimeter varies, depending on the number being made and the skill of the worker, but should average about one hour. Material cost should not exceed 25 cents, including waste, the main cost being cadmium.

TLD's AND GAMMA-RAY RESPONSE

The TLD's used in the albedo dosimeters are the 1/8-by 1/8-by 0.035-in. ^6Li and ^7Li ribbons supplied by Harshaw Chemical Company. To obtain greater accuracy while developing the dosimeter, we used eight TLD's in each. Four of these TLD's (two ^6Li and two ^7Li), wrapped in aluminum foil to keep them clean, are placed in each of the two 3/8-in. holes in the center piece of polyethylene.

The ^6Li and ^7Li TLD's are staggered to prevent contact between the ^6Li TLD's. Any type of TLD that will fit into the holes can be used if it has adequate sensitivity.

The ^7Li TLD readings probably cannot be used to evaluate gamma-ray exposure for two reasons. First, if there is a significant thermal-neutron component present, the gamma rays produced by the capture of thermal neutrons in the cadmium increase the readings of both the ^6Li and ^7Li TLD's. Second, and more important, the ^7Li -TLD readings can be used only for gamma rays whose energies exceed 200 keV, because of the significant absorption of lower energy x or gamma rays in the cadmium. Figure 4 shows TLD response to x and gamma rays when in the neutron dosimeter and when in a plastic film-badge holder. These curves were drawn from results we obtained using the film-badge holder shown in Fig. 1. The response of TLD's located inside the albedo dosimeter drops rapidly for energies below 200 keV and is essentially zero at 30 keV. The difference between the ^7Li TLD readings located inside and outside the dosimeter can be used to infer the energy range of x or gamma rays. For example, the difference is small for a ^{60}Co source, but large for 60-keV x rays from an ^{241}Am source.

TABLE I

RELATIVE TLD SENSITIVITY TO NEUTRON ENERGIES, SOURCES, OR EXPOSURE AREAS

Neutrons	Relative Sensitivity
~220 MeV	~ 0.003
~14 MeV	0.025
PuB	0.077
PuBe	0.080
PuF ₄	0.13
^{238}Pu sphere	0.14
PuLi	0.30
^{239}Pu metal ~3 kg	0.31
^{239}Pu facility	~ 0.34
^{238}Pu facility	~ 0.44
PuF ₄ with 2-in.-polyethylene shielding	0.75
Reactor leakage	1.2

ENERGY DEPENDENCE

The rectangular dosimeter's energy dependence to fast neutrons is the same as that of the other albedo-neutron dosimeters studied.¹⁰ This is true although this dosimeter, which is completely surrounded with cadmium, responds primarily to intermediate-energy neutrons, whereas most of the other albedo-neutron dosimeters studied respond primarily to thermal neutrons. The energy dependence is severe, and the dosimeter sensitivity decreases rapidly as the fast-neutron energy is increased. This effect is shown in Table I for neutron sources of several energies. These observed values agree well with calculations made by

Alsmiller and Barish¹¹ at Oak Ridge National Laboratory which are shown in Fig. 5.

The neutron-energy dependence is so great that these dosimeters are acceptably accurate only if the neutron energy is known.¹⁰ For example, if both PuBe- and PuLi-neutron sources are handled, the dosimeter readings cannot be interpreted correctly, because the dosimeter's sensitivity to PuLi neutrons is a factor of 3.8 higher than its sensitivity to PuBe neutrons. However, at a facility handling only one type of material, such as a plutonium facility, the energy of the neutrons used does not vary greatly and these dosimeters can be used.

CALIBRATION

The dosimeter can be calibrated using either of two procedures. The first is to tape the dosimeter onto a cylindrical 1-gal polyethylene jug filled with water. The front of the jug is positioned at a point where the neutron dose rate is known. The dosimeters and the jug are exposed to the neutron source for a known time.

The thermoluminescent readings of the ^6Li and ^7Li TLD's are averaged and corrected using their respective gamma-ray calibration factors, and the ^7Li reading is subtracted from the ^6Li reading. The difference is divided by the total neutron dose in millirems and multiplied by 0.90 (correction for jug vs manikin, see next paragraph). The result is the neutron calibration factor.

The reading of the dosimeter on the jug will be ~10% higher than that from the upper-chest portion of a water-filled plastic manikin with lung cavities. These dosimeters

Fig. 4.

TLD response to various x- and gamma-ray energies when in a plastic film-badge holder and in the albedo-neutron dosimeter.

Fig. 5.
Calculated response of the albedo-neutron dosimeter.

were designed to be worn on the upper chest, clipped to the shirt collar or on a cord about the neck. If they are worn at the waist, their sensitivity increases by about 35% because of the increase in albedo neutrons at the waist.

Calibration should be done in neutron fields where nearly all of the neutrons are from one direction. Neutron penetration through the gallon jug is much less than that through a manikin with lung cavities. Dosimeters placed on the back of a manikin exposed to PuF_4 neutrons gave 60% of the response obtained on the front, but on the jug the response was only 39%. Consequently, the calibration factor would be incorrect if the neutrons were not primarily from the front. One must also use for calibration neutron energies the same as those found in the exposure area. For example, a PuF_4 source gave a calibration factor of 0.13, but the factor in a PuF_4 processing line averaged about 0.60. The large difference was caused by lower energy neutrons from room scattering and neutron-energy degradation by the process equipment and shielding materials. Ideally, calibration should be performed at the facility where the exposure will occur.

Placing gallon jugs in work areas to obtain calibration factors proved time-consuming and, in some cases, im-

practical. In such situations, the second calibration procedure can be used. This procedure consists of using 3- and 9-in. spheres. The 9-in. sphere was the cadmium-loaded PNR-4 neutron remmeter¹² purchased from Eberline Instrument Corporation. The BF_3 probe can be removed from the 9-in. sphere and placed inside a 3-in. sphere covered with 12-mil cadmium. The counting rates of the 3- and 9-in. spheres are determined, and the ratio of the 9-in. to 3-in. sphere counting rates is calculated. The calibration factor for the albedo-neutron dosimeters is obtained from the experimentally determined curve shown in Fig. 6. This technique requires only a few minutes to obtain the calibration factor, compared with lengthy exposure times required for the gallon-jug calibration procedure.

The curve in Fig. 6 was developed using calibration factors obtained with manikins exposed from the front and 9- to 3-in. sphere ratios obtained at the same position. When the neutron exposure is not frontal but from the rear, for example, the response of an albedo-neutron dosimeter worn on a manikin will be less because of the body shielding. A correspondingly smaller calibration factor should be used to calculate the dose. But the 3- and

Fig. 6.
Curve used to obtain the calibration factor from results obtained with 3- and 9-in. spheres.

9-in.-sphere technique is not sensitive to neutron direction and will indicate the same ratio regardless of the direction of the neutrons. If the neutrons came from the rear, the calibration factor determined using Fig. 6 would be too large and the dose calculated from the dosimeter readings would be too low. (NOTE: The calibration factor is divided into the TLD reading.)

We developed a technique to correct the 3- and 9-in.-sphere data for neutron exposures from the rear. If the BF_3 probe from the 9-in.-sphere instrument is placed against the outside of the sphere at the equator, the count rate is greater when the probe is on the side exposed to the neutron source. For thermal neutrons, the count rate with the probe on the back of the sphere (away from the neutron source) is only ~2% of that on the front of the sphere. For higher energy neutrons, the count rate at the back of the sphere is higher; for PuBe neutrons, it is ~16%, and for plutonium-metal neutrons, it is ~25%. Using the ratio of the count rates at the front and rear of a 9-in. sphere, one can approximate the direction of the incident neutrons if their energy is known.

Neutron penetration through a manikin also changes with neutron energy. A dosimeter reading 70% of that obtained on the front was obtained at the back of a manikin, using PuBe neutrons. For PuF_4 neutrons, it was 60%, and for PuLi neutrons, it was 24%.

We ran a survey at a plutonium facility using the 3- and 9-in.-sphere technique. We corrected the calibration factors by using a value of 25% for the reading on the back of the 9-in. sphere compared to that on the front for a neutron exposure originating from the front. We used a value of 60% for neutron penetration through a manikin. We combined these factors and calculated a curve (Fig. 7) to give the correction factor to apply to the calibration factors obtained with the 3- and 9-in. spheres.

Fig. 7.
Curve used to find correction factor to apply to calibration factor obtained with 3- and 9-in. spheres if the neutron exposure is not primarily from the front. The curve was calculated assuming 60% penetration of neutrons through the body and 25% response of the BF_3 -tube reading on the back of the 9-in. sphere compared with that on the front for a neutron exposure originating from the front.

This technique is subject to numerous errors including: side-on exposure, exposure consisting of various neutron energies, and other than 60% penetration through a manikin. Despite these possible errors, a field test of this technique compared with the results from dosimeters on gallon jugs agreed within $\pm 18\%$.

The preferred calibration technique is to use manikins or gallon jugs. If this is not possible, the sphere technique can be used, but it is subject to greater errors. The sphere technique allows one to obtain data quickly, and if an entire facility is to be surveyed to determine an average calibration factor, the sphere technique would have to be used.

COMPARISON WITH OTHER ALBEDO DOSIMETERS

At least five different albedo-neutron dosimetry systems are presently used in the U.S.^{1,5,6,8} They vary greatly in size, sensitivity, cost, and ease of readout. The dosimeter described here was designed from the results reported

in LA-4832.¹⁰ We wanted a dosimeter that would be small and yet retain as much neutron sensitivity as possible, and whose readings would not be affected by improper wearing.

In the earlier study,¹⁰ we had found that probably the largest source of error in an albedo-neutron dosimeter reading was its response to thermal neutrons. There are several dosimeters that have cadmium on only one side of the TLD. The previous study indicated that if such dosimeters were allowed to pull away from the body, the thermal-neutron sensitivity increased by as much as four times. If the dosimeter was worn backwards, the thermal-neutron sensitivity increased by a factor of 10-100, depending on the thickness and size of the cadmium used. The thermal-neutron sensitivity would then exceed the fast-neutron sensitivity at 1 MeV by a factor of 10 to 100. If the thermal-neutron dose rate is even a few percent of the fast-neutron dose rate, the dose evaluation is seriously overestimated. When the thermal-neutron component is negligible, a PuF₄ source at 30 cm, for example, and dosimeters with cadmium on only one side are worn backwards, the fast-neutron response is low by a factor of ~5. If the dosimeter is oriented properly but allowed to pull 3 cm away from the body, the response to fast neutrons decreases ~30%.

The large errors that can be created by improper (backwards or pulled away from the body) wearing of dosimeters with cadmium on only one side of the TLD have been recognized. To avoid them, one investigator has placed the dosimeter on a belt⁵ and another has sewn an extra pocket for the dosimeter above the shirt pocket of coveralls.⁷ Unless such precautions are taken, use of a dosimeter with cadmium on only one side should not be considered. The possible errors in dosimeter evaluation are so large that the results could well be useless.

Neither fast- nor thermal-neutron response of the dosimeter described here is affected by up to 3-cm distances from the body. It can also be worn backwards without changing its response.

This dosimeter requires only one ⁶Li and one ⁷Li TLD to measure fast and thermal neutrons. LASL dosimetry records have shown that thermal neutrons normally do not contribute significantly to personnel exposure. Albedo-neutron dosimeters that are not completely surrounded with cadmium or ¹⁰B have a significant thermal-neutron response caused by leakage around the cadmium or ¹⁰B. The thermal-neutron dose must be determined by using another pair of TLD's and applying a correction based on their reading to the response of the TLD's in these dosimeters.^{1-8,10,11} Using the extra TLD's to correct for thermal neutrons is not necessary for the dosimeter described here. Because each TLD reading varies somewhat, eliminating two TLD's should make the calculated dose values more accurate.

This dosimeter can be used with as few as one, or as many as four, pairs of ⁶Li and ⁷Li TLD chips, depending on the dose to be measured and the accuracy desired. It does not require a specific type of TLD or TLD reader. The data can be processed without a computer and, because of their simplicity of interpretation, should be relatively free of computational errors. The dosimeter could be completely automated (see section on Future Studies), and if it were to be used on many people, some kind of automated readout system would be required. The time required to unload, read, bake-out, and reload the dosimeters using the present TLD handling procedures would be prohibitive and expensive.

All albedo-neutron dosimeters are very energy dependent when exposed to fast neutrons. Unfortunately, there is nothing that can be done to change this energy dependence or to correct for it.¹⁰ To use albedo-neutron dosimeters accurately, one must have knowledge of the neutron-energy spectrum or the spectrum must remain relatively constant with a calibration performed to it.

The dosimeter described here is about one-sixth as sensitive as some other albedo-neutron dosimeters¹⁰ but is still useful. If greater sensitivity to high-energy neutrons is required, or if the neutron component is a small part of the total dose, a dosimeter containing thick polyethylene and with cadmium on only one side can be used.¹⁰ This dosimeter would be heavy, would probably have to be belt-mounted, and would require two sets of TLD's.

FUTURE STUDIES

The TLD's used with the dosimeter we describe must be individually handled using tweezers. To reduce the time required to evaluate the dosimeters, we are studying how to mount the TLD's on a card containing a code system to identify the wearer. Other TLD's on the same card would be used to determine the beta, gamma, and, possibly, thermal-neutron dose. A slit would be cut into the albedo-neutron dosimeter part of the badge, the center 1/16-in.-polyethylene slab would be removed, and the card would be inserted. A small lip of cadmium would have to be placed around the slit to reduce thermal-neutron leakage. This would give a complete TLD-dosimetry system that would have an automated readout directly into a computer for dose evaluation and records storage.

SUMMARY

The dosimeter described here is small and light and can be worn by taping it to the bottom of the existing film-badge packet or including it in a packet about the

size of a film badge. It is inexpensive and can be made in a standard shop using normally available power equipment. Construction is not difficult, and the dosimeter can be easily and accurately reproduced. It does not have to be worn tight against the body and may be worn backwards without affecting its response. Its readout is not automated and requires a minimal investment for readout equipment, but the lack of automation may be a disadvantage if many people are to be monitored. The energy dependence is strong, and the neutron energy must be known or measured, or the dosimeter must be calibrated to a specific neutron source. The calibration may be performed on water-filled gallon jugs or with 3- and 9-in.-sphere neutron-detection instruments.

REFERENCES

1. R. B. Falk, "A Personnel Neutron Dosimeter Using Lithium Fluoride Thermoluminescent Dosimeters," Dow Chemical Company report RFP-1581 (1971).
2. H. E. Preston, "The Measurement of Personnel Neutron Doses in the Energy Region 0.5 eV to 10 MeV with Thermoluminescent Lithium Fluoride," United Kingdom Atomic Energy Authority Reactor Group report AEEW-M801 (1968).
3. J. B. C. Brown, F. M. Gayton, J. A. Hall, J. R. Harvey, and A. M. Webb, "Recommendations Concerning the Use of the Personnel Neutron Albedo Dosimeter," Berkeley Nuclear Laboratories Research and Development Department report RD/B/R828 (1967).
4. D. E. Hankins, "Energy Dependence of Albedo Neutron Dosimeters Placed on the Head," Los Alamos Scientific Laboratory report LA-4341 (1970).
5. A. Korba and J. E. Hoy, "A Thermoluminescent Personnel Neutron Dosimeter," *Health Phys.*, 18, 581 (1970).
6. C. N. Unruh, Ed., "AEC Workshop on Personnel Neutron Dosimetry, Sept. 23 and 24, 1969, Bethesda, Md.," Battelle Northwest Laboratory report BNWL-SA-2978 (1969).
7. C. N. Unruh, Ed., "Second AEC Workshop on Personnel Neutron Dosimetry," Battelle Northwest Laboratory report BNWL-1616 (1971).
8. D. E. Hankins, "Design of Albedo-Neutron Dosimeters," IAEA Symposium on Neutron Monitoring for Radiation Protection Purposes, Vienna, Dec. 11-15, 1972.
9. R. V. Griffith, "The Use of ^{10}B -Loaded Plastic in Personnel Neutron Dosimetry," IAEA Symposium on Neutron Monitoring for Radiation Protection Purposes, Vienna, Dec. 11-15, 1972.
10. D. E. Hankins, "Factors Affecting the Design of Albedo Neutron Dosimeters Containing Lithium Fluoride Thermoluminescent Dosimeters," Los Alamos Scientific Laboratory report LA-4832 (1972).
11. R. G. Alsmiller, Jr. and J. Barish, "The Calculated Response of Albedo-Neutron Dosimeters to Neutrons with Energies < 400 MeV," Oak Ridge National Laboratory report ORNL-TM-3984 (1972).
12. D. E. Hankins, "A Modified-Sphere Neutron Detector," Los Alamos Scientific Laboratory report LA-3595 (1967).