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LiF ALBEDO DOSIMETERS FOR PERSONNEL MONITORING IN A FAST-NEUTRON RADIATION FIELD

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Abstract

LiF ALBEDO DOSIMETERS FOR PERSONNEL MONITORING IN A FAST-NEUTRON RADIATION FIELD.

On the basis of albedo theory, the dose-equivalent of fast neutrons can only be measured with a sensitivity of about 1% of that for thermal neutrons. The use of albedo dosimeters for personnel monitoring was therefore limited to the measurement of neutrons in the intermediate and thermal energy ranges. An albedo dosimeter for fast-neutron personnel monitoring, the dosimeter reading of which needs no correction factor for the effect of different neutron spectra, is discussed. It consists of a pair of TLD 600 and TLD 700 ribbons, the TLD reading of which is used to separate the neutron dose and gamma dose fractions. The difference of the dosimeter readings TLD 600 and TLD 700 inside a boron capsule was found to be proportional to the dose-equivalent of neutrons. The calibration of the dosimeter was based on measurements with a rem counter and activation or threshold detectors. Phantom irradiations were performed in a radiation field of ^{252}Cf fission neutrons, ^{238}PuBe neutrons, 14-MeV neutrons and thermal neutrons to study the effect of moderation and scattering in the body, the floor and walls of a room, and the shieldings around the source. The albedo dosimeter system proposed for routine monitoring of personnel measures the dose-equivalent of fast neutrons with a response which is 0.54 of that for gamma rays. The influence of source shielding, scattered radiation and direction of radiation incidence was reduced by a separate measurement of incident neutrons and albedo neutrons and was found to be within ±30% of the actual dose-equivalent in the energy range from above 100 keV to 14 MeV.

1. INTRODUCTION

Fast neutrons are currently detected by means of nuclear track emulsions which enable a measurement to be made of the dose-equivalent in the energy range between 0.6 and 5 MeV within ±60% [1]. The high gamma sensitivity, the narrow range of measurement and the fading, especially at low neutron energies, limit the usefulness of this kind of personnel monitoring.

Nuclear track detectors other than photographic emulsions are being introduced into routine monitoring work to an increasing extent. These detectors have a wide dose range together with optimum gamma discrimination. On the other hand, the relatively high gamma background of thick layers of fissionable material (U, Th, Np) and the insufficient sensitivity of thin detector layers indicate that they could find application in accident dosimetry in particular. One major disadvantage of nuclear detectors is the energy threshold, which allows them to detect fast neutrons only above 0.7 MeV, if at all. By contrast, albedo dosimeters do not have this energy threshold because of the detection of low-energy neutrons backscattered by the body. This method of neutron detection has so far been used to detect thermal and intermediate neutrons. Dennis, Smith and Boot [2] were able to show that Cd-covered films and nuclear emulsions may also be able to detect thermal and intermediate neutrons. For purposes of personnel monitoring at reactors, Harvey et al. [3, 4] developed a LiF dosimeter for measuring thermal and intermediate neutrons.

Series of measurements performed more recently by Hankins [5] were supposed to furnish experimental data for the design of an albedo dosimeter intended to detect fast neutrons in addition to thermal and intermediate neutrons. This became desirable after Korba and Hoy [6] had developed an albedo dosimeter at Savannah River which consists of a combination of two pairs of LiF dosimeters arranged within a polyethylene hemisphere of 5-cm diameter and partly covered with Cd. This dosimeter was able to measure the dose-equivalent of neutrons from ^{252}Cf and PuBe sources and of those from various critical assemblies. If the radiation field is known – scattered or unscattered neutrons – it is possible, as with a Harvey dosimeter in the range of intermediate neutrons at reactors, to use a calibration factor dependent on the locality in order to determine the dose-equivalent with a sufficient degree of accuracy.

Our studies at the Karlsruhe Nuclear Research Centre were directed towards the development of a lightweight, simple albedo dosimeter for measuring the dose-equivalent of fast neutrons and which would not require any additional information about radiation conditions in situ, i.e. no correction factors depending on the locality. Work was started with measurements in the radiation field of a ^{252}Cf source with different source shieldings and set up in a radiation field without scattered radiation. Later, the influence of scattering from the wall, the floor and the shielding was investigated. The results of these studies are described below; they led to the development of an albedo dosimeter for fast neutrons, indicating the dose-equivalent relatively independently of the neutron energy and the direction of radiation incidence in the presence of a continuous spectrum.

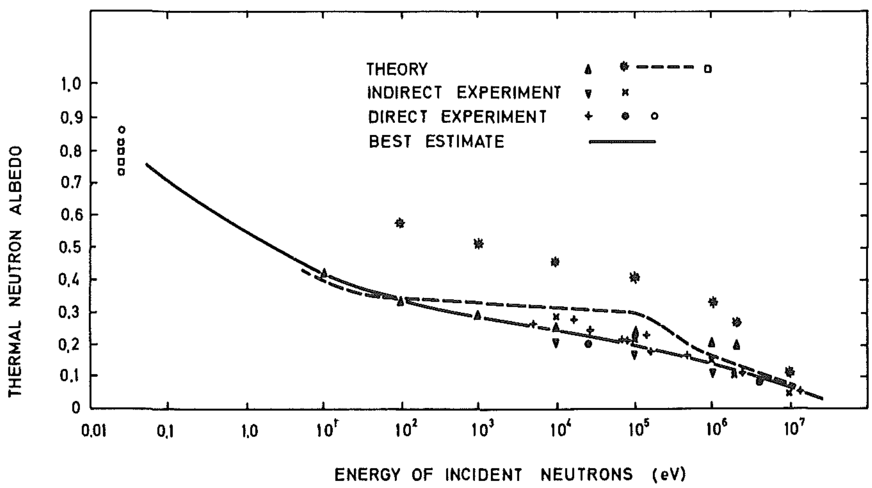


FIG.1. Thermal neutron albedo as a function of incident neutron energy, after Ref. [4].

2. MEASUREMENT METHOD

Albedo dosimetry is based on the principle that high-energy neutrons leave the body as thermal and intermediate neutrons after having been scattered in the body and are detected at the surface of the body by means of a detector for thermal neutrons. Theoretical and experimental investigations have shown the albedo factor for thermal neutrons, defined as

$$\frac{\text{thermal neutron fluence scattered from the body}}{\text{total incident neutron fluence entering the body,}}$$

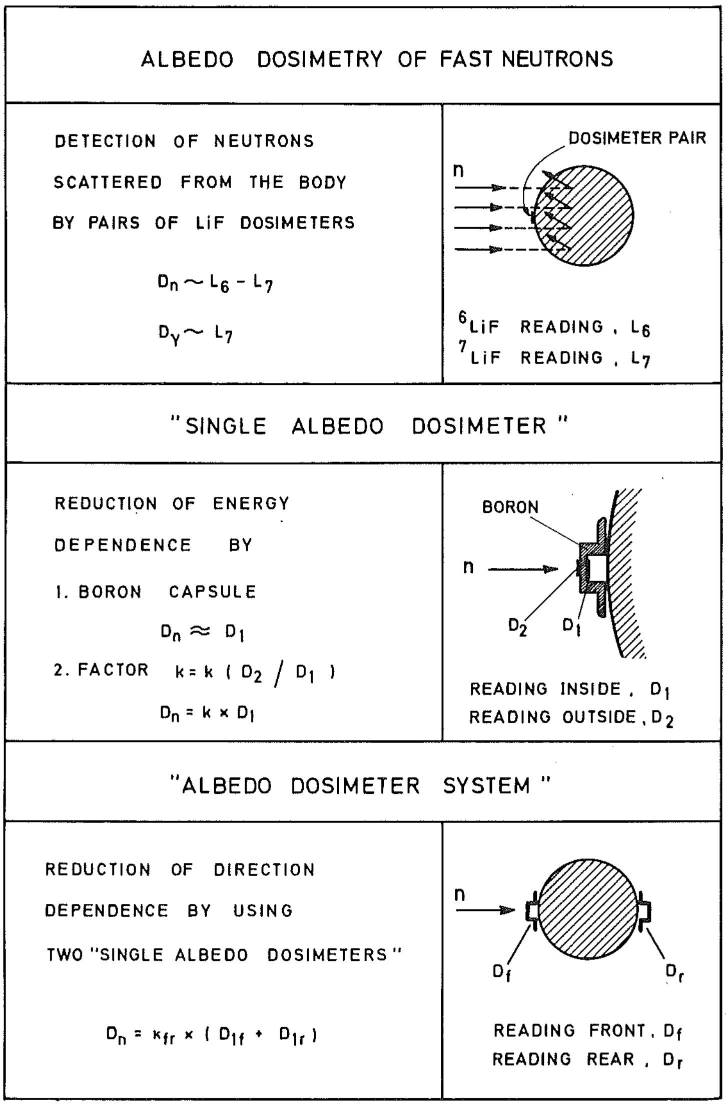


FIG. 2. Application of albedo dosimetry to the measurement of fast neutrons.

to be oversensitive to directly incident thermal neutrons by a factor of up to 4 compared with intermediate neutrons (see Fig. 1). When equipped with a cadmium or boron shield albedo dosimeters furnish readings of thermal and intermediate neutrons up to energies of 10 keV, which are approximately correct in terms of the dose-equivalent. However, albedo dosimeters will be able to detect fast neutrons only with a low sensitivity corresponding to approximately 1-5% of that for intermediate neutrons. For these reasons, it was thought meaningless to try to use this kind of detector for the detection of fast neutrons.

More recent investigations performed at the Karlsruhe Nuclear Research Centre have shown that LiF albedo dosimeters are able to detect fast neutrons from a ^{252}Cf neutron source with a sensitivity corresponding to approximately 50% of the gamma sensitivity.

A dosimeter of this kind consists of a pair of ^{6}LiF and ^{7}LiF dosimeters exposed at the surface of a human phantom. The difference in dosimeter readings of the pair of dosimeters (TLD 600 - TLD 700) is proportional to the neutron dose.

Further investigations performed with ^{252}Cf neutrons indicated that the influence of scattered neutrons from the environment is relatively small in free air exposures. However, with increasing fractions of scattered neutrons from the floor, the wall and the shielding of the source, these conditions of detection change. To obtain readings which were correct in terms of the dose-equivalent, it was necessary to reduce the relatively high sensitivity of albedo dosimeters to scattered neutrons from the environment in the manner described below (see Figure 2).

(1) By covering the pair of dosimeters with a boron capsule on the side facing away from the body for absorption of incident neutrons.
(2) By separate measurements of incident neutrons and neutrons scattered in the body, with one dosimeter for each on each side of the boron capsule (reading of outer dosimeter, D_2, of inner dosimeter, D_1). The ratio of readings D_2/D_1 are used to determine a correction factor k.
(3) By measuring the dose both on the front and the rear of the body, with one dosimeter for each, to reduce the direction dependence of the dosimeter reading. In this "albedo dosimeter system", the readings of both dosimeters are added and assigned the correction factor determined from the respective ratio of the dosimeter readings.

The results of our measurements showed that these steps were adequate to reduce the dependence on energy and direction of the dosimeter reading for measuring the dose-equivalent of fast neutrons in the energy range between several 100 keV and 14 MeV.

3. DOSIMETER AND CALIBRATION

Extruded LiF dosimeters with dimensions $3 \times 3 \times 1$ mm^3 were used, which are commercially available from the Harshaw Company as TLD 600 and TLD 700. The dosimeters were calibrated with ^{137}Cs gamma rays and evaluated in a Harshaw TLD Reader Model 2000A - 2000B. The maximum heating temperature during measurement was 240°C. So that the dosimeters couldbe re-used, they were regenerated at a temperature of 400°C

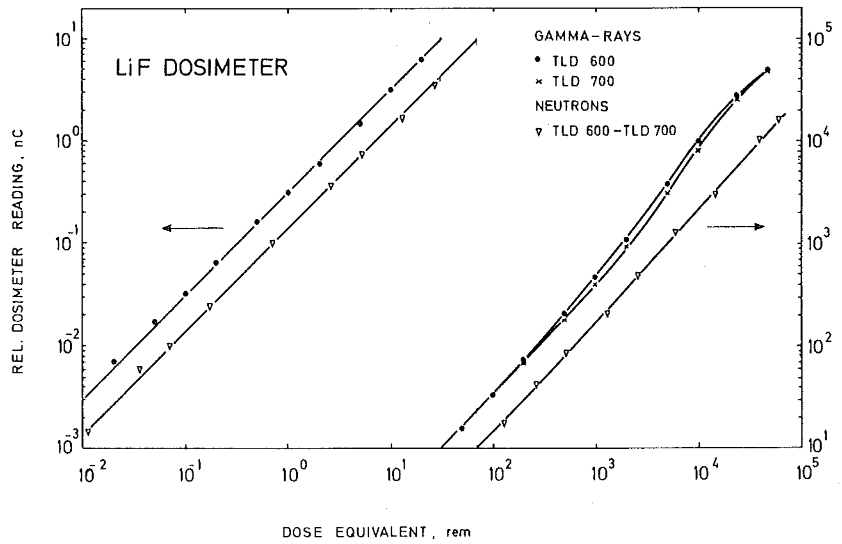


FIG. 3. Relative dosimeter reading of LiF dosimeters as a function of the dose-equivalent for gamma irradiation and of an albedo dosimeter for fast-neutron irradiation.

(one hour) and 100°C (two hours). Because of variations by more than ± 5% in the sensitivities of the individual dosimeters within one batch, each dosimeter was individually calibrated before the measurements were begun. Moreover, precautions were taken to avoid changes due to regeneration in the individual calibration factor.

A TLD 600/TLD 700 pair of dosimeters was used to separate the gamma dose fraction. The TLD 700 dosimeter is regarded as being sufficiently insensitive to thermal neutrons for the measurements conducted here. Its reading is a measure of the gamma dose. TLD 600, however, also indicates thermal neutrons in addition to gamma radiation because of its high ^{6}Li content. The difference in the readings of TLD 600 and TLD 700 indicates the neutron fraction of the radiation.

The dosimeter readings of the TLD 600 and TLD 700 dosimeters are shown in Fig.3 as a function of the dose-equivalent of ^{137}Cs gamma rays and the neutron radiation of ^{252}Cf measured by an albedo dosimeter at a heating temperature of 240°C. Relative to gamma irradiation above 100 rem, both TLD 600 and TLD 700 exhibit similar supralinear behaviour. In this case, the fraction of the dosimeter reading simulating the neutron fraction due to the small differences in gamma sensitivity of TLD 600 and TLD 700 is less than 10% up to a gamma dose of 1000 rem and less than 20% of the measured gamma dose up to 10^5 rem.

The difference between the TLD 600 and TLD 700 readings is proportional to the dose-equivalent for neutrons in the dose range between 20 mrem and 1000 rem, showing more favourable supralinear behaviour above this dose, which is in contrast to the gamma dose reading. After correcting the supralinear indication of the difference in readings by a factor of not more than 1.75, the range of neutron dose-equivalent can be extended up to

10^5 rem. Separation of the gamma and neutron dose fractions is possible as long as either of these dose fractions amounts to approximately 10% of the total dose. Accordingly, the albedo dosimeter containing TLD 600 and TLD 700 as detectors is capable of detecting fast neutrons from a ^{252}Cf source over a dose range between 20 mrem and 10^5 rem.

As a shield against incident scattered neutrons, a boron capsule developed by Harvey et al. was used which represents an optimization of the capsule size (diam. 48 mm) and the depth of the detector in the capsule (9 mm) with respect to discrimination of incident neutrons. The capsule is made of phenol resin with a boron carbide fraction of 560 mg/cm^3. The wall thickness is 3 mm, which corresponds to an attenuation factor of 1000 for thermal neutrons.

Exposures with the albedo dosimeter were conducted in connection with a human phantom consisting of a bottle of water 20 cm in diameter and 40 cm high which, unless indicated otherwise, was always set up at a height of 1.40 m (chest level). The reading of the albedo dosimeter at the surface of the phantom was related to the dose-equivalent as determined by a rem counter in the same place. Calibration with 14-MeV neutrons and thermal neutrons was performed with additional activation and fission detectors (neptunium, sulphur, gold).

The rem counter (Andersson and Braun type) was calibrated with an AmBe neutron source, the intensity of which was known. This rem counter was deemed to be a suitable instrument for measuring the dose-equivalent in the energy range of interest. Because of oversensitivity of the rem counter in the intermediate neutron range, some inaccuracy had to be accepted in measuring the dose-equivalent rate, which, however, will be less than ±15% with the neutron spectra used in this case. The response of the albedo dosimeter is recorded as roentgens of the dosimeter reading after a TLD reader calibration with ^{137}Cs gamma rays divided by the neutron dose-equivalent in rem, which was measured with the rem counter.

4. DETECTION SENSITIVITY OF THE ALBEDO DOSIMETER FOR FAST NEUTRONS

4.1. Radiation field with a low level of backscatter

Calibration of the albedo dosimeter in the fast neutron range was performed by a 1 mg ^{252}Cf source with an effective source strength of 2.1×10^9 n/s and a ^{238}PuBe source of 10 Ci. Exposures were conducted at a height of 1.4 m above the floor (concrete) in an experimental hall 10×20 m^2 and 10 m in height and at a distance from the source of 5, 3, 2, 1 and 0.5 m. Exposures to the ^{252}Cf source were made in free air and behind various shieldings. The materials used for the 5-cm-thick shieldings were PVC, concrete, aluminium and iron. The results of these series of measurements with the albedo dosimeter system are given in Fig. 4. The influence of neutrons scattered from the floor for distances from the source of between 0.5 and 5 m and the change in energy distribution as a result of the source being shielded on all sides result in a dosimeter reading which is proportional to the dose-equivalent within ±30% for the three directions of radiation incidence selected, namely 0°, 90° and 180°. The mean detection response of the albedo dosimeter system is 0.54 R/rem for the

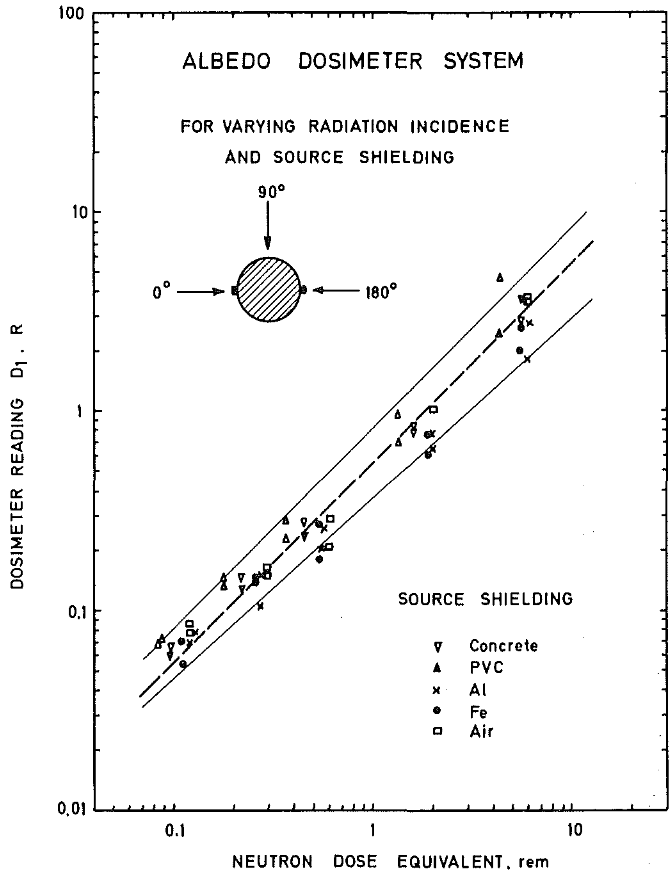


FIG. 4. Dosimeter reading D_1 of the albedo dosimeter system as a function of the dose-equivalent for varying radiation incidence angles and a source shielding of 5-cm thickness.

neutron spectra used in this case. Exposure in free air without any shielding resulted in a response of 0.4 R/rem for ^{252}Cf neutrons; for ^{238}PuBe neutrons, the corresponding value is 0.3 R/rem.

4.2. Influence of scattered neutrons

The conditions shown in Fig. 4 may be expected only for neutron sources with thin-walled shieldings and in relatively large rooms with a low number of scattered neutrons. To assess the influence upon the dosimeter reading of larger fractions of scattering, the following experiments were performed:

(1) assessment of the dosimeter response for various thicknesses of the source shielding;
(2) assessment of the dosimeter response at varying distances from a radiation source set up close to the wall in a small room;

(3) assessment of the dosimeter response for a neutron source kept in a pool of water, with variable thickness of the water shield;
(4) assessment of the dosimeter response for varying distances from a concrete wall.

Figure 5 shows the variation in the dosimeter response R/rem for the influence of scattering in a small room 2.4 × 3.7 m^2, when the source is set up at a height of 1.4 m above ground in one corner of the room. The detection of scattered neutrons changes the relative response (a value of 1.0 corresponding to 0.54 R/rem) of albedo dosimeters by not more than a

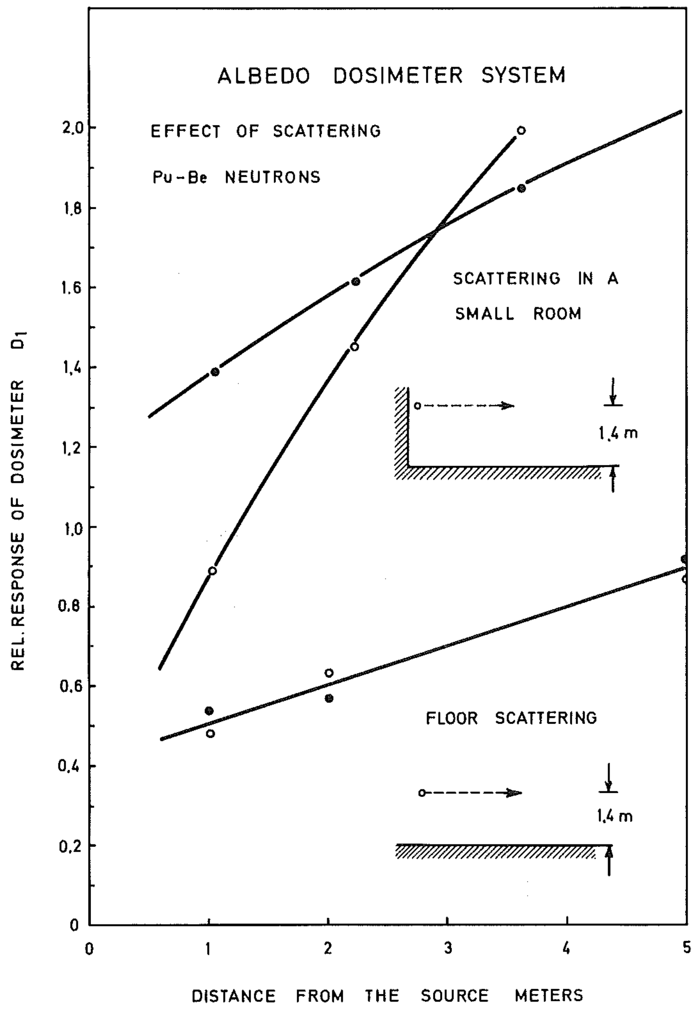


FIG. 5. Relative response of dosimeter reading D_1 as a function of the distance from the source for irradiations with PuBe neutrons in a small room, the source in contact with the walls at the corner of the room and under free air conditions.

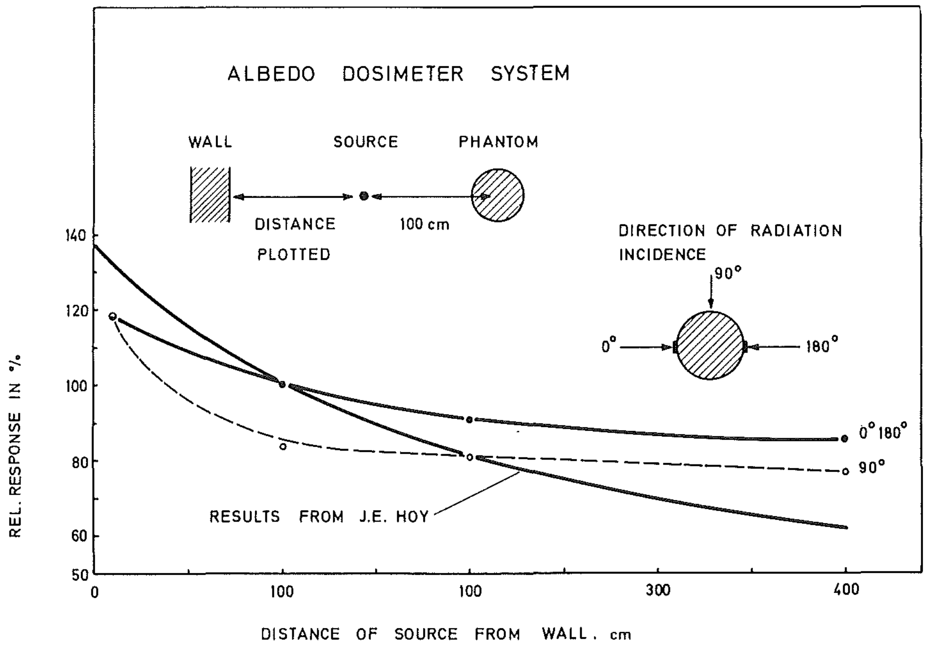


FIG. 6. Relative response of dosimeter reading D_1 as a function of the distance of the ^{252}Cf source from the concrete wall for the albedo dosimeter system with directions of radiation incidence of 0°, 90° and 180° and of the albedo dosimeter developed by J. E. Hoy after Ref. [7].

factor of 4. Therefore, a dose measurement is possible only after additional correction for the neutrons incident from the outside, e.g. by separate measurement of incident and scattered neutrons through the ratio of readings D_2/D_1 (cf. Fig. 2).

Figure 6 shows the influence of wall scattering on the reading of albedo dosimeters. After appropriate standardization at a distance of 1 m, these results can be directly compared with the results obtained with the albedo dosimeter by J.E. Hoy [7]. Both types of dosimeter show the same higher sensitivity to neutrons backscattered from the wall.

4.3. 14-MeV neutrons

With 14-MeV neutrons, albedo dosimeters show a much lower sensitivity. Exposures were conducted in an experimental hall with a fused neutron tube via the (d, T) reaction at distances of 1 m (free air), 3 m (scattering from a water tank), 1.5 m (scattering in front of a wall) and 2 m (scattering behind a wall). The neutron dose-equivalent was determined both by the rem counter (50% sensitivity) and by non-photographic nuclear track detectors (combination of ^{237}Np and Makrofol) and via the $^{31}S(n, p)^{32}P$ reaction. Additional measurements of thermal and intermediate neutrons were conducted with gold foils. Free air exposure resulted in a neutron response of 0.11 R/rem for the single albedo dosimeter and 0.17 R/rem for the albedo dosimeter system.

4.4. Influence of thermal neutrons

Because of the oversensitivity of albedo dosimeters to scattered neutrons, a phantom exposure was performed with thermal neutrons. Calibration in the thermal column of the FR-2 reactor required a smaller phantom, i.e. a water bottle 15 cm in diameter and 30 cm high (see Section 5.4). Exposure was made to delayed neutrons with the reactor shut down; the neutron fluence was measured with gold foils.

The single albedo dosimeter resulted in a response of 4.5 R/rem for D_1 and 99 R/rem for D_2 for exposure of the dosimeter capsule in contact with the phantom. This result is in good agreement with the corresponding values by Harvey et al. [4], taking into account the fact that LiF dosimeters of different sizes were used and the author's free air exposure experiments of LiF dosimeters in the thermal column. However, the response to thermal neutrons is extremely dependent on the distance of the capsule from the surface of the phantom. At a distance of the dosimeter capsule of 1 cm, the response D_1 will be increased by a factor of 1.6.

TABLE I. EXPERIMENTAL RESULTS OF FUST-NEUTRON IRRADIATION OF THE ALBEDO DOSIMETER

NEUTRON SOURCE	SINGLE ALBEDO DOSIMETER						ALBEDO DOSIMETER SYSTEM					
	Response R/rem			Ratio D_2/D_1			Response R/rem		Ratio D_2D_1		Rel. Response %	
	0°	90°	180°	0°	90°	180°	0°/180°	90°	0°/180°	90°	0°/180°	90°
^{252}Cf in air	0.33	0.2	0.075	0.79	0.82	1.06	0.41	0.4	0.84	0.82	89	88
+ 5 cm Pb	0.36	0.24	0.08	0.75	0.80	1.2	0.44	0.48	0.82	0.8	97	107
+ 5 cm Al	0.43	0.21	0.073	0.73	0.89	1.36	0.49	0.41	0.82	0.88	108	86
+ 5 cm Fe	0.42	0.23	0.08	0.72	0.94	1.24	0.50	0.46	0.8	0.94	111	90
+ 16 cm Fe	0.62	0.34	0.11	1.05	1.0	1.75	0.72	0.68	1.16	1.05	119	119
+ 5 cm concrete	0.43	0.25	0.08	1.02	0.95	1.41	0.5	0.5	1.1	0.95	87	98
+ 5 cm PVC	0.61	0.34	0.094	1.13	1.44	1.64	0.6	0.67	1.2	1.15	96	112
+ 11 cm PVC	0.77	0.39	0.115	1.4	1.47	1.95	0.88	0.78	1.46	1.47	122	105
^{252}Cf wall effect												
at 0 cm	0.45	0.26	0.065	1.15	0.83	1.08	0.43	0.36	1.15	0.71	85	125
at 1 m	0.37	0.18	0.068	0.66	0.74	0.93	0.39	0.35	0.71	0.74	105	87
at 2 m	0.33	0.18	0.063	0.52	0.72	0.88	0.37	0.33	0.58	0.72	113	85
at 4 m	0.32	0.17	0.057	0.4	0.56	0.86	0.51	0.51	0.47	0.55	127	101
^{252}Cf in water tank												
at 4 cm	0.83	0.37	0.117	3.0	2.05	2.4	0.95	0.74	2.93	2.05	72	77
at 12.5 cm	1.04	0.47	0.13	4.9	2.13	3.46	1.17	0.94	4.75	2.12	62	96
at 43 cm	1.4	0.92	0.24	5.64	4.2	5.85	1.64	1.84	5.7	3.5	75	123
at 51 cm	1.70	1.02	0.41	3.08	3.4	3.95	2.19	2.04	3.74	3.4	138	140
^{238}PuBe in air at 1 m	0.225	0.110	0.064	0.36	0.34	0.51	0.29	0.26	0.38	0.35	119	113
at 2 m	0.24	0.168	0.067	0.61	0.54	0.8	0.31	0.34	0.62	0.53	84	107
^{238}PuBe in small room												
at 1 m	0.57	0.24	0.1	1.4	1.12	1.8	0.75	0.48	1.3	1.13	113	82
2.3 m	0.57	0.39	0.3	2.16	2.12	2.17	0.87	0.78	2.16	2.13	87	77
2.2 m	0.61	0.46	0.26	1.9	1.8	2.26	0.87	0.92	2.0	1.8	93	106
3.6 m	0.68	0.54	0.32	2.34	2.15	2.68	1.0	1.68	2.45	2.15	89	108
14 MeV in air at 1 m	0.116	0.165	0.108	2.02	1.07	0.95	0.17	0.17	1.0	1.0	107	107
1.5 m	0.202	0.25	0.23	1.45	1.44	2.1	0.22	0.25	1.78	1.44	90	115
2 m	0.44	0.36	0.24	2.6	2.33	3.25	0.34	0.36	2.52	2.33	98	114
3 m	0.57		0.25	3.6		3.7	0.41		3.6		86	
THERMAL NEUTRONS	4.5			22			4.5		22		68	
							9.0		22		137	

5. MEASURING THE DOSE EQUIVALENT OF FAST NEUTRONS

5.1. Correction of the energy dependence

To correct the energy dependence of the dosimeter reading, use is made of the ratio of readings D_2/D_1 (see Fig. 2). On the basis of the results of all exposures (see Table I), the response of the single albedo dosimeter, D_1, was plotted over the ratio of readings of D_2/D_1 in Fig. 7. As was to be expected, the results measured by the single albedo dosimeter scatter within a factor of 10 for the directions of exposure of 0°, 90° and 180° as a consequence of the direction dependence of the dosimeter reading.

Figure 8 shows the measured results of the albedo dosimeter system. On the assumption that the increased sensitivity of albedo dosimeters to scattered neutrons occurs in both the thermal and the intermediate range of energies, no ratio D_2/D_1 increased by the respective amount is anticipated for higher dosimeter response D_1, since it is correct that the fraction of intermediate neutrons increases the response of the dosimeter in the same way as do thermal neutrons, without increasing the ratio of readings D_2/D_1. Nevertheless, the measured results of ^{252}Cf and ^{238}PuBe exposures show that there is a functional relationship between the dosimeter response D_1 and

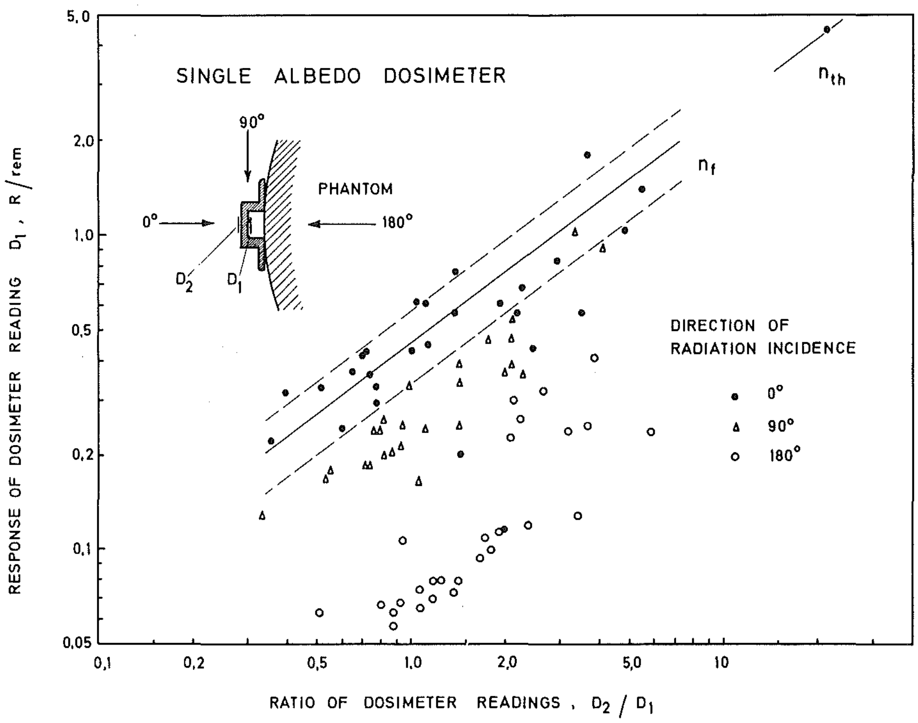


FIG. 7. Response of single albedo dosimeter reading D_1 as a function of the ratio of the dosimeter readings D_2/D_1 for directions of radiation incidence of 0°, 90° and 180° after irradiation with ^{252}Cf, PuBe and 14-MeV neutrons.

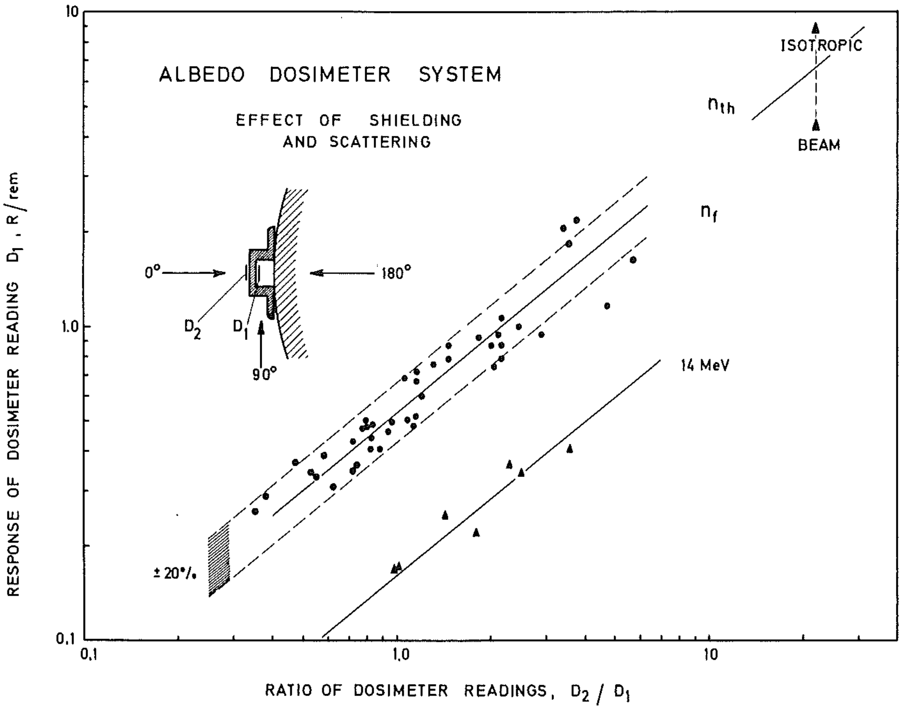


FIG. 8. Response of the albedo dosimeter system reading D_1 as a function of the dosimeter readings D_2/D_1 for irradiation with various neutron spectra, including the effect of shielding and scattering and directions of radiation incidence of 0°, 90°, 180°.

TABLE II. EFFECT OF SCATTERED NEUTRONS ON THE RESPONSE OF THE ALBEDO DOSIMETER SYSTEM

Neutron source		Response D_1 R/rem	Ratio D_2/D_1
n_{th}		4.5	22
^{252}Cf	High scattering	2.2	3.74
	Air	0.4	0.84
$^{238}PuBe$	High scattering	1.0	2.45
	Air	0.29	0.38
14 MeV	High scattering	0.41	3.6
	Air	0.17	1.0

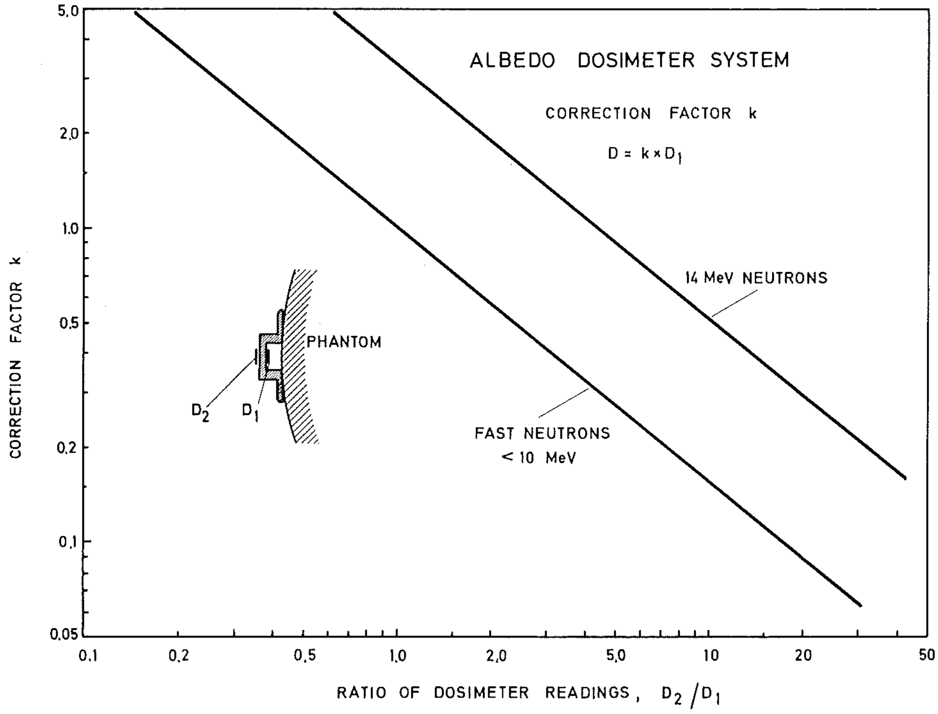


FIG. 9. Correction factor $k = k\,(D_2/D_1)$ for the albedo dosimeter system as a function of the ratio of dosimeter readings D_2/D_1 for fast neutrons below 10 MeV and for 14-MeV neutrons.

the ratio of readings D_2/D_1 (see Table II). In this case, the deviation of the readings from a mean straight line is within ±20%. The assignment of the dosimeter response D_1 to the corresponding ratio of readings D_2/D_1 is a factor of 2.5 smaller for 14-MeV neutrons. The increased response of dosimeters in the presence of scattered neutrons is obviously due to thermal neutrons only. The measured value for thermal neutrons is approximately on the same straight line as the results for ^{252}Cf neutrons (ratio of readings $D_2/D_1 = 22$).

From these results, a correction factor $k = k\,(D_2/D_1)$ was determined, which is shown in Fig. 9 and is used to correct dosimeter reading D_1. In this case, the correction turns out to be:

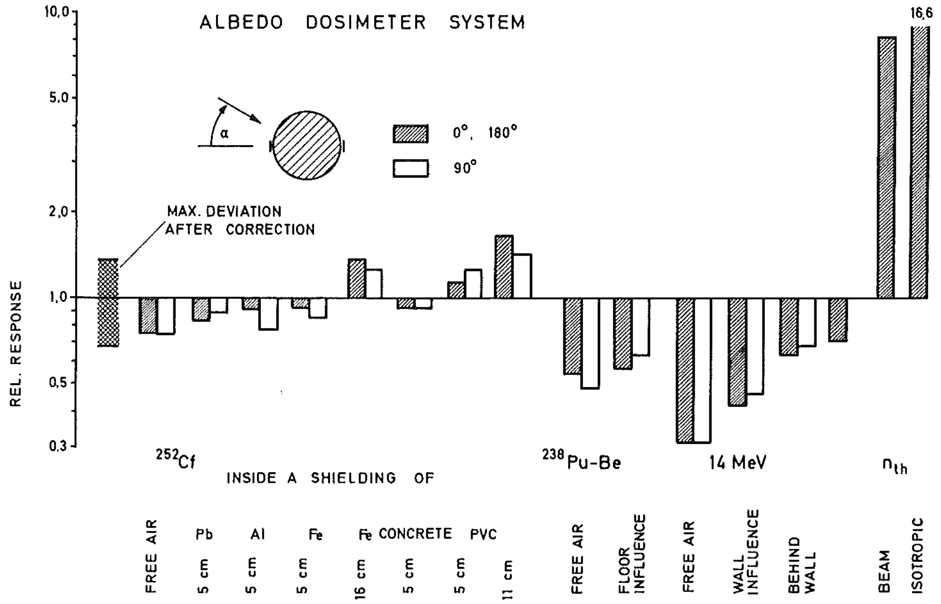
$D_n = k \cdot D_1$ for the single albedo dosimeter;

$D_n = k_{f,r} \cdot (D_{f1} + D_{r1})$ for the albedo dosimeter system.

$k_{f,r}$ is obtained from the corresponding ratio of readings $(D_{f2} + D_{r2})/(D_{f1} + D_{r1})$.

5.2. Total error in determining the dose-equivalent

The uncorrected readings obtained with the different ^{252}Cf spectra, with ^{238}PuBe neutrons, 14-MeV and thermal neutrons, are shown in Fig. 10 for



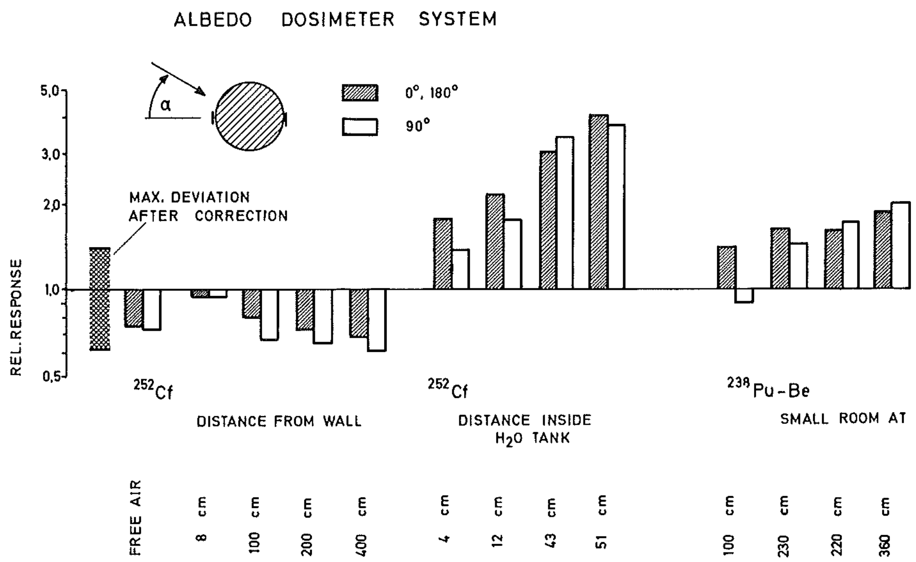


FIG. 10. Relative response of the albedo dosimeter system without correction for the effect of scattered neutrons for various sources and exposure conditions and directions of radiation incidence of 0°, 90°, 180°.

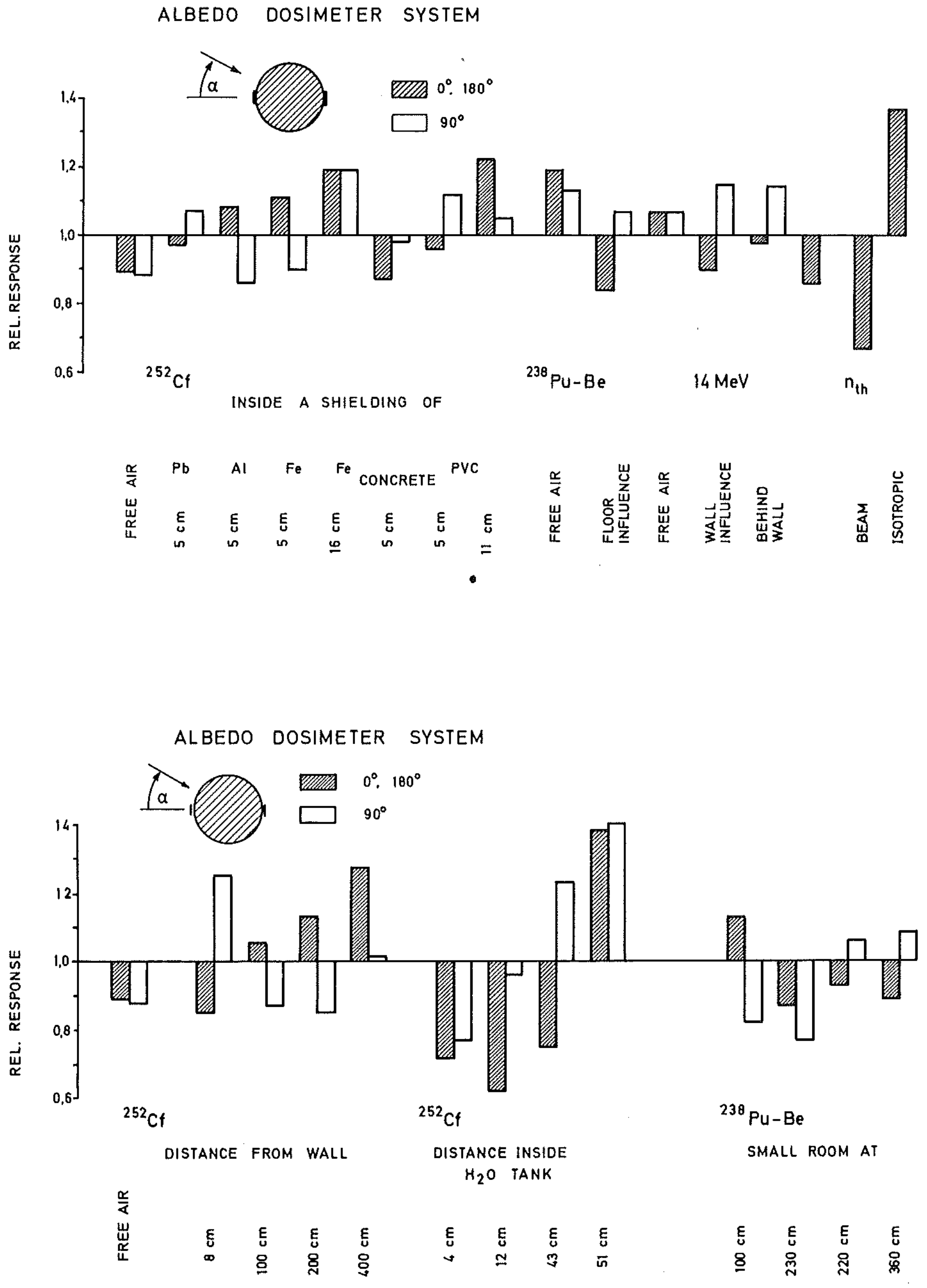


FIG. 11. Relative response of the albedo dosimeter system after correction for the effect of scattered neutrons for various exposure conditions (see also Fig. 12 and Table I).

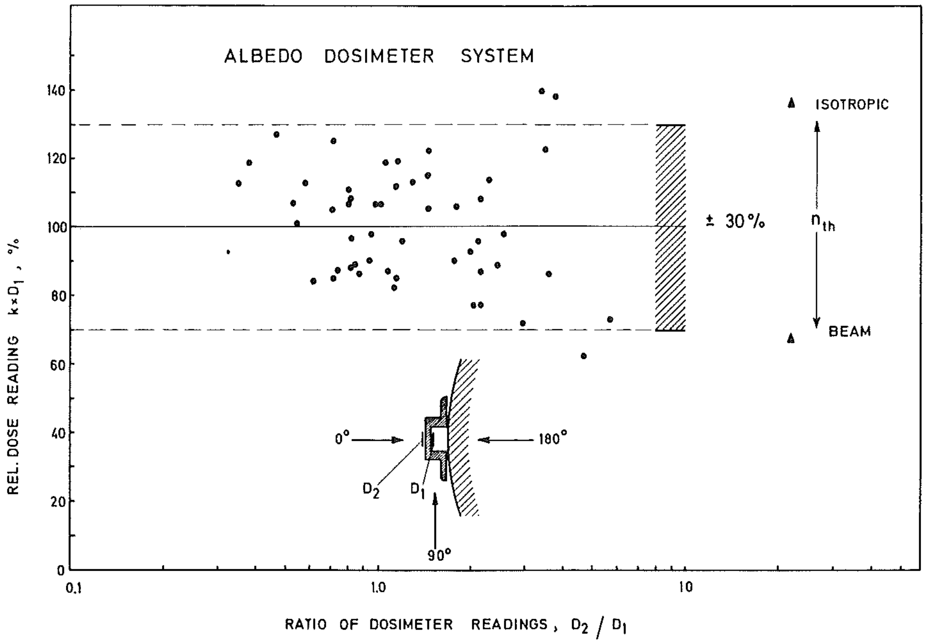


FIG. 12. Relative dose reading $k \cdot D_1$ of the albedo dosimeter system after correction for the effect of scattered neutrons as a function of the ratio of the dosimeter readings D_2/D_1 for all irradiations with fast neutrons (see Table I) and directions of radiation incidence of 0°, 90°, 180°.

the albedo dosimeter system and an exposure under 0°, 90° and 180° incidence. Maximum errors arise mainly from the source in the water pool, a fraction of scattered neutrons from the environment, and with 14-MeV neutrons without any shielding. For comparison, the maximum deviation of readings obtained after correction of the dosimeter reading is shown.

The results, after correction of reading D_1 with correction factor k, are shown in Fig. 11. With a few exceptions, the maximum amount of scatter is within ±30% for the directions of radiation incidence assumed, namely 0°, 90° and 180°. Since fractions of radiation may be scattered from various directions, major differences can be received both in the dosimeter response D_1 and the ratio D_2/D_1, depending upon the directions of radiation incidence; hence, there is still some direction dependence of the dosimeter reading even after correction of the measured value. Thermal neutrons are detected with an approximately correct dose response. The readings obtained with 14-MeV neutrons were corrected with a special correction factor. For energies below 10 MeV, it is not necessary to know the neutron source. The situation is different with respect to intermediate neutrons, especially for reactor monitoring, which will be dealt with in Section 6.

The relative deviation from the true dose-equivalent in the dosimeter reading of the albedo dosimeter system is shown in Fig. 12 for the exposures described here as a function of the ratio of readings D_2/D_1. As was to be

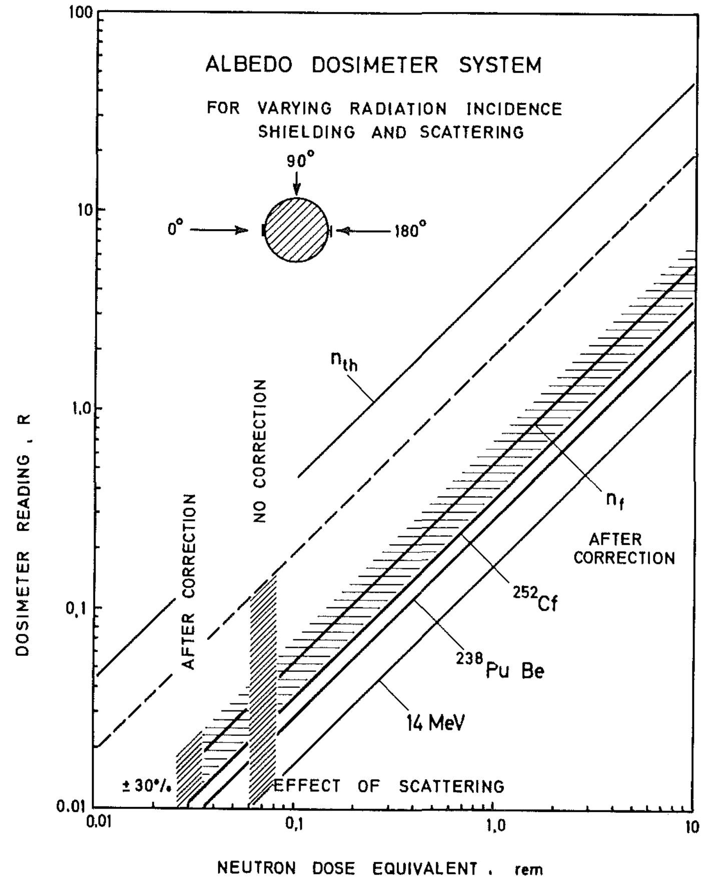


FIG. 13. Dosimeter reading D_1 of the albedo dosimeter system before and after correction for the effect of scattered neutrons as a function of the neutron dose-equivalent for directions of radiation incidence of 0°, 90°, 180°.

expected, the deviation from the theoretical value becomes higher at high values of D_2/D_1.

The advantages arising from the application of the correction factor in measurements of fast neutrons with the albedo dosimeter system can be explained on the basis of Fig. 13. Without correction of the scattered neutrons, the response of the dosimeter reading in the range of energies between 14-MeV neutrons and scattered ^{252}Cf neutrons is between 0.17 and 2.2 R/rem. After correction of the dosimeter reading D_1 by means of the ratio D_2/D_1, a mean dosimeter response of 0.54 R/rem is obtained with a maximum deviation of only ±30%. This total error was assessed for directions of radiation incidence of 0°, 90° and 180°. Accurate data on the dosimeter response are compiled in Table III for various exposure conditions.

TABLE III. EFFECT OF ENERGY AND DIRECTION DEPENDENCE ON THE RESPONSE OF THE ALBEDO DOSIMETER FOR FAST NEUTRONS

Dosimeter	Source	Direction of radiation incidence	Dosimeter response		
			R/rem	Deviation	Deviation after correction
Single albedo dosimeter	Low scattering[a]	0°	0.5	± 30%	--
	^{252}Cf, PuBe	0°, 90°, 180°	0.05 - 0.68	Factor 13	--
	High scattering	0°	0.17 - 2.2	Factor 13	± 30%
	^{252}Cf, PuBe 14 MeV	0°, 90°, 180°	0.05 - 1.8	Factor 36	Factor 10
Albedo dosimeter system	All irradiations Fast neutrons	0°, 90°, 180°	0.54	Factor 13	± 30%

[a] Including effect of source distance 0.5 - 5 m and source shielding of 5-cm thickness.

5.3. Direction dependence of the dose-equivalent reading

Dosimeters were exposed to a radiation field of ^{252}Cf + 5 cm of PVC to assess the dependence on direction of the dosimeter reading. Figure 14 shows the relative change of the dosimeter reading as a function of the direction of radiation incidence of the incident primary radiation for the single albedo dosimeter and for the albedo dosimeter system. The dosimeter reading D_1 was related to the reading of the rem counter in this location. As compared with the unfavourable conditions of detection experienced by the single albedo dosimeter, the albedo dosimeter system shows deviations which are already within the error margin indicated above for the energy dependence at 0° and 90°. In practice, the existing deviations will be smaller because the wearer of the dosimeter will move in the radiation field and short-term exposure from one preferential direction is improbable.

5.4. Influence of phantom size

The influence of the phantom size on the reading of the albedo dosimeter system was investigated with phantoms of various sizes. In addition to water bottles of 15-, 20- and 27-cm diameter, an elliptical phantom of 20×30 cm^2 cross-section was used. Figure 15 shows that the relative differences in reading the single albedo dosimeter are compensated in the albedo dosimeter system.

6. PRACTICAL APPLICATION OF ALBEDO DOSIMETRY

Different methods of neutron detection by means of albedo dosimetry are shown in Fig.16 for various types of albedo dosimeter. They are listed below.

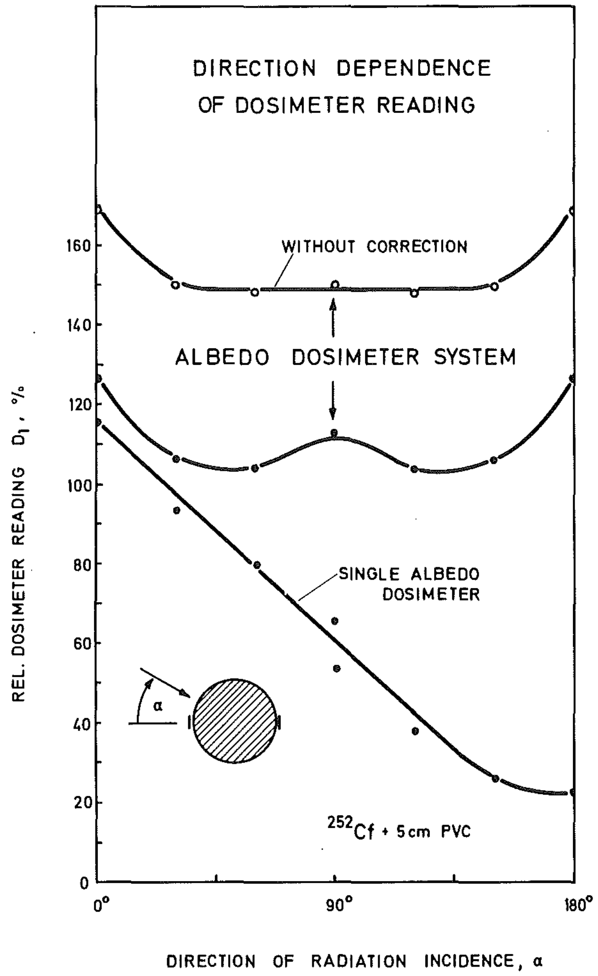


FIG. 14. Relative dosimeter reading D_1 of the single albedo dosimeter and the albedo dosimeter system without and with correction for scattered neutrons as a function of the direction of the radiation incidence angle α for irradiation with ^{252}Cf + 5 cm PVC.

Dosimeter 1: Albedo dosimeter according to Korba and Hoy [6, 7]. Here, the difference in readings between a LiF dosimeter facing the source and another facing the surface of the body is used to determine the neutron dose.

Dosimeter 2: Albedo dosimeter according to Harvey et al. [4]. With a single albedo dosimeter, only the D_1 reading in the boron capsule is used to detect thermal and intermediate neutrons.

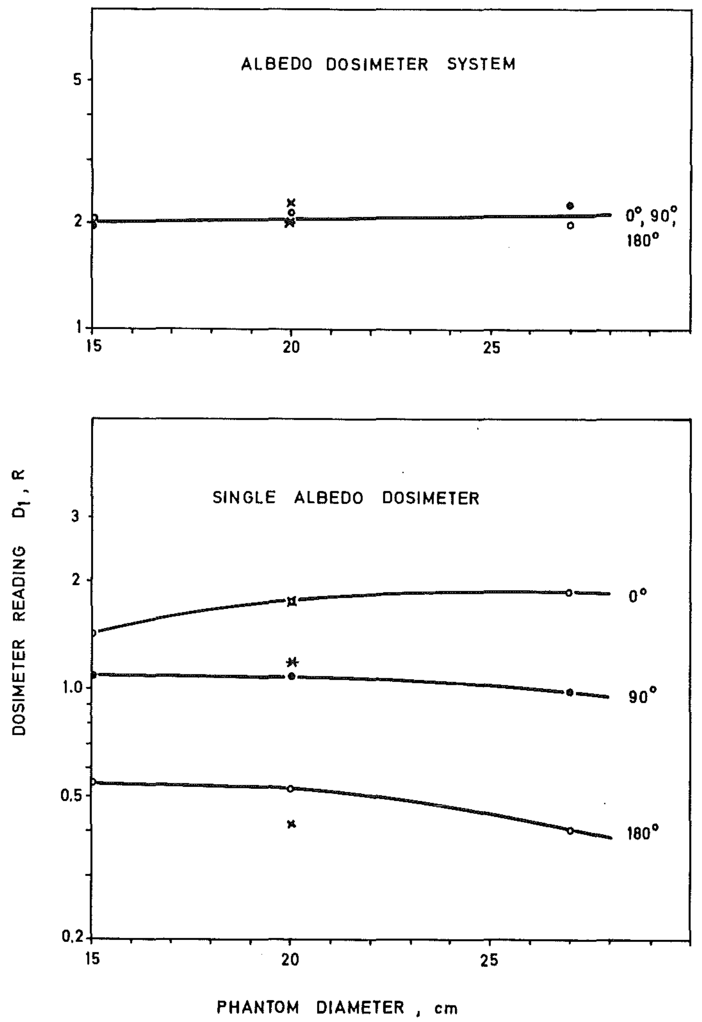


FIG. 15. Dosimeter reading D_1 of the single albedo dosimeter and the albedo dosimeter system as a function of phantom diameter for an irradiation with ^{252}Cf neutrons.

Dosimeter 3: Albedo dosimeter system as described in this report [8, 9]. Here the ratio between readings D_2/D_1 is used for correction of the D reading.

No correction factors depending on energy are taken into account in the calculated energy dependence of dosimeter 1 [10] and dosimeter 2 [4]. The readings obtained with a single albedo dosimeter before correction and with the albedo dosimeter system after correction, respectively, are represented in Fig. 16 and compared with the results measured by Hoy [7].

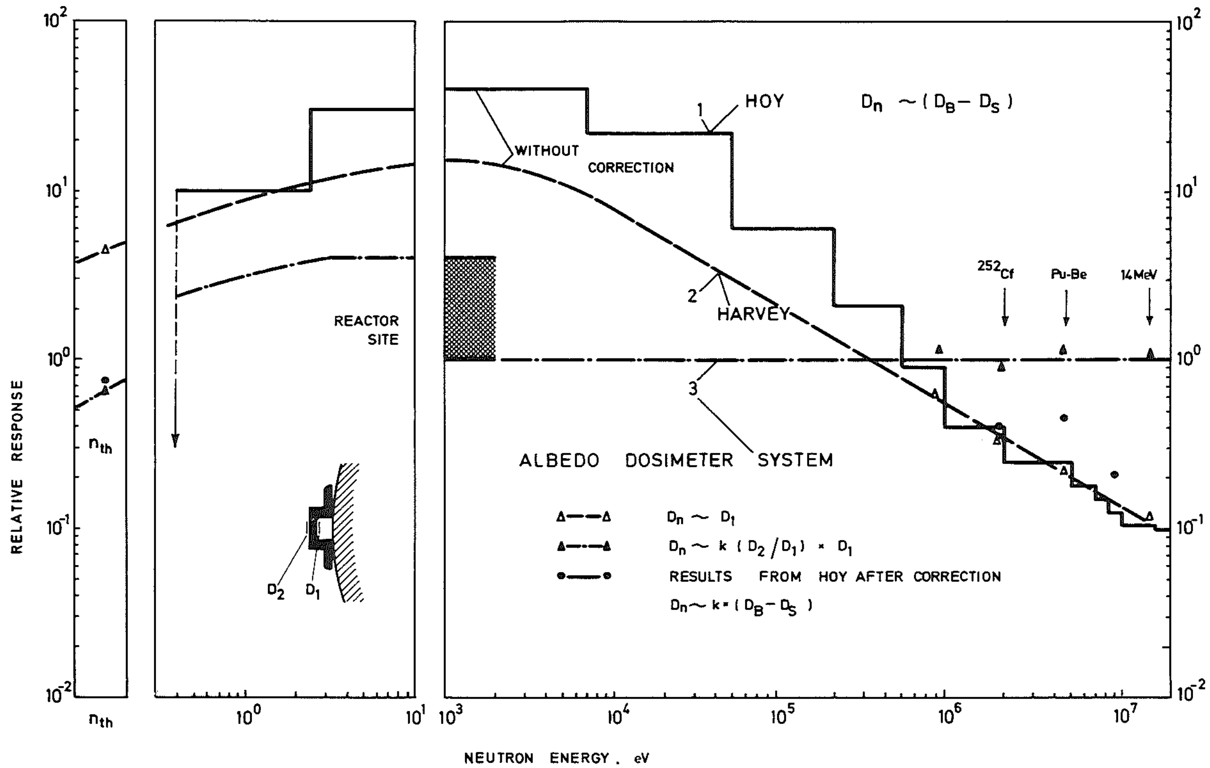


FIG.16. Relative response of different albedo dosimeters as a function of neutron energy, with experimental results for the single albedo dosimeter, the albedo dosimeter system and after J.E. Hoy: (1) albedo dosimeter after J.E. Hoy [7], calculation after Ref. [10]; (2) albedo dosimeter after Harvey [4], normalized to own results; (3) albedo dosimeter system, approximation in the energy range of intermediate neutrons, no calculation.

The latter were obtained on the basis of an appropriate correction factor. No measurements have been performed for the range of intermediate neutrons; hence, data referring to the response of the albedo dosimeter system in this range refer only to the corresponding types of exposure performed in reactors. Measurements near reactors, especially behind the shieldings of beam holes, resulted in oversensitivity of up to a factor of 4 compared with the dosimeter response in the fast-neutron energy range. This improves the detection conditions in the intermediate-neutron range, only slightly as compared with dosimeter 2. In this field also, supplementary information is required about the neutron spectrum.

The oversensitivity of the albedo dosimeter system to intermediate and thermal neutrons limits the application of this dosimeter to three types of personnel monitoring:

(1) work with spontaneous fission neutron and (α, n) neutron sources; a correction is made for the scattered radiation fraction through D_2/D_1, and no additional information is required about the neutron spectrum;
(2) work with 14-MeV neutrons; again, a correction of the scattered radiation fraction via D /D is possible;
(3) monitoring at reactors; a corresponding calibration factor derived from rem counter measurements can be used for given shielding conditions, which means that additional information about the dosimeter response related to the neutron spectrum at this location is required for evaluation of the albedo dosimeter reading.

TABLE IV. COMPARISON OF THE RESPONSE OF FAST-NEUTRON DOSIMETERS FOR CONTINUOUS NEUTRON SPECTRA

	Response of dosimeter reading[a] in %					
	Detector	Energy range (MeV)	PuBe-neutrons		^{252}Cf neutrons	
			Air	Scattered	Air	Scattered
Nuclear track detector	Nuclear track film	> 0.7	100	~80	60	~40
	^{232}Th	> 1.2	80	~60	60	~35
	Recoils + α in Makrofol	> 1.0	85	~70	80	~45
	^{237}Np	> 0.7	90	~80	90	~60
Albedo dosimeter	Single albedo dosimeter (uncorrected)	> 0.1	45	110 - 130	65	65 - 280
	Albedo dosimeter system[b]		110 - 120	80 - 110	90	70 - 130
	Albedo dosimeter, Hoy (corrected)		47	85 - 125	40	40 - 125

[a] Relative dosimeter reading for frontal direction of radiation incidence.
[b] For a radiation incidence angle of 0°, 90°, 180°.

A comparison with nuclear track detectors shows that albedo dosimeters are also capable of indicating fast neutrons below 0.7 MeV, and probably up to energies of some 100 keV, with the correct dose response (see Table IV). Track detectors, especially with respect to scattered ^{252}Cf neutrons, will detect from one-third to half the dose-equivalent. By contrast, albedo dosimeters 1 and 2 indicate only half the dose-equivalent in unscattered, unshielded radiation fields; there is hardly any difference between dosimeter 1 and dosimeter 2. However, after correction for the energy without using local correction factors, dosimeter 3 described in this paper supplies readings of unscattered as well as scattered and shielded neutrons with a correct dose response and, in addition, is independent of the direction of the radiation incidence and the position of the person relative to the radiation source.

In comparison with track detectors, it is mainly the handling, the evaluation and the dose assessment, together with the accuracy of evaluation and negligible fading, which should be mentioned as positive characteristics. The drawbacks are the relatively high purchasing price and the cost of evaluation of the albedo dosimeter system, which consists of eight dosimeters, two boron capsules and a belt, if necessary. The amount of evaluation work can be reduced if only two dosimeters (front of body behind boron) are used for monthly evaluation and all dosimeters are evaluated once a year within the framework of a long-term monitoring system.

7. CONCLUSION

The use of an albedo dosimeter for the detection of fast neutrons offers the primary advantage of detecting neutrons without an energy threshold above an energy of some 100 keV up to 14 MeV practically independently of energy and direction. On the one hand, this is achieved by measuring both the incident neutrons and the neutrons backscattered by the body by means of a boron capsule, and on the other, by wearing two dosimeters on the body: one in front and one behind.

The dose-equivalent of fast neutrons is measured in the dose range from 20 mrem to above 1000 rem with a response about 50% of the corresponding gamma response of the LiF dosimeters. The fraction of the dosimeter reading due to neutrons is separated from the gamma fraction by difference formation of the dosimeters readings of one TLD 600 and one TLD 700 dosimeter, up to gamma doses of 1000 R, by simultaneous measurement of the gamma dose with the TLD 700 dosimeter. The accuracy of the measurement of a single evaluation of the LiF dosimeter is ±3%; the total error due to energy and direction dependence is ±30%.

ACKNOWLEDGMENTS

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DISCUSSION

H. MURILLO RAMOS: Congratulations on your excellent paper. I should like to ask you whether your TL dosimeters would be suitable for intercomparison studies in Mexico?

E. PIESCH: So far we have only the results of phantom exposures in fast neutron fields with continuous spectra. Accordingly, it would be desirable to carry out intercomparison studies in routine personnel monitoring as well as phantom studies in other neutron fields, for instance monoenergetic neutrons up to energies of 100 keV. You can of course use our TL dosimeter, which is commercially available.

T. NIEWIADOMSKI: We and some other authors have found ^{7}LiF to be sensitive to thermal neutrons in so far as dose-equivalent is concerned. Did this fact affect the use of lithium fluoride in your system?

E. PIESCH: The thermal neutron sensitivity of TLD 700 is 0.14 R/rem, which is lower by a factor of about 1000 than that of TLD 600. As we are looking for the difference between the readings of TLD 600 and TLD 700, there is practically no influence on the reading of the neutron dose fraction.

D.E. HANKINS: I would like to mention a report entitled "The Calculated Response of Albedo-Neutron Dosimeters to Neutrons with Energies $\leq$ 400 MeV", prepared recently by Alsmiller and Barish at Oak Ridge (to be published as ORNL TM-3984). It gives the calculated responses of the Hoy dosimeter and of the LASL dosimeter. The response of the former is similar to that of a boron-covered dosimeter, the only significant difference being at the lower end of the intermediate-energy region. For fast neutrons, the responses are similar. I think it is doubtful whether a thermal-neutron reading can be used in all cases to make a correction for the energy dependence of fast neutrons.

H. PILTINGSRUD: Have you studied the angular response versus the energy characteristics of the dosimeters? Preliminary investigations of this dependence indicate that the effects may be very large for one of the dosimeters you discussed. It has been suggested that such measurements should play an important part in determining the utility of any personnel radiation dosimeter, but they rarely seem to be done.

E. PIESCH: With our albedo dosimeter we have studied the angular response for all neutron energies, using three directions of radiation incidence – 0°, 90° and 180°. After making a correction for scattered thermal neutrons, we found the total error due to the effect of energy and direction dependence was ± 30% for the albedo dosimeter system. We have made a detailed study of the angular response in the field of a ^{252}Cf source and of a ^{252}Cf source behind a PVC shield 5 cm thick.

I agree with you that the direction dependence of the dosimeter reading at the surface of the phantom limits the application of an albedo dosimeter, especially if the dosimeter detects scattered thermal neutrons coming from a direction other than that of the incident neutrons. In this case, over-sensitivity to thermal neutrons does make the dosimeter reading dependent on direction.

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