KERNFORSCHUNGSZENTRUM

KARLSRUHE

August 1968 KFK 831

Abteilung Strahlenschutz und Dekontamination

Routine Dosimetry with Phosphate Glasses

E. Piesch

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- Strahlenmeßdienst -

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Abstract

At the Karlsruhe Nuclear Research Center phosphate glasses were used as routine personnel dosimeters for all persons but also as long-time accumulating dosimeters outside the installations and reactors in the vicinity of the center. The Karlsruhe spherical dosimeter consists of a perforated tin-plastic-boron casing and a Yokota type glass with a lower γ-exposure limit of about 40 mR. for one year of dose accumulation. The dosimeter reading is energy and direction independent for quantum energy above 45 keV and shows the dose-equivalent of thermal neutrons.
Moreover, the dosimeter serves as a criticality dosimeter. In case of an accident, the neutron induced ß-radioactivity of the glass - resulting from thermal neutrons by the reaction P-31 (n,γ)P-32 and from fast neutrons by the reaction P-31(n,p)Si-31 - will be measured in the first 15 hours after the accident. The lower detection limit for the dose indication of fission neutrons is 0.5 rad.

As a result of past years routine dosimetry, examples of Health Physics applications will be given:

- Comparison studies with other personnel dosimeters in different installations,
- the measuring accuracy for calibration exposure and for routine monitoring,
- measurement of the accumulated annual dose from background radiation inside and outside the installations.

A resume will be given on recent developments of phosphate glass dosimeters in the Karlsruhe Nuclear Research Center. A new method of fluorescence measurement (multi-scanning technique) offers the possibility to measure the depth dose distribution in the glass and the radiation quality for quantum radiation below 100 keV.

1) Introduction

On the basis of seven years of testing and development, phosphate glass dosimeters are used at the Karlsruhe Nuclear Research Center as routine dosimeters for general monitoring of all personnel and for monitoring the radiation level in buildings and in the vicinity of the Center. In these applications the spherical dosimeter used serves as a routine dosimeter for γ-radiation and likewise as a criticality dosimeter for the detection of thermal and fast neutrons.

The use of glass dosimeters instead of the previous film dosimeters has the advantages of energy independent and non-directional dose indication, good measuring accuracy, stable storage of the measuring value and, above all, sufficient sensitivity for long-time dose accumulation.

As glass dosimeters are used routinely only by a few measurement services up to now while the results of the dosimeter tests justify major routine application, the example of the Karlsruhe dosimeter system will be used to describe completely the practical possibilities of using phosphate glass dosimeters and the results of long-time exposures. In view of these problems it is not useful to give a complete review of the familiar basic dosimetry characteristics of the phosphate glass or to enter into the details of other dosimeter capsules and developments of phosphate glass dosimetry.

Hence, the measurement techniques and requirements will be described below which are necessary to achieve the necessary reproducibility within routine evaluation. Some results will be given of calibration exposures and intercomparison measurements in routine dosimetry and of different applications in radiation protection monitoring.

Among the requirements of a routine employment of phosphate glass dosimeters in personnel dosimetry are these:

- Use of a phosphate glass with the properties of uniform dose sensitivity and pre-dose, with a favourable temperature behaviour and low fading fabricated in large series. The Toshiba glass, but also glasses by other manufacturers+) fulfill these requirements.

+) Manufacturer: Messrs. Toshiba, Tokyo, Japan; Messrs. Schott und Gen., 65 Mainz, Western Germany; Messrs. C.E.C., Montrouge, France

- Use of a high voltage stabilized and sufficiently sensitive evaluation equipment for phosphate glasses with a good long-time constancy+).
- Use of a suitable dosimeter capsule with optimum energy compensating filters for the energy independent and non-directional dose reading but also to protect the glass from UV light and from the influence of the humidity.
- Establishment of a standard washing procedure to safeguard sufficient reproducibility in the measurement of low doses and establishment of a regeneration process for quenching of the dose reading and repeated use of the glass.

2) The Karlsruhe Phosphate Glass Dosimeter for Routine and Criticality Dosimetry

2.1 Fluorescence Measurement for Routine Dosimetry

2.11 Dosimeter Capsule and Energy Dependence

The spherical dosimeter contains a Yokota Glass (1) of the size 8 x 8 x 4.7 mm^3 in a plastic sphere which is covered by two hemispherical shells equipped with conical bores for energy compensation (2 mm of tin with 15 % hole aperture) (2). The plastic encapsulation protects the glass from UV light, contamination, dirtiness, and mechanical damage. A boron additive in the plastic reduces the hypersensitivity of the glass to thermal neutrons. The spherical dosimeter is fastened to a plastic case with a clip which contains an additional combination of activation foils (criticality dosimeter), or it may be welded directly into the polythene tube.

In the energy range between 45 keV and 1.2 MeV the spherical dosimeter shows an energy dependence of ± 8 % in one direction of radiation incidence (see Fig. 1), for all directions of radiation incidence this dependence is ± 18 %. If the dosimeter is exposed on the front of the Alderson phantom, the energy dependence of the dose reading is ± 10 % for the indication of the exposure and ± 18 % for the absorbed dose in the testes with frontal exposure (see Fig. 2). The absorbed dose in the organs such as bone marrow and ovaries, however, is overestimated for quantum radiation of lower energy. The indication of the spherical dosimeter is proportional the absorbed dose in the critical organs within ± 20 % above 60 keV, i.e. bone marrow, ovaries, testes, gut mucosa, and eye lenses, if a uniform direction of radiation incidence (exposure of the rotating phantom) is used as the basis of the definition of the absorbed dose in the organ (3).

+) Manufacturer: Messrs. Toshiba, Tokyo, Japan; Messrs. Total, Ladenburg, Western Germany

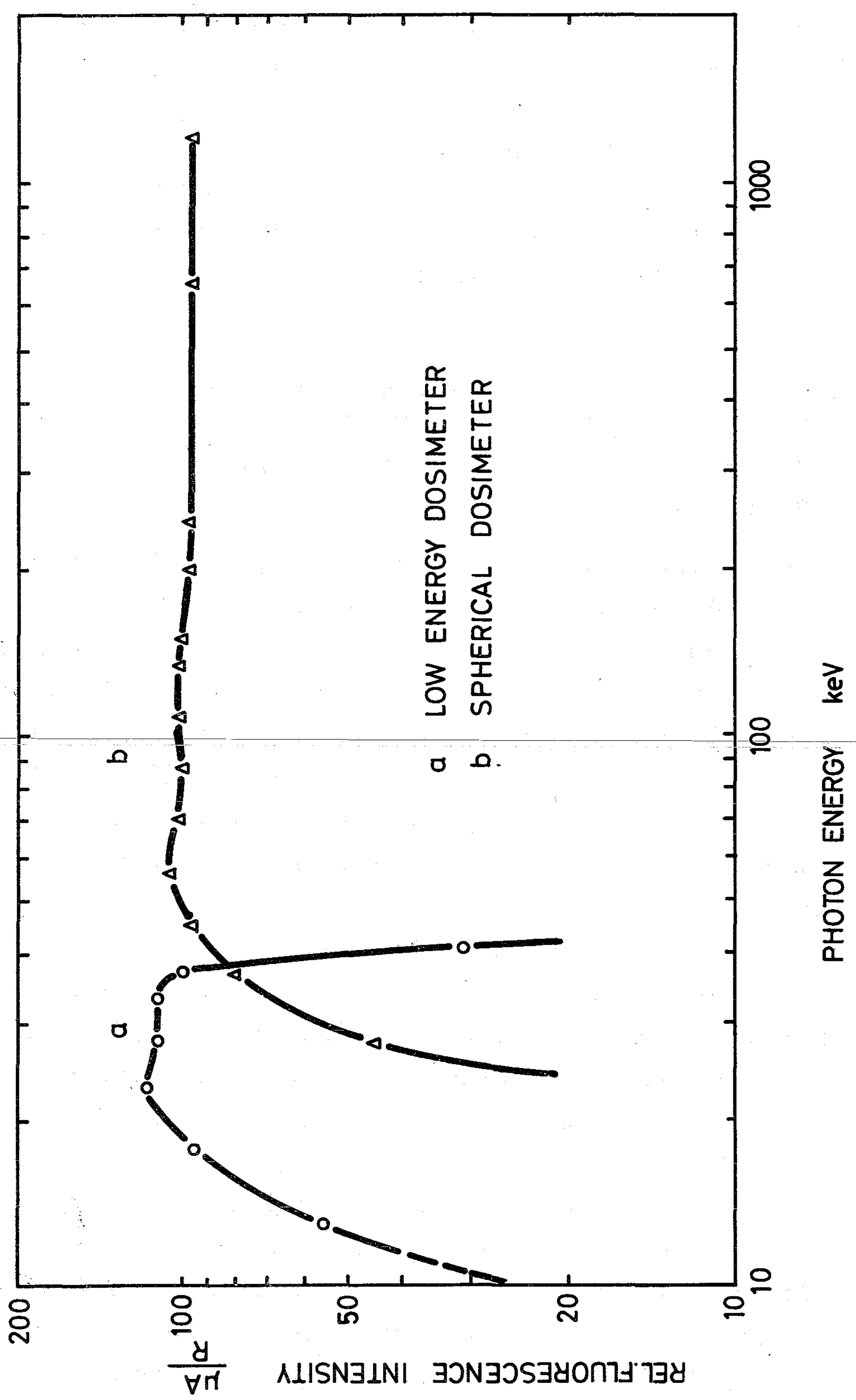

200
100
50
20
10
$\frac{\mu A}{R}$
REL.FLUORESCENCE INTENSITY
10
100
1000
PHOTON ENERGY keV
a
b
a LOW ENERGY DOSIMETER
b SPHERICAL DOSIMETER

FIG. 1.

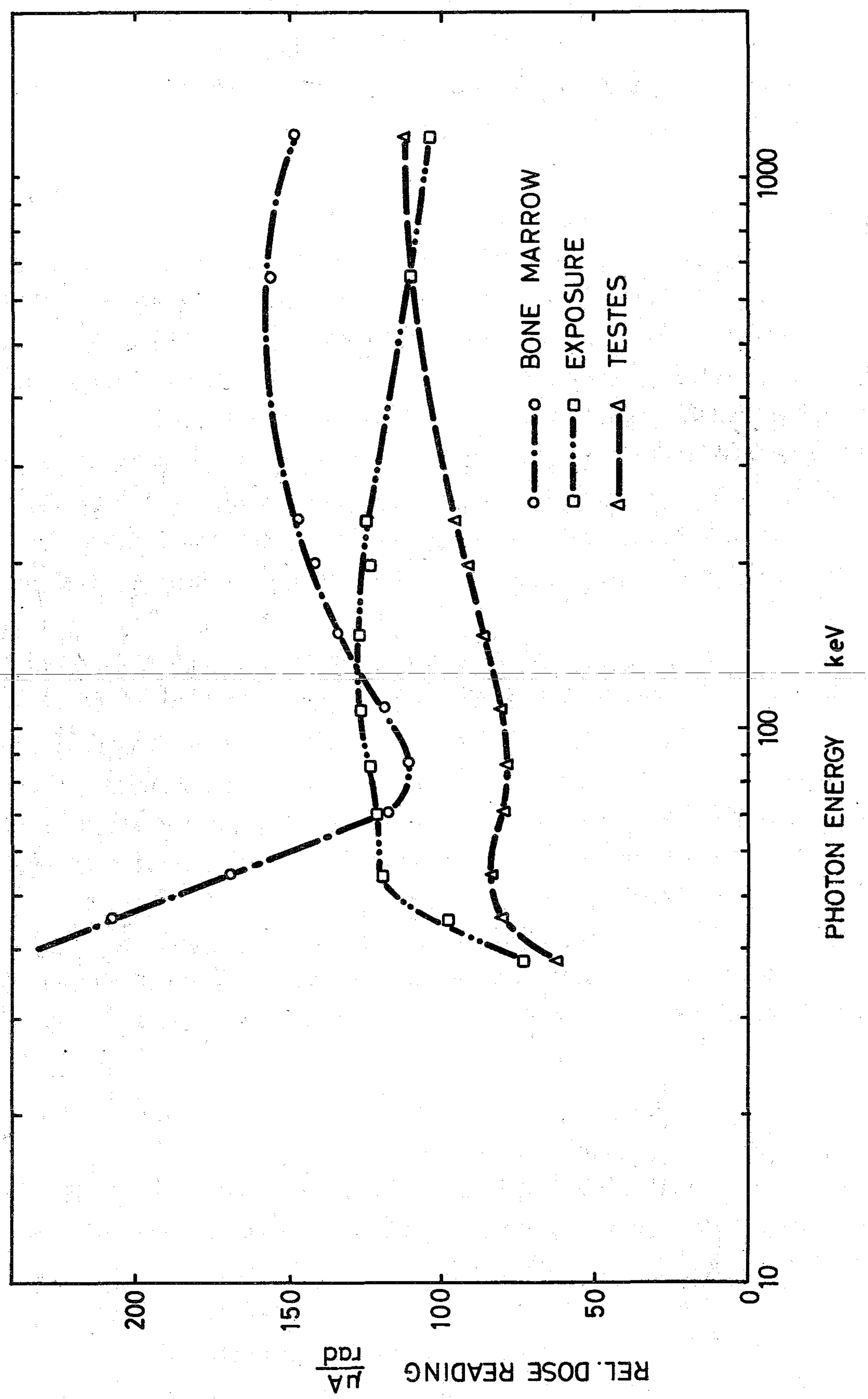

BONE MARROW
EXPOSURE
TESTES
REL. DOSE READING
µA/rad
PHOTON ENERGY keV
0
50
100
150
200
10
100
1000

FIG. 2.

For the detection of low-energy quantum radiation in the energy range between 15 and 45 keV a low energy dosimeter is worn in addition to the spherical dosimeter; it contains two glasses with one plastic and one copper filter each (4). The difference in readings between these two glasses is proportional the exposure in the energy range below 45 keV (see Fig. 1).

2.12 Dose Measurement and Evaluation

For the routine evaluation of the glass dosimeters in the linear range of measurement between 10 mR and 3.000 R a Toshiba evaluation equipment type FGD-3B is used. The indication of the evaluation equipment is referred to an exposure via a calibration. For this purpose, samarium activated reference glasses, but also normal phosphate glasses, exposed to a known dose, are used.
An important stage in routine evaluation is the washing of the glasses prior to the measurement. For this purpose frames are used containing 100 glasses which were washed in a single process in the following sequence: Ultrasonic washing, running-water washing, distilled water washing and alcohol washing (5-7).

In all measurements of routine monitoring the measured value of the pre-dose (characteristic fluorescence of the glass in the reader between 100 and 150 mR) is taken into account. The glass dosimeters are evaluated, when required, after one, three or six months of wearing. In long-time exposures probably the natural background of some 100 mR/year will be detected. Also with one monthly intermediate evaluation of the dosimeter the determination of an annual dose for exposures 40 mR is possible.
After a dose accumulation of 1 R, the measured value is quenched by a heat treatment of 20 min at 400°C. The glass may be regenerated between 10 and 15 times without significantly changing the dose sensitivity and the amount of the pre-dose.

2.13 Reproducibility of the Dose Measurement

The accuracy of a dose measurement depends mainly on careful cleaning of the glass, maintenance of a standard washing procedure, taking into account the individually different pre-doses and, in the case of repeated use of the glass, on the observation of the regeneration instructions. Therefore, potential influence of errors of the evaluation equipment, the long-time behaviour of the glass and the washing procedure determine the reproducibility of the dose reading.
Influences of the calibration and the long-time stability of the evaluation equipment were found to be lower than ± 5 mR.

In a routine washing procedure in which some 100 glasses are washed at the same time residues of the washing agent or the detergent on the surface of the glass can influence the dose reading. If a multitude of glasses is washed twice and measured after each washing, the influence of glass dirtiness and, at the same time, the influence of the constancy of the measuring equipment can be determined statistically from the difference in dose readings. Fig. 3 shows the variation of dose readings of 485 glass dosimeters after two washings and measurements of the same glass (reading some 300 mR, routine evaluation of dosimeters of environmental monitoring). A difference in readings of more than ± 10 mR was encountered with 2 to 15 % of the dosimeters evaluated.

In dose measurements above 1 R a reproducibility of the dose measurement better than 3 % is obtained.
During long-time dose accumulation in personnel and environmental monitoring we found no considerable fading or climatic influences on the dose reading.

2.14 Sensitivity to Other Types of Radiation

The spherical dosimeter is practically insensitive to ß-radiation. The sensitivity to thermal neutrons is reduced by a 19 % boron fraction of the plastic capsule to such an extent that a sum reading in rem of γ-radiation and thermal neutrons is obtained. An exposure of 1 R accordingly produces the same dose reading as a fluence of 1.56×10^9 n/cm^2 of thermal neutrons or 3.6×10^9 n/cm^2 of fast neutrons (see Fig. 4).

The phosphate glass dosimeter is practically insensitive to a surface contamination of the dosimeter cladding. Only activities of 0.1 µCi result in a dose increase measurable with monthly evaluation of the glass. An α/ß-contamination of the dosimeter cladding can be assessed through an activity measurement (8).

2.2 Activity Measurement for Criticality Dosimetry

2.21 Method of Measurement

In a criticality accident a neutron induced activation of the phosphate glass and of the dosimeter capsule can be used for the dose measurement of thermal and fast neutrons. Of particular interest is the activation of phosphorous in the glass. Fast neutrons in the energy range above 2.5 MeV, through an (n,p)-reaction, result in Si-31 (T_h = 2.6 h, $ß_{max}$ = 1.6 MeV), thermal neutrons

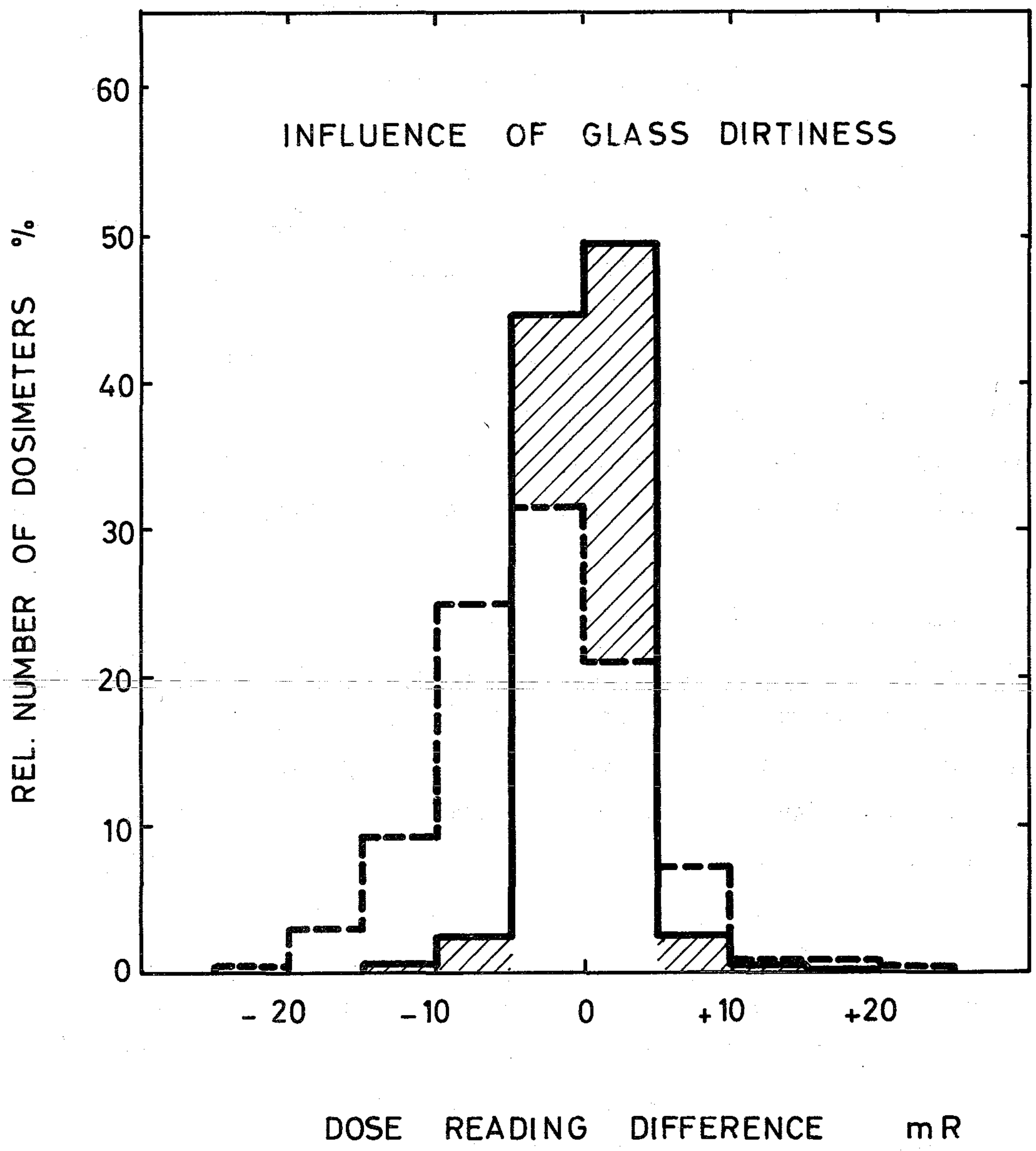
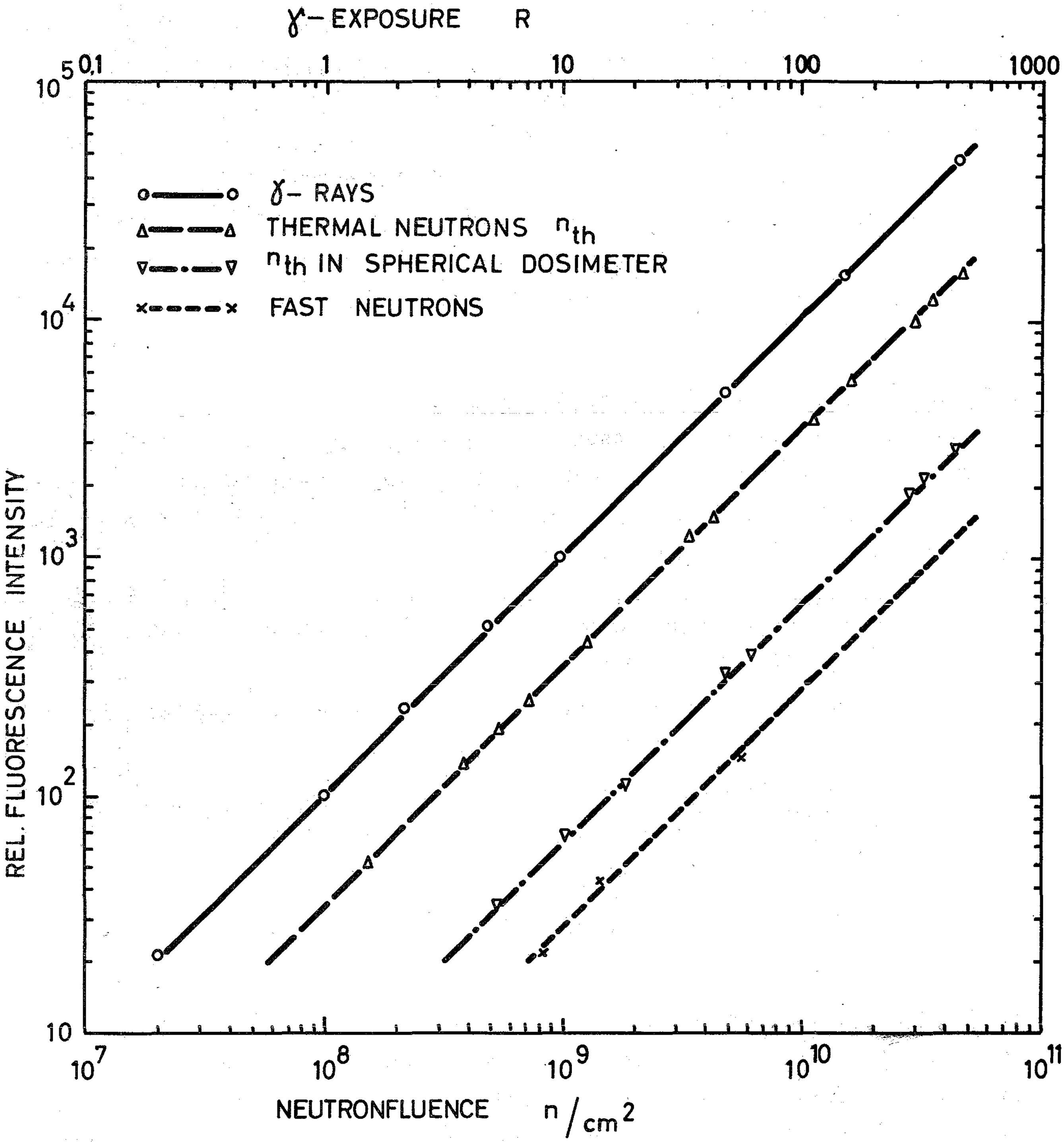

INFLUENCE OF GLASS DIRTINESS
REL. NUMBER OF DOSIMETERS %
60
50
40
30
20
10
0
- 20
-10
0
+10
+20
DOSE READING DIFFERENCE mR

FIG. 3.



γ- EXPOSURE R
0,1
1
10
100
1000
10^5
10^4
10^3
10^2
10
REL. FLUORESCENCE INTENSITY
γ- RAYS
THERMAL NEUTRONS n_{th}
n_{th} IN SPHERICAL DOSIMETER
FAST NEUTRONS
10^7
10^8
10^9
10^{10}
10^{11}
NEUTRONFLUENCE n/cm^2

FIG. 4:

through an (n,γ)-reaction result in P-32 (T_h = 14 d, β_{max} = 1.4 MeV).

The ß-activity of both radionuclides can be detected advantageously with an efficiency of 60 % through the measurement of the Cerenkov radiation generated in the glass in a measuring setup for tritium liquid scintillation counting (9). The sensitivity of such Cerenkov measurement is indicated in Fig. 5 for the Yokota glass irradiated in the spherical dosimeter due to the absorbed dose of thermal neutrons, fission neutrons, and 3 MeV neutrons. The different halflives of Si-31 and P-32 permit the separation of the activating fractions of thermal and fast neutrons and the determination of the absorbed dose of 1 rad fission neutrons within the initial ten hours after a criticality accident (see Fig. 6).

2.22 Application of the Method of Measurement

The spherical phosphate glass dosimeter thus can be used as an accident dosimeter in a nuclear research center or in nuclear installations in general. The dose determination of different dose fractions after a criticality accident requires measurements in this sequence:

Measurement of fast neutrons (activity measurement)	1 - 15 hours after exposure
Measurement of thermal neutrons (activity measurement)	25 hours after exposure
Measurement of the γ-dose and the thermal neutron dose (fluorescence measurement)	more than 24 hours after exposure
Subtraction of the thermal neutron fraction, if necessary, to obtain the γ-dose	

If the activity is measured 5, 10, or 15 hours after exposure, a constant increase in the activation fraction of thermal neutrons must be anticipated. In Fig. 7 the relative counting rate fraction of thermal neutrons is plotted as a function of the relative fluence fraction of thermal neutrons, referred to the fission neutron fraction of the respectice neutron spectrum, if the activity measurement is carried out at different times after a short-time exposure. For orientation purposes the approximated fluence values Φ_{th} / Φ_f of the well-known criticality accidents have been included in the figure.

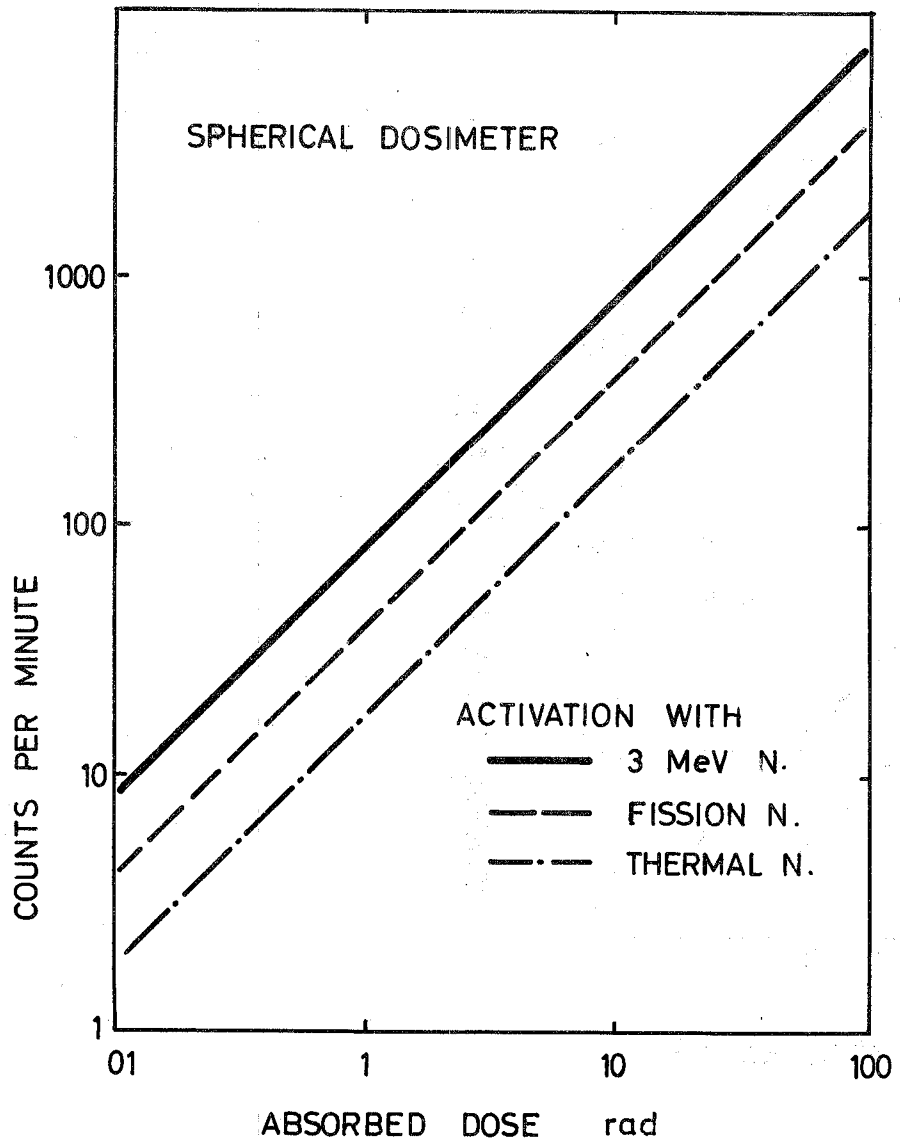

SPHERICAL DOSIMETER
COUNTS PER MINUTE
1000
100
10
1
01
1
10
100
ABSORBED DOSE rad
ACTIVATION WITH
3 MeV N.
FISSION N.
THERMAL N.

FIG. 5.

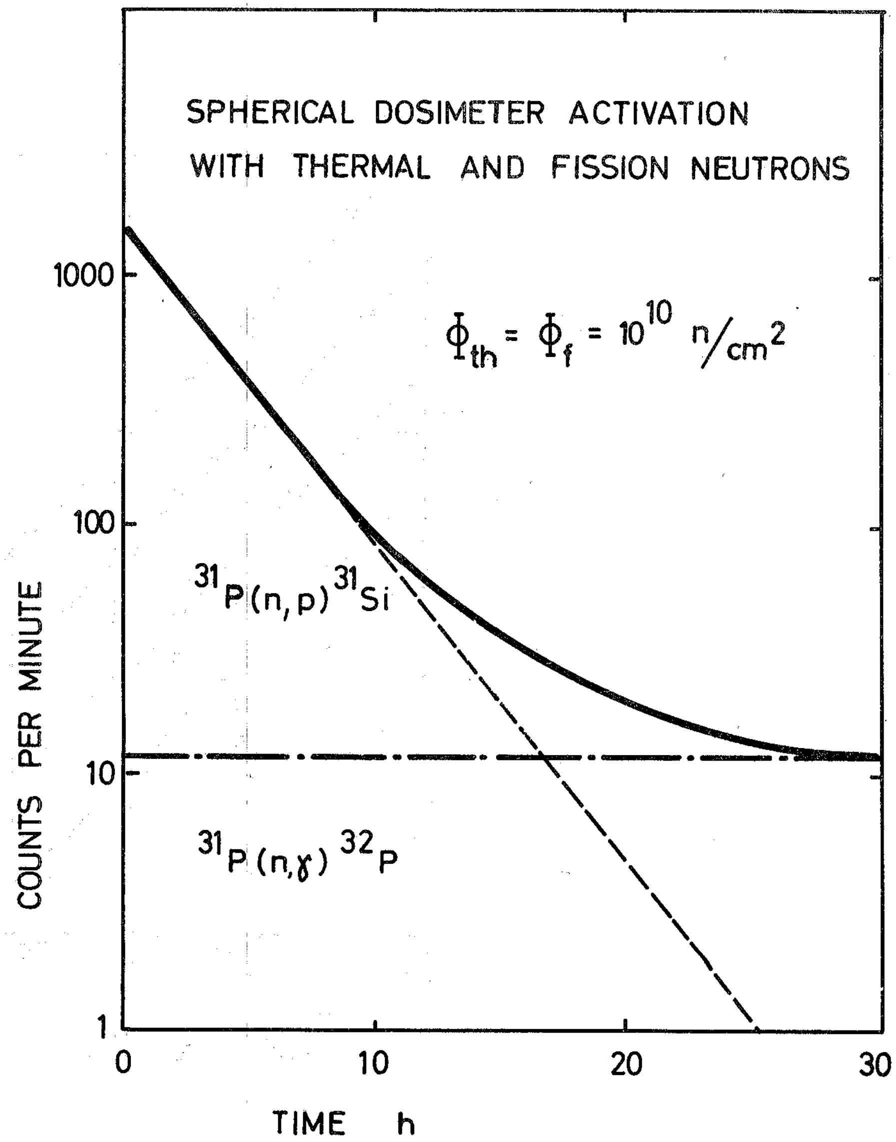

SPHERICAL DOSIMETER ACTIVATION
WITH THERMAL AND FISSION NEUTRONS
$\Phi_{th} = \Phi_f = 10^{10}$ n/cm^2
COUNTS PER MINUTE
1000
100
10
1
$^{31}P(n,p)^{31}Si$
$^{31}P(n,\gamma)^{32}P$
0
10
20
30
TIME h

FIG. 6.

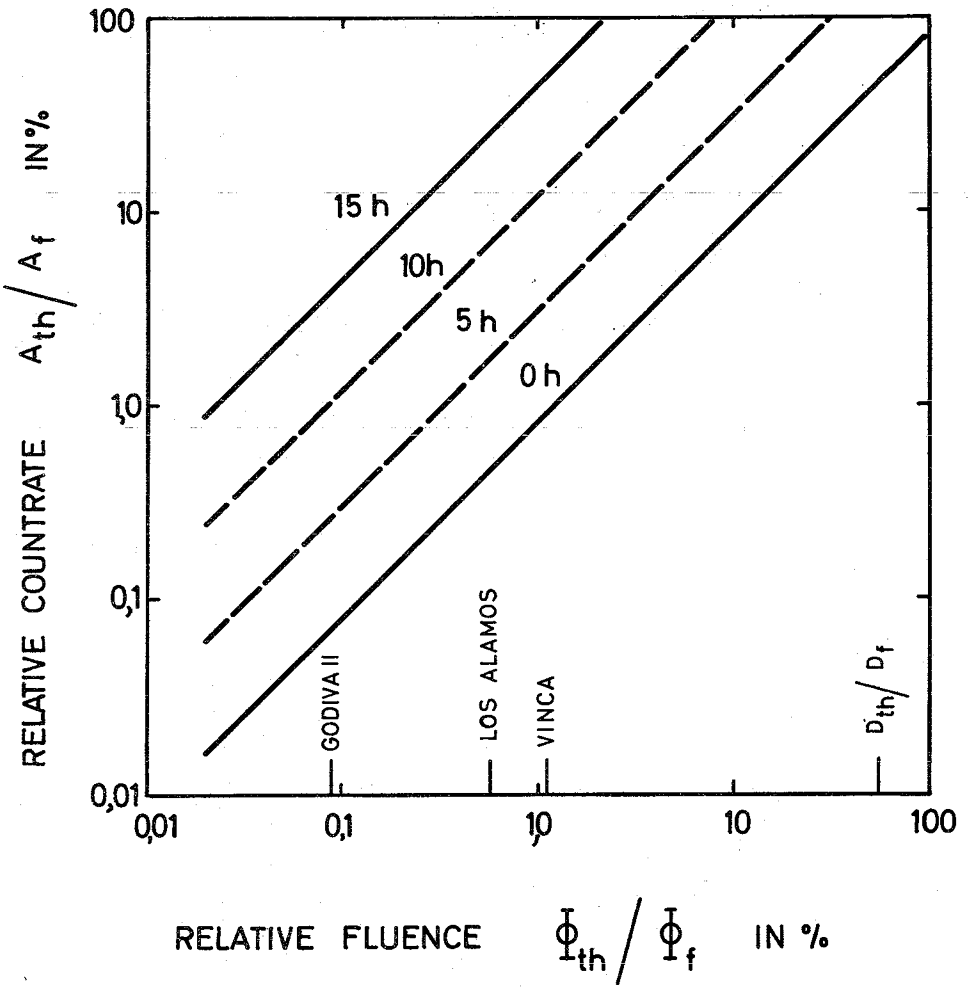

100
10
1,0
0,1
0,01
0,01
0,1
1,0
10
100
15 h
10h
5 h
0 h
GODIVA II
LOS ALAMOS
VINCA
D_{th}/D_f
RELATIVE COUNTRATE A_{th}/A_f IN%
RELATIVE FLUENCE Φ_{th}/Φ_f IN %

FIG.7.

After activation with high neutron fluence (>10 rad of thermal neutrons), the neutron induced γ-activity of the phosphate glass can be employed to get an information about the time of burst due to the different halflives of Ag-110 m (T_h = 253 d) and 0.51 MeV γ-radiation component (T_h = 1.8 h, β^+-rays, possibly of F-18) (γ-spectroscopy).

3) Practical Applications in Health Physics Dosimetry

3.1 Results of Routine Personnel Dosimetry

3.11 General

Testing of the spherical dosimeter over several years by the governmental dosimeter service+) (10) and the Karlsruhe Nuclear Research Center resulted in its official recognition as a personnel dosimeter instead of the previous film dosimeter and in the general introduction of phosphate glass dosimeters in the Karlsruhe Nuclear Research Center. 4.000 persons have been equipped with a spherical dosimeter at the Karlsruhe Nuclear Research Center. The phosphate glass in this case serves as a long-time dosimeter to assess the occupational radiation burden (intermediate evaluation every month and every three months, respectively) and to determine the radiation burden resulting from the background (annual dose accumulation). In this way, all employees are equipped with an accident dosimeter (γ-dosimeter and criticality dosimeter). For routine personnel monitoring in isotope laboratories, reactors, and nuclear installations phosphate glass dosimeters in the spherical capsule are worn instead of film dosimeters if no unshielded radioactive substances are handled and if there is no quantum radiation below 40 keV. For personnel monitoring in Plutonium laboratories and X-ray facilities as well as in the medical field the low-energy phosphate glass dosimeter is worn in addition to the spherical dosimeter.

3.12 Results of Calibration Exposures and Intercomparison Measurements in Routine Dosimetry

The energy independent and non-directional dose reading of the spherical dosimeter achieves a measuring accuracy in routine use of about ± 15 %. This is the result of many years of testing glass dosimeters in routine dosimetry and of numerous calibration exposures.

+) Landesinstitut für Arbeitsschutz und Arbeitsmedizin, 75 Karlsruhe, Kaiserallee 66, Western Germany

Fig. 8 shows the result of the intercomparison measurements carried out in Germany. What was represented in test exposures was that relative deviation of the dosimeter reading referred to the actual dose - in the case of the results of routine monitoring that deviation of the dose reading from the simultaneously worn pairs of dosimeters - within which 85 % of all dosimeter exposures were encountered. The exposure of glass and film dosimeters (German film dosimeter) was carried out under the same conditions in each case. The test exposures at Physikalisch-Technische Bundesanstalt, Braunschweig, were performed with Co-60, Cs-137, and X-rays above 40 keV in the dose range of 40 mR to 14 R (11). A test exposure at the Jülich Nuclear Research Establishment (12) was based on exposures with quantum radiation in the range between 45 keV and 1.2 MeV and doses between 60 mR and 870 mR. However, storage and exposure of the dosimeters corresponded to the conditions of routine monitoring (exposure of the front and the back of the dosimeters, storage for one month at 25 to 35°C and 0 - 80 % relative humidity of the air).

In the case of monthly routine monitoring a person in an isotope laboratory wore pairs of dosimeters always in the same place of the body (the laboratory was concerned with the production of radioactive sources such as Ra-226, Ir-192, Co-60, Cs-137, Sr-90). The monthly doses ranged from 40 mR to 1 R. The deviation in the dose reading of the dosimeter pairs can be regarded as the reproducibility of the dose measurement under the practical conditions of exposure in routine monitoring. Non-uniform exposures of dosimeter pairs are equally probable with the multitude of evaluations with both types of dosimeter. Hence, a better reproducibility of the dose measurement exists with the glass dosimeter compared to the film dosimeter, also in routine dosimetry (see Fig. 9).

3.2 Long-Time Dosimetry with Phosphate Glasses

3.21 Determination of the Annual Dose in Buildings

Since a majority of the persons monitored at the Karlsruhe Nuclear Research Center has no occupational contact with ionizing radiation, it is possible with this group of persons to determine the annual dose on the basis of the natural exposure in buildings. The evaluation of these dosimeters is carried out every six months. Fig. 10a shows the frequency distribution of the annual dose for this group of persons.

Accordingly the annual dose as a result of natural background radiation in Karlsruhe proved to be about 100 mR/year (average value by 490 persons).

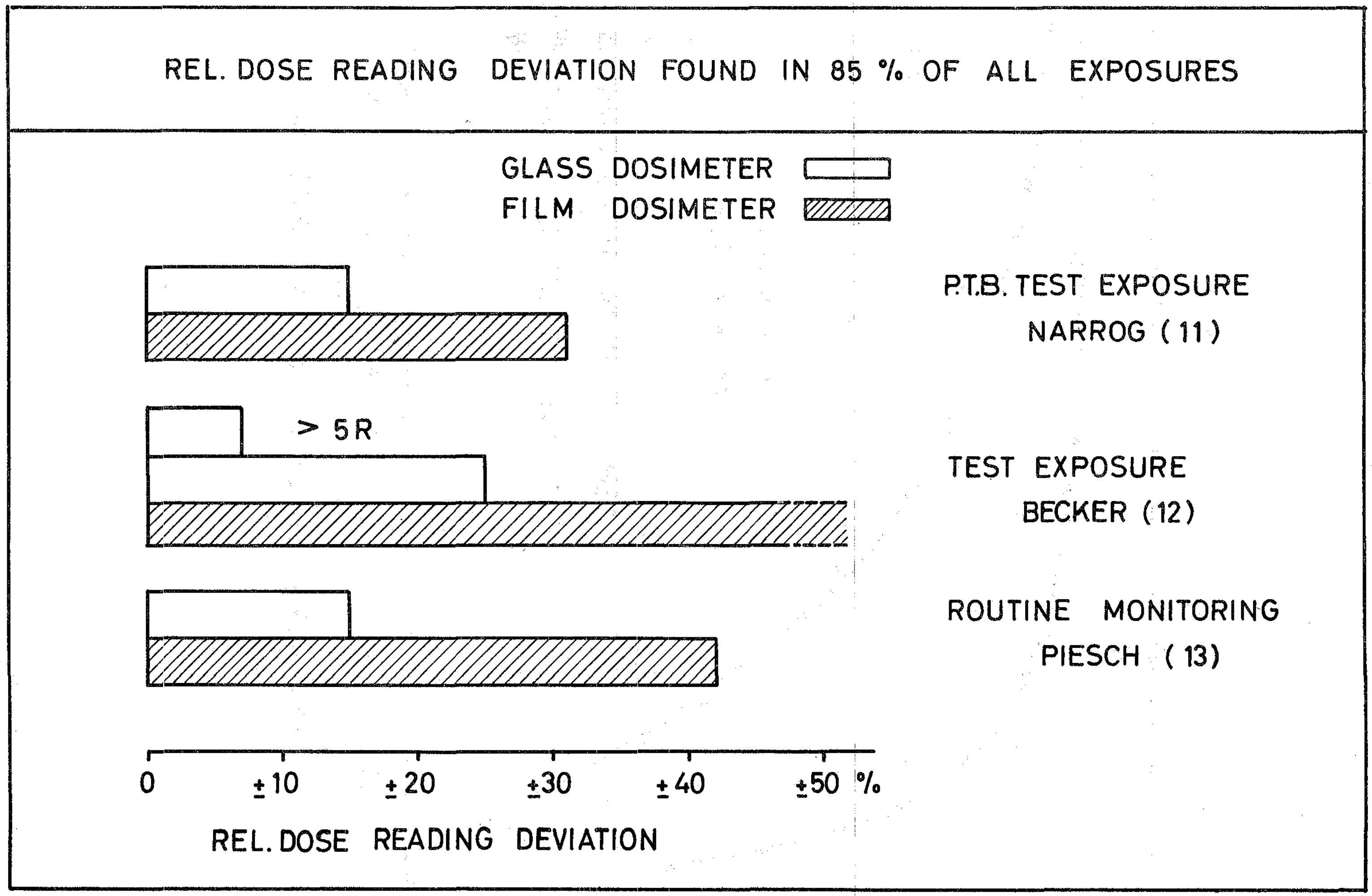


FIG. 8. RESULTS OF INTERCOMPARISON MEASUREMENTS

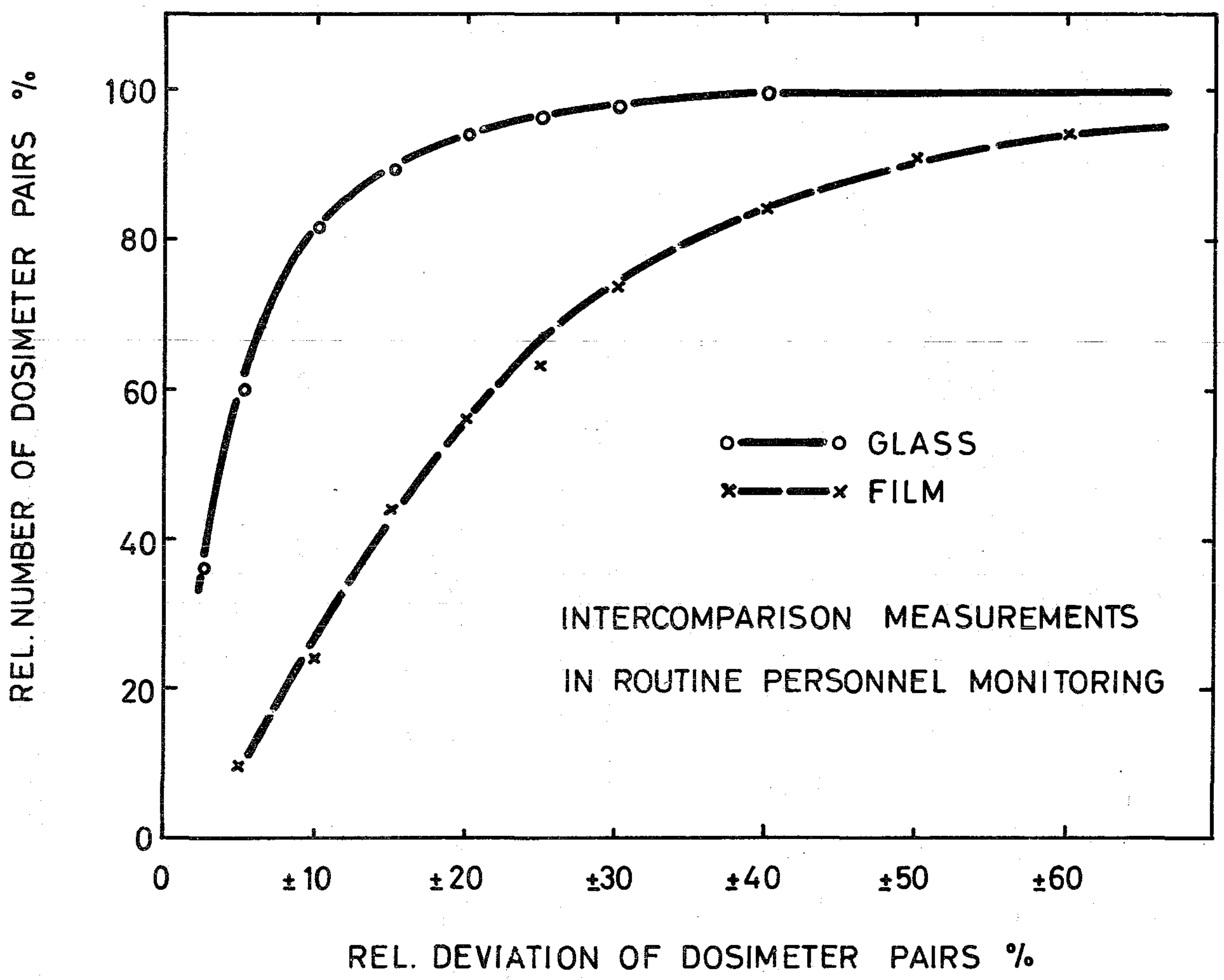
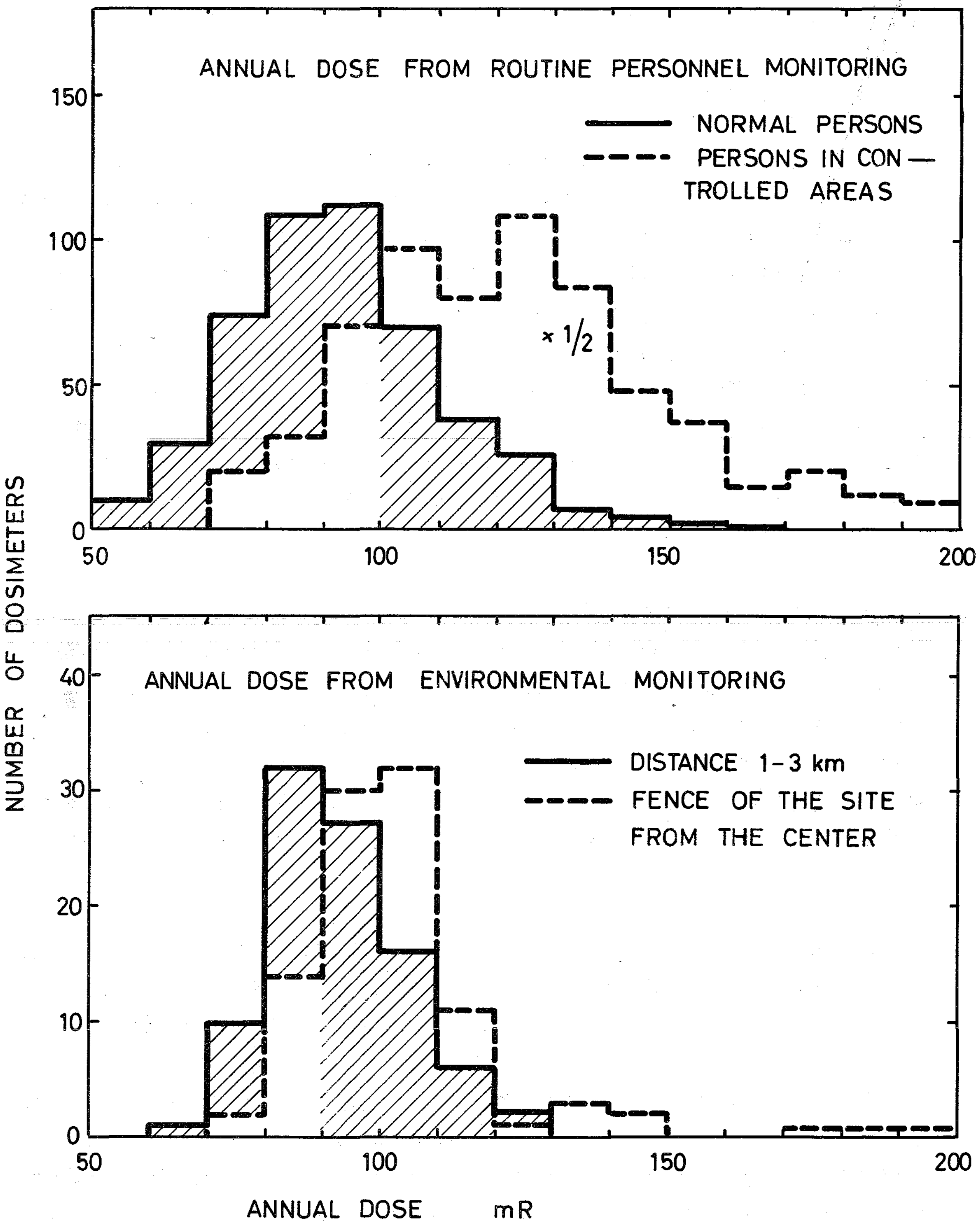

REL. NUMBER OF DOSIMETER PAIRS %
100
80
60
40
20
0
0
±10
±20
±30
±40
±50
±60
GLASS
FILM
INTERCOMPARISON MEASUREMENTS
IN ROUTINE PERSONNEL MONITORING
REL. DEVIATION OF DOSIMETER PAIRS %

FIG.9 .



DISTRIBUTION OF THE ANNUAL DOSES

FIG. 10.

For persons working in controlled areas or nearby nuclear installations, the annual dose increases by a value of some 10 to 50 mR per year (found by 1280 persons).

3.22 Determination of the Annual Dose in the Environment of the Nuclear Research Center

For the measurement of the local distribution of exposure in the vicinity of the Karlsruhe Nuclear Research Center phosphate glass dosimeters were set up in 250 measurement places (14) in the close range around the fence of the site and in concentric rings at distances of 1, 2, and 3 km outside from the Center. The dosimeter pairs welded into polythene bags were set up on tripods of 3.5 m height or suspended from trees. This is to assess the local distribution of the natural radiation field and any additional increase resulting from the influence of the Center (nuclear facilities) through a long-time accumulation. In cases of accidental uncontrolled releases of radioactive material such dosimeter in addition may be an important help in the first estimate of the population dose.

The local distribution of the annual dose near the fence around the site is shown in Fig. 11. The consecutive numbers of the equidistant measuring points are listed on the abscissa (distances of 50 m). Single increases in the dose were found in the environment of the waste storage facility. However, they may as well be due to the influence of the Ar-41 exhaust air trail of the FR 2. The corresponding frequency distribution of the annual dose readings is shown in Fig. 10 b. Accordingly, the annual dose in free air is between 80 and 110 mR.

To ascertain the influence of errors due to evaluation or to partial coverage of the dosimeters at the point of measurement it is reasonable to expose pairs of dosimeters at every measuring point and to repeat the measurement after a second washing. Fig. 12 shows the differences in readings of the annual doses of dosimeter pairs after exposure in the vicinity. The influences of errors mentioned above including those due to glass dirtiness are about ±10 mR. Hence, a change of about more than 10 % in the mean annual dose could be regarded as a genuine variation of the local dose distribution within one series of measurements. As a result of the series of measurements continued over six months it was possible to detect changes of the natural radiation background of more than 20 mR/year depending upon the place and the season.

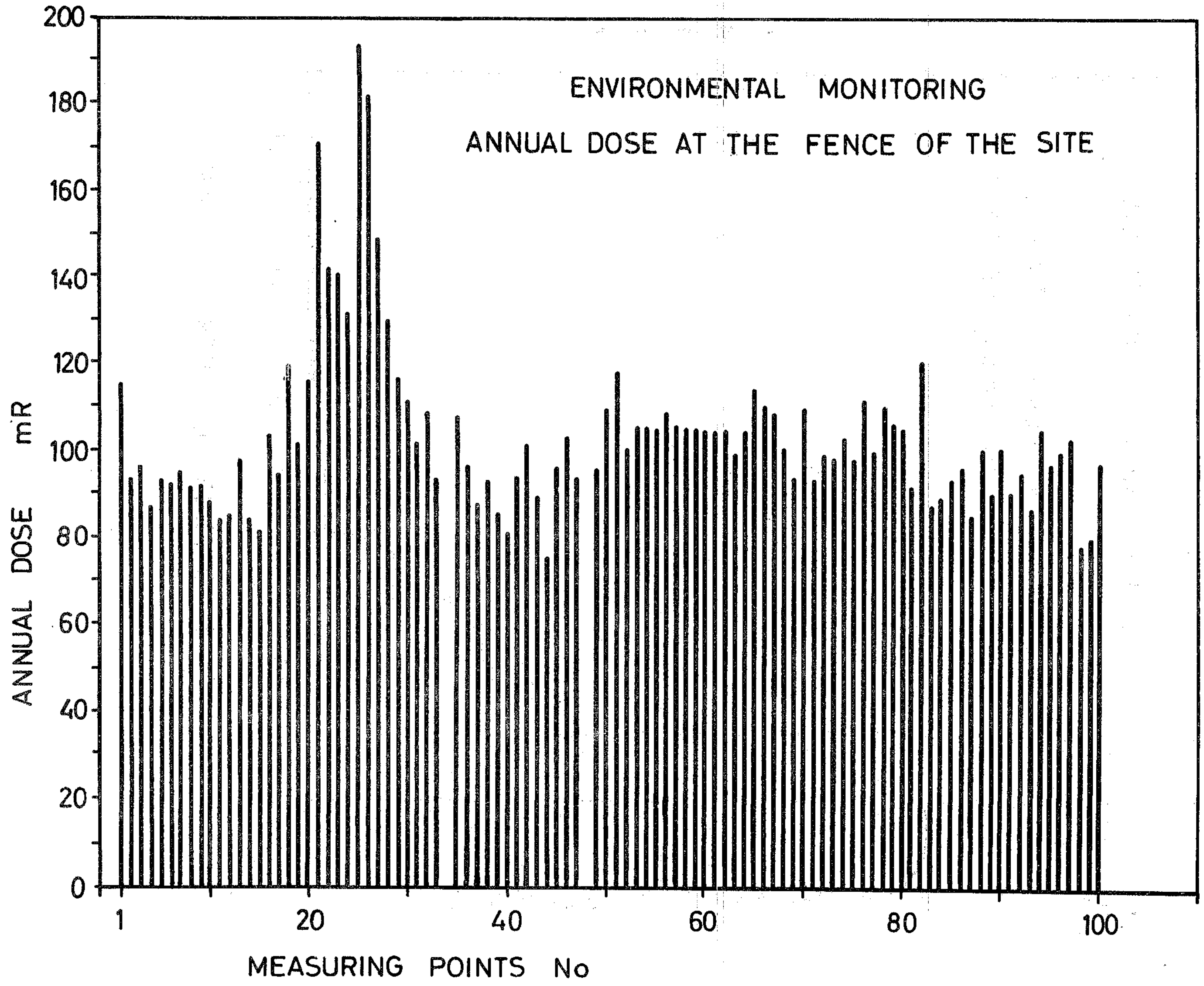

ENVIRONMENTAL MONITORING
ANNUAL DOSE AT THE FENCE OF THE SITE
ANNUAL DOSE mR
200
180
160
140
120
100
80
60
40
20
0
1
20
40
60
80
100
MEASURING POINTS No

FIG. 11.

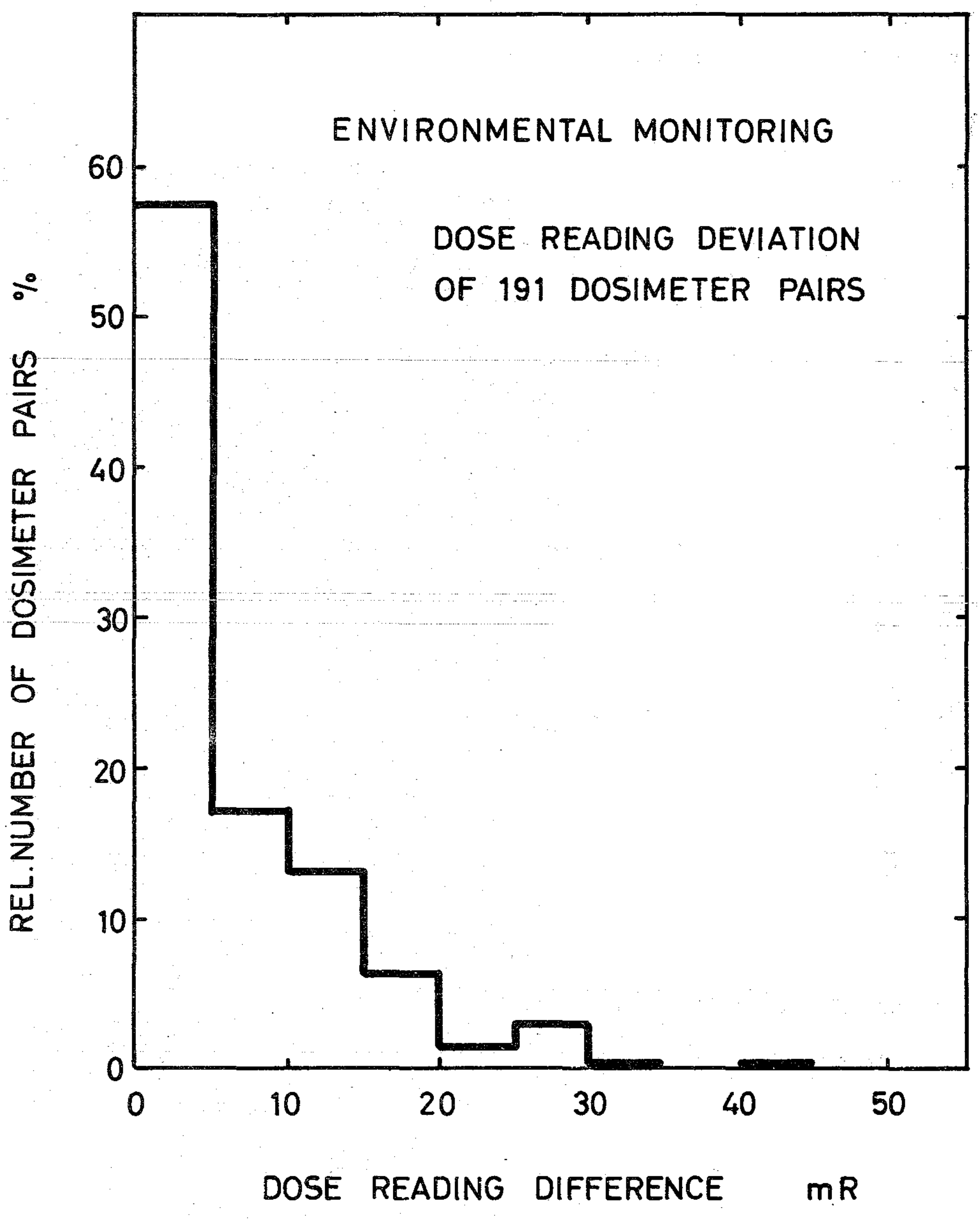

ENVIRONMENTAL MONITORING
DOSE READING DEVIATION
OF 191 DOSIMETER PAIRS
REL. NUMBER OF DOSIMETER PAIRS %
0
10
20
30
40
50
60
0
10
20
30
40
50
DOSE READING DIFFERENCE mR

FIG. 12.

Measuring points directly located at the exhaust air stack of the FR 2 reactor (15) or in the immediate vicinity of a radioactive emitter are intended for the control of an average Ar-41 emission and for monitoring of the local radiation level, respectively.

4) New Aspects of Phosphate Glass Dosimetry

The results of using phosphate glass dosimeters over a prolonged period reveal not only the advantages of an energy independent and non-directional reading and of a better measuring accuracy (see Table 1) compared to previous routine monitoring by film dosimeters but, above all, also the possibilities of long-time dose accumulation. Routine monitoring carried out every three months may result in remarkable cost savings. The determination of the annual dose, on the other hand, permits radiation detection of 40 mR/year.

A particular simplification of personnel monitoring in nuclear installations is the fact that the phosphate glass dosimeter used in Karlsruhe is a single dosimeter which is employed for the dose measurement of quantum radiation as well as for criticality dosimetry of thermal and fast neutrons simultaneously.

Further development work at the Karlsruhe Nuclear Research Center is to improve the conditions of a routine evaluation of the glass dosimeters but also the method of measurement and the present concept of personnel dosimetry. This work has had these results, among others:

- A new dosimeter capsule with a magnetic vacuum lock is to simplify practical handling during evaluation and, after attachment of the glass to a dosimeter section, permit automatic evaluation of glass dosimeters (16).
- A spherical dosimeter was calibrated the energy independent dose reading of which is proportional within ± 16 % to the absorbed dose in all critical organs of interest (3,17), i.e. testes, ovaries, bone marrow, gut mucosa, eye lenses.
- A dosimeter design was realized which reduces the influence of the person wearing the dosimeter on the dose reading above all, for radiation incidence from the rear and thus permits an organ dose measurement also for rear exposures in the tests and gut mucosa, with a certain correction factor taken into account (18) in the ovaries and bone marrow.

Table 1: Reproducibility and Measuring Accuracy Obtained Experimentally within Routine Evaluation

Measuring Series to determine the Influence of the Measuring Errors	Number of dosimeters	Measuring Error	
		Rel. Number of Dosimeters	within the Dose Reading Deviation of ...
REPRODUCIBILITY			
Evaluation equipment (calibration and long-term stability):			
deviation of 100 evaluations of one glass	1	100 %	± 5 mR
+ Glass dirtiness: deviation after a second washing	485	85 - 98 %	± 10 mR
+ Glass Dose Sensitivity: deviation from the actual dose > 1 R	50	100 %	< 3 %
+ Spherical Dosimeter Capsule (energy and direction dependence): deviation of dosimeter pairs			
environmental monitoring: annual dose 100mR	191	88 %	15 mR
routine personnel monitoring: 40mR - 1 R	94	90 %	± 15 %
MEASURING ACCURACY			
Total measuring error:			
PTB test exposure 40 mR - 14 R deviation from actual dose:	66	85 %	± 15 %

- A new method of differential fluorescence measurement was developed by which the differential fluorescence intensity can be measured and recorded directly as a function of the glass depth by continuous scanning of the glass in the direction of radiation incidence (19).

By the new method of fluorescence measurement the radiation quality can be determined in the energy range of 10 to 300 keV from the decrease of the dose reading in a definite depth of the phosphate glass, from the half-value layer or from a simple comparison with calibration curves. Fig. 13 shows the differential depth dose distribution for radiation mixtures with different dose components of quantum energies of 38 keV and 240 keV. Based on the knowledge of radiation quality and the differential dose sensitivity in the respective glass depth the free-air exposure can be obtained from the dose reading at any glass depth without using an energy compensating filter.

Especially in local dosimetry there is the possiblity of long-time accumulation spectroscopy of radiation fields and scattered radiation. The new method of differential dose determination was proved with a graphical evaluation method but also with a simple procedure for two-component radiation mixtures and inhomogeneous X-rays. The accuracy of dose measurement found in these experiments was 5 % and 30 %, respectively. (20)
In personnel dosimetry this method permits the assessment of the direction of radiation incidence and the determination of the radiation quality. From there the absorbed dose in a respective depth of tissue can be obtained.
Through fluorescence measurement and activity measurement the phosphate glass dosimeter may be employed for the detection of X-rays and, in criticality accidents, also for the additional detection of thermal and fast neutrons. The distinction between frontal and rear exposure realized by an improvement of the energy compensation filter and the measuring technique (18) allows an independent reading of such a dosimeter,within certain limits, of the body orientation relative to the radiation incidence.

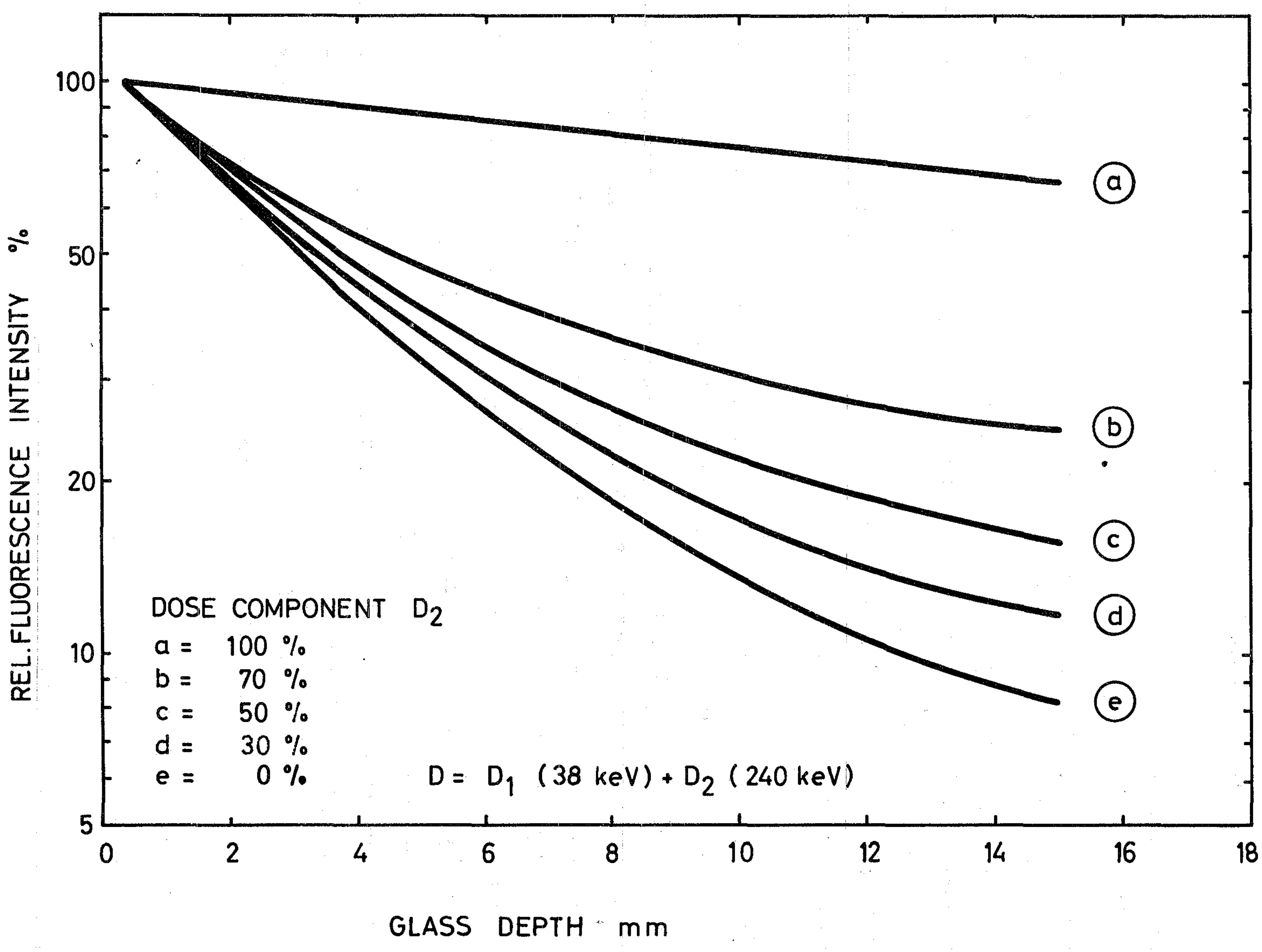

REL. FLUORESCENCE INTENSITY %
100
50
20
10
5
0
2
4
6
8
10
12
14
16
18
GLASS DEPTH mm
a
b
c
d
e
DOSE COMPONENT D2
a = 100 %
b = 70 %
c = 50 %
d = 30 %
e = 0 %
D = D1 (38 keV) + D2 (240 keV)

FIG. 13.

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Fig. 1 The relative fluorescence intensity of the spherical dosimeter containing a Yokota glass ($8 \times 8 \times 4.7\ mm^3$) and of the low energy dosimeter (double dosimeter) as a function of photon energy.
Double dosimeter measuring value $0.8 \times (F_p - 1.1 \times F_{Cu})$ with
F_p - Fluorescence intensity of a Yokota glass in a 1 mm plastic filter
F_{Cu} - Fluorescence intensity of a Yokota glass in 0.06 mm copper filter

Fig. 2 The dose reading of the spherical dosimeter referred to a free-air exposure and to the absorbed dose in the critical organ such as testes and bone marrow as a function of photon energy

Fig. 3 The difference of the dose reading of the same glass after a second washing process found by 485 glass dosimeters

Fig. 4 Relative fluorescence intensity of a Yokota glass ($8 \times 8 \times 4.7\ mm^3$) depending on the γ-radiation dose and the neutron fluence for thermal neutrons and 3 MeV neutrons

Fig. 5 The count rate of Cerenkov radiation of the Yokota glass in the spherical capsule as a function of the surface dose for 3 MeV neutrons, fission neutrons and thermal neutrons immediately after a short-time exposure (1 rad of surface dose of heavy charged particles corresponds to the neutron fluence of $2.2 \times 10^8\ n/cm^2$ for 3 MeV neutrons, $2.76 \times 10^8\ n/cm^2$ for fission neutrons and $1.59 \times 10^{10}\ n/cm^2$ for thermal neutrons)

Fig. 6 The count rate of Cerenkov radiation of the Yokota glass in the spherical capsule as a function of the time after exposure. Neutron activation with $10^{10}\ n/cm^2$ of thermal and of fission neutrons

Fig. 7 The relative count rate fraction of thermal neutrons as a function of the relative fluence fraction of thermal neutrons relative to the fission neutron component of a neutron spectrum. Measurement of Cerenkov radiation at different times of measurement after a short-time exposure

Fig. 8 Results of intercomparison measurements with film and phosphate glass dosimeters in the spherical capsule. The relative dose reading deviation to the actual exposure or the deviation of dosimeter pairs worn by one person simultaneously in routine monitoring

Fig. 9 The relative number of glass and film badge dosimeter pairs within a given dose reading deviation of dosimeter pairs. Results of an intercomparison measurement within routine monitoring in an isotope laboratory found for dosimeter pairs worn by the same person

Fig. 10 The distribution of annual doses measured by normal persons and persons working in controlled areas in routine personnel monitoring (a) and measured on the fence of the site and in a distance of 1 to 3 km from the center in environmental monitoring (b)

Fig. 11 The local distribution of the annual dose measured with phosphate glass dosimeters on the fence of the site of the Karlsruhe Nuclear Research Center

Fig. 12 The difference of the dose readings found by 191 glass dosimeter pairs exposed one year in the vicinity of the Karlsruhe Nuclear Research Center

Fig. 13 Depth dose distribution curves found by the differential fluorescence measurement in Yokota glasses for an exposure with X-rays of two different components and an energy of 38 keV and 240 keV