KERNFORSCHUNGSZENTRUM

KARLSRUHE

August 1972

KFK 1666
EUR 4846

Abteilung Strahlenschutz und Sicherheit

Personnel Monitoring with a LiF Albedo Dosimeter in the Radiation Field of a ^{252} Cf Source

E. Piesch
B. Burgkardt
(Kernforschungszentrum Karlsruhe)
J. Vaane
(Europäisches Institut für Transurane)

GESELLSCHAFT FÜR KERNFORSCHUNG M. B. H.

KARLSRUHE

GESELLSCHAFT FÜR KERNFORSCHUNG M.B.H.

KARLSRUHE

KERNFORSCHUNGSZENTRUM KARLSRUHE

August 1972

KFK-1666

EUR-4846

Abteilung Strahlenschutz und Sicherheit

PERSONNEL MONITORING WITH A LiF ALBEDO DOSIMETER IN THE RADIATION FIELD OF A ^{252}Cf SOURCE

E. Piesch, B. Burgkhardt

Kernforschungszentrum Karlsruhe

J. Vaane

Europäisches Institut für Transurane, Karlsruhe

Gesellschaft für Kernforschung m.b.H., Karlsruhe

In Zusammenarbeit mit dem Europäischen Institut für Transurane

Abstract

The use of albedo dosimeters for personnel monitoring was up to now limited to the measurement of neutrons in the intermediate and thermal energy range. Results of phantom irradiations in the radiation field of a ^{252}Cf-source however show the possibility of measuring the dose equivalent from fast neutrons.

The albedo dosimeter consists of a pair of TLD 6oo and TLD 7oo dosimeters, from which the separate fractions of the neutron and of the gamma dose can be evaluated. The TLD 6oo dosimeter measures neutrons moderated and backscattered from the body, as well as gamma rays. The TLD 7oo dosimeter measures practically only gamma rays. The difference of the dosimeter readings (TLD 6oo - TLD 7oo) was found to be proportional to the dose equivalent of neutrons. The calibration of this albedo dosimeter was based on the results of Rem-counter measurements.

Phantom irradiations were performed in the radiation field of ^{252}Cf fission neutrons, using various source shieldings, distances to the source and phantom sizes. The albedo dosimeter system proposed for routine personnel monitoring measures the neutron dose equivalent in the field of a ^{252}Cf-source with an overall error of ± 3o % which is mainly due to the influence of source shielding and backscattered radiation as well as of the variations in the angle of the radiation incidence.

Zusammenfassung

Die Anwendung von Albedodosimetern in der Personenüberwachung beschränkte sich bisher auf die Messung von Neutronen im mittelschnellen und thermischen Energiebereich. Die Ergebnisse von Phantombestrahlungen, die im Strahlungsfeld einer ^{252}Cf-Quelle durchgeführt wurden, zeigten jedoch die Möglichkeit, die Äquivalentdosis schneller Neutronen zu messen.

Das Albedodosimeter besteht aus einem Paar von TLD 600 und TLD 700 Presslingen, um den Dosisanteil von Neutronen und Gammastrahlung zu trennen. Das TLD 600 Dosimeter weist hierbei sowohl vom Körper moderierte und rückgestreute Neutronen als auch Gammastrahlung nach, das TLD 700 Dosimeter praktisch nur Gammastrahlung. Die Differenz der Dosimeteranzeigen (TLD 600 - TLD 700) ist proportional zur Neutronen-Äquivalentdosis. Die Kalibrierung des Albedodosimeters basiert auf den Meßergebnissen eines Rem-counters.

Es wurden Phantombestrahlungen im Strahlungsfeld von ^{252}Cf-Spaltneutronen durchgeführt, wobei die Quellenabschirmung, der Abstand zur Quelle und die Phantomgröße verändert wurden. Das für einen routinemäßigen Einsatz in der Personenüberwachung vorgeschlagene Albedodosimeter-System zeigt für die Messung der Neutronen-Äquivalentdosis an einer ^{252}Cf-Quelle einen Gesamtfehler von etwa ± 30 %; dies ist vor allem auf den Einfluß einer Quellenabschirmung und auf rückgestreute Neutronen, aber auch auf den Einfluß einer Richtungsabhängigkeit zurückzuführen.

C o n t e n t s

Figure Captions

Fig. 1 The thermal neutron albedo as a function of incident neutron energy [3]

Fig. 2 The dose reading of LiF dosimeters (TLD 6oo - TLD 7oo) in the field of a ^{252}Cf neutron source for free air and phantom irradiation.

Fig. 3 The dose reading of LiF dosimeters irradiated at the surface of a phantom and the Rem-counter reading as a function of distance from the ^{252}Cf source without influence of backscattered neutrons.

Fig. 4 The dose reading of LiF dosimeters irradiated at the surface of a phantom and the Rem-counter reading as a function of distance from the ^{252}Cf source at a height of 1.4o m above the floor.

Fig. 5 The relative dosimeter reading of LiF dosimeters as a function of dose equivalent for gamma irradiation and of an albedo dosimeter for ^{252}Cf neutron irradiation.

Fig. 6 The response of the LiF albedo dosimeter with the boron shield, worn on the body, as a function of incident neutron energy [3].

Fig. 7 Phantom irradiations with LiF albedo dosimeters in the field of the ^{252}Cf source.

Fig. 8 The dosimeter reading of TLD 7oo and the Rem-counter reading in the field of the ^{252}Cf source for various source shieldings.

Fig. 9 The neutron-energy distribution of ^{252}Cf-neutrons for various source shieldings of 5 cm thickness.

Fig.1o The dosimeter reading of LiF albedo dosimeters as a function of distance from the ^{252}Cf source at positions 1.4o m above the floor and a radiation incidence angle of 0^o, without shielding (a), and for a source shield of concrete (b), PVC (c), aluminium (d), stainless steel (e).

Fig.11 The dosimeter reading of a single albedo dosimeter without boron shield as a function of neutron dose equivalent for radiation incidence angles of 0^o (a), $9o^o$ (b) and $18o^o$ (c).

Fig.12 The dosimeter reading of a single albedo dosimeter with the boron shield as a function of neutron dose equivalent radiation incidence angles of 0^o (a), $9o^o$ (b) and $18o^o$(c).

Fig.13 The neutron response of the single albedo dosimeter with the boron shield as a function of the distance from the ^{252}Cf source for various source shieldings and radiation incidence angles.

Fig.14 The direction dependence of the single albedo dosimeter reading

Fig.15 The dosimeter reading of the albedo dosimeter system with the boron shield as a function of dose equivalent without shielding (a), and for a source shield of concrete (b), PVC (c), aluminium (d), stainless steel (e).

Fig.16 The dosimeter reading of the albedo dosimeter system with the boron shield as a function of dose equivalent for varying radiation incidence angle and source shielding.

Fig.17 The dosimeter reading of the albedo dosimeter system without boron shield as a function of dose equivalent for varying radiation incidence angle and source shielding.

Fig.18 The neutron response of the albedo dosimeter system with the boron shield as a function of distance form the ^{252}Cf source for various source shieldings and radiation incidence angles.

Fig.19 The dosimeter reading of the albedo dosimeter system as a function of distance from the ^{252}Cf source as well as neutron dose equivalent, for varying radiation incidence angle and source shielding.

Fig.2o The gamma dose reading of TLD 7oo on the front of the phantom as a function of distance from the source for radiation incidence angles of 0^{o} (a), $9o^{o}$ (b) and $18o^{o}$(c).

Fig.21 The direction dependence of the albedo dosimeter system in the field of the ^{252}Cf source.

Fig.22 The dosimeter reading of the albedo dosimeter with (b) and without (a) boron shield as a function of phantom size for various radiation incidence angles

*) phantom with elliptical cross section

1. Introduction

The NTA-film emulsion has been the only device available in the past years to measure the neutron dose in personnel monitoring. In recent years new kind of detectors were developed and tested as a replacement for the film. Non-photographical nuclear track detectors, which utilize a method of microscopical counting of etch pits induced in plastic foils by fission fragments, recoils and (n,α) reactions, have a low response and an energy threshold only above o,75 MeV (^{237}Np). So the method of measuring back-scattered neutrons - so called albedo neutrons - at the surface of the body becomes more and more attractive. During the thermalization in the human body some of the incident neutrons are back-scattered. The fluence of these neutrons of various energies when leaving the body can be related to the total fluence of incident neutrons, under certain conditions.

Albedo dosimetry is thus based on the principle that incident neutrons after interaction with tissue in the body may leave the body as thermal or intermediate neutrons. These albedo neutrons can then be detected at the body surface with a thermal neutron detector.

Earlier experiments performed by Dennis, Smith and Boot [1] have shown that the cadmium-covered film and the nuclear track emulsion can measure the dose equivalent for thermal and intermediate neutrons. Their results and further work by Harvey [2] have shown that the albedo factor, defined as the ratio of

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

is a function of the neutron energy; it varies between approximately o.8 for thermal neutrons and o.1 for neutrons of 1 MeV (see Fig. 1).

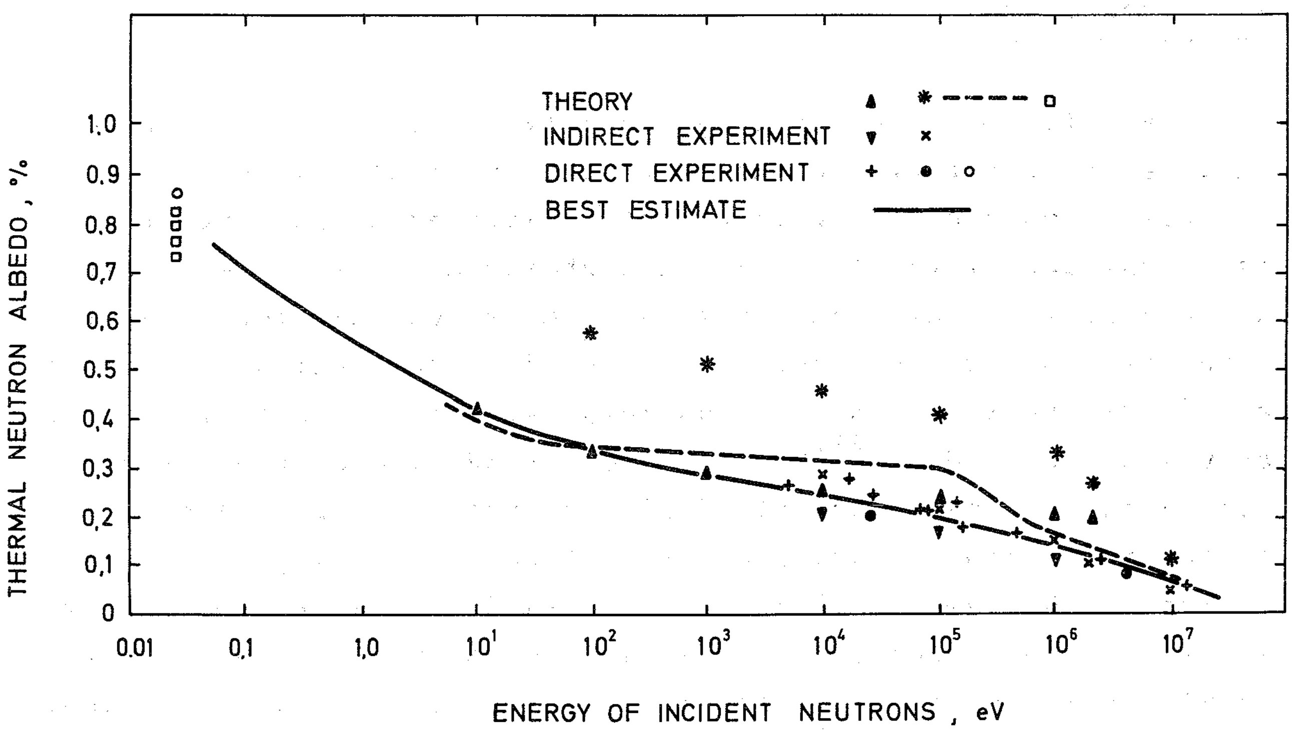

Fig. 1: The thermal neutron albedo as a function of incident neutron energy [3].

The thermal-neutron albedo-factor takes into account thermal neutrons as well as intermediate neutrons, leaving the body and measured at the surface with an 1/v-detector (e.g. a BF_3-counter or a LiF dosimeter). An albedo dosimeter worn on the body surface would therefore overestimate the fluence of incident neutrons of thermal energies, compared with intermediate neutrons, by a factor of 4. By using a cadmium- or boron shield to absorb the incident neutrons the albedo dosimeter gives a good approximate value of the dose equivalent of thermal and intermediate neutrons up to an energy of 1o keV [3].

Such an albedo dosimeter consisting of a pair of ^{6}LiF- and ^{7}LiF dosimeters has been developed by Harvey, Hudd and Townsend [3] to monitor the personal dose of intermediate neutrons at reactor stations. Based on these considerations this type of albedo dosimeter would detect the dose equivalent from fast neutrons with an efficiency of only 1 %; it therefore seemed useless to utilize an albedo dosimeter for the detection of fast neutrons until now [3, 4].

For the detection of fast neutrons Korba and Hoy [5] placed two pairs of LiF dosimeters in a moderating hemisphere of 2 inches diameter, fixed on a belt. One dosimeter pair measures a fraction of the incident neutrons, the other one is shielded from incident thermal neutrons by a cadmium foil. This moderator-type detector provides a correction for the over-response to low energy neutrons, as well as in the energy range of o.1 - o.5 MeV.

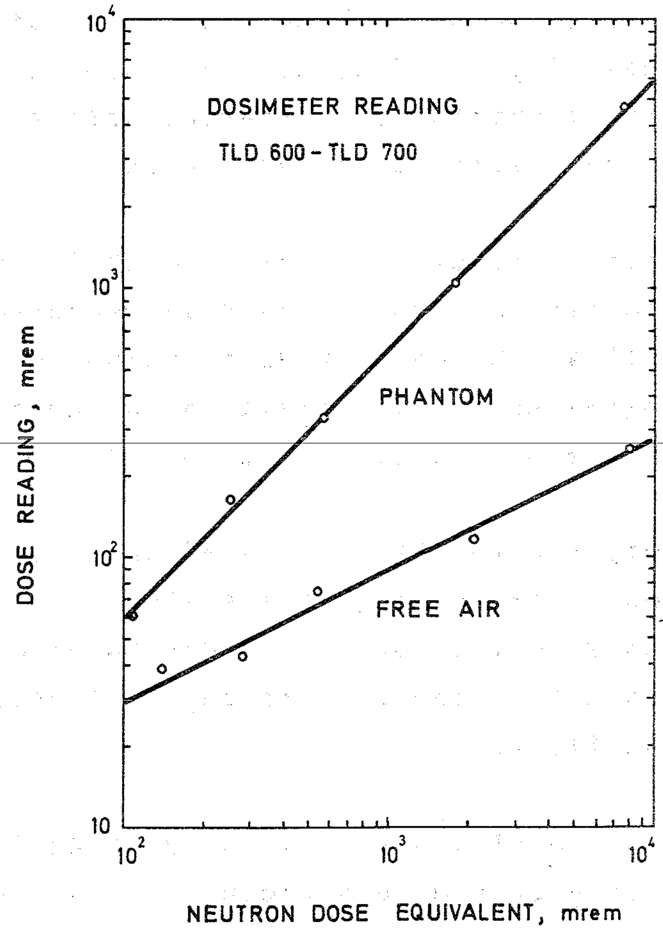

Fig. 2:

The dose reading of LiF dosimeters (TLD 6oo - TLD 7oo) in the field of a ^{252}Cf neutron source for free air and phantom irradiation.

Recent experiments performed at the Karlsruhe Nuclear Research Centre have shown that fast neutrons of a ^{252}Cf-source could be detected by a single LiF albedo dosimeter with a reasonable sensitivity (see Fig. 2).

The difference of the dosimeter readings (dosimeter reading) of a pair of LiF dosimeters (TLD 600 and TLD 700) fixed on the surface of a human phantom can be related to the neutron dose equivalent measured at the same place. We found the dosimeter reading due to fast neutrons to be approximately 0.5 R/rem, based on measurements of the dose equivalent with a Rem-counter. The TLD-reader was calibrated with a LiF dosimeter, which was irradiated with ^{137}Cs gamma rays.

Fig. 3 and 4 show the properties of an albedo dosimeter when measuring the fast neutron dose in the field of a ^{252}Cf-source with a phantom at different heights above the floor as a function of the distance to the source.

These figures give the dose equivalent rates measured with a Rem-counter, and the gamma dose measured with the TLD 700 dosimeter as well as the neutron dose evaluated from the dosimeter reading. The dosimeters were irradiated on the surface of a human phantom (Plastic bottle with water, 20 cm diam).

Compared to the results of the Rem-counter measurements, the relative dosimeter reading of the albedo dosimeter increases with the distance to the source and decreases with the distance of the phantom above the floor, due to the influence of backscattered neutrons from the floor.

Additional source shielding as well as the presence of back-scattered neutrons around the source may greatly influence the neutron energy spectrum. It was therefore desirable to calibrate the LiF albedo dosimeter at different distances from the source, for various source shieldings.

Fig.3 and 4:
The dose reading of LiF dosimeters irradiated at the surface of a phantom and the Rem-counter reading as a function of distance from the ^{252}Cf source without influence of backscattered neutrons (Fig.3) and at a height of 1.4o m obove the floor (Fig. 4)

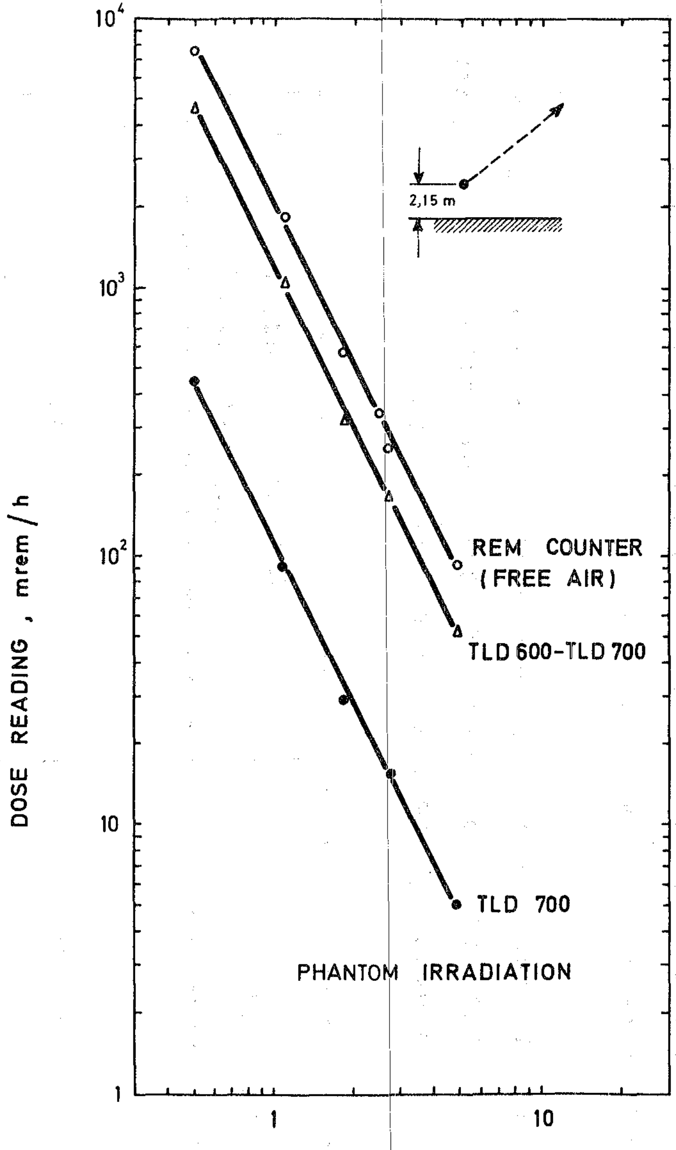

Fig. 3.

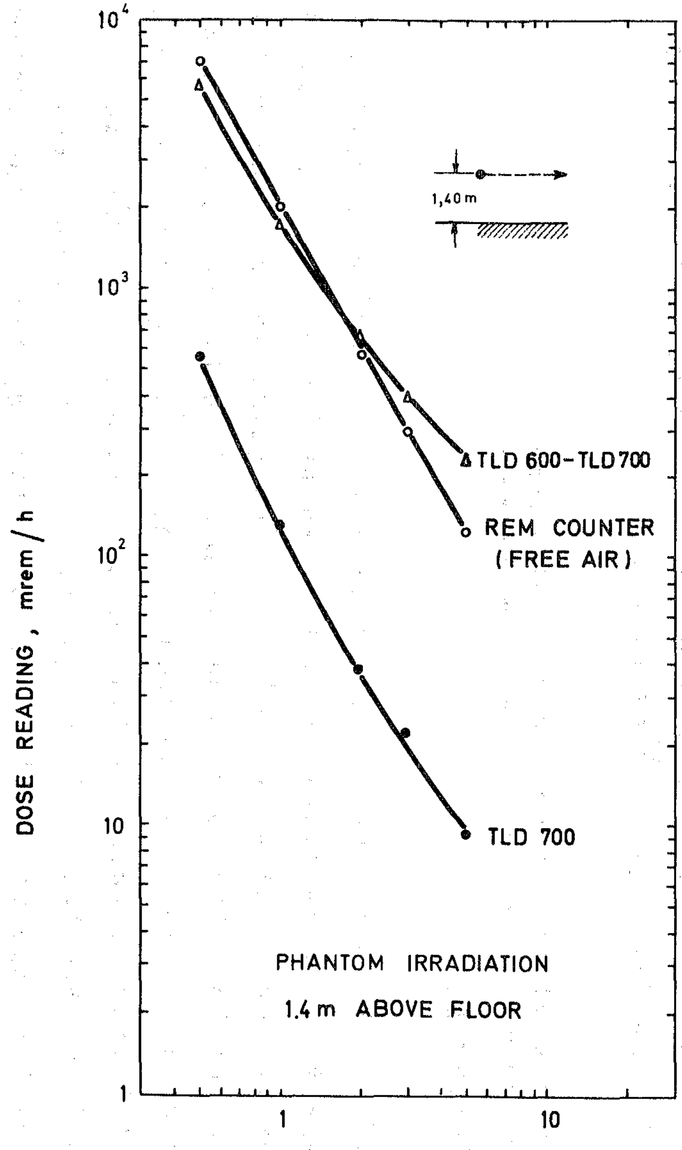

Fig. 4.

The main purpose of our experiments was to study the properties of a simple LiF albedo dosimeter to monitor the personal neutron dose in the field of a ^{252}Cf-source.

2. Method of measurement and calibration

2.1 Dosimeter

Extruded LiF dosimeters of the size 3 x 3 x 1 mm^3 were used which are commercialy available from Harshaw as TLD 6oo and TLD 7oo. The dosimeters were calibrated with a ^{137}Cs gamma source, and evaluated with a Harshaw TLD-reader Model 2ooo A / 2ooo B. The maximum heating temperature during the measurement was 24o°C. In order to re-use the dosimeters a regeneration was carried out at a temperature of 4oo°C (1 h) and 1oo°C (2 h). We made sure that the dosimeter reading per exposure of 1 R did not change by the heating treatment. Because the variation in sensitivity between individual LiF dosimeters was found to be ± 5 %, each dosimeter was calibrated by a test exposure with ^{137}Cs gamma rays.

Table 1: Thermal neutron response of LiF dosimeters based on integral measurement of the luminescence light up to a heating temperature of 24o°C [6].

Dosimeter	Dosimeter reading in rad for $1o^{1o}$ n/cm^2
TLD 6oo	6oo
TLD 1oo	213
TLD 7oo	1.3

*) Harshaw ribbons 3 x 3 x 1 mm^3

The sensitivity of LiF dosimeters to thermal neutrons (table 1) is based on the reaction $^{6}Li\ (n,\alpha)^{3}H$, with a cross section for thermal neutrons of 945 barns. A TLD 600 dosimeter with 95.6 % of ^{6}Li measures the thermal neutron dose. To separate the gamma dose fraction, a TLD 700 dosimeter with only 0.01 % of ^{6}Li is used, which has a neglectable sensitivity to thermal neutrons (dosimeter reading of 1.3 rad per $10^{10} n_{th} \cdot cm^{-2}$). Both, TLD 600 and TLD 700, have practically the same sensitivity to gamma radiation.

The dosimeter readings of the TLD 600 and TLD 700 are shown in Fig. 5 as a function of the dose equivalent for an irradiation with ^{137}Cs gamma rays, and for an irradiation with neutrons of a ^{252}Cf source with the albedo dosimeter at the surface of the phantom, using a heating temperature of 240°C. TLD 600 and TLD 700 show a similar supra-linear characteristic for gamma irradiations greater than 200 rem. The difference in the dosimeter readings of TLD 600 and TLD 700 simulates a neutron dose after a gamma irradiation This effect was found to be < 10 % of the dose for gamma doses up to 1000 rem and < 20 % for gamma doses up to 10^{5} rem.

The dosimeter reading of the albedo dosimeter is, for fast neutrons in the dose range of 20 mrem to 1000 rem, proportional to the dose equivalent and, for larger doses, less supra-linear than the gamma dose reading. After correction for the supra-linearity of the dosimeter reading with a factor of 1.75 at the maximum, an extension of the neutron dose range up to 10^{5} rem is possible. In this range also a radiation damage would occur.

The neutron dose contribution can therefore be separated from a simultaneous gamma dose up to 1000 rem for a neutron dose equivalent ranging between 20 mrem and 1000 rem. This means that an albedo dosimeter consisting of TLD 600- and TLD 700 detectors can be used to measure the dose equivalent of a ^{252}Cf-source (E_{eff} = 1.9 MeV) over a dose range of 20 mrem - 10^{5} rem.

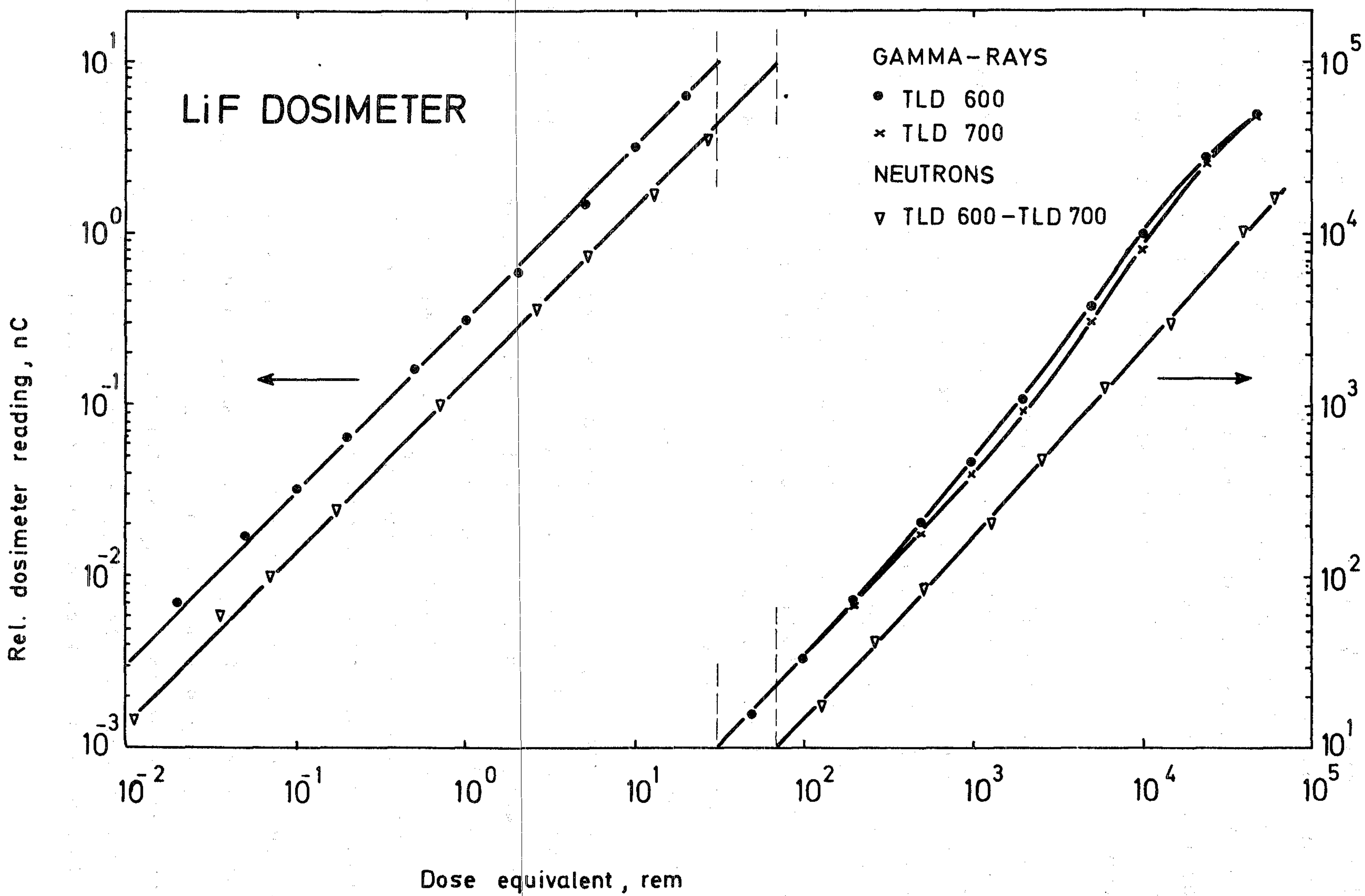

Fig.5: The relative dosimeter reading of LiF dosimeters as a function of dose equivalent for gamma irradiation and of an albedo dosimeter for ^{252}Cf neutron irradiation

The irradiation runs described in this report were carried out with a pair of unshielded LiF dosimeters as well as with a LiF dosimeter pair shielded against incident neutrons with a boron capsule. This boron capsule, experimentally developed and calibrated for neutrons of thermal and intermediate energy by Harvey at al. [3]*) represents an optimization of the capsule size (48 mm diam) and the depth of the detector in the capsule (9 mm) with respect to the discrimination of incident neutrons. The capsule is made of phenol resin with boron carbide (56o $mg \cdot cm^{-3}$). The wall thickness of 3 mm corresponds to an attenuation factor of 1ooo for thermal neutrons. The distance of the LiF dosimeters from the body surface is 1-2 cm.

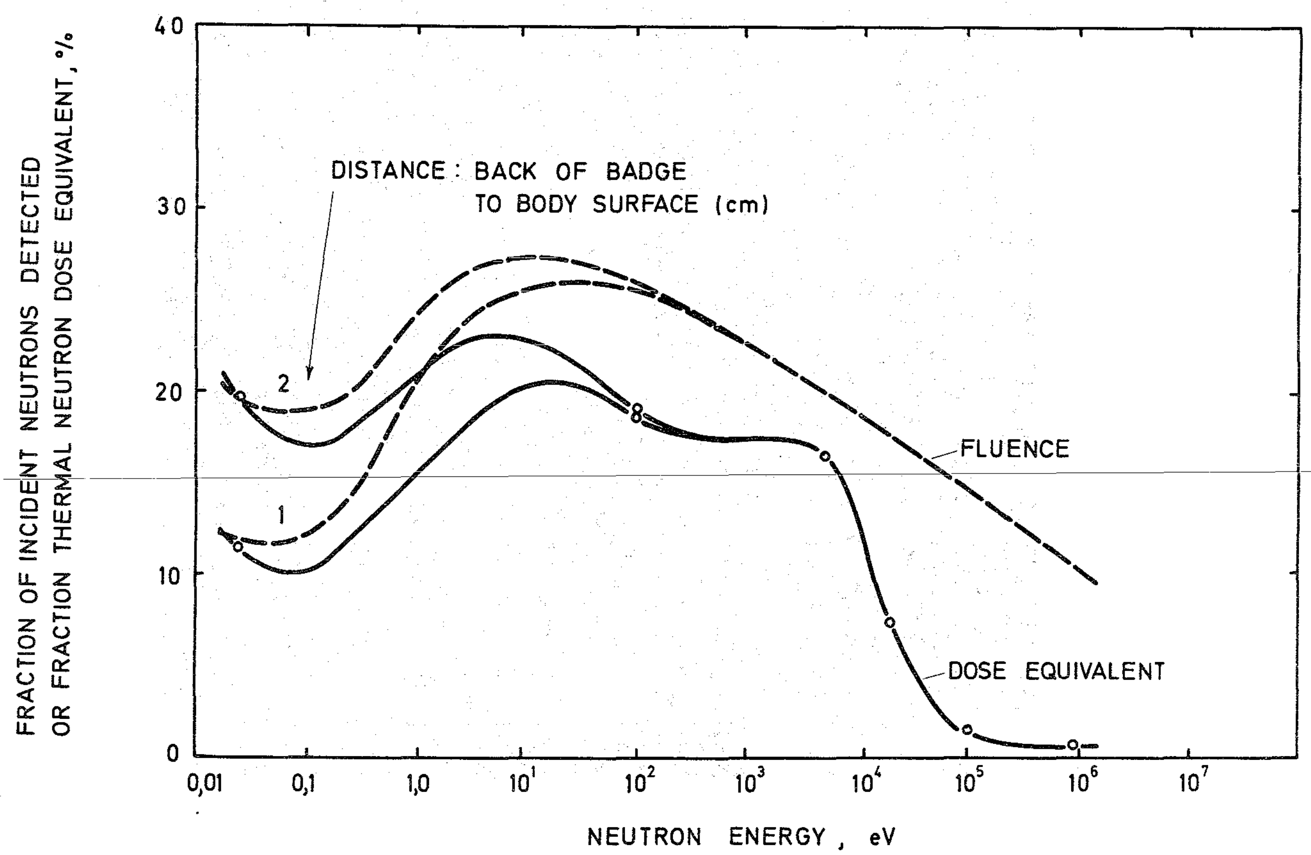

Fig. 6: The response of the LiF albedo dosimeter with the boron shield, worn on the body, as a function of incident neutron energy [3].

*) These capsules are commercially available from:
Parametron, Stroud (Gloucestershire) United Kingdom.

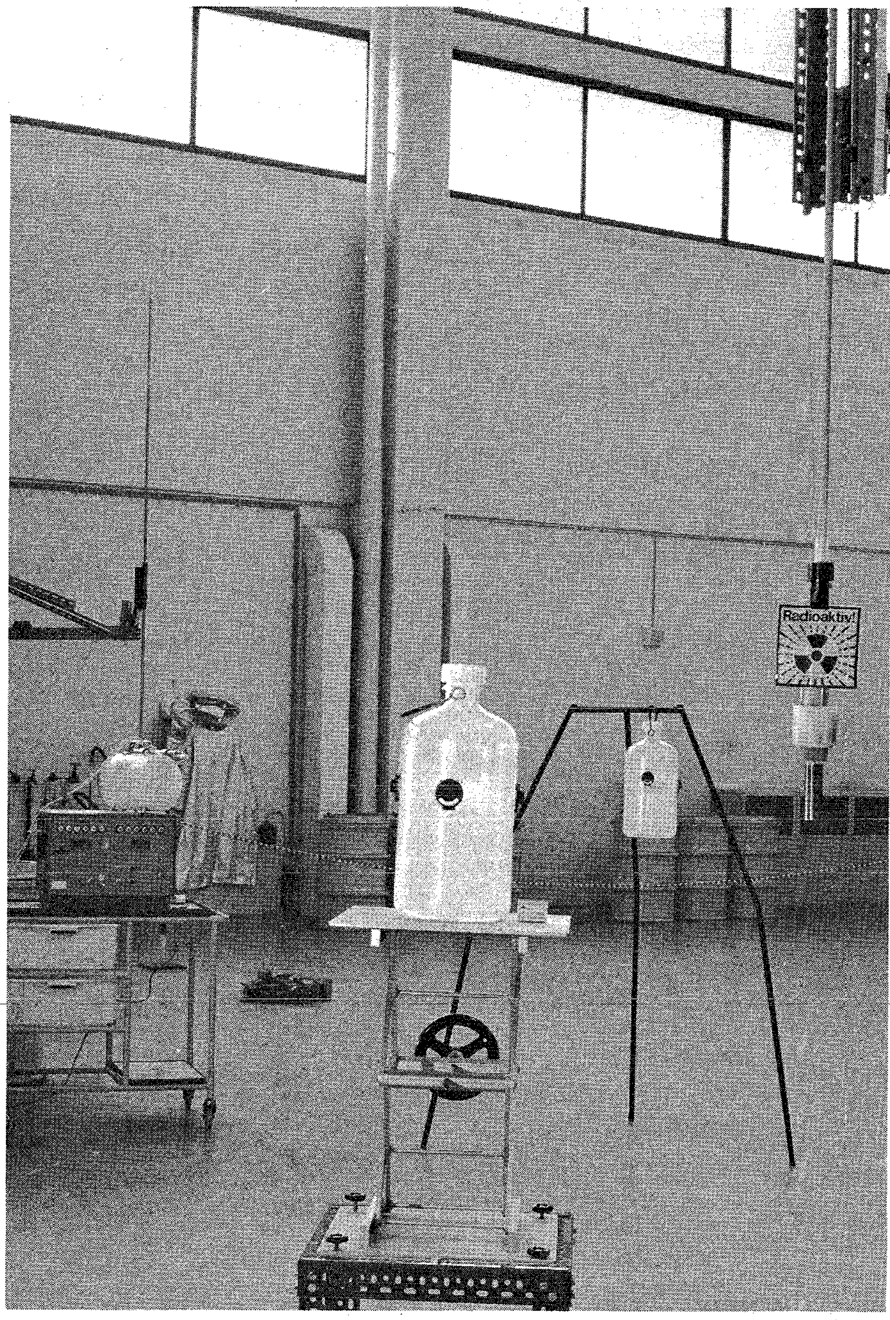

Fig. 7: Phantom irradiations with LiF albedo dosimeters in the field of the ^{252}Cf source (Europaen Institute for Trans-uranium Elements; Karlsruhe Nuclear Research Centre)

This albedo dosimeter detects primary incident neutrons as well as backscattered neutrons leaving the body in the intermediate energy range. The calculated energy dependence of the albedo dosimeter reading based on an 1/v cross section of the boron shield (^{10}B) and of the ^{6}Li-detector is shown in Fig. 6 for the neutron fluence and for the dose equivalent.

The excited ^{7}Li-nuclei from the reaction $^{10}B\ (n,\alpha)^{7}Li$ in the boron capsule giving a 48o keV gamma radiation will increase the gamma-reading of TLD 7oo to o.o4 R/rem for neutrons of 1 keV and o.3 R/rem for thermal neutrons [3]. This relatively high value for thermal neutrons is caused by the incident neutron fluence being reduced by a factor of 1ooo through absorption in the boron capsule.

The gamma dose of an unshielded ^{252}Cf-source related to the neutron dose equivalent was expected to be o.o7 R/rem [3]. From our own measurements on a 1 mg ^{252}Cf-source we found a relative gamma dose of o.o3 R/rem for the unshielded source and o.12 R/rem for the source shielded by 5 cm PVC. These are contributions from the incident gamma radiation of the source as well as backscattered radiation from the surrounding material and gamma radiation from the boron capsule. On the other hand no essential differences between the dose measured by CaF_2 - and LiF dosimeters were found. These results show that the contribution of the captured radiation in the phantom due to the reaction $^{1}H(n,\gamma)^{2}H$ and from the boron capsule can be neglected for the radiation conditions under consideration.

2.2 Calibration and irradiation experiments

The reading of the albedo dosimeters at the surface of a phantom (bottle of water of 2o cm diam, 4o cm high) has been related to the dose equivalent at the same place measured with a Rem-counter.

The Rem-counter (Andersson and Braun type) was calibrated with an Am-Be neutron source of known intensity. The Rem-counter seems to be the best suited instrument to measure the dose equivalent rate

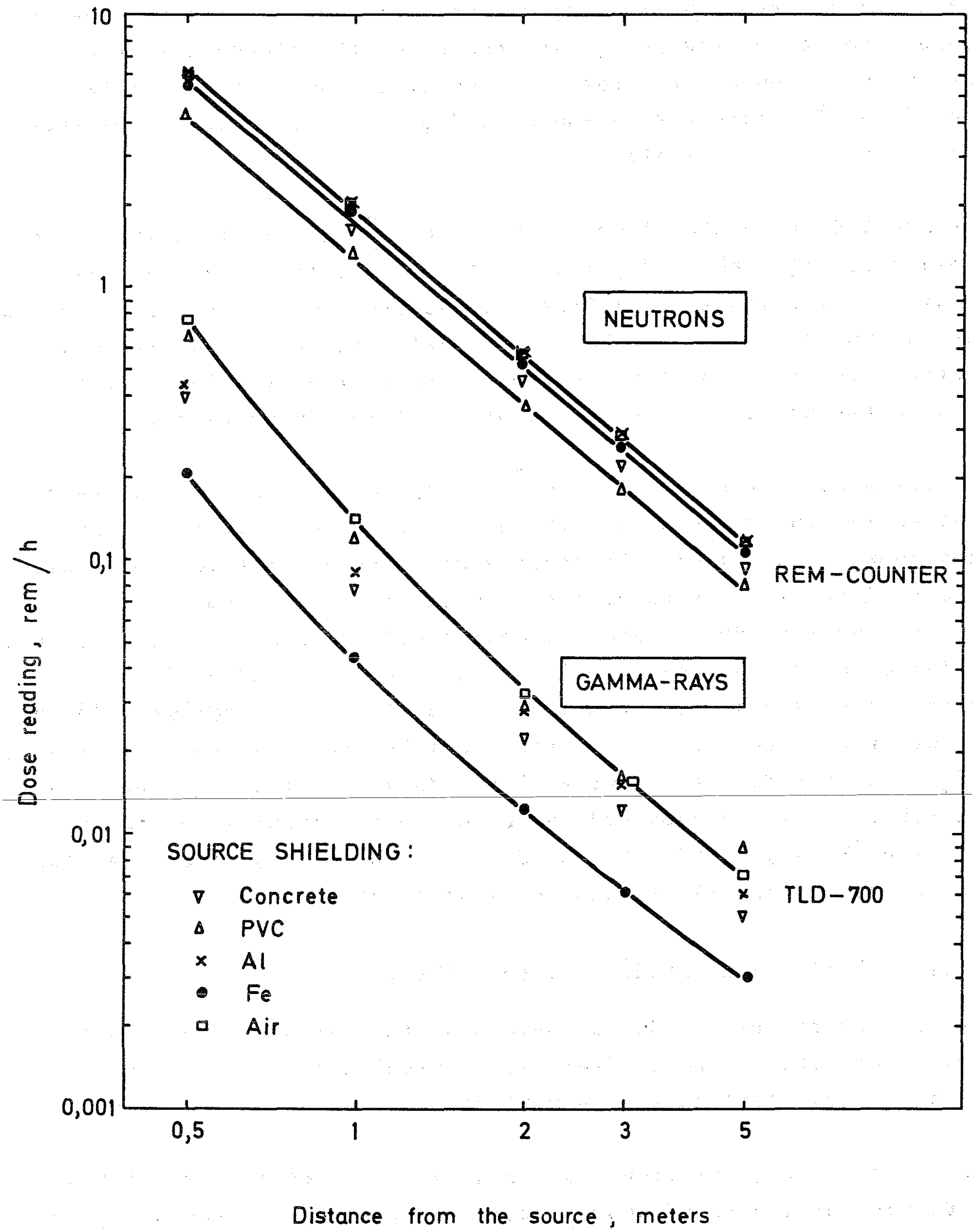

Fig.8: The dosimeter reading of TLD 7oo and the Rem-counter reading in the field of the ^{252}Cf source for various source shieldings.

of incident and backscattered neutrons. The inaccuracy due to the energy dependence of this detector is probably lower than ±15 % for the neutron spectra used in these experiments. A calculation of the dose equivalent based on the neutron energy spectra from threshold and activation detectors involves more errors, especially in the energy range of intermediate neutrons, where only 1/v detectors are available.

The gamma dose of the ^{252}Cf-source was measured with CaF_2- and TLD 7oo dosimeters. We used a 1 mg ^{252}Cf-source contained in a stainless steel cylinder of 1 cm wall strengh and 3 cm diameter for the experiments. The source could be taken from its shielded storage tank with a special revolvable arm (Fig. 7).

The irradiation runs were carried out in a hall of 1ox2ox1o m^3 (width x length x height) with a concrete floor. The height above the floor for the source as well as for the dosimeter on the phantom was 1.4o m. The albedo dosimeter in connection with the phantom was placed at positions of 5, 3, 2, 1 and o.5 m from the source. Results from measurements with the Rem-counter as well as the gamma-dose rate at the phantom surface measured with TLD 7oo are given in Fig. 8.

When handling a ^{252}Cf-source it should be realized that the source may be used under various conditions of shielding and moderation which will cause a change in the neutron energy spectrum. The contribution of scattered neutrons, depending on the local conditions (size of room, wall thickness and material, height above the floor, distance to the source and to the wall) may be several times that of the primary neutron fluence of the ^{252}Cf-source.

Therefore measurements of the spectral distribution under the following conditions, which could be met in laboratories, have been carried out.

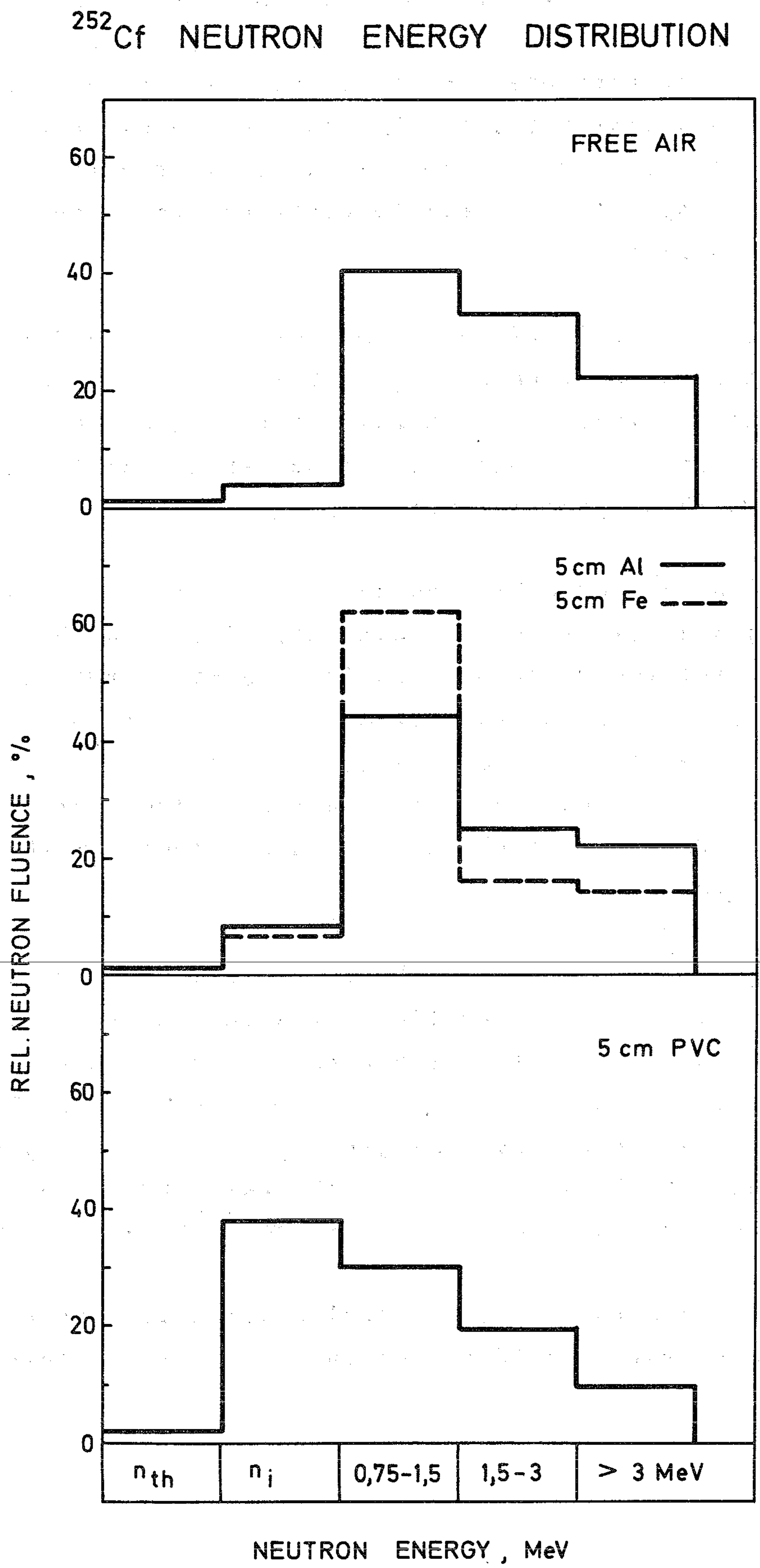

Fig.9: The neutron-energy distribution of ^{252}Cf-neutrons for various source shieldings of 5 cm thickness

- ^{252}Cf-source in the capsule, unshielded
- " " behind a 5 cm PVC-shield
- " " " 5 cm concrete shield
- " " " 5 cm aluminium shield
- " " " 5 cm iron shield

The neutron energy histograms were evaluated from the data obtained from irradiating a conventional combination of threshold detectors at a distance of 2o cm from the source. The relative values of the neutron fluences are shown in Fig. 9 for thermal neutrons (^{198}Au and ^{198}Au behind Cd), intermediate neutrons (^{198}Au), neutrons in the energy interval o.75 - 1.5 MeV (^{237}Np and ^{238}U), the energy interval 1.5 MeV - 3 MeV (^{238}U and ^{31}S) and neutrons of energies above 3 MeV (^{31}S).

Shielding with PVC results in a considerable fraction of neutrons of intermediate energies while the steel shield reduces the mean neutron energy to 1 MeV.

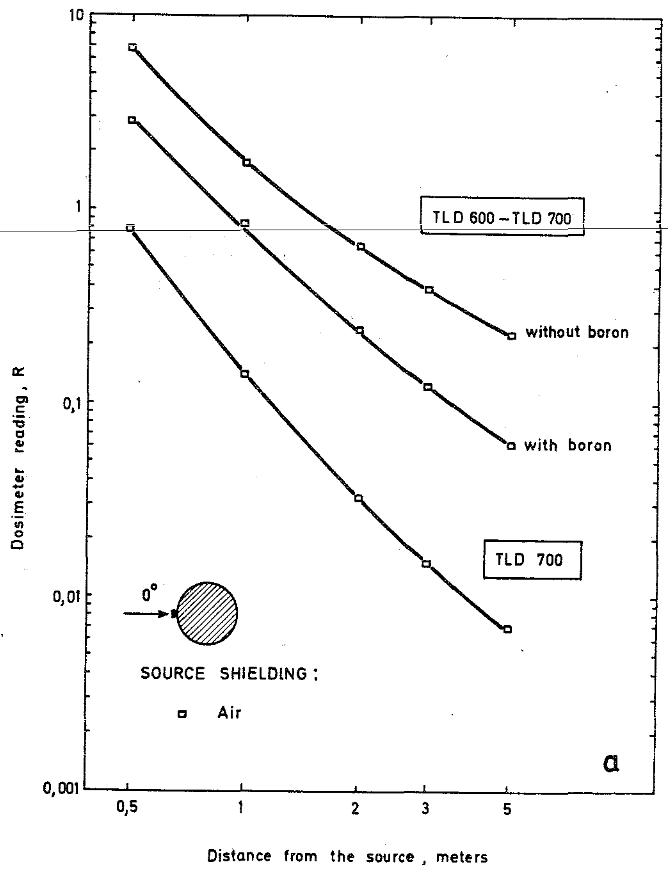

Fig.1o:
The dosimeter reading of LiF albedo dosimeters as a function of distance from the ^{252}Cf-source at positions 1.4o m above the floor and a radiation incidence angle of 0° without shielding (a), and for a source shield of concrete (b), PVC (c), aluminium (d), stainless steel (e)

(see also page 16)

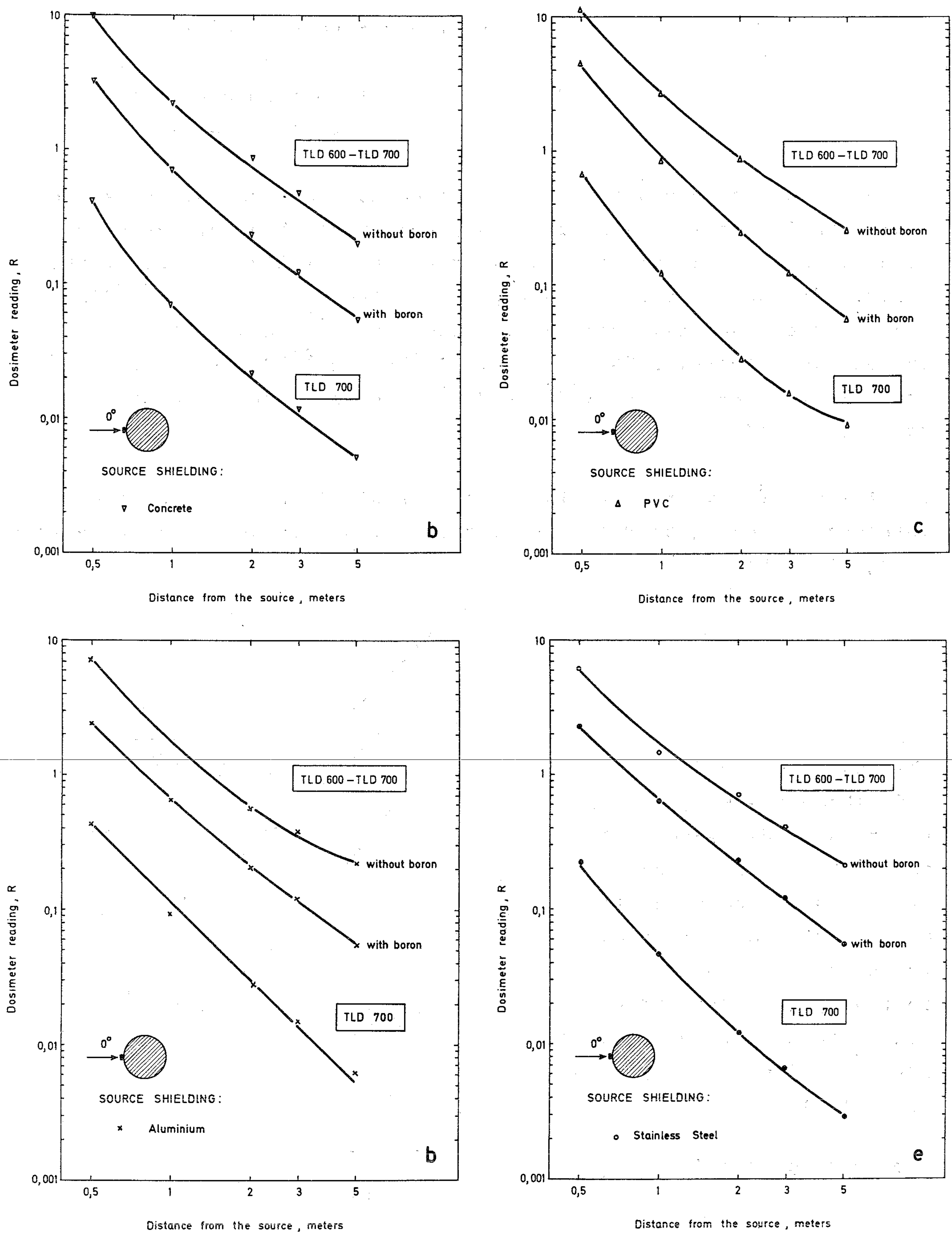

Fig.1o: legend see page 15

The irradiation experiments were performed to study the following features of the LiF albedo dosimeter:

- Energy dependence of the dosimeter reading by irradiation of the albedo dosimeter with the ^{252}Cf-source, using different shielding materials.
- Direction dependence of the dosimeter reading by irradiation of the dosimeter at the front side of a phantom under a radiation incidence angle of 0^{o}, $9o^{o}$ and $18o^{o}$.
- Evaluation of the neutron fraction scattered back from the floor by irradiation of the dosimeter at a distance of 5, 3, 2, 1 and o.5 m from the source.
- Evaluation of the neutron fraction scattered back from the body by using a boron shield at one side of the dosimeter.
- Influence of the phantom size on the dosimeter reading.
- Energy and directional dependence of the dosimeter reading for a number of irradiation conditions which are met in routine personnel monitoring.

The results of measurements with the LiF albedo dosimeter at 1.4o m above the floor and under 0^{o} radiation incidence angle, are shown in Fig. 1o for the experiments performed with various neutron spectra. In this figure the dosimeter readings of the albedo dosimeter with and without boron capsule are given, as well as the reading of the TLD 7oo dosimeter, which approximately represents the gamma dose. The dosimeter reading of the unshielded dosimeter shows, especially at greater distances from the source, a higher value than that of the boron-shielded albedo dosimeter. This can be explained by the over-response to low energy neutrons, which are backscattered from the floor. The readings of the albedo dosimeter in the boron capsule are to a first approximation in accord with the inverse square distance law.

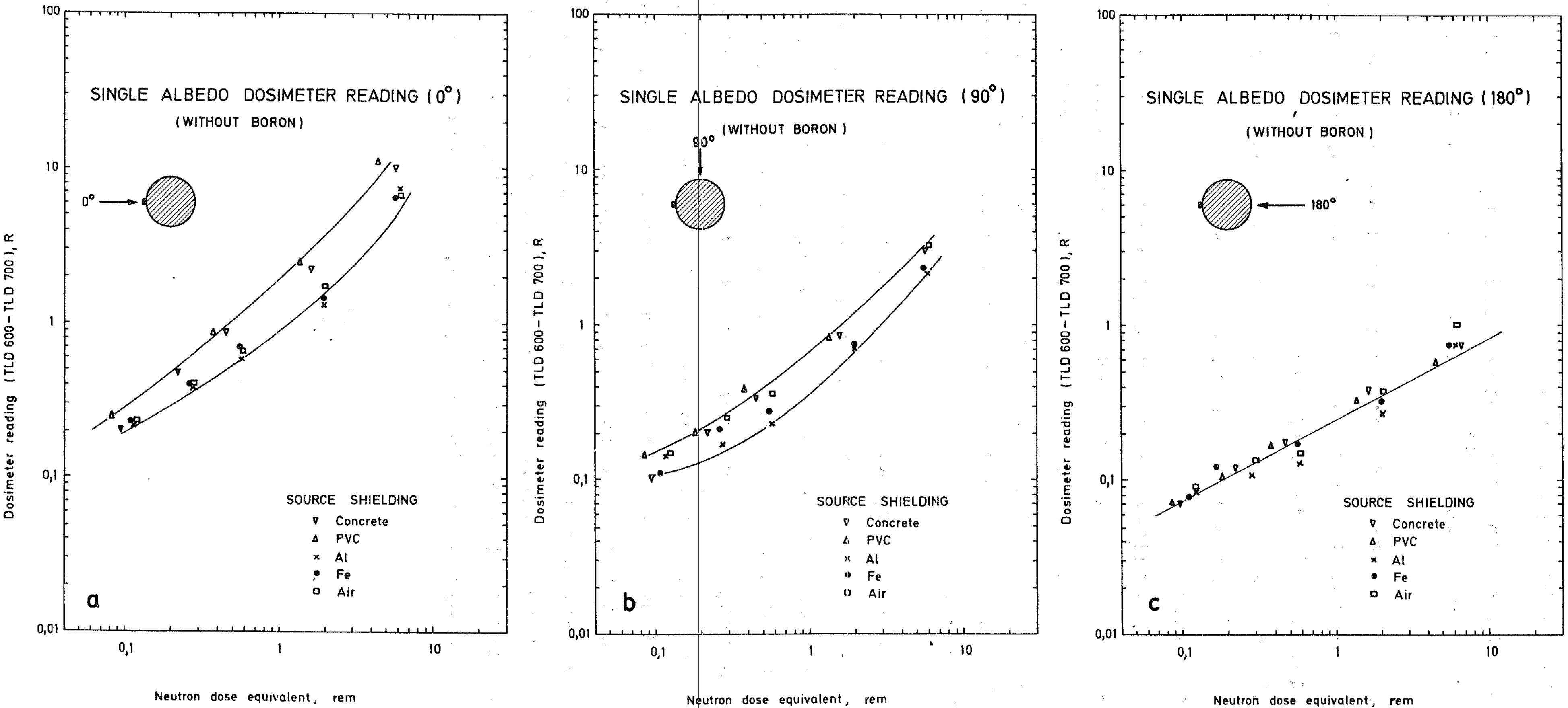

Fig.11: The dosimeter reading of a single albedo dosimeter without boron shield as a function of neutron dose equivalent for radiation incidence angles of 0° (a) 90° (b) and 180° (c)

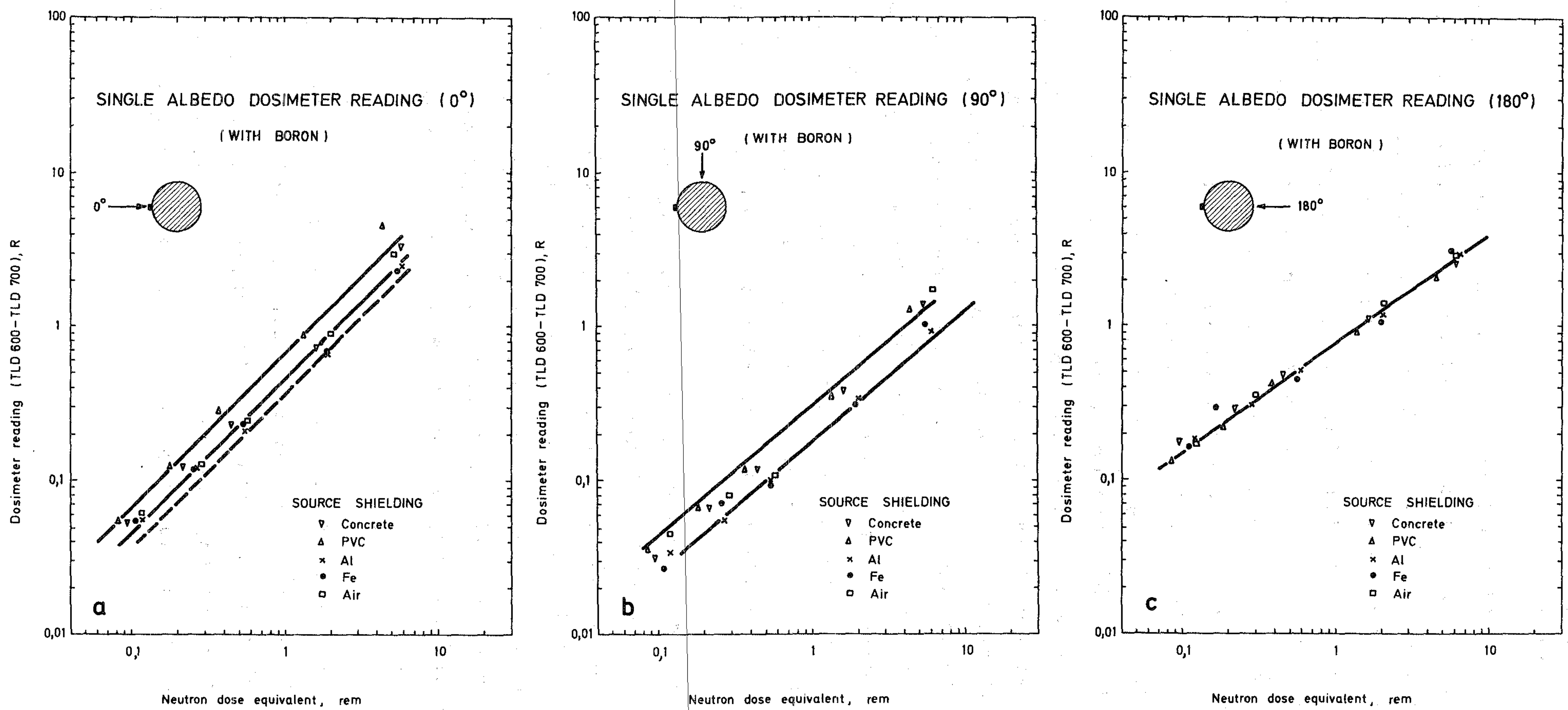

Fig.12: The dosimeter reading of a single albedo dosimeter with the boron shield as a function of neutron dose equivalent for radiation incidence angles of 0^{o} (a), $9o^{o}$ (b) and $18o^{o}$ (c)

3. Single albedo dosimeter

The energy and direction dependences of the dosimeter reading is an important aspect of the practical use of an albedo dosimeter. The albedo dosimeter readings (TLD 6oo - TLD 7oo) resulting from our measurements were evaluated as a function of the dose equivalent measured with the Rem-counter. Fig. 11 and Fig. 12 show the energy dependence of the dosimeter reading for radiation incidence angles of 0^o, $9o^o$ and $18o^o$, with and without boron capsule. It was found that at an angle of 0^o, the boron capsule assures a correct dose reading from fast neutrons; this is also true for the backscattered neutrons from the floor at greater distances from the source. The dosimeter reading of this albedo dosimeter is therefore directly proportional to the dose equivalent and only slightly dependent on the neutron energy spectrum. However, the albedo dosimeter reading is very much dependent on the angle of the radiation incidence. For a radiation incidence of $9o^o$ and $18o^o$ the dosimeter readings are no longer dose proportional. For $18o^o$, however, the dosimeter reading is independent of the neutron spectrum. Therefore, the single albedo dosimeter with the boron capsule is a personal dosimeter, the neutron sensitivity of which is practicially independent of the neutron energy for greater distances than 1 m from the source.

The dosimeter reading per dose equivalent was evaluated for the various energy distributions of neutrons from the ^{252}Cf-source and was found to be o.5 R/rem for 0^o, o.28 R/rem for $9o^o$ and o.1 R/rem for $18o^o$ (Fig. 13). These values are related to an integral measurement of the luminescence light up to a heating temperature of $24o^oC$. By using a maximum heating temperature of $34o^oC$ the corresponding neutron response of the albedo dosimeter is o.75 R/rem for 0^o.

Fig. 14 shows the relative dosimeter readings of the albedo dosimeter as a function of the radiation incidence angle for an irradiation with the unshielded ^{252}Cf-source. The dosimeter readings were related to the dosimeter reading of the dosimeter with boron capsule and a radiation incidence of 0^o. The results

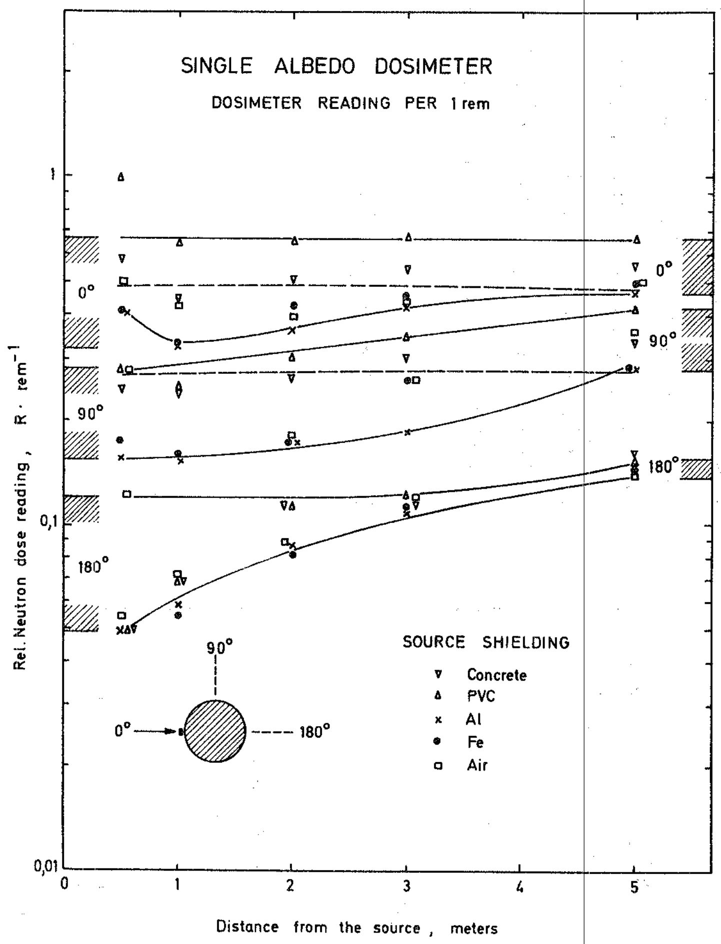

Fig.13: The neutron response of the single albedo dosimeter

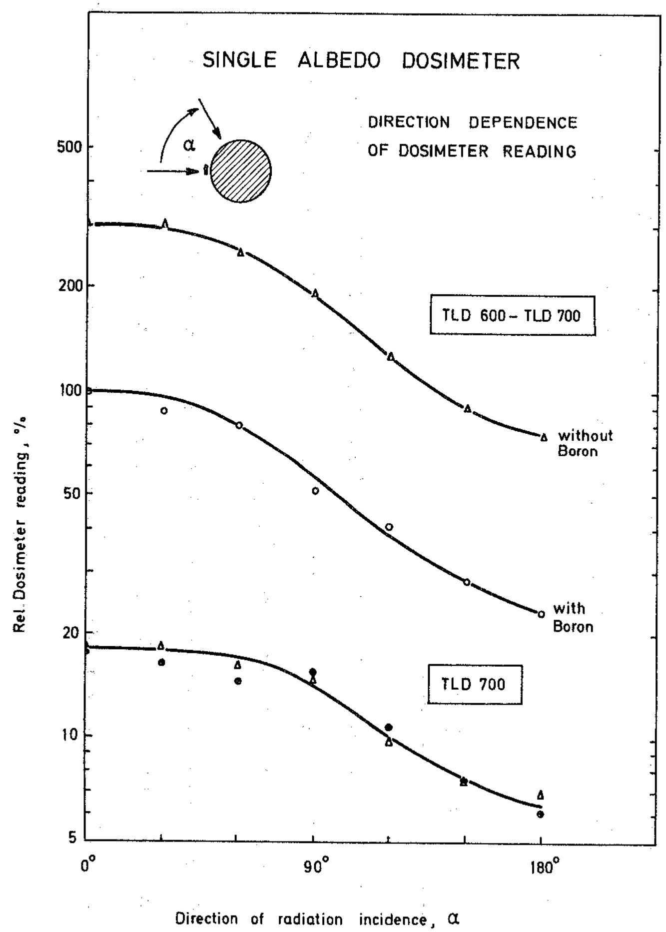

Fig.14: The direction dependence of the single albedo dosimeter reading

show a maximum value for 0^{o} and a minimum value for $18o^{o}$. The boron capsule reduces the reading of the LiF dosimeter to 1/3. The sensitivity of the albedo dosimeter without boron capsule in this case is therefore 1.5 R/rem for 0^{o}. The directional dependence of the gamma dose fraction of the ^{252}Cf source is given by the TLD 7oo reading.

4. The albedo dosimeter system

We studied the properties of an albedo dosimeter system, which consists of two single albedo dosimeters, one to be worn at the front of the body, the other at the back.

By this method the directional dependence of the dosimeter reading is decreased compared with a single albedo dosimeter. The dosimeter readings of the two dosimeters are added; this sum - the dosimeter

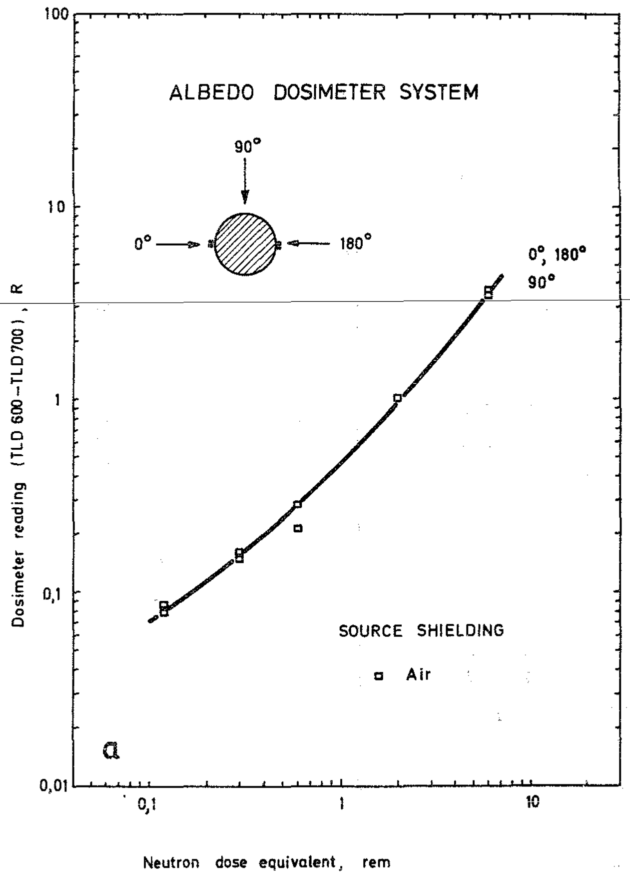

Fig. 15:
The dosimeter reading of the albedo dosimeter system with the boron shield, as a function of dose equivalent without shielding (a), and for a source shield of concrete (b), PVC (c), aluminium (d), stainless steel(e)

(see also page 23)

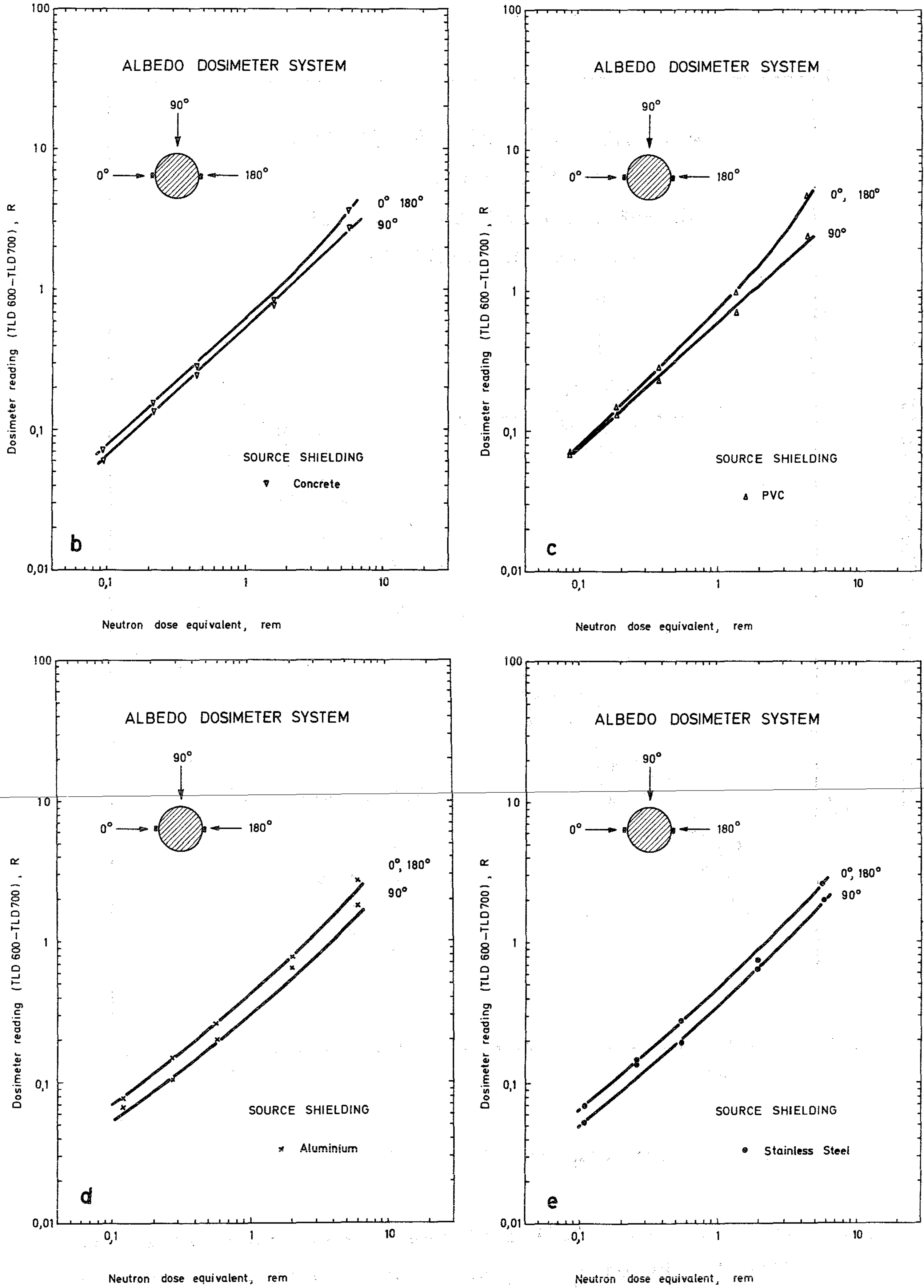

Fig.15: legend see page 22

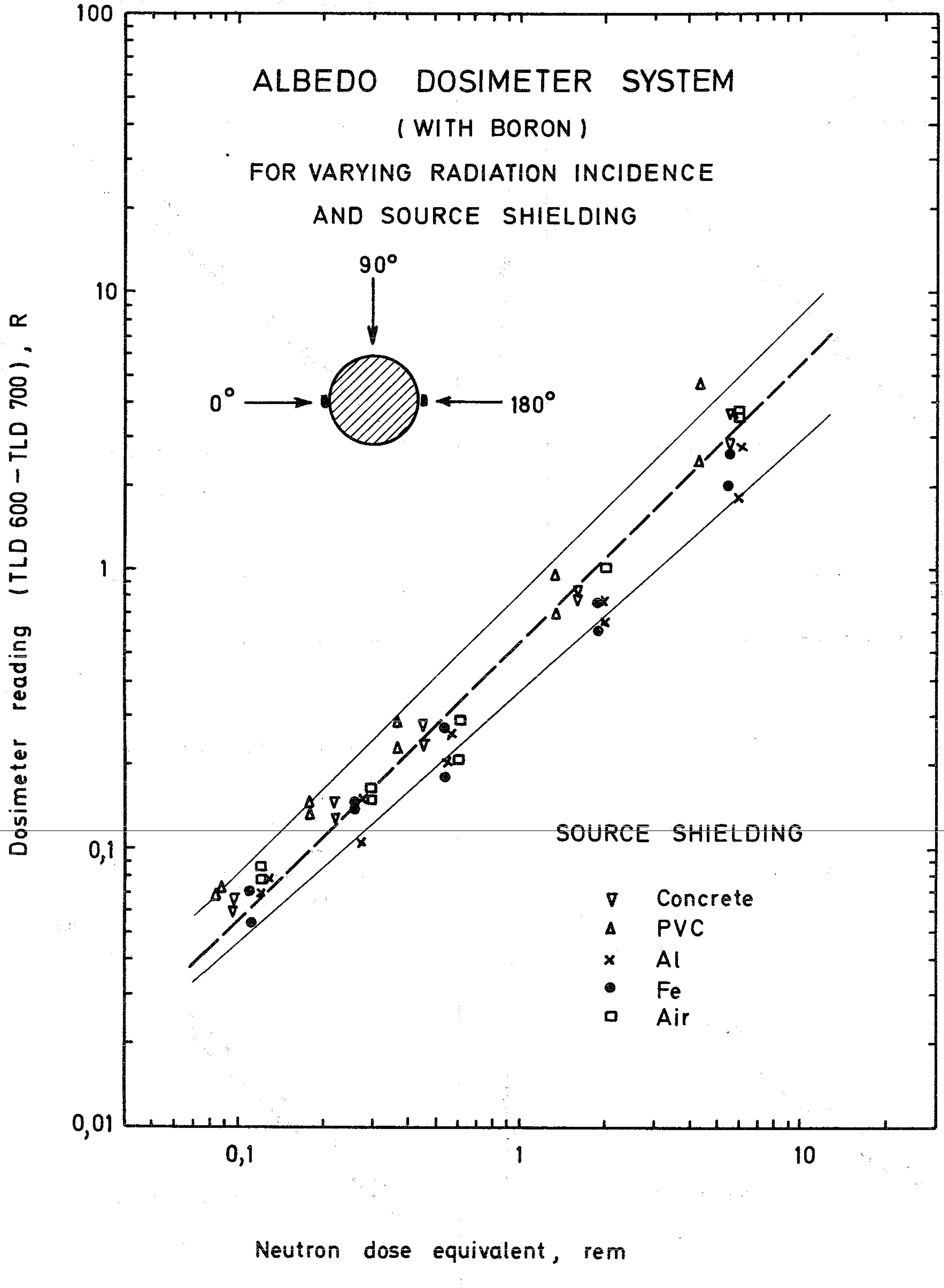

Fig.16: The dosimeter reading of the albedo dosimeter system with the boron shield as a function of dose equivalent for varying radiation incidence angle and source shielding.

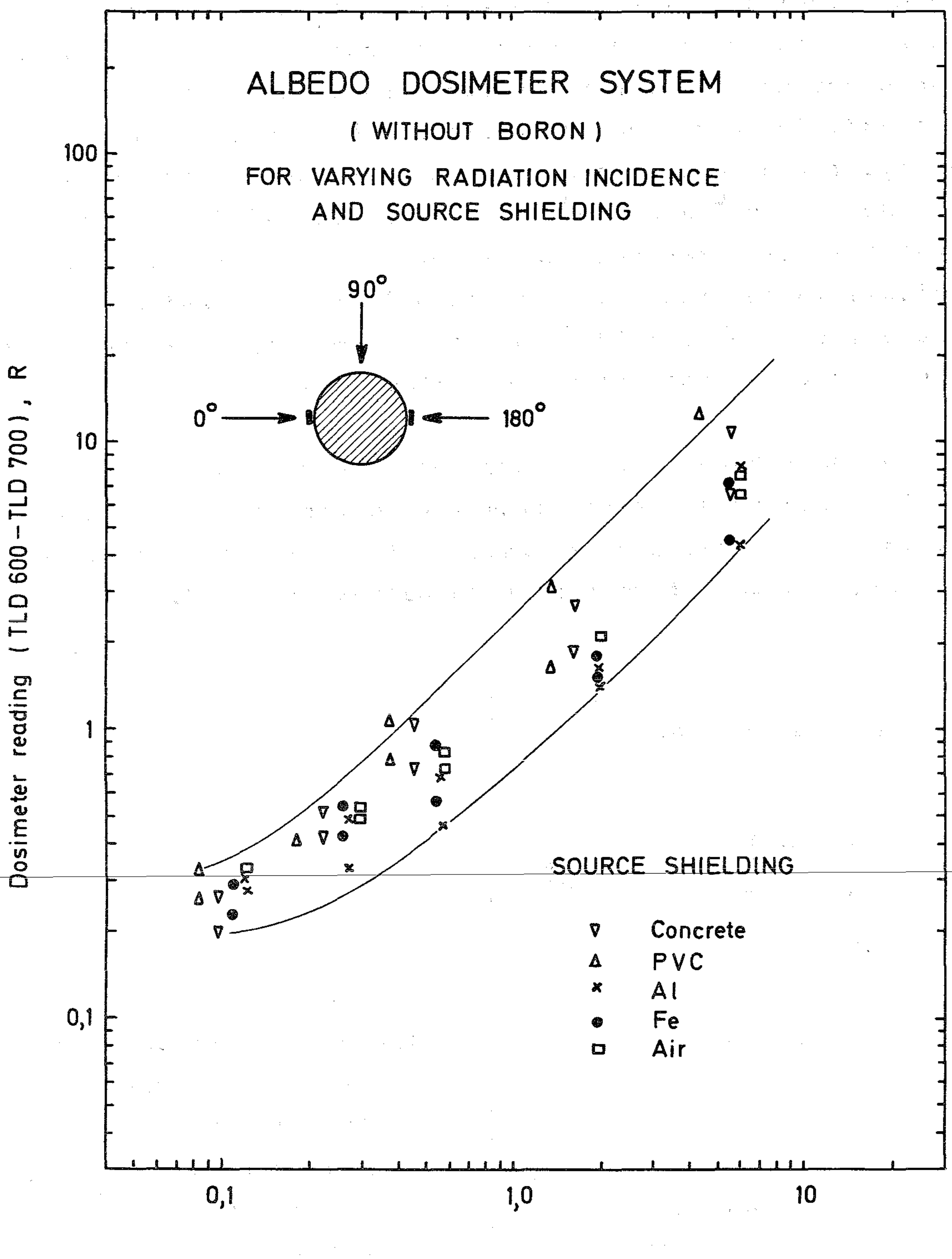

Fig.17: The dosimeter reading of the albedo dosimeter system without boron shield as a function of dose equivalent for varying radiation incidence angle and source shielding.

reading of the albedo dosimeter system - represents the actual neutron dose equivalent at the location of the person better than the dosimeter reading of the single albedo dosimeter at the front. Fig.15 shows the sum of the dosimeter readings after the exposure of the single dosimeters with boron capsules at the front and the back of the body for each source shielding. Fig.16 shows these total readings for each of the neutron energy spectra and a radiation incidence under 0^{o}, $9o^{o}$ and $18o^{o}$. It may be concluded from these figures that the dosimeter reading of the albedo dosimeter system is proportional to the neutron dose equivalent for a radiation incidence under 0^{o}, $9o^{o}$ and $18o^{o}$, and approximately independent of the neutron energy and the radiation incidence angle.

The results without boron capsule are more energy dependent, especially for greater distances from the source. This may be explained by the system being oversensitive for low energy neutrons which are scattered back from the surroundings (Fig. 17).

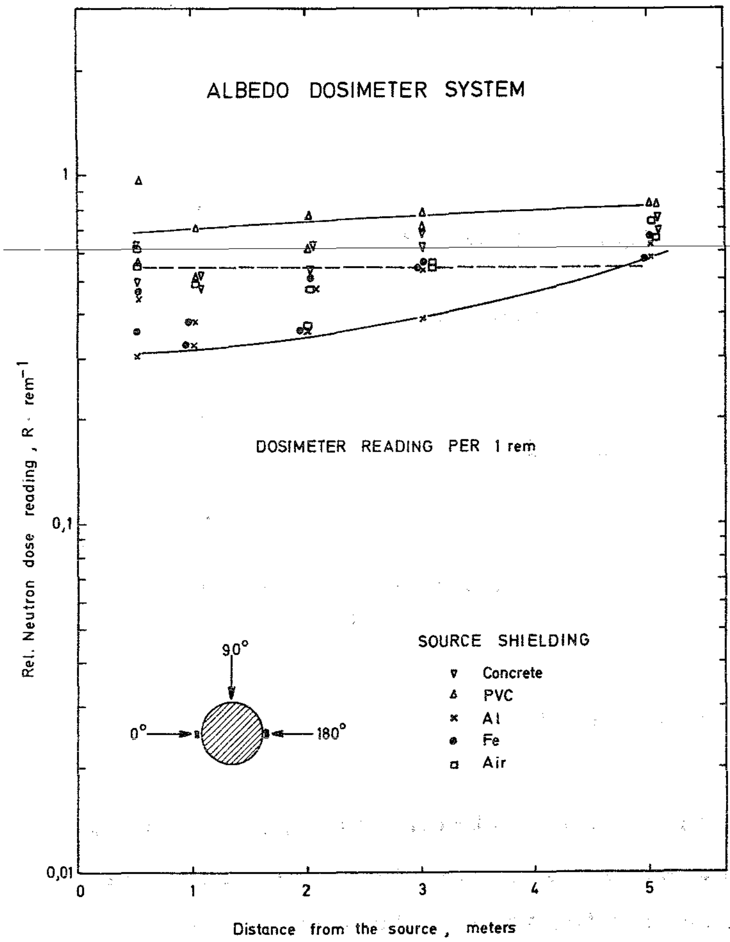

Fig.18:
The neutron response of the albedo dosimeter system with the boron shield as a function of distance from the ^{252}Cf source for various source shieldings and radiation incidence angles

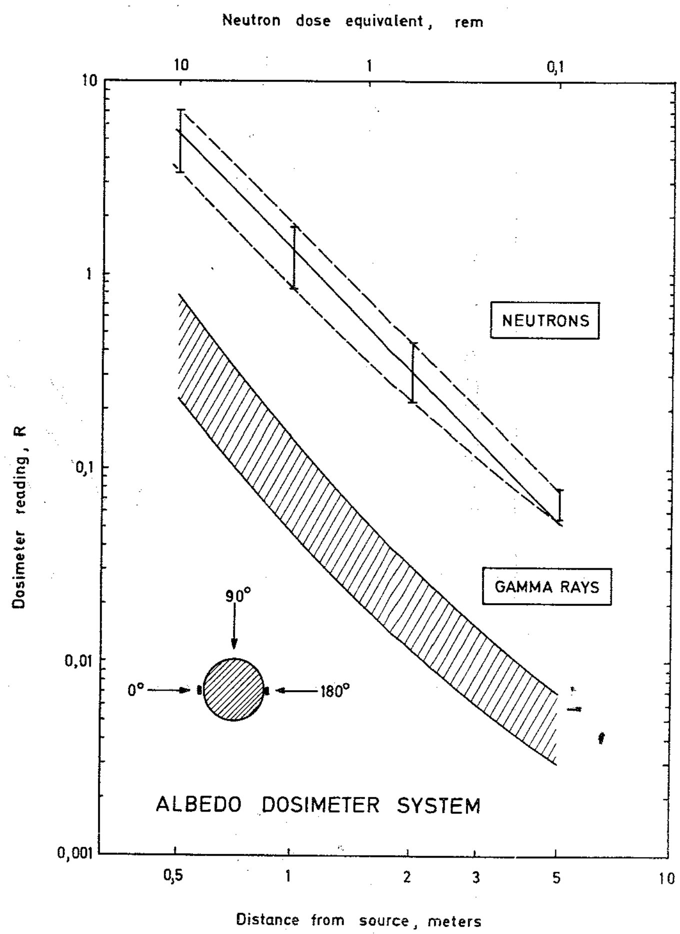

Fig. 19:
The dosimeter reading of the albedo dosimeter system as a function of distance from the ^{252}Cf source as well as neutron dose equivalent, for varying radiation incidence angle and source shielding.

The dosimeter readings per dose equivalent of 1 rem are shown in Fig. 18 as a function of the distance to the ^{252}Cf source. For distances of more than 1 m from the source we find an average value of o.54 R/rem, which is 1o % greater than the corresponding value of the single albedo dosimeter.

The dosimeter readings of the albedo dosimeter system as a function of the distance to the source are shown in fig.19, together with the corresponding values of the gamma readings for all source shieldings and directions of the radiation incidence. The results of our experiments show that changes in the neutron spectrum and in the direction of radiation incidence cause maximum deviations of ± 3o %, for distances to the source of approximately 1 m. For distances of 3 to 5 m the dosimeter reading increases, caused by backscattering from the

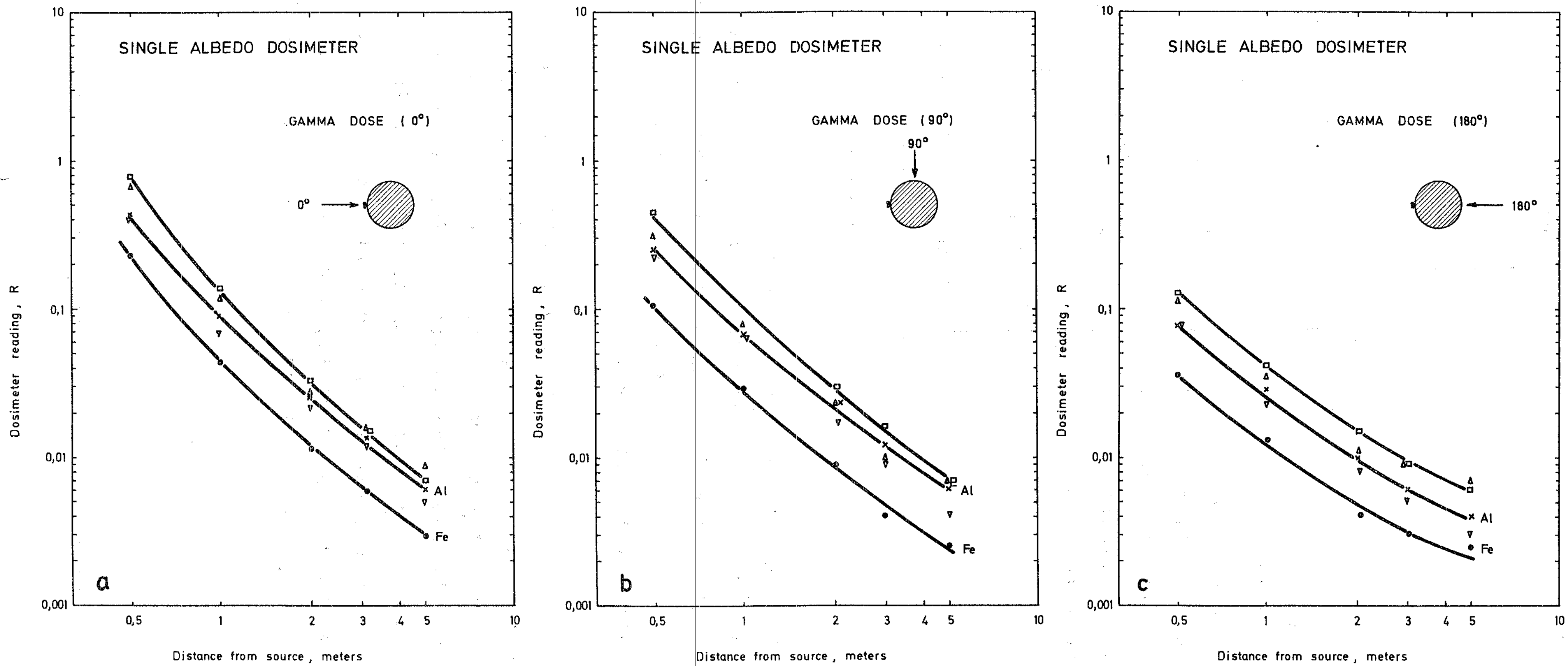

Fig.2o: The gamma-dose reading of TLD 7oo on the front of the phantom as a function of distance from the source for radiation incidence angles of 0° (a), 9o° (b) and 18o° (c)

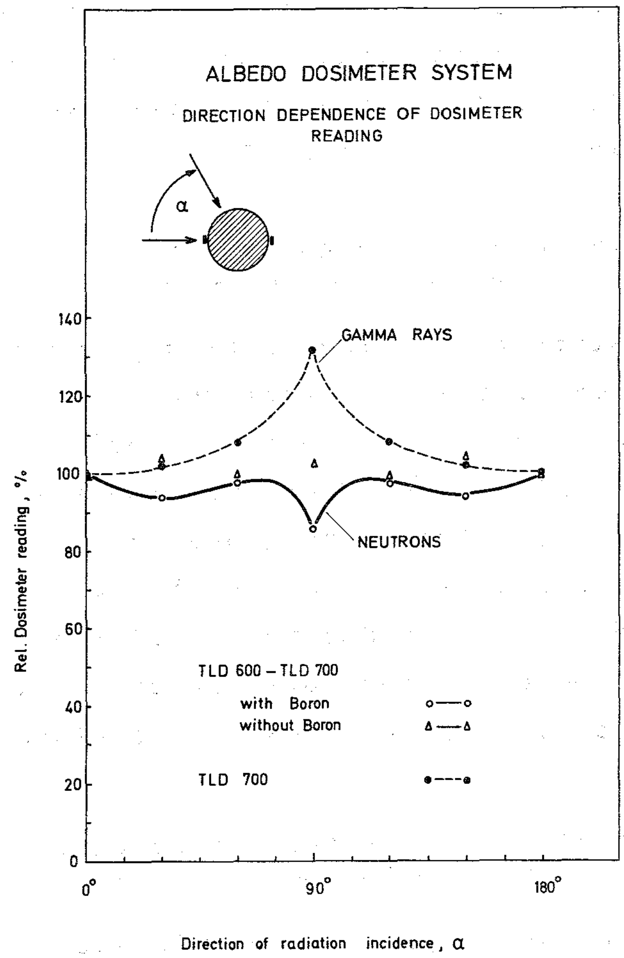

Fig. 21:
The direction dependence of the albedo dosimeter system in the field of the ^{252}Cf source.

floor. This backscattered fraction causes the total error to decrease for increasing distances to the source. The gamma dose near the ^{252}Cf source is approximately 1o % of the neutron dose equivalent. The results of the corresponding gamma dose measurements are shown in Fig.2o for the albedo dosimeter with the boron capsule.

As the albedo dosimeter system detects the gamma dose as well as the neutron dose, we evaluated the total gamma dose from the TLD 7oo dosimeter readings at the front and at the back of the phantom (Fig.2o). Fig.21 shows the relative change of the albedo dosimeter system reading as a function of the direction of the radiation incidence of the primary incident radiation. The gamma dose contribution will be overestimated for a radiation incidence angle of $9o^{o}$ to approximately 3o %, which is not the case for the neutron dose equivalent.

The neutron dose reading reaches the maximum direction dependence at a radiation incidence angle of 9o°. This unfavourable incidence angle has therefore also been taken into account in the total error, shown in fig. 16 and 19.

5. Influence of phantom size

To study the influence of phantom size on the reading of the albedo dosimeter system, experiments with various phantom sizes (15, 2o and 27 cm diam, and with an elliptical phantom of 2o x 3o cm^2 cross section) were carried out. The results of the single albedo dosimeter show only little influence of the size and form of the phantoms used, on the dosimeter reading (Fig.22). The differences between the readings of the dosimeters on the front and on the back side of the phantom are compensated by adding these results, as can be seen from the dosimeter readings of the albedo dosimeter system.

6. Application of the albedo dosimeter

Albedo dosimeters using ^6LiF and ^7LiF will detect neutrons reflected from the body of the exposed individual after thermalization. Such a detector device is more sensitive to intermediate and low-energy fast neutrons than other types of dosimeters. The energy dependence of the dosimeter reading however shows an over-response to thermal and intermediate neutrons and falls off with increasing neutron energies above 1o keV (see also Fig. 6). This disadvantage restricts the use of albedo dosimeters for personnel monitoring to such areas, in which the neutron energy spectra are well known or for which the fraction of intermediate neutrons are given. By knowing this fraction the dosimeter reading can be corrected for the influence of energy dependence.

The dose fraction of intermediate and thermal neutrons can be estimated on the bases of

- neutron surveys of the areas using a Rem-counter, a BF_3 - counter and a proton recoil counter

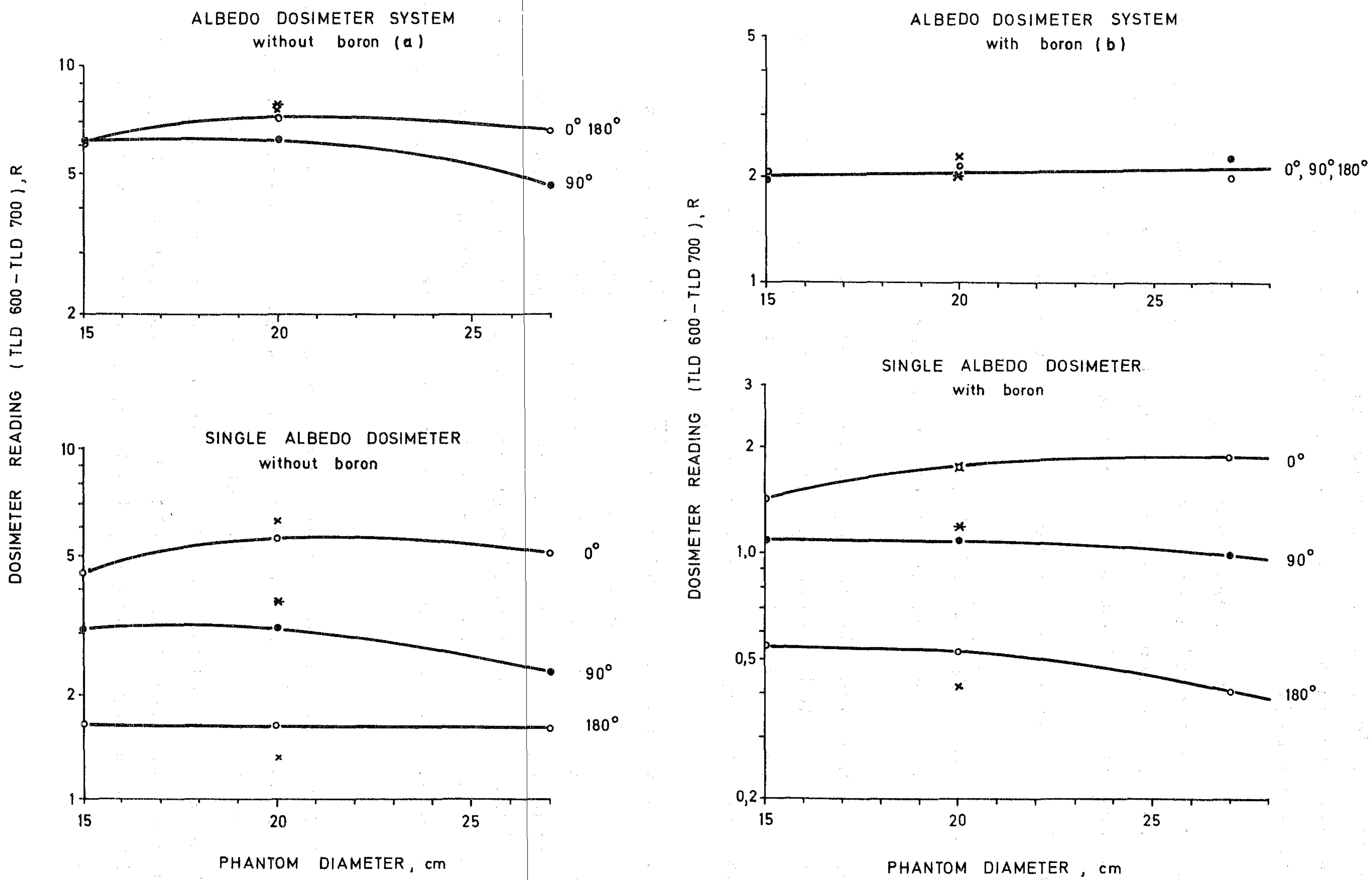

Fig.22: The dosimeter reading of the albedo dosimeter with and without boron shield as a function of phantom size for various radiation incidence angles.

- a separate detection of both incident and reflected neutrons with an albedo dosimeter composed of two pairs of $^{6}LiF/^{7}LiF$ dosimeters which are placed one on each side of the neutron absorber shield.

The results of dose rate measurements at different reactors have shown that the dose equivalent from intermediate and thermal neutrons related to the total neutron dose are in the range of 6 % - 9o % [7]. These values vary from place to place in a given reactor.

Harvey et al. [3] have used a correction factor k,

$$k = \frac{\text{total neutron dose}}{\text{dose of thermal to 3o keV neutrons}}$$

for the boron-shielded albedo dosimeter. k varies around power reactors between 2 and 4 although factors as high as 14 have been measured in extreme conditions [8]; these values are based on neutron survey of the areas, in which the dosimeters are worn.

The neutron spectrum in the environment of a ^{252}Cf source under various conditions of shielding and backscattering ranges from o.1 - 2 MeV. The influence of this energy distribution on the dosimeter reading of the albedo dosimeter is nevertheless low (± 3o %)compared to the situation around a reactor. Results of recent irradiation experiments in the environment of an Am-Be neutron source showed no decrease of the neutron response found for fission neutrons.

These results confirmed the assumption that an albedo dosimeter system composed of a set of $^{6}LiF/^{7}LiF$ dosimeters is almost energy independent for monitoring fast neutrons with energies of o.1 MeV to about 5 MeV. Therefore no energy-correction factor should be used for the evaluation of the dose equivalent because the angular dependence for fast neutrons is of the order of one magnitude greater than the energy dependence

The albedo dosimeter system proposed in this report will nevertheless reduce the total energy dependence as well as the direction dependence to an overall error of the order of ± 3o %. This error should be compared with that of other dosimeters. The NTA emulsion shows an energy dependence of ± 3o % and ±6o % for the estimation of the kerma and of the dose equivalent respectively,for a free air irradiation in the energy range of o.6 - 5 MeV.

The albedo dosimeter can be used for personnel monitoring when the neutron energy distribution is known and the neutron energies do not vary greatly in the area, where the dosimeter is worn. These prerequisites are sufficiently fullfilled in the reactor environment as well as in the neutron field of a ^{252}Cf source.

Acknowledgments

We sould like to thank Dr. I.R. Harvey from the Central Electricity Generating Board, Berkeley, Gloucestershire for his co-operation to provide us with boron shielded capsules which we have used for our experiments.

We also thank Miss B. Kuhn, Mrs. I. Hofmann, Miss Chr. v. Brandenstein and Mr. H. Veldman for their assistance during the experiments.

References

[1] Dennis I.A., Smith I.W. and Boot S.I.: Proc. of IAEA Symposium on Neutron Monitoring, Vienna 1967, p. 547

[2] Harvey I.R.: Report RD/B/N 827, 1967

[3] Harvey I.R., Hudd W.H.R. and Townsend S.: Report RD/B/N 1547

[4] Attix F.H.: Proc. of IAEA Symposium Advances in Phys. and Biol. Rad. Detect., Vienna, 1971, p.3

[5] Korba A., Hoy I.E.: Health Physics 18, p. 581, 1970

[6] Piesch E.: Report KFK-1635, 1972

[7] Nachtigall D.: Report Jül-158-Si, 1964

[8] Gayton F.M., Harvey I.R. and Jackson I.H.: Journ. of Brit. Nucl. Energy Soc. 11, 125, 1972

[9] Piesch E.: Atompraxis 9, p.179, 1963

[10] Burgkhardt B., Piesch E.: Proc. of anual meeting of Fachverband für Strahlenschutz, Karlsruhe, 1972 p. 195