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Results of a co-ordinated research project 1996–1998

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FOREWORD

This TECDOC presents the results of a Co-ordinated Research Project on Intercomparison for Individual Monitoring of External Exposure from photon radiation.

The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources (BSS) have endorsed the use of the *operational quantities* for monitoring purposes. Specifically, personal dose equivalent, $H_p(d)$, is to be used for individual dosimetry to demonstrate compliance with the exposure limit recommendations, while for workplace area monitoring the ambient dose equivalent and the directional dose equivalent are recommended.

In view of the technical difficulties associated with the introduction of these operational quantities the IAEA decided to assist Member States in their provision of appropriate dosimetry for occupational protection. In this respect, intercomparisons have proven to be a cost effective method of providing such support.

A Co-ordinated Research Project (CRP) was started in 1997 on Intercomparison for Individual Monitoring of External Exposure from photon radiation, involving more than twenty laboratories from eastern Europe and the countries of the former Soviet Union, and focusing on personnel dosimetry services for nuclear power plants. This CRP was part of the activities of the IAEA Occupational Protection Programme, the objectives of which are to promote an internationally harmonized approach for optimizing occupational radiation protection through:

- the development of guides, within the IAEA activities for establishing standards for radiation protection, for restricting radiation exposures in the workplace and for applying current occupational radiation protection techniques, and

- the promotion of the application of these guidelines.

The preparatory phase included, in May 1997, a workshop aimed at familiarizing the participants with the new operational quantities.

The support of the European Commission during this project has been highly appreciated and thanks are due, in particular, to K. Schnuer of the Radiation Protection Division for his efficient co-operation.

The IAEA wishes to thank all participants for their contribution to the intercomparison. Special thanks are due to J. Böhm and P. Ambrosi (Physikalisch-Technische Bundesanstalt, Braunschweig, Germany), V.E. Aleinikov (Joint Institute for Nuclear Research, Dubna, Russian Federation), D.T. Bartlett (National Radiological Protection Board, United Kingdom), I. Csete (National Office of Measures, Budapest, Hungary), V. Forminykh (Mendeleyev Institute for Metrology, St. Petersburg, Russian Federation) and H. Stadtmann (Austrian Research Centre Seibersdorf, Austria) for providing excellent technical co-ordination and review of the CRP results.

M. Gustafsson, of the IAEA's Division of Radiation and Waste Safety initiated the CRP and guided the project until March 1997. R. Ouvrard of the same Division continued the work and was responsible for the final compilation of this TECDOC.

EDITORIAL NOTE

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CONTENTS

ANNEX: GRAPHIC REPRESENTATION OF RESULTS

INTRODUCTION

IAEA ACTIVITIES IN THE FIELD OF OCCUPATIONAL RADIATION PROTECTION

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Abstract

The Co-ordinated Research Project on Intercomparison for Individual Monitoring of External Exposure to Photon Radiation is placed into the context of the IAEA occupational protection programme by describing related activities such as development of standards and guidelines, technical co-operation programmes and the information system on occupational exposure (ISOE). A brief summary of former intercomparisons is also included.

1. INTRODUCTION

The objective of the IAEA Occupational Protection Programme is to promote an internationally harmonized approach for optimizing occupational radiation protection through:

- the development of standards for restricting radiation exposures in the workplace and for occupational radiation protection techniques, and
- the provision for the application of these standards.

This paper is intended to place the Co-ordinated Research Project (CRP) on Intercomparison for Individual Monitoring of External Exposure to Photon Radiation into the context of this programme, focusing on activities related to the CRP.

2. SETTING THE STANDARDS

Basic guidance for IAEA Member States is provided through the hierarchical Safety Standards Series - Fundamentals, Requirements (previously called Safety Standards) and Guides. While the Safety Standards Series documents are directed at national Regulatory Authorities, the Safety Guides may present detailed information that is also of value for senior management in the contractor or licensee organizations responsible for establishing and managing occupational radiation protection programmes. Publications in this series are consensus documents drafted during one or more expert advisory group meetings, and refined through subsequent consultations with the experts before review by the Radiation Safety Standards Advisory Committee - RASSAC - and final publication recommendation by the Advisory Commission on Safety Standards - ACSS.

In the area of radiation and transport safety, the Safety Fundamentals, Safety Series 120, is the top level document, presenting basic safety principles, concepts and objectives for radiation protection. For radiation safety, the next level is represented by the International *Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources* (BSS) [1]. The BSS specify requirements to ensure safety governed by the principles in the Fundamentals. General requirements for occupational protection are presented in Appendix I of the Standards, which, like the Fundamentals, have been co-sponsored jointly by the FAO, ILO, OECD/NEA, PAHO, and WHO.

Other Appendices address radiation protection for medical, public, potential, emergency, and chronic exposures.

Guidance on application of the BSS to occupational protection is elaborated upon in three Safety Guides close to publication - ***Occupational Radiation Protection***, ***Assessment of Occupational Exposure due to External Sources of Radiation***, and ***Assessment of Occupational Exposure due to Intakes of Radionuclides***. The Safety Guide "Occupational Radiation Protection" outlines the elements which are needed to form the basis for an effective worker protection programme. The companion Guides on dose assessment will provide specific guidance required for the accurate assessment of occupational radiation exposure.

Technical Reports Series No.133, Calibration of Radiation Protection Monitoring Instruments, is over 25 years old. A full revision of this report, which includes ICRU and ISO (International Standards Organization) principles, has been prepared and begun its way through the publication process. It is also expected that, by the year 2000, a Safety Report on Dosimetry Services for Individual Monitoring of Occupational Exposure from External Radiation Sources will be published.

3. PROVIDING ASSISTANCE

Referred to as "TC", the Technical Cooperation programme is the mechanism used to provide direct support to meet Member States national needs. There are currently about 150 national, regional and interregional projects in the general area of radiation protection. Many of these are aimed at upgrading national radiation protection infrastructures, with emphasis on safe use of sources and developing occupational monitoring programmes. The national projects may include expert missions, fellowship training for national staff, or provision of equipment.

The radiation protection priority in TC work for the end of this century will be the Interregional Model Project on Upgrading Radiation and Waste Safety Infrastructure, or simply "the Model Project". The Agency recognizes that many Member States do not have a sufficiently developed national radiation protection infrastructure to meet the requirements of the BSS. The Agency's Member States have supported the need for adequate infrastructure as a prerequisite for providing large radiation sources or radiation producing equipment with the potential for serious accidents. The Model Project was established to focus on those countries prepared to participate, and establish Action Plans outlining the actions to be taken by the country and the Agency to achieve strengthened infrastructures.

Originally established with five participating Member States, the Model Project has been expanded to 51 Member States in Africa, Eastern Europe, Latin America and Asia. The goal is to complete activities identified in the Action Plans by the year 2000. Under the Model Project, there are ten areas that are being addressed: Laws and Regulations, Regulatory Authority, Regulatory Control, Occupational Exposure Control, Medical Exposure Control, Emergency Response, Environmental Public Exposure Control, Waste Management, Technical Support, and Manpower. The first priority for each country is the establishment of national systems to identify and locate those sources that have the potential for serious accident consequences through loss or mishandling. Upgrading occupational exposure control, personal dosimetry services and facilitating access to proper calibration services are also key components of the Model Project.

An additional TC supported activity in occupational radiation protection is a Regional Project launched in 1997 on Improving Occupational Radiation Protection in Nuclear Power Plants in

Central and Eastern Europe and in Republics of the former Soviet Union. The objective of this project is to improve the implementation of the optimization principle in accordance with the BSS by facilitating the exchange of feedback experience, ensuring the dissemination of an ALARA culture and assisting in investigations of radiation exposure of workers and in the implementation of proper measures to reduce this exposure.

This project is, for example, supporting meetings for Health Physicists responsible for radiation protection in WWER and RBMK Nuclear Power Plants, Training Courses on Optimization of Radiological Protection in the Design and Operation of Nuclear Power Plants, organized in collaboration with NRPB and CEPN (France) and sponsored jointly by the IAEA and the European Commission (EC), and scientific visits.

4. INTERCOMPARISONS

Complementary to the IAEA's Technical Co-operation Programme is the Agency's Research Contract Programme with the primary objectives of stimulating advances in scientific knowledge, assisting the developing countries whenever possible to increase their participation in nuclear research and to co-ordinate research between the Agency and national centres. Several intercomparisons have been performed and are currently performed as Co-ordinated Research Projects.

International Intercomparison 1988-1992

A CRP on Intercomparison for Individual Monitoring was conducted in two phases over the period 1988-1992 with a total participation of twenty-nine laboratories from twenty-one Member States and three international organizations. The first phase of the project focused on selection of a backscatter phantom for calibration, and identifying systematic differences in the quality of dosimetry. Based on the results [2] and pending modifications of the ICRU guidance on practical use of the operational quantities, a second intercomparison was conducted addressing issues of phantom and angular dependence as well as energy dependence. This second phase of the CRP was summarized in an IAEA TECDOC [3], and reviewed in Radiation Protection Dosimetry [4].

The intercomparison demonstrated that a number of dosimetry systems were capable of measuring the new ICRU quantities to an acceptable degree of accuracy. However, a number of participants were recommended to modify their evaluation technique. It was demonstrated that the performance of TLD systems was usually superior to film based systems. However, a few film based systems that had been carefully characterized and calibrated performed as well as the TLD systems. Dosimeters with simple designs performed as well as the more sophisticated ones. More detailed results are given in the mentioned reports.

IAEA/RCA Personal Dosimeter Intercomparison 1990-1992

The initial programme of the IAEA Regional Co-operative Agreement project (RCA) for strengthening the radiation protection infrastructure in the Asian and Pacific region contained a regional personal dosimetry intercomparison, which was conducted in three phases over the period 1990-1992. Seventeen organizations from all fourteen Member States participated in this programme. It was concluded that this intercomparison contributed significantly to the technical improvement of personal dosimetry and instrument calibration in the region of South East Asia. However some concerns were raised, for example, regarding dosimetry services using film, which prompted another CRP to be organized in the same region.

Ongoing Intercomparisons

Currently intercomparisons for individual dosimetry are being conducted under the RCA programme and in Latin America.

The IAEA/RCA Regional Personal Dosimetry Intercomparison has been initiated with the objectives of evaluating regional dosimetry services' abilities to conduct individual monitoring in terms of the ICRU operational quantities for photons, providing access for the participants to photon field qualities for calibration of their systems that they might not otherwise be able to obtain, and providing a unique opportunity for regional exchange of information regarding personal monitoring.

Another regional CRP has been initiated to encourage regional harmonization of individual monitoring practices in the Latin American region.

5. ISOE

In order to facilitate the exchange of techniques and experience in occupational exposure reduction, the Nuclear Energy Agency (NEA) of the Organisation for Economic Co-operation and Development (OECD) launched the Information System on Occupational Exposure (ISOE) on 1 January 1992. In 1993 the IAEA decided to co-sponsor ISOE by inviting Member States which are not members of the OECD to participate through the IAEA, which acts as Technical Centre for non-NEA countries. Since 1998 the ISOE Secretariat is a joint undertaking of NEA and IAEA.

The objective of the ISOE is to make available to the participants:

- broad and regularly updated information on methods to improve the protection of workers and on occupational exposure in nuclear power plants
- a mechanism for dissemination of information on these issues, including evaluation and analysis of the data assembled, as a contribution to the optimization of radiation protection.

A growing number of IAEA Member States are participating through the IAEA. As of 1 November 1998, there are ten utilities and five authorities from nine countries participating; i.e., all utilities in Armenia, Brazil, China, Lithuania, Romania, Slovak Republic, Slovenia, South Africa and Ukraine (representing 31 reactors) and the regulatory authorities in Armenia, China, Romania, Slovak Republic and Slovenia. Three countries, which earlier participated in the ISOE through the IAEA, have joined the OECD. Invitations to Bulgaria, India, and the Russian Federation are pending.

As Regional Technical Centre the IAEA is collecting and forwarding the annual occupational exposure data from their participants to the central database. Thus the IAEA is responsible for the quality control of the data provided by their participants, which prompted the Agency to include in the current CRP some of the dosimetry services providing these data. In addition the Agency has, for example, organized a one week meeting for representatives from IAEA ISOE participants, supported the participation of ISOE contact persons in the annual ISOE meetings and Topical Sessions and purchased a world-wide (except in OECD countries) license to distribute the software learning program RADIOR and make it available in Russian.

6. THE CURRENT CRP

Taking into account the activities in the Agency's Occupational Protection programme described above, the endorsement of the *operational quantities* for radiation monitoring of

workers in the recently adopted BSS [1] and the concerns about nuclear safety and radiation protection that have developed in Eastern Europe and the Republics of the former Soviet Union, it was found to be appropriate to initiate an intercomparison that would focus on IAEA Member States in Eastern Europe and on personal dosimetry services for nuclear power plants. The outline of the CRP is given in a separate paper.

REFERENCES

[1] IAEA, FAO, ILO, NEA/OECD, PAHO, WHO, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources. Safety Series No. 115, IAEA, Vienna (1996).

[2] BÖHM, J., GRIFFITH R., (Eds), Intercomparison for Individual Monitoring (Proc. IAEA Research Co-ord. Meet. Vienna, 1989). Physikalisch-Technische Bundesanstalt Rep. PTB-Dos-20, Braunschweig (1991).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Intercomparison of radiation dosimeters for individual monitoring. IAEA TECDOC-704, Vienna (1993).

[4] AMBROSI, P., BUCHHOLZ, G., BÖHM, J., GRIFFITH, R.V., HERRMANN, D., AND STRACHOTINSKY, C. Results of the IAEA Intercomparison for Individual Monitoring. Rad. Prot. Dos. 54(1):5-17 (1994).

OUTLINE OF THE 1996–1998 IAEA CO-ORDINATED RESEARCH PROJECT ON INTERCOMPARISON FOR INDIVIDUAL MONITORING OF EXTERNAL EXPOSURE FROM PHOTON RADIATION

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Abstract

The outline of the IAEA Co-ordinated Research Project 1996-1998 on intercomparison for individual monitoring is described. The intercomparison focused on IAEA Member States in Eastern Europe and was based on the operational quantity personal dose equivalent, $H_p(10)$. The three phases of the intercomparison were: the preparatory phase including a workshop, the "type-test" intercomparison, and the "simulated workplace field" intercomparison. Details of the phases are given.

1. INTRODUCTION

Radiation monitoring of workers using personal dosimeters (film, TLD, etc.) is an essential component to assess the effectiveness of any occupational radiation protection programme focused on limiting the exposure to external radiation. The International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources [1] recently adopted by FAO, IAEA, ILO, OECD/NEA, PAHO and WHO have endorsed the use of the operational quantities for monitoring purposes. Specifically, personal dose equivalent, $H_p(10)$, is to be used for individual dosimetry to demonstrate compliance with the exposure limit recommendations, whereas the ambient dose equivalent and the directional dose equivalent are recommended for workplace area monitoring [2]. Comprehensive international guidance on the use of the dose related quantities for radiological protection against external radiation will be provided in the near future by the publication of a report of the Joint Task Group of the International Commission on Radiological Protection and the International Commission on Radiation Units and Measurements.

In view of the technical difficulties associated with the introduction of the new radiation quantities for measurement and reporting, it is important that the Agency assists Member States in their provision of appropriate dosimetry for occupational protection. Dosimetry intercomparisons have proved to be a cost effective method to provide this support. Between 1988 and 1992 [3], the Agency conducted an interregional intercomparison programme, at the same time providing an intercomparison for Asia and Oceania under the RCA (Regional Co-operative Agreement) programme. Intercomparisons were, or are, also being conducted for individual dosimetry under the RCA programme and in Latin America.

This Co-ordinated Research Project focused on IAEA Member States in Eastern Europe and on personnel dosimetry services for nuclear power plants. Its main objectives was to give participants an opportunity to assess :

- the recommendations of the IAEA to use the operational quantity $H_p(10)$ in individual monitoring,

- the energy and angular dependence of the response of their dosimeters,
- their ability to measure external photon radiation fields in terms of $H_p(10)$.

The following outlines the programme for this Co-ordinated Research Project. It not only implied co-operation, but also financial support of the EC.

2. PARTICIPATING LABORATORIES AND SERVICES

The Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany, provided technical co-ordination and support. Several other standards laboratories provided additional technical support:

- Joint Institute for Nuclear Research (JINR), Dubna, Russian Federation;
- Mendeleyev Institute for Metrology (VNIIM), St. Petersburg, Russian Federation;
- Austrian Research Centre (ARCS), Seibersdorf, Austria;
- National Radiological Protection Board (NRPB), Chilton, United Kingdom;
- National Office of Measures (OMH), Budapest, Hungary.

The following services participated with personal dosimeters :

- Department of Radiation Safety, Yerevan, Armenia;
- IAEA Radiation Monitoring & Protection Services Section, Vienna, Austria;
- National Centre of Radiobiology & Radiation Protection, Sofia, Bulgaria;
- National Personnel Dosimetry Ltd., Prague, Czech Republic;
- Nuclear Power Plant Dukovany, Czech Republic;
- Radiation Protection Centre, Tallinn, Estonia;
- "Frederic Joliot Curie" National Research Institute, Budapest, Hungary;
- National Office of Measures, Budapest, Hungary;
- Radiation Protection Centre, Vilnius, Lithuania;
- Nuclear Power Plant Ignalina, Visaginas, Lithuania;
- Central Laboratory for Radiological Protection, Warsaw, Poland;
- Nofer Institute of Occupational Medicine, Lódz, Poland;
- Institute of Hygiene and Public Health, Bucharest, Romania;
- Institute for High Energy Physics, Moscow Region, Russian Federation;
- Mendeleyev Institute for Metrology, St. Petersburg, Russian Federation;
- Joint Institute of Nuclear Research, Dubna, Russian Federation;
- Bohunice Nuclear Power Plant, Jaslovské Bohunice, Slovak Republic;
- Slovak Institute of Metrology, Bratislava, Slovak Republic;

- Josef Stefan Institute, Ljubljana, Slovenia;
- Krsko Nuclear Power Plant, Krsko, Slovenia;
- AMS of Ukraine, Scientific Centre for Radiation Medicine, Kiev, Ukraine;
- Research Institute of Medical Radiology, Kharkov, Ukraine;
- State Enterprise Regional Environmental Monitoring & Dosimetric Control, Chernobyl, Ukraine.

3. PHASES OF THE CO-ORDINATED RESEARCH PROJECT

3.1. Survey

The project consisted of three phases which partly overlapped. The focal point of Phase I, the preparatory phase, was a workshop in May 1997, to familiarize the participants with the new operational dose equivalent quantities, in particular with the operational quantity personal dose equivalent. Phase II, the "type-test" intercomparison, provided the participants with data about the variation of the energy and angular dependence of the response of their dosimeters with respect to this operational quantity. Finally, Phase III, the "simulated workplace field" intercomparison, enabled the participants to judge the performance of their dosimeters under realistic conditions arising in practice. The final results of the project were discussed during a consultants meeting in December 1998 and are published in this technical document. The following explains the three phases in more details.

3.2. Phase I: Preparatory Phase

This phase was the planning phase and provided the prerequisites for the success of the intercomparison. The first consultants meeting was held in Vienna in May 1996. An outline for the intercomparison and for a workshop was prepared to inform participants and observers about the new operational dose quantities and several topics on personnel monitoring. Requests for participation together with detailed questionnaires were sent to potential participants by the IAEA. During a second consultants meeting in December 1996, progress of the work and details of the workshop, in particular the harmonization of the different papers to be presented, were discussed. Pill box dosimeters with TLDs were prepared by the PTB in December 1996 to intercompare the four irradiation laboratories involved in Phase II. Distribution of the dosimeters was performed via the IAEA. In March 1997, it turned out that the results of the intercomparison of the irradiation laboratories were satisfactory. During a workshop in May 1997, all the background information required for the intercomparison were imparted to the participants and interested observers. The participants brought along to the workshop all dosimeters to be irradiated in Phase II. During the workshop, these dosimeters were labelled and distributed to the representatives of the irradiation laboratories. The workshop was combined with the third consultants meeting. The papers presented during the workshop are reproduced in this technical document.

3.3. Phase II: "Type-Test" Intercomparison

Phase II started with the irradiations of the dosimeters distributed during the workshop of Phase I. The dosimeters were irradiated in June, July and August 1997 and then returned to the participants together with all data of the irradiations. The participants forwarded their

results to the IAEA by 1 November 1997, where a statistical analysis was first done, and the results were discussed during a consultants meeting in January 1998, in Luxembourg.

3.4. Phase III: "Simulated Workplace Field" Intercomparison

Final details of Phase III were agreed upon during the Luxembourg meeting. Recently developed passive and electronic dosimeters were also included in this phase. In June 1998, the results of Phase II were discussed with all participants, at a meeting held at the PTB. They also brought their dosimeters for the irradiations under Phase III. After the irradiations in June and July 1998, the dosimeters were sent back to the participants for evaluation. The results were then transmitted to the IAEA, a statistical analysis of the results was done and they were discussed during a consultants meeting in Vienna in December 1998. Final results were sent to each participating laboratory at the end of 1998. They are presented in this technical document.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, Vienna (1996).

[2] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Quantities and Units in Radiation Protection, ICRU Report 51, ICRU Publications, Bethesda, MD (1993).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Intercomparison of Radiation Dosimeters for Individual Monitoring, IAEA-TECDOC-704, Vienna (1993).

DOSIMETER IRRADIATIONS FOR THE 1996–1998 IAEA CO-ORDINATED RESEARCH PROJECT ON INTERCOMPARISON FOR INDIVIDUAL MONITORING OF EXTERNAL EXPOSURE FROM PHOTON RADIATION

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Abstract

This paper gives information on the facilities used by the irradiating laboratories, how the irradiations in both Phase II and Phase III were performed, as well as the procedures followed to ensure that all irradiations were done so that any uncertainty in the dose estimates of the irradiating laboratories, for the purpose of this intercomparison, can be negligible.

1. INTRODUCTION

The irradiations, details of which are given in this section, were carried out for Phases II and III of the Co-ordinated Research Project (CRP).

In Phase II, a 'mini type test' was performed. This had two purposes, firstly to provide some calibration data in terms of $H_p(10)$ for the dosimetry services participating in the CRP, secondly to assist in the harmonization of procedures at secondary standards laboratories in Eastern European States to type test in terms of $H_p(10)$. In addition an intercomparison was carried out of the dosimetry of the participating irradiating laboratories including PTB, ARCS and NRPB. Further details of the Phase II programme are given in section 3 and [1].

In Phase III, an intercomparison was carried out of the performance of dosimeters in simulated workplace fields. In some cases where complex algorithms are applied and where there is limited information on the workplace field, the dosimeter performance characteristics determined using narrow spectral width calibration fields do not give a reliable indication of its performance in fields of broad energy and angle distribution. This could be tested in Phase III. More generally, however, the purpose of the Phase III intercomparison was to examine the performance of the dosimetry systems in radiation fields which were similar to those encountered in practical routine monitoring (see the paper on workplace fields [2]). The simulated workplace fields used in Phase III were devised to reproduce features of fields encountered in practice including higher energy direct components with lower energy broad angle scattered components; photons in the 4 MeV to 7 MeV energy range with and without secondary electron equilibrium; and for a range of doses. The radiation fields used were selected from the ISO recommended fields, either individually or in combination, plus iridium-192.

2. OPERATIONAL QUANTITIES AND PHANTOMS

Effective dose [3, 4] is the radiation protection quantity assessed for control purposes in respect of stochastic effects of ionizing radiation. Operational quantities have been defined [5] which provide, in general, conservative estimates of the protection quantity, effective dose. The operational quantities are used in the routine monitoring of occupational exposure. For the individual monitoring of photon external radiation, the relevant operational quantity is the personal dose equivalent, $H_p(10)$. Personal dosimeters are, in this approach, characterized and routinely calibrated in terms of $H_p(10)$ [6]. The dosimeter reading is then used as an estimate of $H_p(10)$ to be compared with dose limits or investigation levels expressed in terms of effective dose [3], and entered in dose records as an estimate of effective dose.

$H_p(10)$ is defined primarily in the human body. The definition is extended [7] to calibration phantoms. In this case $H_p(10)$ is the dose equivalent at 10 mm depth in a phantom of the same size and shape as that used for calibration but composed of ICRU 4-element tissue equivalent material. The assumption is made that a personal dosimeter whose response matches the energy and angle dependence of response of $H_p(10)$ in the calibration phantom will determine adequately $H_p(10)$ in the human body when worn, and provide an estimate of effective dose of sufficient accuracy. A phantom is, in general, required for the calibration of personal dosimeters in terms of $H_p(10)$ (but see [6] on routine calibration) because the radiation field at the wearing position of the dosimeter on the body comprises an incident component and a backscattered component, the characteristics of which depend on the energy and angle of the incident photons, and also on the body itself, and where on it the dosimeter is positioned. The response of a dosimeter will, in general, depend on both components of the radiation field, incident and backscattered.

A solid material having the composition of the ICRU 4-element tissue equivalent material has not been fabricated. A number of tissue substitute materials are available, among which are polymethyl methacrylate (PMMA), water and a various specially fabricated plastics. The important property of tissue substitute materials is their ability to replicate the backscatter from tissue. The backscattered field, its magnitude and its energy and angle distribution depends not only on the material but on the shape of the phantom (see [8] and references therein). The International Organisation for Standardization (ISO) and the IAEA recommend the use of a calibration phantom which is a 300 mm × 300 mm × 150 mm slab made of thin PMMA walls and filled with water [9] (see also reference [6]), the backscattered field of which adequately matches that calculated for a phantom of the same shape and size, but of ICRU 4-element tissue. Dosimeters are then calibrated on this phantom in terms of $H_p(10)$ calculated for a 300 mm ×300 mm × 150 mm slab of ICRU 4-element tissue, $H_{p,slab}(10)$. Account may need to be taken for the variation across the face of the phantom of both the incident and backscattered components of the field [9].

3. RADIATION QUALITIES, CONVERSION COEFFICIENTS

In Phase II, for the 'mini type test', radiation qualities of the ISO narrow spectrum series [10] were selected to allow detailed information to be determined of the energy and angle dependence of the response, see Table I. In addition, from the readings of the dosimeters No. 24 to 26 the free-in-air calibration with respect to air kerma K_a can be checked.

The conversion coefficients for all radiation qualities were taken from ISO 4037-3 [9] and the irradiation protocols given therein followed.

In Phase III, the performance of dosimeters in simulated workplace fields was to be determined. To simulate the scattered radiation component of workplace fields, radiation qualities of the ISO wide spectrum series [10] were selected and the dosimeters were irradiated for angles of incidence between + 80° and – 80° about the vertical. Depending on the technical equipment at the different irradiating laboratories this was done in one of two ways: oscillating with a constant angular velocity (NRPB, ARCS) or irradiation at discrete angles with step increments of 5° (PTB). These "wide angle" irradiations (WA ± 80°) were done for four different radiation qualities, see Table II.

For this kind of irradiation condition, there are no conversion coefficients $h_{pK}(10)$ from air kerma K_a to personal dose equivalent $H_{p,slab}(10)$ given in the relevant standard, ISO-4037-3. Therefore, appropriate values were calculated using the following algorithm:

Interpolation of missing $h_{pK}(10; E; \alpha_i)$ data between the given values ($\alpha = 0°$, 10°, 20°, ...) for intermediate angles of incidence using a spline or 4-point Lagrangian (linear-linear) interpolation [11] either for 1° steps (oscillating method) or 5° steps (discrete angle method) and determination of the mean value $h_{pK}(10; E;$ WA ± 80°) (over the corresponding angular range from – 80° to + 80°) of these calculated data points. Figure 1 gives an example for this procedure to determine $h_{pK}(10;$ W-300; WA ± 80°) for the discrete angle method.

The resulting conversion coefficients and their estimated standard uncertainties for an oscillating phantom (phantom rotating in the angular range from -80° to +80°) are given in Table III together with those for S-Ir.

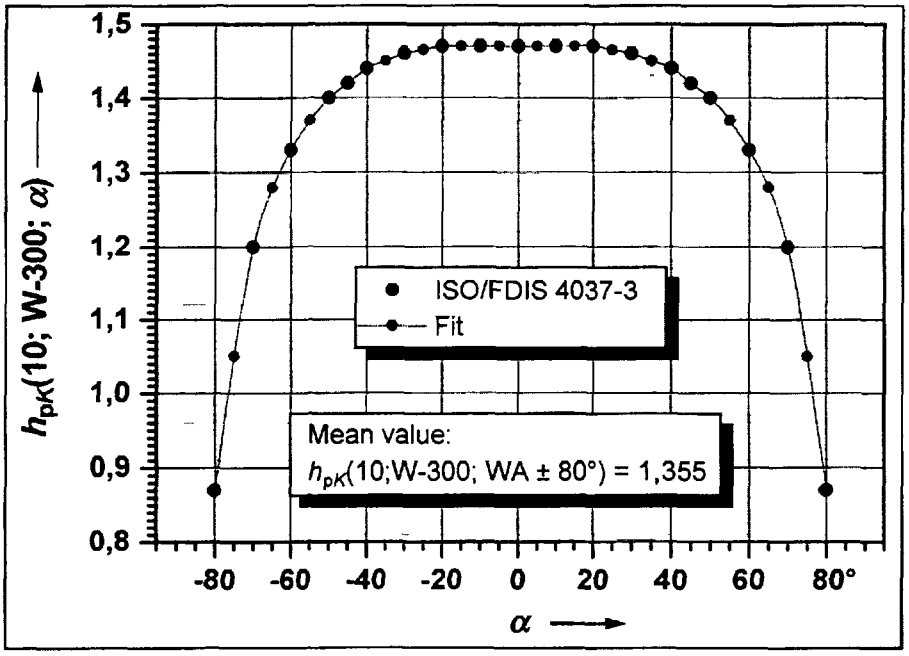

FIG.1. Angular dependence of the conversion coefficient for W-300 radiation quality.

TABLE I. RADIATION QUALITIES, ANGLES OF INCIDENCE AND NOMINAL DOSE VALUES SELECTED FOR PHASE II OF THE CRP TOGETHER WITH SOME ADDITIONAL INFORMATION. THE ABBREVIATIONS OF THE IRRADIATING LABORATORIES AND MORE DETAILS ARE EXPLAINED IN SECTION 4. ALL IRRADIATIONS WITH NOMINAL $H_{P,SLAB}(10)$ DOSE VALUES WERE DONE WITH DOSIMETERS POSITIONED ON THE FRONT SURFACE OF AN ISO WATER SLAB PHANTOM, THOSE WITH NOMINAL K_A VALUES FREE IN AIR.

Dosimeter No.	ISO quality	Irrad. lab.	Mean energy keV	Angle of radiation incidence	Nominal dose value	Conversion coefficient $h_{pK}(10)$ Sv/Gy
01	N-40	OMH	33	0 °	$H_p(10)$ = 3.0 mSv	1.17
02	N-40	OMH	33	30 °	$H_p(10)$ = 3.0 mSv	1.12
03	N-40	OMH	33	60 °	$H_p(10)$ = 3.0 mSv	0.85
04	N-60	OMH	48	0 °	$H_p(10)$ = 3.0 mSv	1.65
05	N-60	OMH	48	30 °	$H_p(10)$ = 3.0 mSv	1.59
06	N-60	OMH	48	60 °	$H_p(10)$ = 3.0 mSv	1.27
10	N-100	VNIIM	83	0 °	$H_p(10)$ = 1.0 mSv	1.88
11	N-100	VNIIM	83	30 °	$H_p(10)$ = 1.0 mSv	1.82
12	N-100	VNIIM	83	60 °	$H_p(10)$ = 1.0 mSv	1.53
13	N-250	VNIIM	208	0 °	$H_p(10)$ = 1.0 mSv	1.48
14	N-250	VNIIM	208	30 °	$H_p(10)$ = 1.0 mSv	1.55
15	N-250	VNIIM	208	60 °	$H_p(10)$ = 1.0 mSv	1.38
19	S-Co	JINR	1250	0 °	$H_p(10)$ = 3.3 mSv	1.15
20	S-Co	JINR	1250	0 °	$H_p(10)$ = 3.3 mSv	1.15
21	S-Co	JINR	1250	0 °	$H_p(10)$ = 3.3 mSv	1.15
22	S-Co	JINR	1250	30 °	$H_p(10)$ = 3.3 mSv	1.15
23	S-Co	JINR	1250	60 °	$H_p(10)$ = 3.3 mSv	1.14
24	S-Co	JINR	1250	0 °	K_a = 8.6 mGy	—
25	S-Co	JINR	1250	0 °	K_a = 8.6 mGy	—
26	S-Co	JINR	1250	0 °	K_a = 8.6 mGy	—
30	R-F	PTB	6610	0 °	$H_p(10)$ = 3.0 mSv	1.12
31	R-F	PTB	6610	30 °	$H_p(10)$ = 3.0 mSv	1.12
32	R-F	PTB	6610	60 °	$H_p(10)$ = 3.0 mSv	1.12

ISO 4037-3 does not give a conversion coefficient $h_{pK}(10; \text{S-Ir}, 0°)$ from air kerma K_a to personal dose equivalent $H_p(10)$ for S-Ir. Therefore this coefficient was calculated from the published values for mono-energetic radiation taking the emission probability for each photon energy into account. For normal incidence a conversion coefficient $h_{pK}(10; \text{S-Ir}, 0°)$ of 1.317 Sv/Gy was obtained.

For the wide angle irradiation the corresponding conversion coefficients $h_{pK}(10; \text{S-Ir}, \alpha_i)$ – for different directions of incidence α – were calculated as described, interpolated (by spline interpolation) between 0°, 10°, ..., 70°, 80° and the mean value used.

TABLE II. RADIATION QUALITIES, ANGLES OF INCIDENCE AND NOMINAL DOSE VALUES SELECTED FOR PHASE III OF THE CRP TOGETHER WITH SOME ADDITIONAL INFORMATION.

Dosi-meter No.	Radiation quality	Irrad. lab.	Nominal $H_p(10)$ dose value
01	S-Ir (WA ± 80°)	ARCS	10 mSv
02	S-Ir (0°) + S-Ir (WA ± 80°) [50 % + 50 %]	ARCS	10 mSv
03	S-Ir (0°)	ARCS	1.0 mSv
04	S-Ir (0°)	ARCS	40 mSv
08	S-Co (0°) + W-80 (WA ± 80°) [50 % + 50 %]	NRPB	3.0 mSv
09	S-Co (0°) + W-80 (WA ± 80°) [80 % + 20 %]	NRPB	80 mSv
10	S-Co (0°) + W-80 (WA ± 80°) [80 % + 20 %]	NRPB	1.0 mSv
11	W-80 (WA ± 80°)	NRPB	0.4 mSv
15	R-F (0°) + W-300 (WA ± 80°) [20 % + 80 %]	PTB	7.2 mSv
16	R-F (0°) + W-300 (WA ± 80°) [50 % + 50 %]	PTB	1.0 mSv
17	R-F (0°)	PTB	1.0 mSv
18	R-F (0°) without electronic equilibrium	PTB	1.0 mSv

The $H_p(10)$ dose value for R-F (0°) irradiations without electronic equilibrium was estimated from the measurement of the charge Q of a 3 cm^3 cylindrical graphite ionization chamber with a wall thickness of 6 mm (corresponding with 1 g/cm^2) when exposed to the field. The same ionization chamber was used for the determination of the air kerma free in air in the R-F field (see sect. 4.2.3). The absorbed dose to air D_{AIR} in the chamber cavity is given by $D_{AIR} = N_D Q$, where N_D is the absorbed dose to air chamber factor. If the air cavity is replaced by ICRU 4-element tissue equivalent material the absorbed dose D_{ICRU} can be estimated by $D_{ICRU} = (\bar{s}/\rho)_{ICRU/AIR} D_{AIR}$ where $(\bar{s}/\rho)_{ICRU/AIR}$ is the mean value of the stopping power ratio of ICRU 4-element tissue equivalent material and air averaged over the electron fluence spectrum in the cavity. $H_{p,slab}(10)$ was then estimated from the product $D_{ICRU}\ k$ where k is a factor which accounts for the difference between the absorbed dose to ICRU tissue measured at the geometrical centre of the chamber and the absorbed dose at 10 mm depth in the ICRU slab phantom when irradiated with R-F radiation.

4. DOSIMETER IRRADIATIONS

4.1. Irradiations at the JINR, Dubna

4.1.1. Irradiation facilities

The irradiations were carried out with a ^{60}Co calibration unit. The source has sufficient shielding and a variable size collimator. The reference ^{60}Co source used was of the activity (on October 13, 1995) to produce an exposure rate of $(1.27 \pm 0.06) \cdot 10^{-4}$ R/s at a distance of 1 m with a collimator of 60 mm in diameter.

4.1.2. Irradiation conditions

The source exposure position is in a cylindrical lead shield, having a ring-collimator with a diameter of 60 mm. For all irradiations the distance between the source and the reference point of the dosimeter was 150 cm. The field homogeneity over the area of the dosimeters was better than 0.5 %.

A carriage system was used to position the dosimeters' reference points at the calibration distance from the source centre. The dosimeters were fixed with adhesive tape at the centre of the front face of the ISO water slab phantom. The variation of the angles of incidence was performed by turning the phantom about a vertical axis through the front surface of the phantom. To provide electronic equilibrium for all irradiations, a 4 mm thick PMMA build-up layer covering the whole dosimeter was used. The average distance between the build-up layer and dosimeter was a few centimetres.

TABLE III. CONVERSION COEFFICIENTS FROM K_A TO $H_P(10)$ FOR THE RADIATION QUALITIES SELECTED FOR PHASE III OF THE CRP.

Radiation quality	Conversion coefficient $h_{pK}(10)$ Sv / Gy	Standard uncertainty
S-Ir (0°)	1.317	0.03
S-Ir (WA ± 80°)	1.262	0.035
W-80 (WA ± 80°)	1.523	0.025
S-Co (0°)	1.15	0.02
R-F (0°)	1.12	0.029
W-300 (WA ± 80°)	1.355	0.025
R-F (0°) without electronic equilibrium	1.41	0.086

4.1.3. Calibration

Table I details the irradiation of individual dosimeters provided by the participants of the CRP at the JINR calibration facility.

The conventional true value of the personal dose equivalent $H_{p,slab}(10,\alpha)$ at the reference point was calculated for each individual irradiation time. $H_p(10,\alpha)$ was obtained by:

$$H_p(10,\alpha) = h_{KX} \cdot h_{pK}(10; S-Co, \alpha) \cdot k_{PMMA} \cdot X$$

where

$H_p(10,\alpha)$ is the conventional true value;

h_{KX} is the conversion coefficient from exposure to air kerma;

$h_{pK}(10; S-Co, \alpha)$ is the conversion coefficient from air kerma to personal dose equivalent;

k_{PMMA} is the correction factor for PMMA build-up plate.

The value of $\dot{X}_{ref}$ in the certificate, traceable to the primary standard VNIIM, is given for the reference date. This value was reduced for the actual date as follows:

$$\dot{X} = \dot{X}_{ref} \cdot \exp\left(-\frac{t}{T_{1/2}} \cdot \ln 2\right)$$

where

$\dot{X}$ is the actual exposure rate at the point of test;

$\dot{X}_{ref}$ is the exposure rate at the point of test at the reference date;

t is the time since the reference date;

$T_{1/2}$ is the half life of the source.

4.2. Irradiations at the PTB, Braunschweig

4.2.1. Irradiation facilities

The irradiations were carried out at a 3.5 MeV Van-de-Graff accelerator and a 420 kV *X ray* unit. The Van-de-Graff accelerator is used to produce the R-F radiation quality and the 420 kV *X ray* unit to produce the W-300 radiation quality.

The R-F radiation quality is produced through the nuclear reaction $^{19}F(p,\alpha\gamma)^{16}O$ by bombarding a CaF_2 layer, 6 mg/cm^2 to 7 mg/cm^2 evaporated onto a 2 mm thick carbon substrate, with 2.7 MeV protons from the accelerator. The proton current can be varied between 50 nA and 10 μA yielding air kerma rates at 1 m of 7.5 μSv/h to 1.5 mSv/h. To avoid destruction of the target at high proton currents through beam heating the beam is defocused and the target is rotated and cooled with water. These precautions allow irradiations cycles at constant dose rates lasting many days. Details of the method of production and field properties are described by Büermann et al. [12]. The *X ray* unit has a constant potential high voltage generator (Seifert Isovolt-420 D) with a voltage divider to measure directly the high voltage. All irradiations were performed using an automatic dosimeter changer with rotational table. The nominal distance and the angle of radiation incidence were measured with high resolution of 0.1 mm and 0.1° respectively.

4.2.2. Irradiation conditions

All irradiations were performed on an ISO water slab phantom. The R-F irradiations were done at 0.5 m distance from the target with 4 dosimeters simultaneously. The dose rate was about 3 mSv h^{-1} and the dosimeters were fixed on the phantom with adhesive tape. According to ISO 4037-3 [9] a 25 mm PMMA plate in front of the dosimeters was used for the R-F irradiations (dosimeters Nos. 15 to 17) to establish secondary electronic equilibrium conditions, for dosimeter No. 18 a PMMA plate was not used. The W-300 irradiations were done at 2.5 m distance from the focus with a beam diameter of 43 cm with one dosimeter at a time. The rotation was done in steps 5° from - 80° to + 80° and the time for every 5° step was constant. The dosimeters were put in small bags made of 0.1 mm PE foil and fixed in PMMA frames to be handled by the automatic dosimeter changer.

As agreed by all irradiating laboratories for Phase III of the CRP the reference point for the irradiations was the geometric centre of the phantom surface and the axis of the rotation was a line on the phantom surface through this point and parallel to one edge.

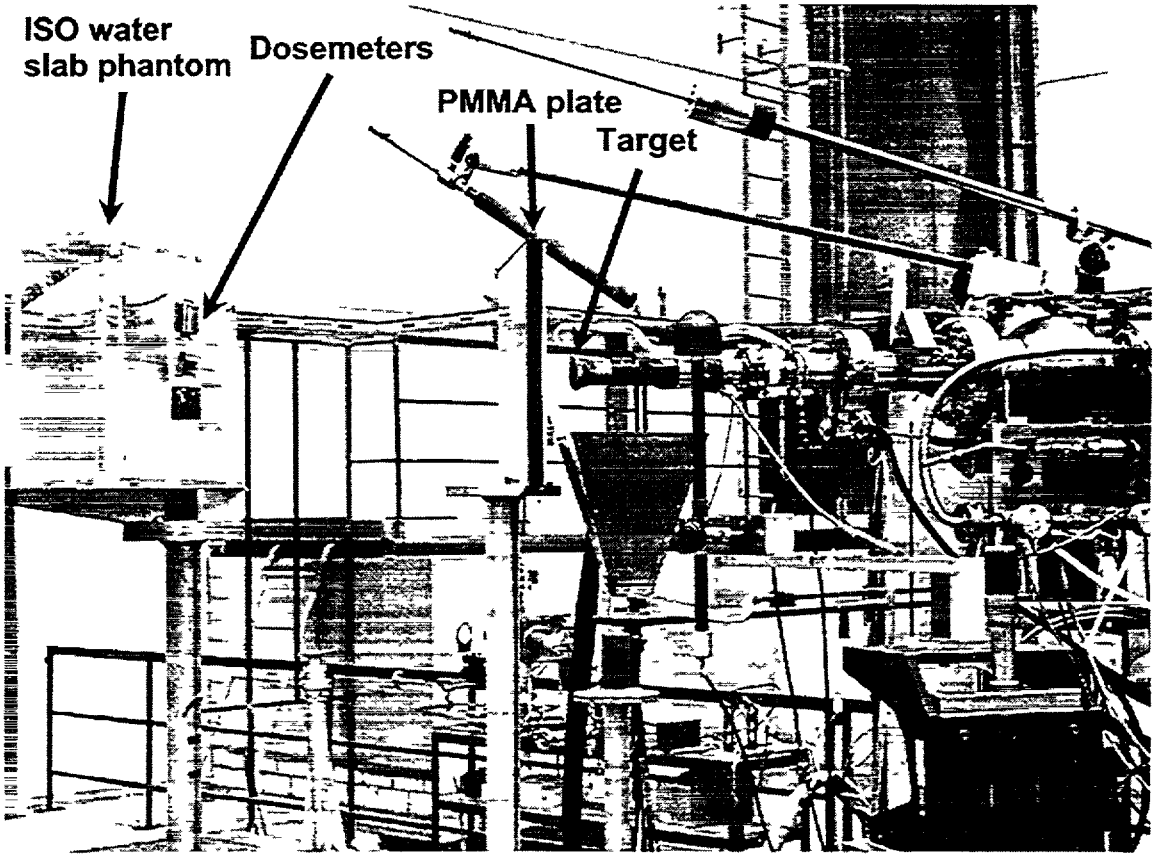

FIG. 2. Experimental setup for R-F irradiations of Phase II.

4.2.3. Calibration

The *X ray* irradiation facility uses a calibrated monitor chamber which is calibrated in terms of air kerma K_a free-in-air using a secondary standard ionization chamber which is directly calibrated against the PTB national standard. The standard uncertainty of the value of the air kerma K_a free in air is less than 1.3 % and those of the personal dose equivalent $H_p(10)$ less than 2.5 %. So the expanded uncertainty (k = 2) of the stated value of $H_p(10)$ is less than 5 %.

The R-F radiation field is calibrated in terms of air kerma K_a free-in-air using a 3 cm^3 graphite ionisation chamber. Details of the calibration procedure are described by Büermann et al. [8]. A Geiger-Müller (GM) counter (Valvo, type 1100) positioned at a distance of about 50 cm from the target and at an angle of about 30° with respect to the beam axis served as a monitor during the irradiations. The standard uncertainty of the value of the air kerma K_a free in air is less than 2,8 % and those of the personal dose equivalent $H_p(10)$ in the cases with and without electronic equilibrium are respectively less than 4 % and 9 %. So the corresponding expanded uncertainties ($k = 2$) of the stated values of $H_p(10)$ with and without electronic equilibrium are respectively less than 8 % and 18 %.

4.3. Irradiations at the NRPB, Chilton

4.3.1. Irradiation facilities

The radiation standards of the facility are based upon those recommended by the International Organization for Standardization (ISO 4037-1, [10]). The air kerma rates are determined by the use of secondary ionization chambers which have been directly calibrated by the U.K National Physical Laboratory. Conversion coefficients from air kerma to $H_{p,slab}(10)$ were taken

from ISO 4037-3, [9]. The ^{60}Co source used was of activity of 250 GBq approximately. The beam is highly collimated, collimator angle of 20°. Filtered (transmission) *X ray's* are produced by a high frequency 300 kV constant potential generator. The ISO filtration is selected from a filter wheel assembly. The stability of the *X ray* intensity is monitored continuously by means of a transmission parallel plate ionization chamber.

4.3.2. Irradiation conditions

All irradiations were performed with dosimeters mounted singly on the front surface of the ISO water slab phantom. The point of test was the geometrical centre of the front face of the phantom and the axis of rotation, the vertical line through this point. For the S-Co irradiations, a 3 mm thick plate of PMMA was put in the beam to ensure secondary electron equilibrium (as described in ISO 4037-3). For this source, the irradiation distance was 1.25 m, air kerma rate 4.4 mGy h^{-1} and the conversion coefficient applied 1.15 Sv Gy^{-1}. For the W-80 (58 keV mean energy) wide angle (- 80°to + 80°) irradiations the phantom was rotated at a constant speed between the angle limits, one complete oscillation taking 20 s. The irradiation distance was 2 m, air kerma rates from 3.3 mGy h^{-1} to 127 mGy h^{-1} with the irradiation time being kept constant at 300 s, conversion coefficient 1.523 Sv Gy^{-1} (calculated as described in section 1.1 above).

4.3.3. Calibration

The air kerma rate at the point of test was determined using Exradin ionization chambers, an A6 of volume 800 ml for the S-Co beam and an A5 of volume 100 ml for the W-80 beam. The calibration of these chambers for the ISO series of reference radiation is carried out periodically at the UK National Physical Laboratory (NPL). The electrometer used to monitor the ionization current for the *X ray* generator monitor chamber is also calibrated at NPL. The dosimetry procedures followed are those recommended in ISO 4037-2, [13].

4.4. Irradiations at the OMH, Budapest

4.4.1. Irradiation facilities

The primary standard dosimetry laboratory of Radiation Physics Section at National Office of Measures (OMH) was chosen to irradiate the dosimeters of participating laboratories using low energy *X ray* beams. One of the main task of the Phase II of the CRP was to investigate the energy and angular dependence of different type of personal dosimeters below 50 keV photon energy, because the recent investigations of the spectrum of the real working place radiation field show large amount of scattered low energy photons. Details of the significant over response of some types of TL and film type of personal dosimeters at low energy photon radiation are shown in reference [8] for example.

The selected beam qualities for the investigation were the N-40 and N-60 from the narrow spectrum series *X rays* (ISO 4037 Part 1, Table IV, [10]). The radiation parameters of these beam qualities are given in the Table I. The collimated *X ray* beams were generated by a constant potential *X ray* system MG 324, using Philips MCN 321 roentgen tube. The air kerma rate at the reference point of measurement without the water phantom was measured using a secondary standard ionization chamber, type ND 1001 No.7808.

4.4.2. Irradiation conditions

One hundred and twenty personal dosimeters provided by the participants of the CRP were irradiated. For the irradiations, an ISO water slab water phantom was used and conversion factors $h_{pK}(10)$ of $H_{p,slab}(10)$ to K_a according to ISO 4037-3 [9].

Arrangement for the irradiation of personal dosimeters at angle α were done according to ISO 4037-3 [9]. The reference point of each dosimeter was taken to be in the mid-plane of the dosimeter unless stated otherwise by the participant.

Three different angles (0° 30° 60°) for both N-60 (48 keV) and N-40 (33 keV) were used, that is 6 irradiation conditions, for each of which 20 dosimeters were irradiated. The irradiation distance was 2.0 m. The beam diameter at the phantom front surface was 25 cm. The personal dose equivalent rate was from 22 $mSvh^{-1}$ to 56 $mSvh^{-1}$. The delivered dose for each dosimeter was controlled by a monitor ionization chamber. The conventional true $H_{p,slab}(10)$ values for all the dosimeters were equal to the nominal 3 mSv within 1 % repeatability.

4.4.3. Calibration

The secondary standard ionization chamber type ND 1001 No.7808 was calibrated again to the primary standard of air kerma. The standard uncertainty of the calibration factor is 0.7 %. The uncertainty of the $h_{pK}(10)$ conversion coefficients is less than 2 % (see e.g. section 7.2 d) of ISO 4034-3). The uncertainty calculation of the delivered personal dose equivalent (conventional true value) was done according to the ISO 4037 part 3 point 7.2 and EAL-R2 (Guide to Expression of Uncertainty in Calibration). The expanded (k = 2) uncertainty of the personal dose equivalent values are less than 5 %.

4.5. Irradiations at the VNIIM, St. Petersburg

4.5.1. Irradiation facilities

For the irradiations of personal dosimeters at the VNIIM, an *X ray* machine ISOVOLT-400 (from Rich. Seifert & Co) with a Z 400/3 tube (AEG, inner filtration of the tube 4 mm Al) was used. The irradiation plan for VNIIM, see Table I, consists of one irradiation of each of the two radiation qualities: N-100 and N-250 (by ISO 4037-3) at angles of incidence of 0°, 30° and 60° for 20 personal dosimeters. In total 120 personal dosimeters were irradiated.

4.5.2. Irradiation conditions

The irradiations of all personal dosimeters were made in a distance of 260 cm from the *X ray* tube. The personal equivalent doses, calculated from the measured air kerma rates free in air were:

$$\dot{H}_p(10) \approx 0{,}49\ \mu Sv/s \text{ for N-100 } (\alpha=0°);$$
$$\dot{H}_p(10) \approx 1{,}5\ \mu Sv/s \text{ for N-250 } (\alpha=0°).$$

A laser system was used to position the dosimeters at the reference point at the calibration distance. Each dosimeter was irradiated separately, the irradiation time being, depending on the angle of radiation incidence, between 35 min and 43 min for N-100 and between 33 min and 38 min for N-250. The field homogeneity over the dosimeter was better then 0,3 %.

The backs of the dosimeters were fixed with adhesive tape at the centre of the front face of an ISO water slab phantom.

4.5.3. Calibration

The air kerma rate at the point of test was determined by means of the *X ray* primary standard of the VNIIM – a free air plate parallel ionization chamber IK 70-300. The combined type A and type B uncertainties of the measured values of air kerma K_a for the radiation qualities N-100 and N-250 are estimated to lie between 0,4 and 0,6 %.

In 1998, the *X ray* primary standard of the VNIIM was compared with the BIPM standard in a field of medium *X ray* energy. The results were in good agreement with the results of other laboratories in the intercomparison.

4.6. Irradiations at the ARCS, Seibersdorf

4.6.1. Irradiation facilities

A ^{192}Ir irradiation facility was used from the multi-source facility, the selected ^{192}Ir source is raised from an underground storage container to the exposure position in a cubic lead shield, having a conical ring-collimator (ISO 4037) with an angular aperture of 15°. For the intercomparison an ^{192}Ir source of 1.5 TBq activity was used.

4.6.2. 4.6.2. Irradiation Conditions

The irradiations with the iridium source were made at a distance of 2000 mm. This radiation quality is referred as S-Ir (note: the quality S-Ir is not given in ISO 4037-3). A carriage system was used to position the reference point (which was assumed to be on the front surface of the slab) at the calibration distance from the source centre. For the wide angle irradiations the vertical axis was also located on the front surface of the phantom.

Each dosimeter was irradiated separately, the irradiation time being between 75 s and 3100 s. For irradiations with the oscillating phantom a device with adjustable rotational speed was used and the number of full oscillations during an irradiation was between 10 and 20. The field homogeneity over the dosimeter was better than 0.3 %.

The dosimeters were fixed with tape at the centre of the front face of the PMMA phantom. A PMMA plate to ensure full secondary electronic equilibrium was not used.

4.6.3. Calibration

The air kerma at the reference point was determined by means of a 1000 cm^3 air equivalent secondary ion chamber, type LS01, operated at - 400 V chamber voltage. The energy dependence of this standard chamber is very well known from measurements in the accredited ARCS calibration laboratory. The calibration factor for air kerma for this chamber varies less than ± 0.5 % over the relevant energy range from 100 keV to 600 keV. The calibration factor for S-Ir was determined from the energy dependence of the calibration factor considering the emission probability for each photon energy. The air kerma rate in the reference point covered the range of 30 mGy/h to 40 mGy/h due to the mean half live time of 73.8 d for ^{192}Ir.

The expanded ($k = 2$) and combined uncertainty of the air kerma K_a at the reference point is estimated to about 1.5 %. The corresponding conversion factors $h_{pk}(10; \text{S-Ir}; \alpha)$ from air kerma K_a to personal dose equivalent $H_p(10)$ for S-Ir are not stated in ISO-4037-3. Therefore these factors were calculated from the published values for mono-energetic radiation, see section 3.

5. CHECK OF IRRADIATION FACILITIES

All irradiating laboratories in Phases II and III of the CRP were checked using a thermoluminescence dosimetry (TLD) system of the Physikalisch-Technische Bundesanstalt (PTB). The check was carried out between November 1996 and July 1998 as a quality control measure to reduce the likelihood of serious errors in the irradiations by the irradiating laboratories. It was

not the aim of the check to detect differences of a few percent in $H_{p,slab}(10)$ values stated at different laboratories. It was done to demonstrate that, if the dosimeter irradiations had been performed at the PTB, the dosimeter readings would have been the same, within the limits of uncertainty.

The TL dosimeters used were irradiated on ISO water slab phantoms with all radiation qualities that were intended to be used during the intercomparison, but only with 0° (perpendicular) radiation incidence. Each irradiating laboratory irradiated the TL dosimeters on the front surface of the ISO water slab phantom with a dose whose value $H_{p,slab}(10)^{LAB}$ was stated including all corrections to their best knowledge. The PTB evaluated the TLDs using a carefully calibrated system resulting in a value M^{PTB}. From this value, the $H_{p,slab}(10)^{PTB}$ value stated by the PTB as conventional true value is calculated as follows:

$$H_p(10)^{PTB} = k_E(\overline{E}, 0°) \cdot M^{PTB}$$

The "energy correction factor" $k_E(\overline{E}, 0°)$ depends on the radiation quality (characterized by the mean photon energy $\overline{E}$) and the angle of radiation incidence, which was always 0°. The values of $k_E(\overline{E}, 0°)$ have been determined for all the irradiation conditions of the intercomparison by at least 5 measurements.

The dosimetry system used was the same as described in [14]. The system uses TLD-700 detectors (LiF with 99.93 % ^{7}Li, dimensions Ø 4.5 mm and 0.38 mm thick) manufactured by Bicron NE Technologies. Each TL dosimeter has one TL detector that is completely contained in an aluminium casing made from two disks and one ring. The front and back disks are 1 mm thick, the wall thickness of the inner ring is 2 mm. In addition the aluminium casing is surrounded on all sides by about 3 mm PMMA. Details of the badge are shown in the sketch in Figure 1 in [14].

The check of the irradiating laboratories included all handling parameters for 'on phantom irradiations'. The TL dosimeters were irradiated in the centre of the front surface of the phantom, and 3 cm above and below the centre of the phantom. No effect of this displacement could be determined. Under ideal conditions the quotient r, $r = H_{p,slab}(10)^{LAB} / H_{p,slab}(10)^{PTB}$, should be unity for all irradiating laboratories. For the PTB this value for S-Co is unity because this value was used for normalization. The results of the check are shown in Figure 3. The error bars give twice the coefficient of variation of the measured mean values of the TLD system. Any additional uncertainties of the dose values of the irradiating laboratories and the PTB have to be added, see data given in section 4. According to ISO 4037-3 these standard uncertainties are for the measurand $H_{p,slab}(10)$ at least 2 %. The PTB irradiated with W-300 and R-F. For R-F no check was possible because no other irradiating laboratory could provide that quality, but for W-300 a check of the PTB irradiations was possible with the help of the NPRB. A W-300 irradiation at PTB would of course give a r-value of unity because the energy correction factor k_E for that quality is determined with the PTB facility, but the fact that the r-value of the NRPB as shown in Figure 3 was also close to unity assures, that the PTB irradiation facility is in accordance with that of the NRPB.

All r values are within $1 \pm 0{,}03$ so that the check of the irradiating facilities demonstrates the agreement of the irradiating facilities of all irradiating laboratories with those of the PTB.

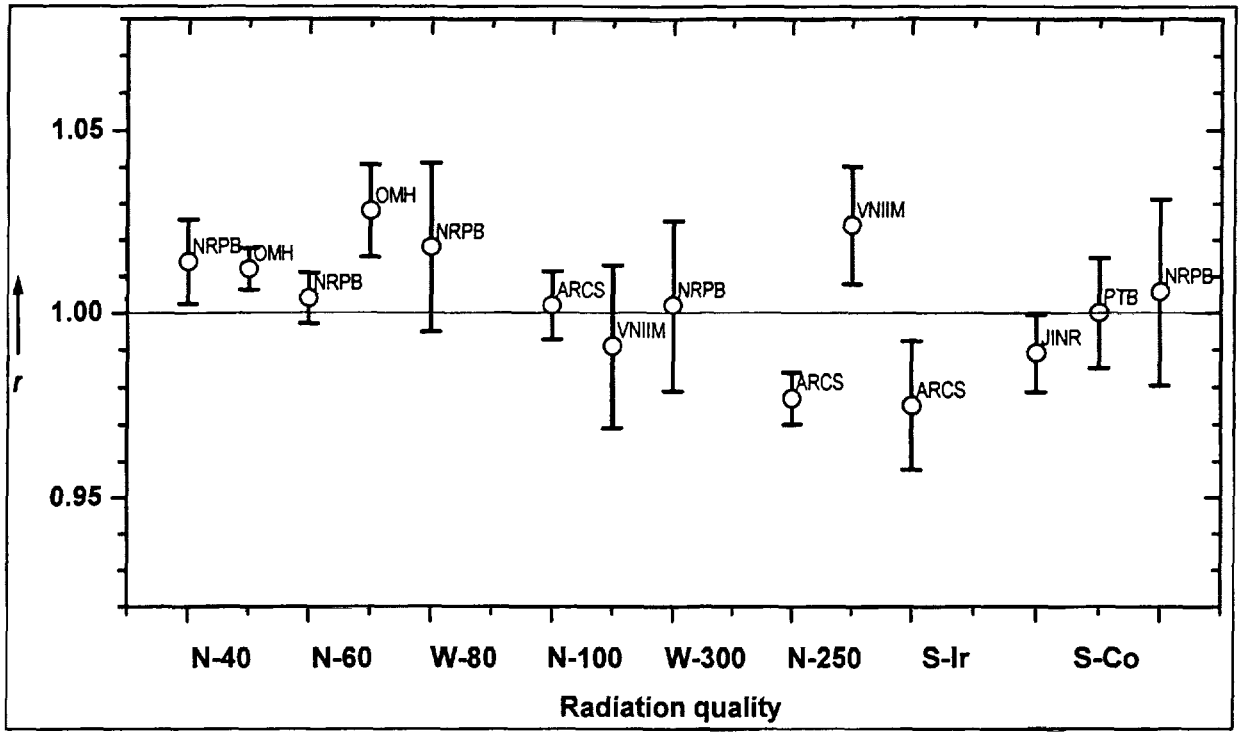

FIG. 3: Results of the check of the irradiation facilities, Phases II and III. The quotient r *is given by* $r = H_p(10)^{LAB} / H_p(10)^{PTB}$ *and the radiation quality is indicated according to ISO 4037-3. See text for the error bars. The irradiating laboratories are indicated besides the measured values.*

REFERENCES

[1] BÖHM, J., GUSTAFSSON, M., GRIFFITH, R.V., Outline of the IAEA Co-ordinated Research Project 1996-1998 on Intercomparison for Individual Monitoring of External Exposure to Photon Radiation, this publication.

[2] BURGESS, P.H., BARTLETT, D.T., AMBROSI, P., Workplace Photon Radiation Fields, this publication.

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna, (1996).

[4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, Pergamon Press, Oxford, (1991).

[5] GRIFFITH, R.V., Quantities and Units for External Dose Assessments, this publication.

[6] BÖHM, J., Calibration of Personal Dosimeters for Photon Radiation with Respect to the Personal Dose Equivalent $H_p(10)$, this publication.

[7] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Measurement of Dose Equivalents from External Photon and Electron Radiations. ICRU Report 47, Bethesda, (1992).

[8] BARTLETT, D.T., STEELE, J.D., Characteristics of Personal Dosemeters to Measure $H_p(10)$ for Photons, this publication.

[9] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, X and Gamma Reference Radiations for Calibrating Dosemeters and Doserate meters and for Determining their Response as a Function of Photon Energy. Calibration of Area and Personal Dosemeters and the Measurement of their Response as a Function of Energy and Angle of Incidence, final draft International Standard ISO/FDIS 4037-3, Geneva, (1998).

[10] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, X and Gamma Reference Radiations for Calibrating Dosemeters and Doserate meters and for Determining their Response as a Function of Photon Energy - Part 1: Radiation Characteristics and Production Methods, International Standard ISO 4037-1, Geneva, (1996).

[11] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Conversion Coefficients for use in Radiological Protection Against External Radiation, ICRU Report 57, Bethesda, (1998).

[12] BÜERMANN, L., GULDBAKKE, S., KRAMER, H.M., Calibration of personal and area dosimeters in high-energy photon fields. PTB-Dos-32, Braunschweig, 1999.

[13] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, X and Gamma Reference Radiations for Calibrating Dosemeters and Doserate meters and for Determining their Response as a Function of Photon Energy - Part 2: Dosimetry over the Energy Ranges 8 keV to 1,3 MeV and 4 MeV to 9 MeV, ISO 4037-2, Geneva, (1998).

[14] AMBROSI, P., Backscattered Radiation measured by the PTB individual dosimetry system type T001. Intercomparison for Individual Monitoring, PTB-Dos-20, Braunschweig, (1991).

STANDARDS IN RADIATION PROTECTION AT THE IAEA DOSIMETRY LABORATORY

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Abstract

Approximately 90% of the Secondary Standard Dosimetry Laboratories (SSDLs) provide users with calibrations of radiation protection instruments, and the Agency is making every necessary effort to insure that SSDLs measurements in radiation protection are traceable to Primary Standards The IAEA provides traceable calibrations of ionization chambers in terms of air kerma at radiation protection levels and ambient dose equivalent calibrations SSDLs are encouraged to use the calibrations available from the Agency to provide traceability for their radiation protection measurements Measurements on diagnostic X ray generators have become increasingly important in radiation protection and some SSDLs are involved in such measurements The IAEA has proper radiation sources available to provide traceable calibrations to the SSDLs in this field, including an X ray unit specifically for mammography dedicated to standardization procedures The different photon beam qualities and calibration procedures available in the Agency's Dosimetry Laboratory will be described

1. INTRODUCTION

The emphasis of the IAEA Dosimetry Programme is focused into services provided to developing Member States through the IAEA/WHO Network of Secondary Standard Dosimetry Laboratories (SSDLs) and dose quality audits. The latter are performed through the IAEA/WHO TLD postal service to SSDLs and radiotherapy centers and through the International Dose Assurance Service (IDAS) for radiation processing facilities, mainly for food-irradiation and sterilization of medical products. The staff of the Dosimetry Section (NAHU) provides the programmatic responsibility, supervision and support required for the measurements at the Agency's Dosimetry Laboratory in Seibersdorf, where all the equipment is located. This consists of a ^{60}Co therapy unit, brachytherapy ^{137}Cs sources, gamma-irradiators and X ray generators for the calibration of ionization chambers and radiation detectors for radiotherapy, radiation protection and diagnostic radiology, thermoluminescence dosimetry (TLD) systems, Electron Spin Resonance (ESR) equipment, and ancillary equipment. Besides, the Dosimetry Laboratory has access to two ^{60}Co irradiators (Gammacell-220) for calibration of dosimeters used for radiation processing. A detailed description of the various irradiators used at the Agency Laboratory is given in Appendix A. Those can be considered a typical equipment of an SSDL.

2. NETWORK OF THE SSDLS

The Agency's Dosimetry Laboratory is the central laboratory of the SSDLs network, establishing the link to the International Measurement System, IMS (Figure 1). The SSDL network presently includes 69 laboratories and 7 SSDL national organizations in 57 Member States; the network also includes 19 affiliated members, mainly PSDLs, ICRU, BIPM, and other international organizations. An updated list of members of the IAEA/WHO SSDL network is published regularly in the IAEA SSDL Newsletter (bi-annual).

The establishment of the network of SSDLs has the responsibility to guarantee that the services provided by the laboratories follow internationally accepted metrological standards.

At present, this is achieved by providing traceable calibrations for therapy level and radiation protection instruments by the Agency. The traceability is accomplished first with the transmission of calibration factors for ionization chambers from the BIPM or PSDLs through the Agency's Dosimetry Laboratory. As a second step, follow-up programmes and dose quality audits (intercomparisons using ionization chambers and TLDs) are implemented for the SSDLs to guarantee that the standards transmitted to users in the Member States are kept within the levels required by the International Measurement System. This second step is presently implemented only for instruments at therapy level although recent recommendations have been made by the SSDL Scientific Committee to extend the quality audits to ^{137}Cs gamma rays at protection level.

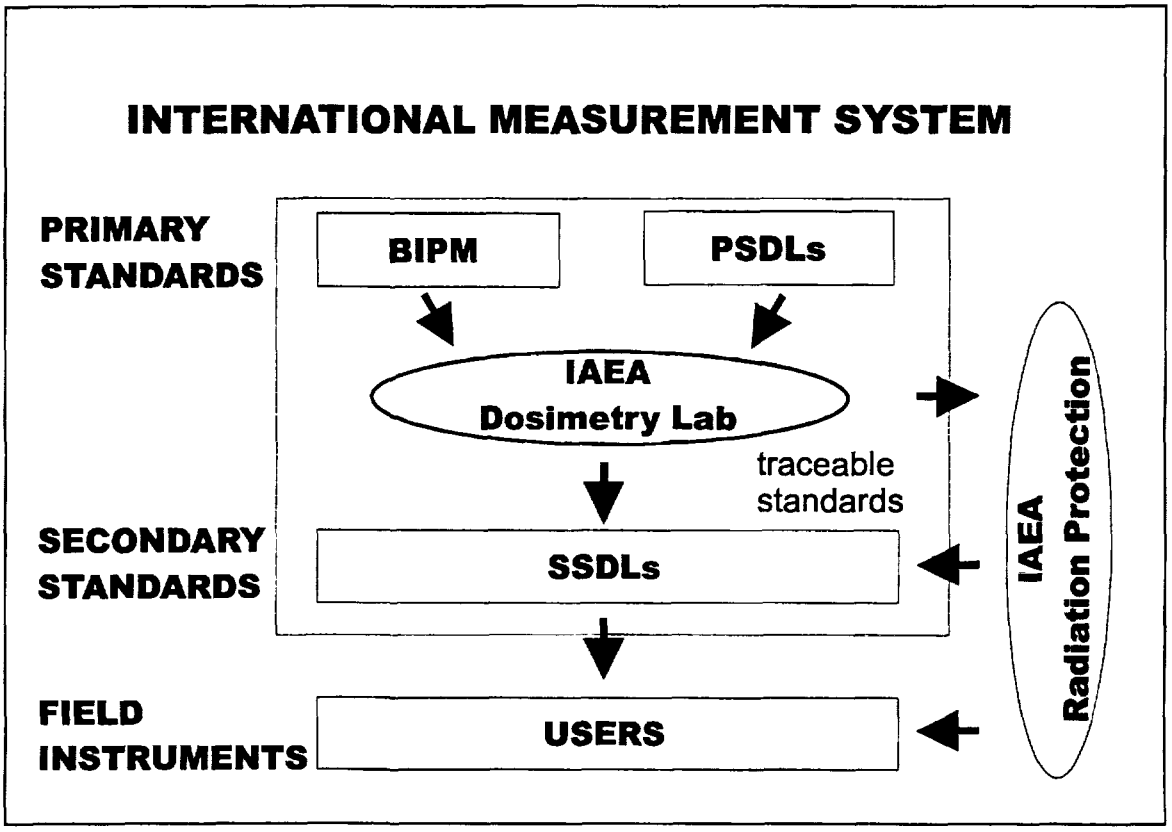

FIG. 1. The International Measurement System (IMS), where traceability of field instruments (users) to Primary Standards is guaranteed through the network of Secondary Standard Dosimetry Laboratories and the Agency's Dosimetry Laboratory. The inner box shows the steps where traceable calibrations are accomplished. By providing also calibrations and reference irradiations to the Agency's Radiation Monitoring and Protection Services, traceability can be guaranteed down to the level of personal and area monitoring in Member States

Figure 2 shows the number of calibrations provided during the last years by the Agency's Dosimetry Laboratory to Member States both at therapy and radiation protection level, where it can be seen that the latter is considerably smaller than the number of calibrations for radiotherapy instruments. The large number of calibrations for therapy during 1995 is due to a biennial campaign of intercomparisons of ion chamber calibrations with a large number of SSDLs. The SSDLs submit to the IAEA Secretariat annual reports on their activities in the

various fields. Data between 1985-1995 show on the average that approximately 8% of the laboratories do radiotherapy calibrations only, 12% do radiation protection calibrations only, and nearly 80% of the laboratories do both types of calibrations.

3. IAEA STANDARDS FOR RADIATION PROTECTION

As is well known, the basic idea of radiation protection quantities defined by ICRP [1] and ICRU [2, 3] is to relate the risk due to exposure with ionizing radiation to a single quantity which takes into account the human body as a receptor. Two types of quantities, limiting and operational, can be related to basic physical quantities which are defined without need for considering specific aspect of radiation protection, e.g. air kerma for photons and fluence for neutrons. In practice, the conventional true value of a radiation protection quantity is usually obtained by multiplying the value of a measured physical quantity by an appropriate factor which relates the two quantities. The calibration of a dosimeter for measurements in radiation protection consists then of a calibration in terms of a physical quantity together with the use of internationally agreed data for conversion from physical into protection quantities.

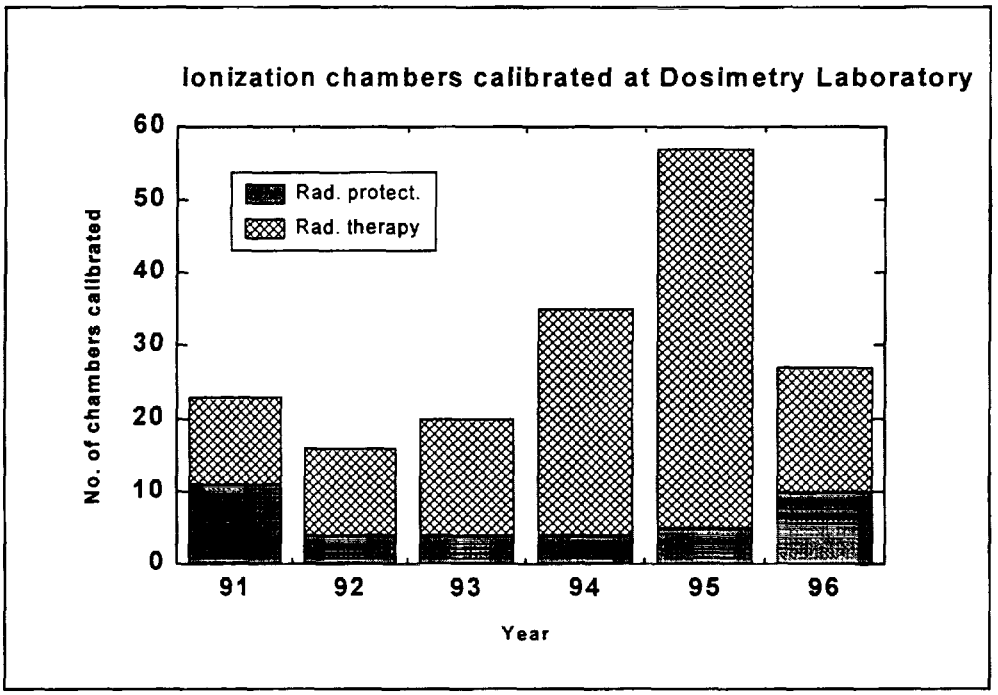

FIG. 2. Calibrations of secondary standards for therapy and radiation protection levels provided by the Agency to SSDLs in Member States during the period 1991-1996.

Because of the low levels of measured currents, secondary standard instruments for radiation protection levels consist of a large ionization chamber (1000 cm^3 approximately), connected to an appropriate electrometer. Their calibration is performed in specific reference conditions at a standards laboratory. The list of all reference ionization chambers used at the Agency's Dosimetry Laboratory is given in Appendix B. The secondary standards for radiation protection level at the Agency's Dosimetry Laboratory are based on spherical ionization

chambers LS-01 and HS-01 designed and manufactured at the Austrian Research Center (ARCS) at Seibersdorf. The energy response of the LS-01 chamber is optimized for measurements of air kerma, K_{air}, while that of HS-01 for the measurement of ambient dose equivalent, H^*. Chambers are calibrated in terms of air kerma and ambient dose equivalent at PTB and BIPM. The ionization current is measured with the programmable electrometer model Keithley 6517 controlled via an IEEE-488.2 interface using an application for data acquisition developed with the LabView software. For monitoring the X ray unit output a Keithley 617 electrometer is used.

The calibration setups at the Agency's Dosimetry Laboratory are shown in Figure 3 for X rays and $^{60}Co/^{137}Cs$ gamma rays respectively. They reproduce the configurations used at BIPM and PTB. Table I gives the ISO 4037 [4] radiation qualities (narrow series) available for calibrations at protection levels. Air kerma and ambient dose equivalent calibrations for these qualities are provided.

4. NEW DEVELOPMENTS

During their last meeting in September 1996, the Standing Advisory Committee "SSDL Scientific Committee", SSC (its members are from ICRU, BIPM and Primary Laboratories), has recommended extending the long experience of the Agency in the field of standardization and monitoring dosimetry calibrations at radiotherapy level for the SSDL network, to the fields of protection and diagnostic X rays dosimetry. It was emphasized that

"Nearly 80% of the SSDLs provide measurements in the radiation protection range. The SSC recommends that the Agency takes every necessary effort to insure that SSDLs measurements in radiation protection are traceable to Primary Standards. As the Agency's Dosimetry Laboratory provides traceable calibrations of ionization chambers in terms of air kerma at radiation protection levels, the SSC encourages the SSDLs to use the service available from the Agency to provide traceability for their radiation protection measurements. Measurements on diagnostic X ray machines have become increasingly important and some SSDLs are involved in such measurements. The Agency's Dosimetry Laboratory should, therefore, have proper radiation sources available to provide traceable calibrations to the SSDLs

The annual postal comparison has been shown to be successful in assuring the coherence of the measurement quality of the SSDL Network in the range of therapeutic doses. This programme should be extended to assure the traceability of secondary standards also at radiation protection irradiation level and diagnostic X rays. The Committee recommends that the Agency's Dosimetry Laboratory should start the task for Radiation Protection measurements using ^{137}Cs gamma radiation at protection levels;..."

The above recommendations have led the Dosimetry Section to start with new activities. Because of the importance of mammographic examinations world-wide, as a first step the Agency's Dosimetry Laboratory has acquired a mammography X ray unit. It is equipped with a tube that has two targets, one of Molybdenum and the other of Rhodium. Seventeen beam qualities have recently been established for tube voltages between 23 and 40 kV that are equivalents of the NIST mammography calibration beams. Experiments have been initiated aiming at the selection of an ionization chamber as the secondary standard for the mammography calibration facility.

General guidance on the basic requirements for protection instruments, e.g. the quantities that should be measured, their overall accuracy, etc. has been given by different international bodies like ICRP [1, 5], ICRU [3, 6,] and IAEA [7]. The overall accuracy of any dosimetry

system is determined from the combined effects of a number of uncertainties. Calibration procedures are typical sources of uncertainties whose influence on the accuracy of a protection level measurement is usually reduced by more important components like the energy and angular dependence of the dosimeter. Nevertheless, large errors in the calibration, if they occur, can have severe consequences. In addition the traceability of any measurement is the only possible link to the IMS, that is, even if large errors can sometimes be accepted in radiation protection, it is necessary to know the reference with which that error can be compared. The extension of activities for checks of the SSDLs ^{137}Cs calibrations thus seems a natural continuation of the Agency role in disseminating international standards to Member States. At present, the Agency's Dosimetry Laboratory is developing the system that will be implemented for this task.

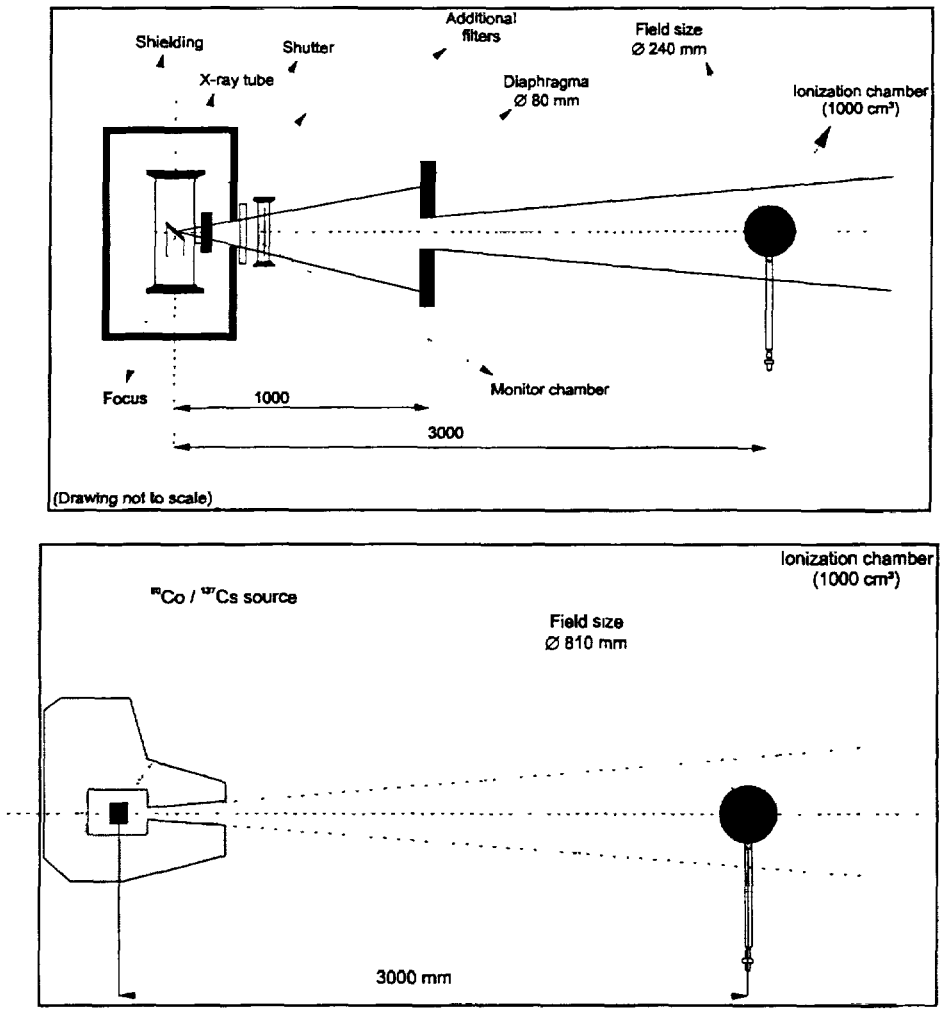

FIG. 3. Setups used at the Agency's Dosimetry Laboratory for the calibration of secondary standards in radiation protection for X rays and $^{60}Co/^{137}Cs$ gamma rays. Beam qualities available at the Laboratory are given in Table I.

TABLE I. RADIATION QUALITIES AT PROTECTION LEVEL AVAILABLE AT THE AGENCY'S DOSIMETRY LABORATORY. (FIXED FILTRATION: 2.2 mm Be + 3 mm Al).

Generating potential	Added filtration				HVL	
[kV]	[mm Al]	[mm Cu]	[mm Sn]	[mm Pb]	[mm Al]	[mm Cu]
40	1.00	0.22	-	-	2.70	
60	1.00	0.59	-	-		0.24
80	1.00	1.85	-	-		0.59
100	1.00	5.30	-	-		1.15
120	1.00	5.00	1.00	-		1.74
150	1.00	-	2.50	-		2.40
200	1.00	2.00	3.00	1.00		4.06
250	1.00	-	2.50	2.50		5.21
300	1.00	-	3.00	5.00		6.19
^{137}Cs						
^{60}Co						

REFERENCES

[1] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, ICRP Publication 60, Ann. ICRP, **21**(1-3), Pergamon Press, Oxford (1991).

[2] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS ICRU, Determination of Dose Equivalents Resulting from External Radiation Sources, ICRU Report 39, ICRU, Bethesda, MD (1985).

[3] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS ICRU, Determination of Dose Equivalents Resulting from External Radiation Sources - Part 3, ICRU Report 47, ICRU, Bethesda, MD (1992).

[4] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, X and γ Reference Radiations for Calibrating Dosemeters and Dose Ratemeters and for Determining their Response as a Function of Photon Energy, ISO 4037-1979, ISO, Geneva (1979).

[5] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, General principles of Monitoring for radiation Protection of Workers, ICRP Publication 35, Ann. ICRP, **9**, (4), Pergamon Press, Oxford (1985).

[6] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS ICRU, Determination of Dose Equivalents Resulting from External Radiation Sources – Part 2, ICRU Report 43, ICRU, Bethesda, MD (1988).

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No.115, IAEA, Vienna (1991).

Appendix A

CALIBRATION SOURCES AT THE IAEA DOSIMETRY LABORATORY

Picker V4M/60

Radionuclide	^{60}Co
Maximum activity	148 TBq
The current activity of the ^{60}Co source	11.8 TBq (on 97-10-01)
Height of the source above the floor	1.10 m
Maximum radiation field-size	400 cm^2 at 100 cm
Calibration field-size	100 cm^2 at 100 cm
Calibration source to detector distance	100 cm
Air kerma rate at the calibration position	455 μGy/min (on 97-10-01)
Dose equivalent rate of leakage radiation at 100 cm	15 μSv/h

OB-85

Radionuclide	^{60}Co
Current activity of the ^{60}Co source	20.5 GBq (on 97-10-01)
Air kerma rate at the calibration position	22.8 μGy/min (on 97-10-01)
Radionuclide	^{137}Cs
Current activity of the ^{137}Cs source	660 GBq (on 97-10-01)
Air kerma rate at the calibration position	191 mGy/min (on 97-10-01)
Height of the source above the floor	1.10 m
Calibration field-size	∅150 cm at 300 cm
Calibration source to detector distance	300 cm
Dose equivalent rate of leakage radiation at 100 cm	<1 μSv/h

X ray units

Philips X ray machine MG 324

Metal-ceramic tube MCN 321 with beryllium window, oil cooling

Target material	Wolfram
Generating potential continuously adjustable	16 to 320 kV
Tube current continuously adjustable	0.1 to 10 mA at 320 kV
Inherent filtration	3 m Be
Added filters, changeable	medium or heavy filtration
Height of X ray tube above floor	1.10 m
Maximum field size area at 100 cm	576 cm^2
Min. focus to target distance	50 cm
Leakage dose equivalent rate through shutter at 100 cm distance from focus	< 6 μSv/h

Philips X ray machine MG 164

Metal-ceramic tube MCN 165 with beryllium window, oil cooling

Target material	Wolfram
Generating potential continuously adjustable	up to 160 kV
Tube current continuously adjustable	0.1 to 18 mA at 160 kV
Inherent filtration	1 mm Be
Added filters, changeable	medium or heavy filtration
Height of X ray tube above floor	1.10 m
Maximum field size area at 50 cm	144 cm^2
Min. focus to target distance	50 cm
Leakage dose equivalent rate through shutter at 50 cm distance from focus	< 25 μSv/h

Senographe DMR

Dual target X ray tube GS 412-49

Target material	Molybdenum (Vanadium-doped) Rhodium
Target angle with respect to the reference axis	f 0.1 - 6°, f 0.3 - 20°
Nominal focal spot values	0.1 and 0.3
Generating potential	22 to 49 kV in steps of 1 kV
Tube current	20 to 130 mA
Inherent filtration	0.8 mm Be
Added filters, changeable	1 mm Al, 0.03 mm Mo, 0.025 mm Rh
Maximum field size area at 50 cm	325 cm^2
Min. focus to target distance	20 cm

Appendix B

SECONDARY STANDARD EQUIPMENT USED AT THE IAEA DOSIMETRY LABORATORY

Chamber model	Ser. No.	Measured quantity	Traceability
NE-2561	321	K_{air} and D_w for ^{60}Co	BIPM
NE-2561	265	K_{air} for X rays (100-300 kV)	BIPM
LS-01	114	K_{air} for X rays (40-300 kV), ^{137}Cs, ^{60}Co	BIPM, PTB
HS-01	102	H^* for X rays (40-300 kV), ^{137}Cs, ^{60}Co	BIPM, PTB
LS-01	130	K_{air} for ^{137}Cs, ^{60}Co	PTB
PTW-23342	1128	K_{air} for X rays (25-50 kV)	PTB

THE USE OF OPERATIONAL QUANTITIES FOR INDIVIDUAL MONITORING OF EXPOSURE TO EXTERNAL RADIATION

CALIBRATION OF PERSONAL DOSIMETERS: QUANTITIES AND TERMINOLOGY

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Abstract

The numerical results obtained in the interpretation of individual monitoring of external radiation depend not only on the accurate calibration of the radiation measurement instruments involved, but also on the definition of the quantities in term of which these instruments are calibrated. The absence of uniformity in terminology not only makes it difficult to understand properly the scientific and technical literature but can also lead to incorrect interpretation of particular concepts and recommendations. In this paper, brief consideration is given to definition of radiation quantities and terminology used in calibration procedures.

1. INTRODUCTION

By the end of the 1980s, a vast amount of new information had accumulated, prompting a new look at the basis of protection against exposure to ionizing radiation. Following these developments, the ICRP, in 1990, revised its standing recommendations [1]. The new recommendations included, amongst other things a new definition of body dose quantities to which the limits are related. Body dose quantities are not measurable as they are defined as average doses in organs and tissues of the human body. Moreover, their values depend on the individual person and on the orientation of the person in the radiation field. For radiation protection practice, special "operational" quantities are therefore important whose values can be determined from measurements and in the units of which measuring instruments can be calibrated. As early as in 1985 the International Commission on Radiation Units and Measurements (ICRU) presented a concept of radiation protection quantities for measurements in area and individual monitoring of external radiation [2]. In this concept, the "operational" quantities are defined so as to be applicable to all types of ionizing radiation, and provide a reasonable and conservative approximation to the effective dose for most photon energies. The concept was further developed by the ICRU in the following years [3 – 5]. The new ICRU quantities are increasingly accepted world-wide. Recent draft standards of the International Organization for Standardization (ISO) in the field of dosimetry make use of the new ICRU quantities. Many countries are preparing for the introduction of these quantities.

The numerical results obtained in the interpretation of individual monitoring of external radiations depend not only on the accurate calibration of the radiation measurement instruments involved, but also on the definition of the quantities in term of which these instruments are calibrated. The absence of uniformity in terminology not only makes it difficult to understand properly the scientific and technical literature but can also lead to incorrect interpretation of particular concepts and recommendations. It is this which has led to the need for the compilation of a unified glossary on calibration of personal dosimeters to be used by participants of the IAEA CRP on Intercomparison for Individual Monitoring of External Exposure to Photon Radiation.

2. OPERATIONAL QUANTITIES AND PHANTOMS

2.1. Personal Dose Equivalent, $H_p(d)$

To obtain an estimate of the effective dose, the operational quantity for the personal dose, **personal dose equivalent, $H_p(d)$,** is used. The **personal dose equivalent, $H_p(d)$,** is the dose equivalent in ICRU 4-element tissue, at an appropriate depth, d, below a specified point on the body.

Unit: J kg^{-1}

The special name for the unit of personal dose equivalent is sievert (Sv).

Any statement of personal dose equivalent should include a specification of the reference depth, d. In order to simplify notation, d should be expressed in mm.

For weakly penetrating radiation, a depth of 0.07 mm for the skin and 3mm for the eye are employed. The personal dose equivalent for these depths is then denoted by $H_p(0.07)$ and $H_p(3)$, respectively.

For strongly penetrating radiation, a depth of 10 mm is frequently employed, with analogous notation.

2.2. Phantoms

For the calibration of personal dosimeters the definition of $H_p(d)$ is considered to include the following phantoms [6] consisting of ICRU 4-element tissue:

- **slab phantom** of 300 mm x 300 mm x 150 mm depth to represent the human torso (for the calibration of whole body dosimeters);
- **pillar phantom,** a circular cylinder with the diameter of 73 mm and the length of 300 mm, to represent a lower arm or leg (for the calibration of wrist or ankle dosimeters);
- **rod phantom,** a circular cylinder with the diameter of 19 mm and the length of 300 mm, to represent a finger (for the calibration of finger dosimeters).

Personal dosimeters should, in principle, be calibrated using standardized phantoms. Three phantoms have been selected for calibrations and type tests with photon, beta and neutron radiations:

a) ISO water slab phantom

The phantom to represent the human torso with regard to backscattering of the incident radiation is the ISO water slab phantom of 30 cm x 30 cm x 15 cm depth. The front face of the water phantom consists of a 2.5 mm thick PMMA (PMMA is polymethyl methacrylate with a density of 1.19 g cm^{-3} and a mass composition of 8.05% H, 59.99% C and 31,96% O) plate. The other phantom sides are 10 mm thick PMMA.

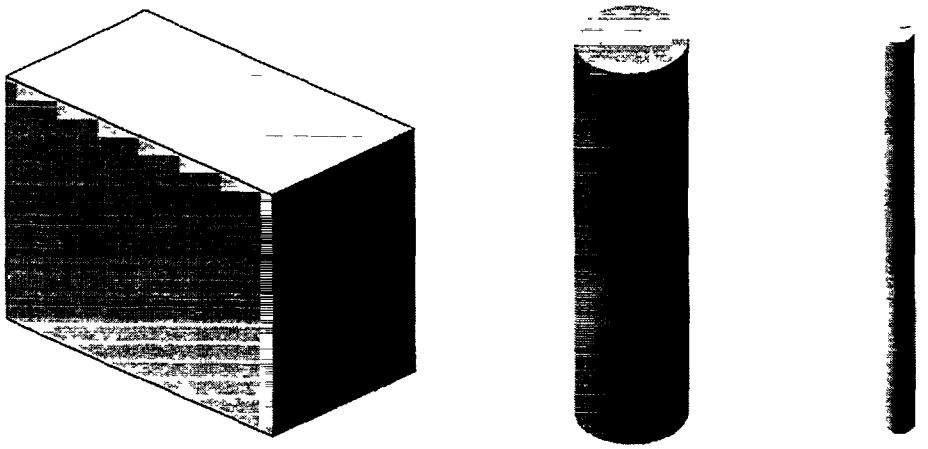
b) ISO water pillar phantom

The phantom to represent a lower arm or leg with regard to backscattering of the incident radiation to test wrist or ankle dosimeters, is the water pillar phantom, a right circular cylinder with a diameter of 73 mm and length of 300 mm. The walls of the phantom consist of PMMA; the circular walls are 2.5 mm thick, the end walls have a thickness of 10 mm.

c) ISO PMMA rod phantom

The phantom to represent a finger with regard to backscattering of the incident radiation to test finger dosimeters, is the PMMA rod phantom, a right circular cylinder with a diameter of 19 mm and a length of 300 mm. The phantom consist of PMMA.

A schematic drawing of the phantoms is given in Figure 1.



(a) **(b)** **(c)**

FIG. 1. Phantoms for the calibration of personal dosimeters: ISO water slab phantom (a) (300 mm x 300 mm x 150 mm), ISO water pillar phantom (b) (73 mm in diameter, 300 mm in height) and ISO PMMA rod phantom (c) (19 mm in diameter, 300 mm in height).

It is obvious that these three types of phantoms are only approximate representations of the respective parts of the body. They do, however, serve the purpose because

- according to the definition of $H_p(d)$, a personal dosimeter should be constructed in such a way that it is sensitive to radiation backscattered from the body; the difference in backscatter between the standardized phantom and the actual part of the body where the dosimeter is worn is thereby, in principle, automatically measured;
- the three different shapes of phantoms cover the needs of calibrations and type-testing

    1) of whole body dosimeters worn, for example, on the trunk to estimate the effective dose, and

    2) of wrist or ankle dosimeters and of finger dosimeters to estimate the partial body doses;

- reference phantoms in which the quantity $H_p(d)$ is defined for calibration of personal dosimeters are consistently composed of ICRU 4-element tissue and are the same shapes as the phantoms actually used; the conversion coefficients given in the standards only relate to the reference phantoms;

- the use of reference phantoms enable consistent calibration conditions to be established at different laboratories.

When these phantoms are used, no correction factors shall be applied to correct for any differences in backscatter relative to ICRU tissue.

3. TERMINOLOGY

Primary Standard

A standard which has the highest metrological quantities in a specified field. Primary standards are maintained at national laboratories that a) perform research for the purposes of metrology and b) participate in recognized international intercomparisons of primary standards laboratories.

Secondary Standard

A standard whose value is fixed by direct comparison with a primary standard, and is accompanied by a certificate which documents that traceability.

Tertiary Standard

A standard whose value is fixed by comparisons with a secondary standard.

National Standard

A standard recognized by an official national decision as the basis for fixing the value, in a country, of all other standards of the given quantity.

Reference Source

A reference source shall be a secondary standard source calibrated with primary standards by a national primary laboratory or at an acknowledged reference laboratory which holds appropriate standards.

Influence quantity

An influence quantity (parameter) is a quantity which may have a bearing on the result of a measurement without being the objective of measurement.

Conventional True Value (of a Quantity)

The conventional true value of a quantity is the best estimate of the value of the quantity to be measured, determined by a primary or secondary standard or by a reference instrument that has been calibrated against a primary or secondary standard.

Response

The response, R, of a measuring instrument is the quotient of the indication, M, of the instrument and the conventional true value of the measured quantity. The type of response should be specified. For example "fluence response" R_Φ (response with respect to fluence, Φ)

$$R_\Phi = M/\Phi$$

or "dose equivalent response" R_H (response with respect to dose equivalent H)

$$R_H = M/H$$

Calibration

A calibration is the set of operations that establish, under specified conditions, the relationship between the quantity indicated by a dosimeter and the corresponding value realised by standards.

Arrangement for the calibration of personal dosimeters at angle α is given in Figure 2.

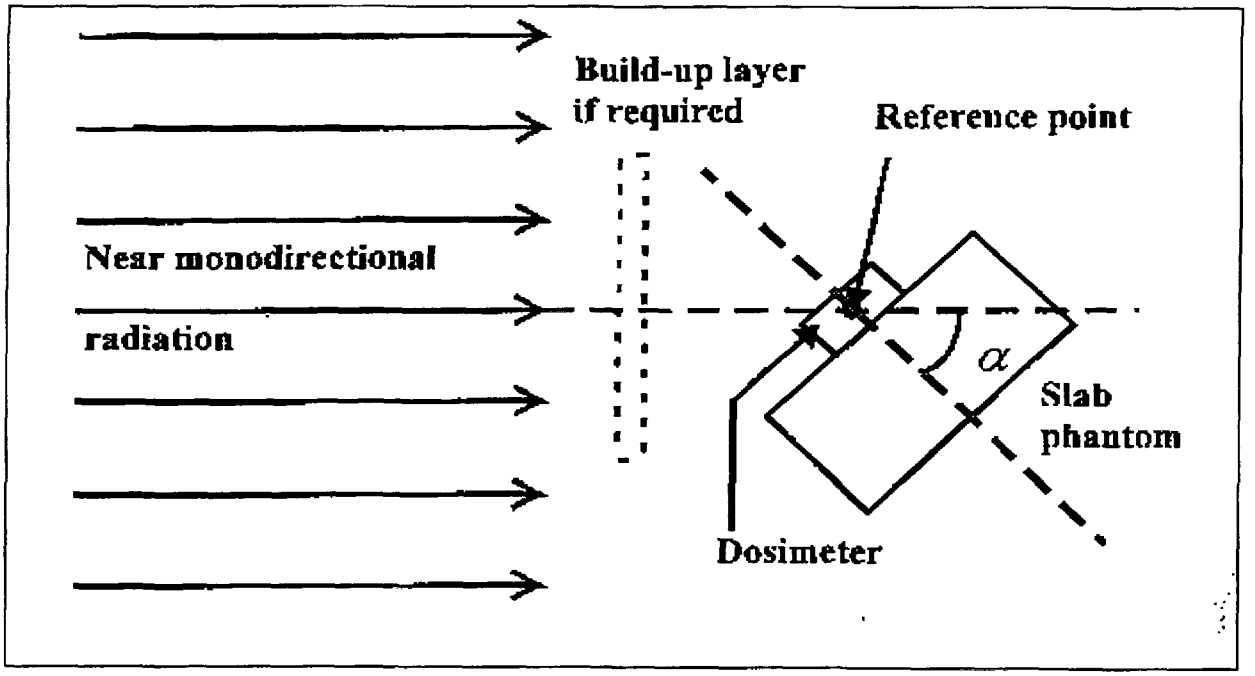


FIG. 2. Arrangement for the calibration of personal dosimeters at angle α.

Calibration Factor

The calibration factor, N, is the conventional true value of the quantity the instrument is intended to measure (measurand), H, divided by the indication, M, (corrected if necessary) given by the instrument under reference conditions i.e.

$$N = \frac{H}{M}$$

Reference conditions

The reference conditions represent the set of influence quantities for which the calibration factor is valid without any correction.

Note: The value for the quantity to be measured may be chosen freely in agreement with the properties of the instrument to be calibrated. The quantity to be measured is not an influence quantity.

Standard test conditions

The standard test conditions represent the range of values of a set of influence quantities under which a calibration or a determination of response is carried out.

Calibration conditions

The calibration conditions are those within the range of standard test conditions actually prevailing during the calibration.

Before any calibration is made the dosimeter shall be examined to confirm that it is in a good serviceable condition and free of radioactive contamination. The set-up procedure and the mode of operation of the dosimeter shall be in accordance with its instruction manual. The calibration conditions represent the range of a set of influence quantities under which a calibration actually is carried out. These conditions should lie within the range of standard test conditions recommended in international standards. Ideally, calibrations should be carried out under reference conditions. As this is not always achievable (e.g. for ambient air pressure) or convenient (e.g. for ambient temperature) a (small) interval around the reference values can be used. The deviations of the calibration factor from its value under reference conditions caused by these deviations should in principle be corrected for. In practice the uncertainty aimed at serves as a criterion as to which influence quantity has to be taken into account by an explicit correction or whether its effect may be incorporated into the uncertainty. The standard test conditions together with the reference conditions recommended by ISO are given in Tables I and II.

Reference direction

The reference direction is the direction, in the co-ordinate system of a dosimeter, with respect to which the angle to the direction of radiation incidence is measured in unidirectional fields.

Reference orientation

The reference orientation of the dosimeter is that for which the direction incident radiation coincides with the reference direction of the dosimeter.

Reference point of a measuring instrument (dosimeter)

The reference point of a measuring instrument is the point to be used in order to position the instrument at the point of test. The reference point should be marked on the instrument by the manufacturer. If this proves impossible, the reference point should be indicated in the accompanying documentation supplied with the instrument.

Note: When calibrating or type-testing a personal dosimeter, the dosimeter and the recommended standard test phantom should be regarded as a unit. The reference point of this unit by convention is the reference point of the dosimeter and this should be positioned at the point of test.

Point of test

The point of test is the point in the radiation field at which the reference point of the instrument is placed for purposes of calibration or type test and at which the conventional true value of the quantity to be measured is known.

TABLE I. RADIOLOGICAL PARAMETERS

Influence quantities	Reference conditions	Standard test conditions (unless otherwise indicated)
Photon energy	^{137}Cs (1)	^{137}Cs (1)
Angle of radiation incidence	Reference orientation	Reference orientation ± 5^0
Contamination by radioactive elements	Negligible	Negligible
Radiation background	Ambient dose equivalent rate $H^*(10)$ 0.1 μSv h^{-1} or less if practical	Ambient dose equivalent rate $H^*(10)$ less than 0.25 μSv h^{-1}

(1) Another radiation quantity may be used if the rated range for the photon energy does not comprise the energy emitted by ^{137}Cs.

TABLE II. OTHER PARAMETERS

Influence quantities	Reference conditions	Standard test conditions (unless otherwise indicated)
Ambient temperature	20^0	18^0C to 22^0C 1)2)
Relative humidity	65%	50% to 75% 1)2)
Atmospheric pressure	101.3 kPa	86 to 106 kPa 1)2)
Stabilisation time	15 min	>15 min
Power supply voltage	Nominal power supply voltage	Nominal power supply voltage ± 3%
Frequency 3)	Nominal frequency	Nominal frequency ± 1%
A.C. power supply	Sinusoidal	Sinusoidal with total wave form harmonic distortion less than 5% 3)
Electromagnetic field of external origin	Negligible	Less than the lowest value that causes interference
Magnetic induction of external origin	Negligible	Less than twice the value of the induction due to the earth's magnetic field
Assembly controls	Set up for normal operation	Set up for normal operation

(1) The actual values of these quantities at the time of test shall be stated.

(2) The values in the table are intended for calibrations performed in temperate climates. In other climates, the actual values of the quantities at the time of calibration shall be stated. Similarly, a lower limit of pressure of 70 kPa may be permitted where instruments are to be used at higher altitudes.

(3) Only for assemblies which are operated from the main voltage supply.

Kerma to Dose Equivalent Conversion Coefficient

The kerma - to - dose equivalent conversion coefficient, h_k, is the quotient of the dose equivalent, H, and the air kerma, K_a, at a point in the radiation field:

$$h_k = H / K_a$$

Any statement of these conversion coefficients requires the statement of the type of dose equivalent, e.g. ambient, directional or personal dose equivalent.

Relative intrinsic error, I(%)

The relative intrinsic error is defined as the quotient, expressed as a percentage, of the error of the indication, H-M, of a quantity and the conventional true value of the measurand, H, when the measuring instrument is subjected to a specified reference radiation under specified reference conditions

$$I(\%) = 100 \cdot (H-M)/H$$

Half value layer (air kerma), HVL

The half value layer (air kerma), HVL, is the thickness of specified material which attenuates the photon beam to an extent such that the air kerma rate is reduced to one half of its original value. In this definition, the contribution of all scattered photon radiation other than any which might be present initially in the beam concerned, is deemed to be excluded.

Effective energy, E_{eff}

The effective energy, E_{eff}, of radiation comprised of X rays with a range of energies, is the energy of those monoenergetic X rays which have the same HVL.

Backscatter factor

The backscatter factor is the ratio of air kerma in front of a phantom to the air kerma at the same position free in air. The field is considered to be unidirectional with a direction of incident perpendicular to the phantom surface.

Traceability

Calibrations should be traceable to an appropriate national standard. This means:

- That each reference instrument used for calibration purposes has itself been calibrated against a reference instrument of higher quality up to the level at which the higher quality instrument is the accepted national standard.
- That the frequency of such calibration, which is dependent on the type, quality, stability, use and environment of the lower quality standard, is such as to establish reasonable confidence that its value will not move outside the limits of its specification between successive calibrations.
- That the calibrations of any instrument against a reference instrument is valid in exact terms only at the time of calibration, and its performance thereafter must be inferred from a knowledge of the factors mentioned above.

The mode of operation of the reference instrument shall be in accordance with its calibration certificate and the instrument instruction manual, e.g. set zero control, warm up time, battery check, application of range or scale correction factors. The time interval between periodic calibrations of the reference instrument shall be within the acceptable period defined by

national regulations. Where no such regulations exist, the time interval should not exceed 3 years. Measurement shall be made regularly, using either a radioactive check source or a calibrated radiation field, to determine that the reproducibility of the reference instrument is within 2% of the certificated value. Corrections shall be applied for the radioactive decay of the source and for changes in air density from the conditions when applicable.

4. CONCLUDING REMARKS

Most of the quantities and terms discussed have been defined by the ICRU and the ISO. The relevant definitions have been extracted from ISO standards [6] and IAEA draft Handbook on Calibration [7] to which reference should be made for further details and explanatory information.

REFERENCES

[1] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Annals of ICRP **21**, 1–3, Pergamon Press, New York (1991).

[2] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS. Determination of Dose Equivalents Resulting from External Radiation Sources, ICRU Report 39, ICRU, Bethesda, MD (1985).

[3] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS. Determination of Dose Equivalents from External Radiation Sources -Part 2, ICRU Report 43, ICRU, Bethesda, MD (1988).

[4] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS. Measurement of Dose Equivalents from External Photon and Electron Radiations, ICRU Report 47, ICRU, Bethesda, MD (1992).

[5] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS. Quantities and Units in Radiation Protection Dosimetry, ICRU Report 39, ICRU, Bethesda, MD (1993).

[6] INTERNATIONAL STANDARDS ORGANIZATION. Reference Photon Radiation: Calibration of Area and Personal Dosemeters and the Determination of their Response as a Function of Photon Energy and Angle of Incidence, ISO/DIS 4037-3.

[7] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA Calibration Handbook.

QUANTITIES AND UNITS FOR EXTERNAL DOSE ASSESSMENT

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Abstract

Three sets of quantities are relevant for occupational radiation protection purposes - physical quantities, protection quantities and operational quantities. *While the* protection quantities *have been defined by the International Commission on Radiological Protection and recommended by the IAEA for dose limitation purposes, they are not measurable. Measurable* operational quantities *have been defined by the International Commission on Radiation Units and Measurements and recommended by the IAEA for practical demonstration of compliance with the dose limits.*

A Joint ICRP/ICRU Task Group has prepared a report, published by each Commission, which reviews the relationship of these quantities in detail. The report includes detailed sets of dose conversion coefficients which are recommended for use in calibration and interpretation of dosimeters and instruments. Additional dose conversion coefficients for reference radiation fields specified by the International Organization for Standardization has been calculated and are recommended for use in dosimeter and instrument calibration.

The result of the work of these international organizations - IAEA, ICRP, ICRU and ISO - is a coherent, harmonized and comprehensive set of data that is recommended for use in occupational radiation protection.

1. INTRODUCTION

Monitoring of workers potentially exposed to external radiation constitutes an integral part of any radiation protection programme and aids in assuring acceptably safe and satisfactory radiological conditions in the workplace. The general objective of operational monitoring programmes is the assessment of workplace conditions and individual exposures. The specific purposes of individual monitoring include:

- Demonstration of good working practices which indicate the adequacy of supervision, training and engineering standards ;
- Estimation of the actual radiation exposure of workers, to demonstrate compliance with prescribed limits; and
- Contribution to the development of safer radiation working practices by evaluating and developing improved operating procedures.

The internationally accepted quantities used for radiation measurement and radiation protection have been defined by the International Commission on Radiological Protection (ICRP) [1] and the International Commission on Radiation Units and Measurements (ICRU) [2]. In addition, the International Standards Organization (ISO) provides guidance on calibration and use of dosimeters and instruments in terms of these quantities [3, 4, 5]. The IAEA uses the recommendations and definitions of the ICRP, ICRU and ISO as a basis for its guidance in radiation protection [6].

Three types of quantities have been defined for radiation measurement and radiation protection:

Physical quantities - Directly measurable quantities defined by the ICRU, and universally accepted for characterization of radiation fields.

Protection quantities - Quantities defined by the ICRP for dose limitation purposes, but are not directly measurable.

Operational quantities - Quantities defined by the ICRU in terms that can be measured. These quantities are used for demonstration of compliance with dose limits recommended by the ICRP and the IAEA.

The relationship between these quantities is illustrated in Figure 1 [7]. A detailed review of this relationship has been conducted by a Joint Task Group of the ICRP and ICRU [7].

2. QUANTITY DEFINITIONS

Physical Quantities

Three physical quantities are of particular relevance for radiation protection:

- Fluence
- Kerma
- Absorbed dose

These quantities are defined as follows:

Fluence

The quantity ϕ is the quotient of dN by da, where dN is the number of particles incident on a sphere of cross section da, thus

$$\phi = \frac{dN}{da}$$

unit of fluence is m^{-2}

Kerma

The quantity K defined as:

$$K = \frac{dE_{tr}}{dm}$$

where dE_{tr} is the sum of the initial kinetic energies of all charged ionizing particles liberated by uncharged ionizing particles in a material of mass dm. The SI unit of kerma is the joule per kilogram ($J.kg^{-1}$), termed gray (Gy).

Absorbed dose

The fundamental dosimetric quantity D, defined as:

$$D = \frac{d\varepsilon}{dm}$$

where $d\varepsilon$ is the mean energy imparted by ionizing radiation to matter in a volume element and dm is the mass of matter in the volume element. The energy can be averaged over any defined volume, the average dose being equal to the total energy imparted in the volume divided by the mass in the volume. The SI unit of absorbed dose is the joule per kilogram ($J.kg^{-1}$), termed the gray (Gy).

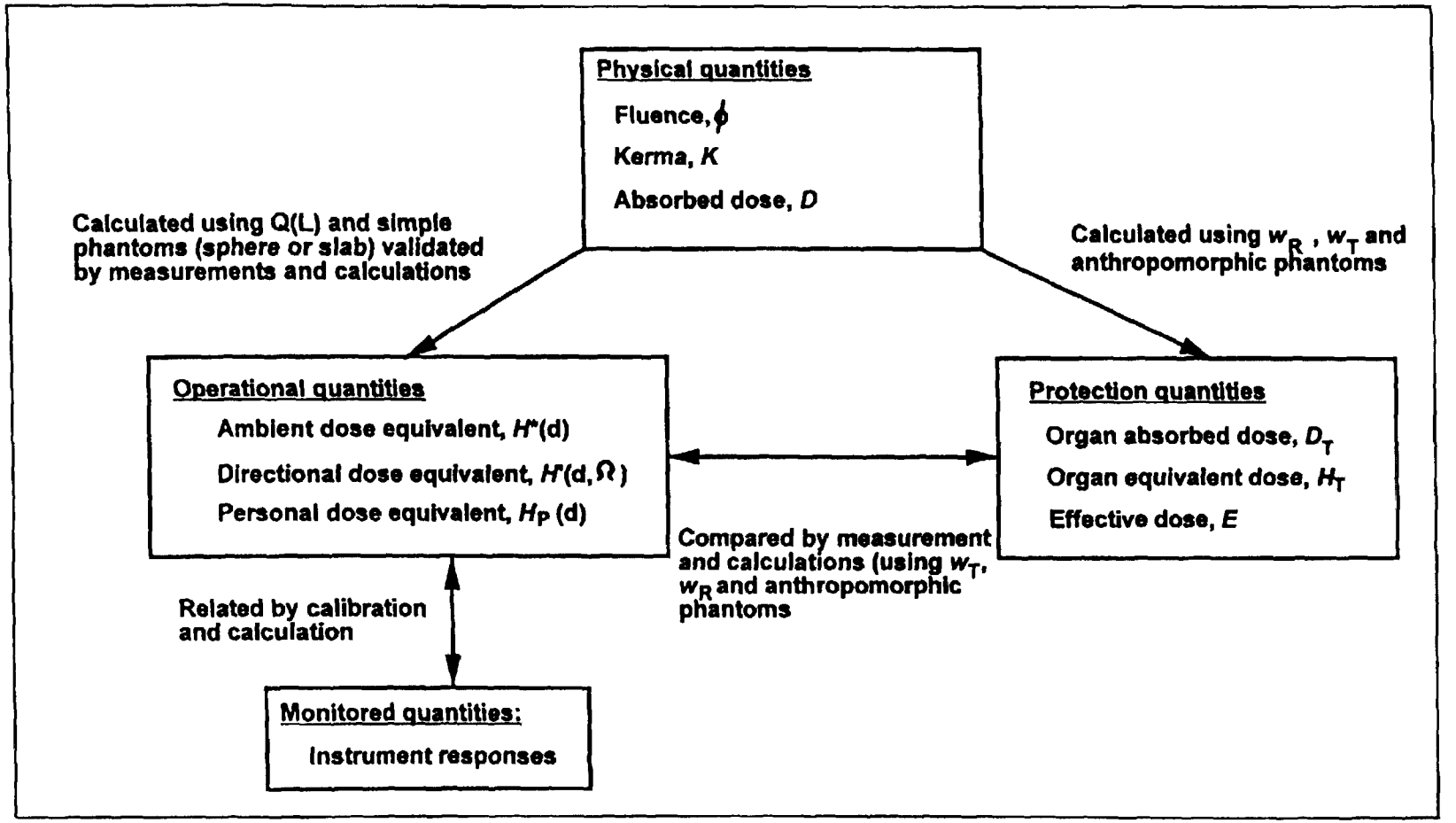

FIG. 1. Relationship of radiation related quantities for external dosimetry purposes [7].

Protection quantities

Primary physical quantities are not used directly for dose limitation purposes because;

- The same dose levels of different radiations (i.e. photons, electrons, neutrons, etc.) do not have the same level of biological effect. The ICRP has defined the ***radiation weighting factor***, w_R, as a measure of the biological effectiveness of different radiations and energies; and,

- Different body tissues have different biological sensitivities to the same radiation type and dose. This has lead the ICRP to introduce the ***tissue weighting factor***, w_T, as a measure of the radiosensitivity of the various organs and tissues.

The dose limits recommended by the ICRP for occupational protection are specified in terms of the protection quantities, ***equivalent dose*** for individual organs and tissues, and ***effective dose*** for the whole body. The definitions of ***equivalent dose*** and ***effective dose*** include w_R to account for the relative effectiveness of different types of radiation in inducing health effects. The definition of ***effective dose*** includes w_T as a weighting factor to account for the differences in radio-sensitivity of the various organs and tissues.

Radiation weighting factors

Multipliers (as follows) of absorbed dose used for radiation protection purposes to account for the relative effectiveness of different types of radiation in inducing health effects.

Type and energy range of radiation[1]		Radiation weighting factor w_R
Photons, all energies		1
Electrons and muons, all energies[2]		1
Neutrons, energy	< 10 keV	5
	10 keV to 100 keV	10
	> 100 keV to 2 MeV	20
	> 2 MeV to 20 MeV	10
	> 20 MeV	5
Protons, other than recoil protons, energy > 2 MeV		5
Alpha particles, fission fragments, heavy nuclei		20

1 The choice of values for other radiations is discussed in Annex A of ICRP 60, and the definition of w_R presented in the Basic Safety Standards [1, 6].

2 Excluding Auger electrons emitted from nuclei to DNA, for which special microdosimetric considerations apply.

Tissue weighting factors

Multipliers (as follows) of the equivalent dose to an organ or tissue used for radiation protection purposes to account for the different sensitivities of different organs and tissues to the induction of stochastic effects of radiation.

Tissue or organ	Tissue weighting factor w_T
Gonads	0.20
Bone marrow (red)	0.12
Colon[a]	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Oesophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Remainder[b]	0.05

[a] Lower large intestine.

[b] For the purposes of calculation, the remainder is composed of adrenal glands, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus and uterus. In those exceptional cases in which a single one of the remainder tissues or organs receives an equivalent dose in excess of the highest dose in any of the twelve tissues or organs for which a weighting factor is specified, a weighting factor of 0.025 shall be applied to that tissue or organ and a weighting factor of 0.025 to the average dose in the rest of the remainder as defined here.

Equivalent dose

The quantity H_T, defined as:

$$H_T = D_T \bullet w_R$$

where D_T is the absorbed dose delivered by radiation type R averaged over a tissue or organ T and w_R is the radiation weighting factor for radiation type R.

When the radiation field is composed of different radiation types with different values of w_R, the equivalent dose is:

$$H_T = \sum_R w_R \bullet D_T$$

The unit of equivalent dose is $J.kg^{-1}$, termed the sievert (Sv).

Effective dose

The quantity E, defined as a summation of the tissue equivalent doses, each multiplied by the appropriate tissue weighting factor:

$$E = \sum_T w_T \bullet H_T$$

where H_T is the equivalent dose in tissue T and w_T is the tissue weighting factor for tissue T.

From the definition of equivalent dose, it follows that:

$$E = \sum_T w_T \sum_R w_R \cdot D_{T,R} = \sum_R w_R \sum_T w_T \cdot D_{T,R}$$

where w_R is the radiation weighting factor for radiation R, and $D_{T,R}$ is the average absorbed dose in the organ or tissue T. The unit of effective dose is $J.kg^{-1}$, termed the sievert (Sv).

Operational quantities

The *protection quantities* are not measurable. This means that they have been defined in a way that does not permit direct measurement in terms of either *equivalent dose* or *effective dose.* Although it is possible, with adequate information about the conditions of exposure (radiation intensity, energy spectrum, irradiation geometry, etc) to calculate the magnitude of exposure in terms of the *protection quantities*, this does not offer a practical option for operational radiation protection.

The ICRU, with the responsibility for providing guidance on issues related to radiation measurement, has defined a set of measurable quantities - *operational quantities* - that can be used to demonstrate compliance with the dose limits recommended by the ICRP and IAEA. These quantities are defined in a way that is intended to provide a reasonably conservative estimate of the *protection quantities*. They are based on the *dose equivalen*t, H, at a specific point in a tissue or tissue equivalent material

$$H = Q \bullet D$$

D is the absorbed dose at a point of tissue or tissue equivalent material, and Q is the linear energy dependent radiation quality factor. Three quantities have been defined for 1) area monitoring and 2) individual monitoring.

Area Monitoring

Ambient dose equivalent (for strongly penetrating radiation)

Directional dose equivalent (for weakly penetrating radiation)

Individual Monitoring

Personal dose equivalent

The quantities for area monitoring have been defined using the concepts of **expansion** and **alignment** in describing the geometrical characteristic of the radiation field. These concepts are illustrated in Figures 2 and 3. **Expansion** (Figure 2) means that the radiation field is large enough to completely and uniformly "illuminate" or irradiate the detector or instrument. The length of the arrows or vectors represents radiation energy, while the field direction is represented by the direction of the arrow. The arrows in Figure 2 b indicated that the field is **isotropic**, or the same from all directions. Figure 3 illustrates the **expanded** and **aligned** field used in the definitions below. As indicated by the direction of the arrows, the **aligned** field is monodirectional. The specific definitions of *ambient dose equivalent, directional dose equivalent*, and *personal dose equivalent* follow.

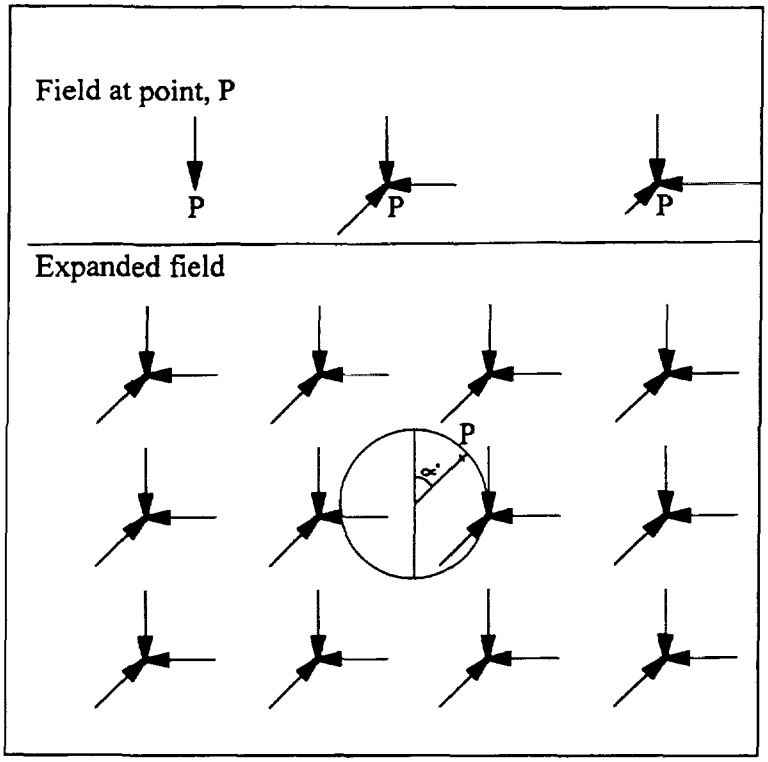

FIG. 1. Expanded field at point P.

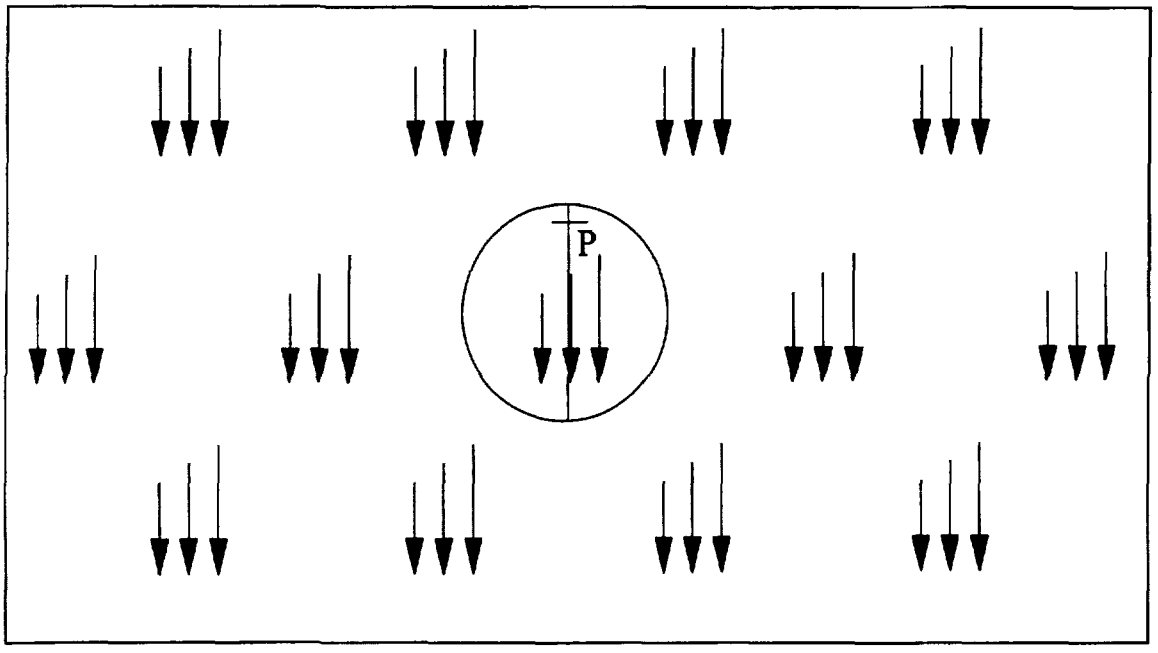

FIG. 2. Expanded and aligned field at point P.

Ambient dose equivalent

The quantity $H^*(d)$ at a point in a radiation field, defined as the dose equivalent that would be produced by the corresponding aligned and expanded field in the ICRU sphere at a depth d on the radius opposing the direction of the aligned field. A depth d = 10 mm is recommended for strongly penetrating radiation.

Directional dose equivalent

The quantity $H'(d,\theta)$ at a point in a radiation field, defined as the dose equivalent that would be produced by the corresponding expanded field in the ICRU sphere at depth d on a radius in a specified direction θ. A depth d = 0.07 mm is recommended for weakly penetrating radiation.

Personal dose equivalent

The quantity defined for both strongly and weakly penetrating radiations as $H_p(d)$, the dose equivalent in soft tissue below a specified point on the body at an appropriate depth d. The relevant depths for the purposes of the Basic Safety Standards are generally d = 10 mm for strongly penetrating radiation and d = 0.07 mm for weakly penetrating radiation.

Dose Conversion Coefficients

The relationship between the three sets of quantities - *physical, protection, and operational* - is obviously complex. Therefore, a Joint Task Group representing the ICRP and ICRU was established to established to conduct a comprehensive review of this relationship, with emphasis on the use of the *operational quantities* as a valid estimate of the *protection quantities* for demonstration of compliance with the dose limits. The Joint Task Group was asked to provide:

- Fluence to Effective Dose calculations for a variety of radiations and energies for reference man and 15 year old, 5 year old, and 3 month old children
- Fluence to ambient dose equivalent, directional dose equivalent, individual dose equivalent (penetrating), and individual dose equivalent (superficial) calculations
- A detailed discussion of the relationship between the two sets of calculations

The report of the Joint Task Group has been published by both Commissions [7], including detailed sets of dose conversion coefficients for both sets of quantities in terms on the relevant *physical quantities*. The dose conversion coefficients are essential to arrive at an adequate understanding of the relationship between the quantities, and to serve as a basis for the calibration and interpretation of dosimeters and instruments, particularly in terms of the *operational quantities*. The Joint Task Group prepared Figure 1 for inclusion in the report as a graphical illustration of the relationship between the three sets of quantities, and the means that are used in practice (measurement, calculation, etc.) to quantify this relationship.

The dose conversion coefficients for both the *protection* and *operational quantities* were based on data published in open the literature. The available data sets were compared and combined to produce single sets of energy dependent dose conversion coefficients for each radiation type (photons, electrons and neutrons) and each quantity. Conversion coefficients for the *protection quantities* where determined using a four step process. Steps 1 and 2 had been carried out by the authors of the data used in the Joint Task Group study in conducting their studies. As indicated below, the Joint Task Group then used the available data sets to obtain single sets of *equivalent dose* conversion coefficients for each of the organs and tissues that

contribute to the *effective dose.* The single set of data is presented in the Joint Task Group report, and was used to calculate the dose conversion coefficients for *effective dose.*

1. Calculate D_T for critical organs and tissues
2. Use w_R to calculate H_T
3. Joint Task group determined single set of H_T values from published data.
4. Using proper tissue weighting convention, calculate E.

Conversion coefficients for the *operational quantities* were obtained in a similar way using published data for each quantity. For the area quantities, the original calculations are performed with radiation transport codes using a 30 cm diameter sphere of ICRU muscle substitute ("ICRU sphere") as illustrated in Figures 2 and 3. Although personal dose equivalent is defined in the body, the value of $H_P(d)$ depends on the location of measurements. Moreover, a water filled slab is normally used as a backscatter phantom for calibration of personal dosimeters. Therefore, calculation of the *personal dose equivalent* dose conversion coefficients were performed using a 30 cm x 30 cm x 15 cm thick slab of ICRU muscle substitute ("ICRU slab") to obtain an unambiguous set of dose conversion coefficients. Muscle substitute is used rather than water for consistency with the calculation of the area quantities, and to obtain a slightly better match with human tissue than is obtained with water. The results of these calculations for photons are presented in Tables I to IV below.

The dose conversion coefficients for *effective dose* are shown in Figure 4. These calculations are presented for five exposure orientations: Anterior-Posterior (AP); Posterior-Anterior (PA); Lateral (LAT); Isotropic (ISO); and Rotational (ROT). The conversion coefficients for *ambient dose equivalent* and *directional dose equivalent* are presented in Figure 5. As noted, the relationship between the *protection quantities* and *operational quantities* is critical to effective use of the *operational quantities* for demonstration of compliance with the appropriate dose limits. Figure 6 presents the relationship between E and $H_P(d)$ for normal photon incidence (AP), and indicates that, in this situation, the *personal dose equivalent* is a valid surrogate for *effective dose.* Figure 7 shows the relationship between E and $H^*(d)$, with the same conclusion. Comprehensive information for neutrons and electrons has been compiled by the Joint Task Group [7].

ISO Reference Radiations

The information presented to this point is only for monoenergetic radiations. However, the fields found in operational situations, and most calibration fields have spectra that are distributed over some energy range. The ISO has specified the conditions that should be used to produce well characterized calibration fields [3]. The characteristics associated with a number of these Reference Radiations are presented in Table V. The photon spectra associated with six of these fields are illustrated in Figures 8 and 9. The dose conversion coefficients recommended by the ICRP/ICRU Joint Task Group have been used together with the reference radiation field spectra to provide spectrum weighted dose conversion coefficients for a number of these fields (Table VI).

TABLE I. CONVERSION COEFFICIENTS FROM AIR KERMA TO $H_P(10,0^O)$ IN AN ICRU SLAB PHANTOM AND ANGULAR DEPENDENCE FACTORS (*PHOTONS*) [7]

Photon energy	H_P $(10,0^o)/K_a$	Ratio H_P $(10,\alpha)/H_P(10,0^o)$					
(MeV)	($Sv.Gy^{-1}$)	0°	15°	30°	45°	60°	75°
0.010	0.009	1.000	0.889	0.556	0.222	0.000	0.000
0.0125	0.098	1.000	0.929	0.704	0.388	0.102	0.000
0.015	0.264	1.000	0.966	0.822	0.576	0.261	0.030
0.0175	0.445	1.000	0.971	0.879	0.701	0.416	0.092
0.020	0.611	1.000	0.982	0.913	0.763	0.520	0.167
0.025	0.883	1.000	0.980	0.937	0.832	0.650	0.319
0.030	1.112	1.000	0.984	0.950	0.868	0.716	0.411
0.040	1.490	1.000	0.986	0.959	0.894	0.760	0.494
0.050	1.766	1.000	0.988	0.963	0.891	0.779	0.526
0.060	1.892	1.000	0.988	0.969	0.911	0.793	0.561
0.080	1.903	1.000	0.997	0.970	0.919	0.809	0.594
0.100	1.811	1.000	0.992	0.972	0.927	0.834	0.612
0.125	1.696	1.000	0.998	0.980	0.938	0.857	0.647
0.150	1.607	1.000	0.997	0.984	0.947	0.871	0.677
0.200	1.492	1.000	0.997	0.991	0.959	0.900	0.724
0.300	1.369	1.000	1.000	0.996	0.984	0.931	0.771
0.400	1.300	1.000	1.004	1.001	0.993	0.955	0.814
0.500	1.256	1.000	1.005	1.002	1.001	0.968	0.846
0.600	1.226	1.000	1.005	1.004	1.003	0.975	0.868
0.800	1.190	1.000	1.001	1.003	1.007	0.987	0.892
1	1.167	1.000	1.000	0.996	1.009	0.990	0.910
1.5	1.139	1.000	1.002	1.003	1.006	0.997	0.934
3	1.117	1.000	1.005	1.010	0.998	0.998	0.958
6	1.109	1.000	1.003	1.003	0.992	0.997	0.995
10	1.111	1.000	0.998	0.995	0.989	0.992	0.966

TABLE II. CONVERSION COEFFICIENTS FROM AIR KERMA TO $H_P(0.07,0^O)$ IN AN ICRU SLAB PHANTOM AND ANGULAR DEPENDENCE FACTORS (PHOTONS) [7]

Photon energy	$H_P(0.07,0^o)/K_a$	Ratio $H_P(0.07,\alpha)/H_P(0.07,0^o)$					
(MeV)	(Sv Gy)	0°	15°	30°	45°	60°	75°
0.005	0.750	1.000	0.991	0.956	0.895	0.769	0.457
0.010	0.947	1.000	0.996	0.994	0.987	0.964	0.904
0.015	0.981	1.000	1.000	1.001	0.994	0.992	0.954
0.020	1.045	1.000	0.996	0.996	0.987	0.982	0.948
0.030	1.230	1.000	0.990	0.989	0.972	0.946	0.897
0.040	1.444	1.000	0.994	0.990	0.965	0.923	0.857
0.050	1.632	1.000	0.994	0.979	0.954	0.907	0.828
0.060	1.716	1.000	0.995	0.984	0.961	0.913	0.837
0.080	1.732	1.000	0.994	0.991	0.966	0.927	0.855
0.100	1.669	1.000	0.993	0.990	0.973	0.946	0.887
0.150	1.518	1.000	1.001	1.005	0.995	0.977	0.950
0.200	1.432	1.000	1.001	1.001	1.003	0.997	0.981
0.300	1.336	1.000	1.002	1.007	1.010	1.019	1.013
0.400	1.280	1.000	1.002	1.009	1.016	1.032	1.035
0.500	1.244	1.000	1.002	1.008	1.020	1.040	1.054
0.600	1.220	1.000	1.003	1.009	1.019	1.043	1.057
0.800	1.189	1.000	1.001	1.008	1.019	1.043	1.062
1.000	1.173	1.000	1.002	1.005	1.016	1.038	1.060

TABLE III. CONVERSION COEFFICIENTS FOR THE AMBIENT DOSE EQUIVALENT, H*(10), AND DIRECTIONAL DOSE EQUIVALENT, H'(0.07,0°), FROM PHOTON KERMA FREE-IN-AIR [7]

Photon energy (keV)	$H^*(10, 0°)/K_a$ (Sv.Gy^{-1})	$H'(0.07, 0°)/K_a$ (Sv.Gy^{-1})
10	0.008	0.95
15	0.26	0.99
20	0.61	1.05
30	1.10	1.22
40	1.47	1.41
50	1.67	1.53
60	1.74	1.59
80	1.72	1.61
100	1.65	1.55
150	1.49	1.42
200	1.40	1.34
300	1.31	1.31
400	1.26	1.26
500	1.23	1.23
600	1.21	1.21
800	1.19	1.19
1000	1.17	1.17
1500	1.15	1.15
2000	1.14	1.14
3000	1.13	1.13
4000	1.12	1.12
5000	1.11	1.11
6000	1.11	1.11
8000	1.11	1.11
10000	1.10	1.10

TABLE IV. PHOTON CONVERSION COEFFICIENTS FROM AIR KERMA TO H'(0.07, 0^{O}), AND ANGULAR-DEPENDENCE FACTORS UP TO 180^{O} [7]

E (MeV)	$H'(0.07, 0^0)/K_a$ (Sv.Gy^{-1})	Ratio $H'(0.07,\alpha^0)/H'(0.07, 0^0)$ for $\alpha^0 = 0^0$ to 180^0							
		0^0	15^0	30^0	45^0	60^0	75^0	90^0	180^0
0.005	0.76	1.00	0.96	0.87	0.79	0.41	0.00	0.00	0.00
0.010	0.95	1.00	0.99	0.98	0.98	0.96	0.89	0.19	0.00
0.020	1.05	1.00	1.00	0.99	1.00	1.00	0.98	0.54	0.00
0.030	1.22	1.00	0.99	0.99	0.99	0.98	0.94	0.62	0.00
0.050	1.53	1.00	0.99	0.98	0.98	0.97	0.92	0.69	0.02
0.100	1.55	1.00	0.99	0.99	0.99	0.98	0.94	0.77	0.05
0.150	1.42	1.00	0.99	0.99	0.99	0.99	0.97	0.87	0.07
0.300	1.31	1.00	1.00	1.00	1.00	1.02	1.00	0.89	0.10
0.662	1.20	1.00	1.00	1.00	1.00	1.00	0.98	0.89	0.18
1.25	1.16	1.00	1.00	1.00	1.00	1.00	0.98	0.90	0.30
2	1.14	1.00	1.00	1.00	1.00	1.00	0.98	0.90	0.39
3	1.13	1.00	1.00	1.00	1.00	1.00	0.98	0.90	0.46
5	1.11	1.00	1.00	1.00	1.00	1.00	0.98	0.91	0.54
10	1.10	1.00	1.00	1.00	1.00	1.00	0.98	0.94	0.63

TABLE V. SPECIFICATION FOR ISO PHOTON REFERENCE RADIATIONS, NARROW SPECTRUM SERIES (X RAYS AND GAMMA RADIATIONS) [3]

FLUORESCENT RADIATIONS				
Mean energy (keV)	Tube high voltage (kVp)	Total primary filtration ($g.cm^{-2}$)	Radiator	Secondary filtration ($g.cm^{-2}$)
9.88	60	Al 0.135	Germanium	GaO 0.020
17.4	80	Al 0.27	Molybdenum	Zr 0.035
23.1	100	Al 0.27	Cadmium	Ag 0.053
25.2	100	Al 0.27	Tin	Ag 0.071
30.9	100	Al 0.27	Caesium	TeO_2 0.132

FILTERED X RAYS								
Mean energy[1] (keV)	Resolution R_e (%)	Constant potential[2] (kV)	Additional filtration[3]			1st HVL	2nd HVL	Homogeneity coefficient
			Pb (mm)	Sn (mm)	Cu (mm)	(mm of copper)		
33	30	40	--	--	0.21	0.09	0.12	0.75
48	36	60	--	--	0.6	0.24	0.29	0.83
65	31	80	--	--	2.0	0.59	0.64	0.93
83	28	100	--	--	5.0	1.11	1.2	0.93
100	27	120	--	1.0	5.0	1.73	1.74	0.99
118	36	150	--	2.5	--	2.4	2.58	0.93
163	32	200	1.0	3.0	2.0	3.9	4.29	0.91
205	30	250	3.0	2.0	--	5.2	5.2	1.00
248	34	300	5.0	3.0	--	6.2	--	--

(1) The value of the mean energy adopted with a tolerance of α 3%.
(2) The constant potential is measured under load.
(3) The total filtration includes, in each case, the fixed filtration adjusted to 4 mm of aluminum.

GAMMA RADIATIONS		
(Mean) Energy (keV)	Gamma source	First HVL Cu (mm)
662	Caesium-137	10.3
1250	Cobalt-60	14.6

TABLE VI. CONVERSION COEFFICIENTS FROM AIR KERMA FOR $H_P(10)$ AND HP(0.07) IN AN ICRU SLAB FOR ISO PHOTON REFERENCE RADIATIONS [5]

Radiation Qualities		$H_p(10, \alpha)/K_a$				$H_p(0.07, \alpha)/K_a$			
Reference Radiation[1]	Mean Energy keV	$\alpha = 0^o$	$\alpha = 20^o$	$\alpha = 40^o$	$\alpha = 60^o$	$\alpha = 0^o$	$\alpha = 20^o$	$\alpha = 40^o$	$\alpha = 60^o$
F60	9.88	--	--	--	--	0.951	0.946	0.941	0.919
F80	17.4	0.449	0.420	0.342	0.184	1.01	1.01	1.00	0.987
F100a	23.1	0.778	0.757	0.678	0.484	1.09	1.08	1.08	1.06
F100b	25.2	0.879	0.861	0.782	0.583	1.12	1.12	1.11	1.09
F100c	30.9	1.15	1.13	1.04	0.830	1.25	1.24	1.22	1.17
N40	33	1.22	1.20	1.10	0.89	1.29	1.28	1.26	1.23
N60	48	1.68	1.64	1.53	1.26	1.57	1.56	1.52	1.42
N80	65	1.89	1.86	1.74	1.46	1.72	1.71	1.66	1.54
N100	83	1.87	1.85	1.74	1.48	1.71	1.71	1.66	1.56
N120	100	1.80	1.78	1.69	1.45	1.67	1.65	1.62	1.53
N120	118	1.72	1.71	1.63	1.41	1.61	1.60	1.58	1.50
N200	161	1.57	1.55	1.49	1.34	1.49	1.49	1.48	1.43
N250	205	1.48	1.47	1.42	1.30	1.42	1.42	1.41	1.39
N300	248	1.42	1.42	1.38	1.27	1.37	1.38	1.37	1.36
^{137}Cs	662	1.21	1.21	1.20	1.20	1.21	1.21	1.22	1.23
^{60}Co	1250	1.15	1.15	1.15	1.15	1.15	1.15	1.16	1.20

(1) F - Fluorescent series

N - Narrow Spectrum Series
Number denotes Tube Potential

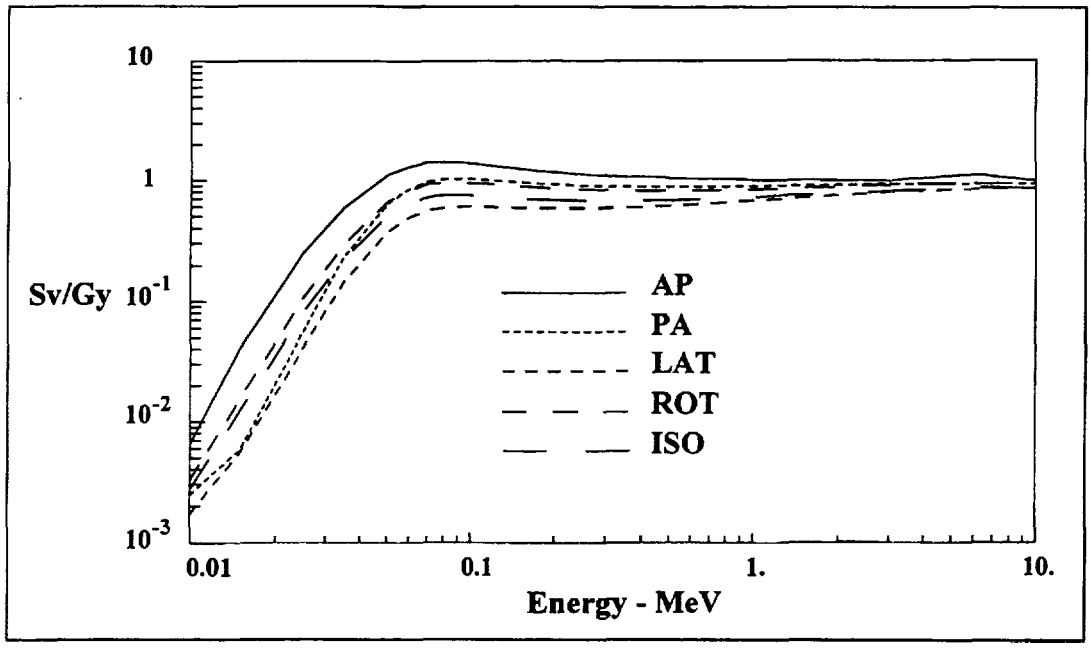

FIG. 3 Photon dose conversion coefficients for effective dose, E.

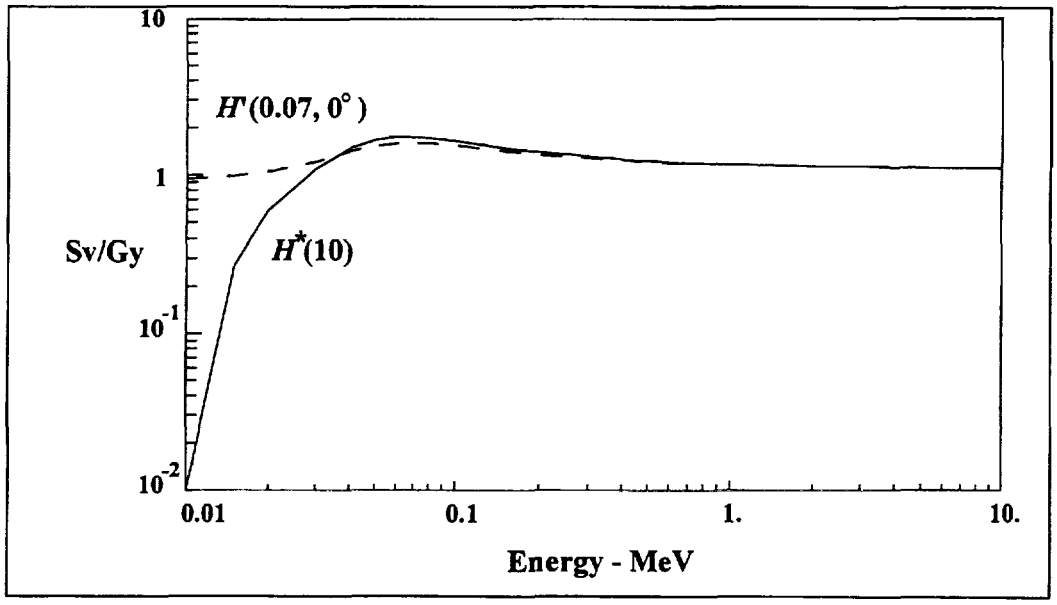

FIG. 4. Photon dose conversion coefficients for the operational quantities for area monitoring.

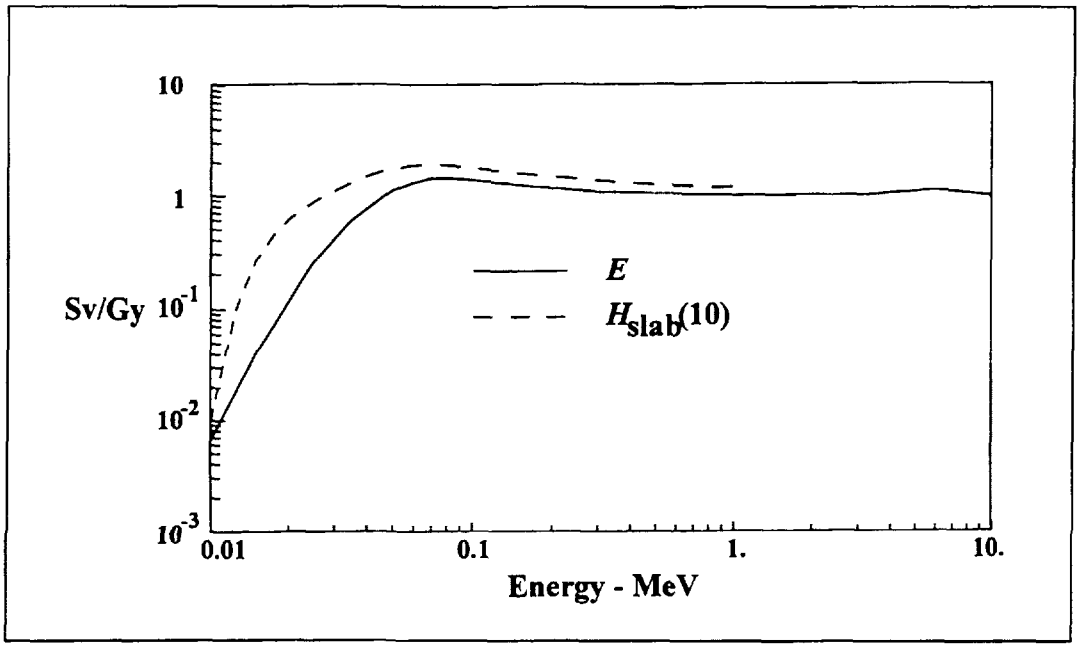

FIG. 5. Photon dose conversion coefficients for E and H_{slab}.

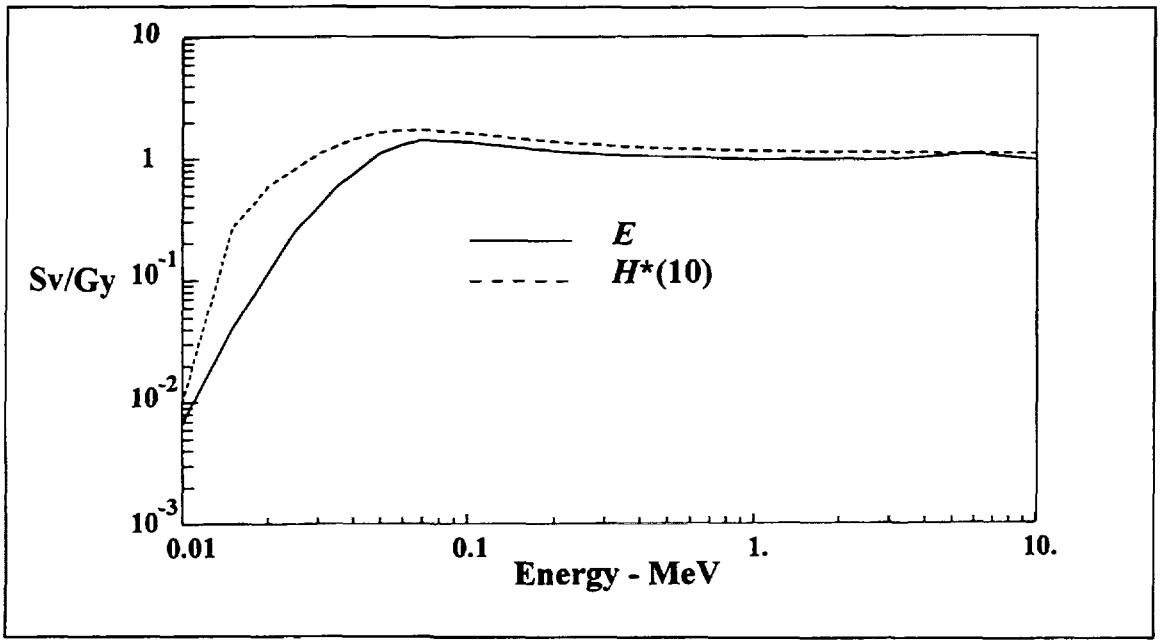

FIG. 6. Photon dose conversion coefficients for E and H^*

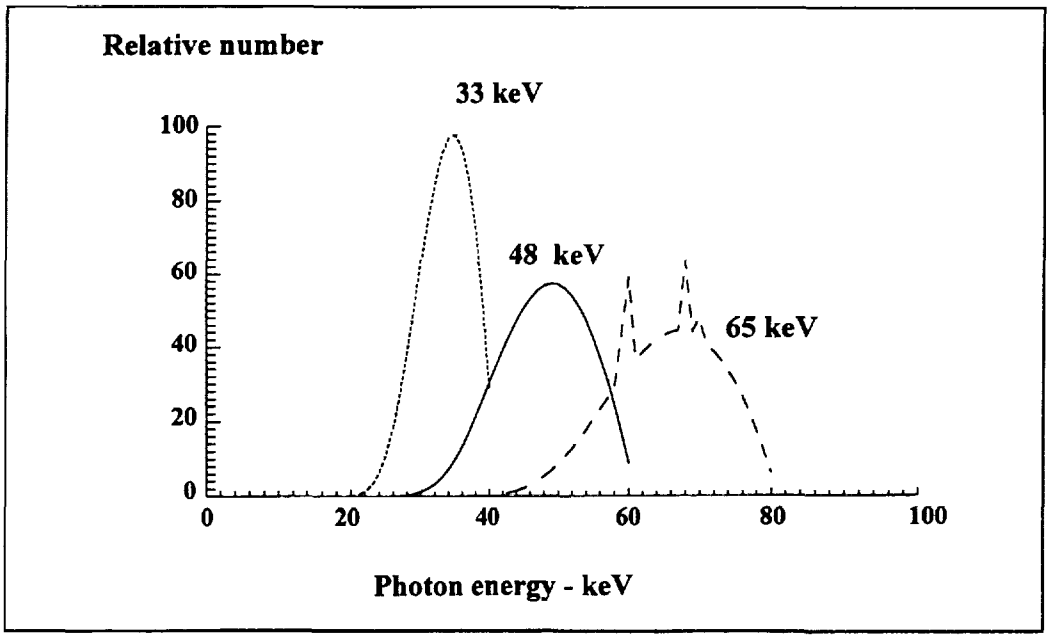

FIG. 7. ISO reference photon radiations for calibration (33 keV, 48 keV and 65 keV).

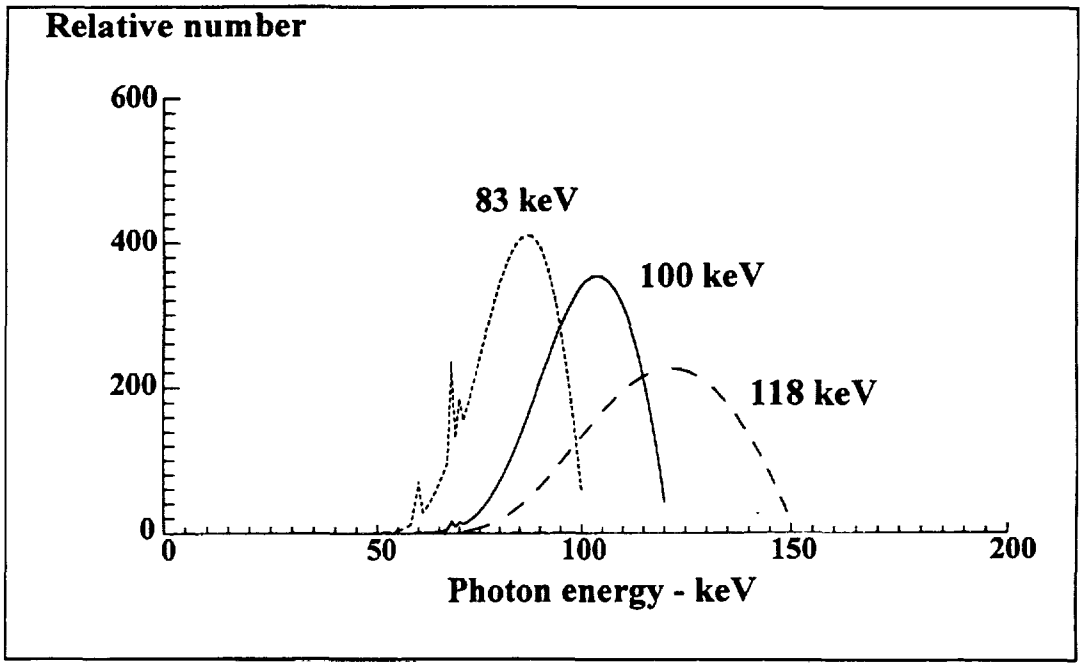

FIG. 8. ISO reference photon radiation for calibration (83 keV, 100 keV and 118 keV).

REFERENCES

[1] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the ICRP, Publication 60, Oxford, Pergamon Press (1991).

[2] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Quantities and Units in Radiation Protection Dosimetry, ICRU Report 51, Bethesda, MD (1993).

[3] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Characteristics of the Radiations and their Methods of Production, X and Gamma Reference Radiations for Calibrating Dosemeters and Dose Ratemeters and for Determining Their Response as a Function of Photon Energy, ISO 4037/Part 1. Geneva (1997).

[4] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Dosimetry of X and Gamma Reference Radiations for Radiation Protection over the Energy Range from 8 keV to 1.3 MeV and from 4 MeV to 9 MeV, X and Gamma Reference Radiations for Calibrating Dosemeters and Dose Ratemeters and for Determining Their Response as a Function of Photon Energy, ISO 4037/Part 2. (Approved for publication).

[5] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, Reference Photon Radiations: Calibration of Area and Personal Dosemeters and the Determination of their Response as a Function of Photon Energy and Angle of Incidence X and Gamma Reference Radiations for Calibrating Dosemeters and Dose Ratemeters and for Determining Their Response as a Function of Photon Energy, ISO 4037/Part 3. (Approved for publication).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, IAEA Safety Series No. 115, Vienna (1996).

[7] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Conversion Coefficients for Use in Radiological Protection Against External Radiation, Report of the Joint Task Group, ICRP Report 74 (1997), ICRU Report 57 (1997).

WORKPLACE PHOTON RADIATION FIELDS

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Abstract

The knowledge of workplace radiation fields is essential for measures in radiation protection Information about the energy and directional distribution of the incident photon radiation was obtained by several devices developed by the National Radiation Protection Board, United Kingdom, by the Statens Strålskyddsinstitut, Sweden, together with EURADOS and by the Physikalisch-Technische Bundesanstalt, Germany The devices are described and some results obtained at workplaces in nuclear industry, medicine and science in the photon energy range from 20 keV to 7 MeV are given

1. INTRODUCTION

Based to a large extent on the radiological protection principles developed by the International Commission on Radiological Protection (ICRP) [1], the Basic Safety Standards Directive of the European Union [2] and the IAEA International Basic Safety Standards [3] express requirements for dose limitation and optimisation in terms of the protection quantities effective dose and equivalent dose. Operational quantities are recommended for monitoring purpose, which are intended to be generally conservative but which do not overestimate the protection quantity by too great a margin. For individual monitoring for penetrating radiation we are concerned with the operational quantity personal dose equivalent, $H_p(10)$, and for the purpose of this paper, photon radiation.

In practical situations personal dosimeters are required to estimate the quantity of interest with reasonable accuracy for the workplace photon radiation field, which, in principle, may be distributed over all angles and for the energy range 15 keV to 7 MeV. We may generally take this as meaning that the dosimeter indication is within a factor of 1.5 of the conventional true value (ICRP Publication 75) [4].

There are several reasons for making measurements of the energy and angle distributions of photon workplace fields. One reason is to assess the suitability of the dosimetric model to estimate the protection quantity effective dose (see ICRP Publication 75, paragraph 239). This was the main reason for the two investigations of NRPB reported here. Figure 1 shows the relationships of $H_p(10)$ and effective dose. At photon energies less than 100 keV there is a progressive overestimate by $H_p(10)$ of effective dose (E), reaching, for the anterior-posterior (AP) direction, a factor of five at 20 keV.

A second reason is the consideration of the performance of practical designs of personal dosimeter in estimating $H_p(10)$. Practical dosimeters do not have ideal performance characteristics. Examples of the energy and angle response characteristics of personal dosimeters are shown in Figures 2 and 3 (refer also to the presentations at this meeting by Trousil and Thompson). This was the main purpose of the investigations by SSI (Statens Strålskyddsinstitut) and EURADOS (European Radiation Dosimetry Group) some of whose results are given in Section 3.

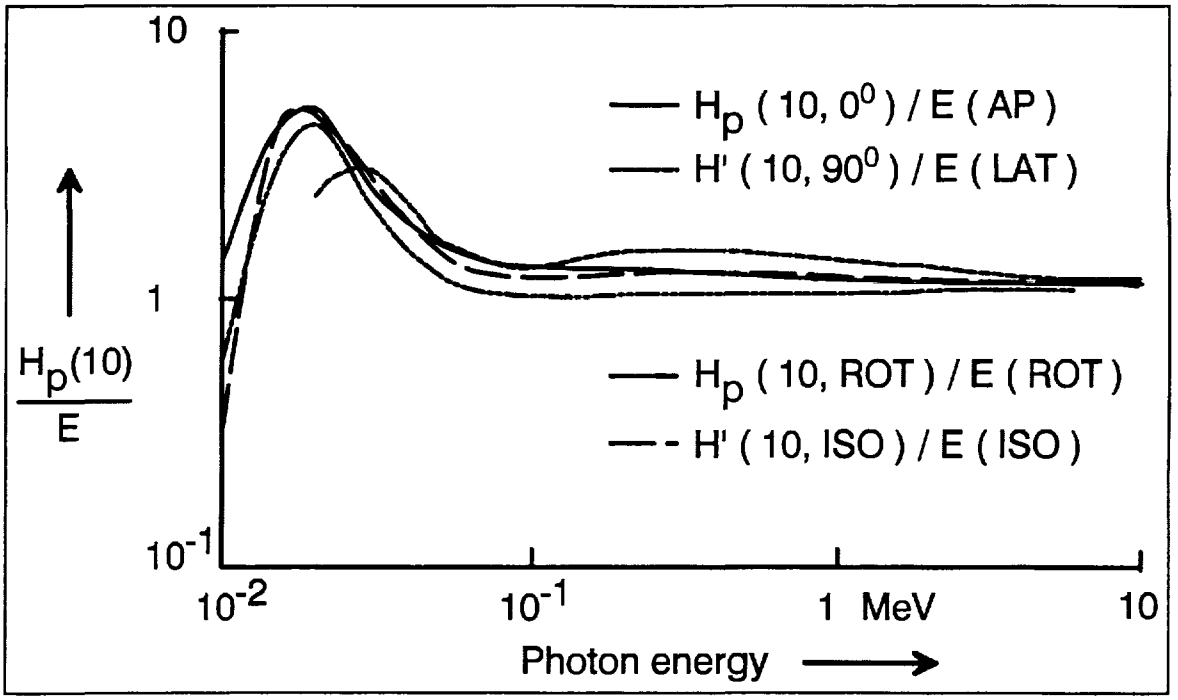

FIG. 1. E/H_p – Various geometries.

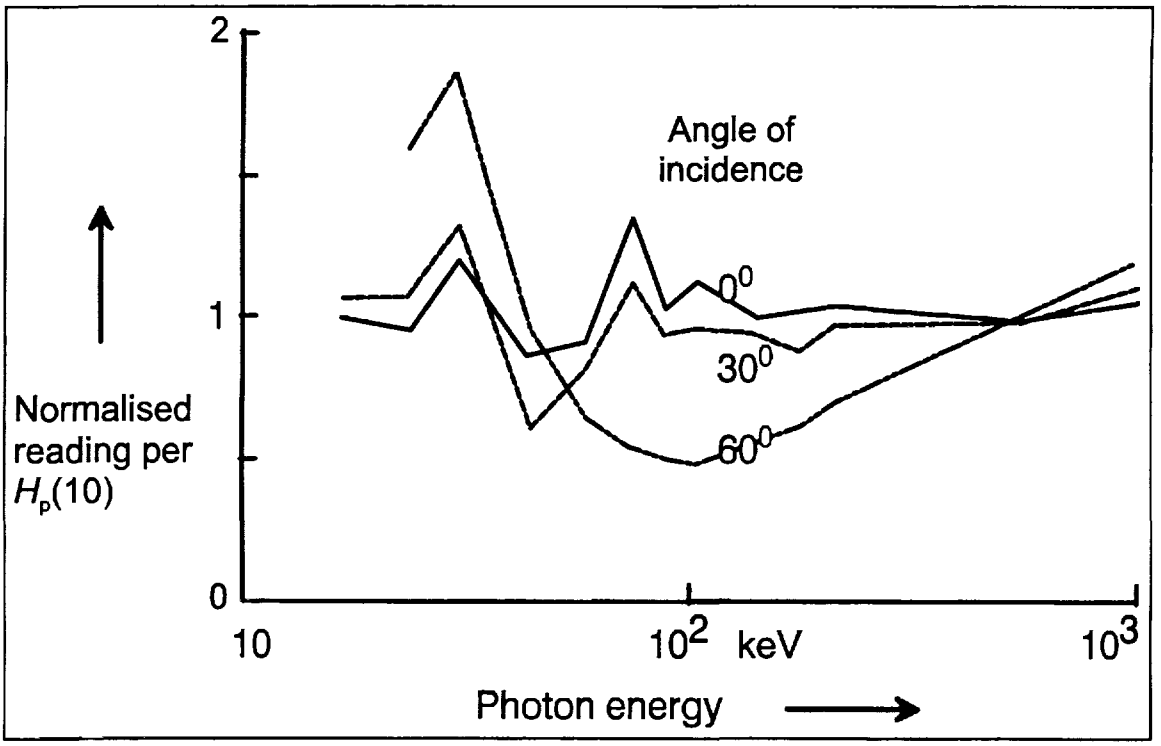

FIG. 2. Film badge response (NRPB – R236 algorithm).

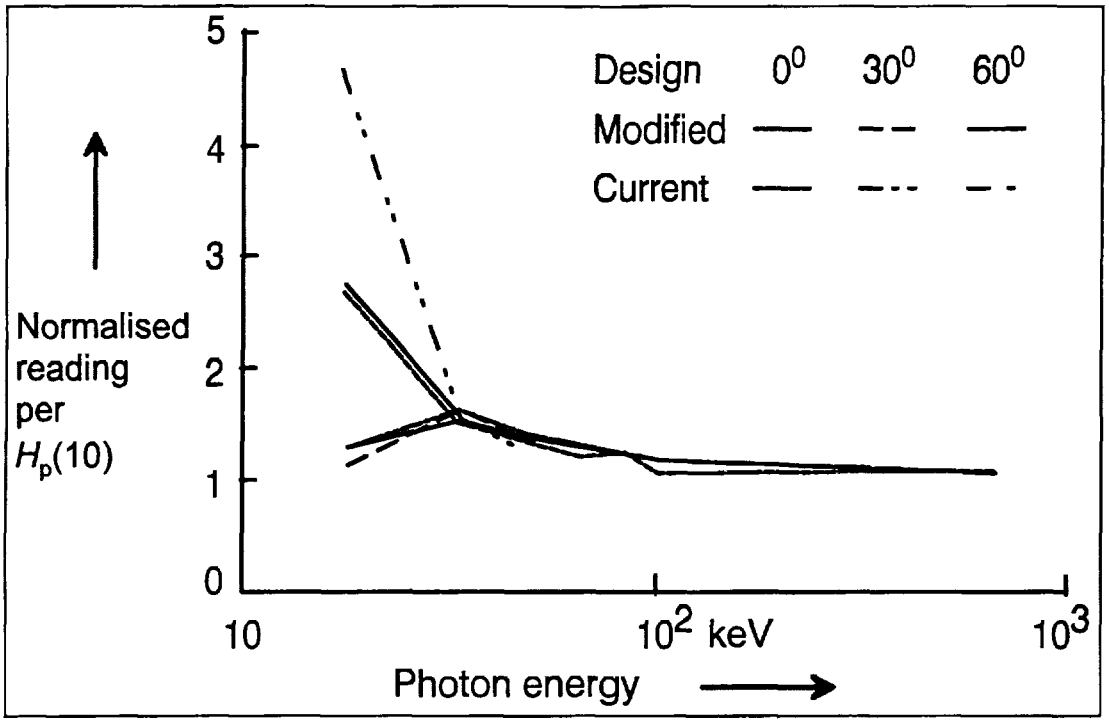

FIG. 3. NRPB TLD response.

The third reason, and the purpose for the PTB investigations reported in section 4, is to assess the suitability or adequacy of the dosimeter performance requirements. In the case of the PTB investigations the angle performance requirement in particular was under consideration.

In summary, good knowledge of workplace fields i.e. data on energy spectra, angular distributions, dose rates, worker orientation and occupancy factors, is useful in order to assess the dosimetric model used to calculate $H_p(10)$; predict the performance of practical, non ideal dosimeters; optimise the design of dosimeters; frame the dosimeter performance requirements sensibly; and assist the retrospective interpretation of dosimeter readings if required.

2. NRPB MEASUREMENTS

NRPB has performed a study on practical fields which was supported by the European Commission (EC) [5,6]. At that time the decision was made to use an array of filtered Geiger Müller detectors connected to portable scalers to characterise the radiation field. This was because multichannel analysers, which would be required for true spectrometry, were of limited portability and were expensive. This meant we could not use them in difficult access areas and we could not risk them becoming contaminated. We understood the limitations of using Geiger Müller detectors, in that we would get very limited information, but it seemed to us that portability, ease of use and low cost were more important.

The unit that was constructed is shown in Figure 4. Filters were designed for each detector to produce energy data. The measured responses are shown in Figure 5. An algorithm was produced to extract useful data from the measured count rates. This is illustrated in Figure 6.

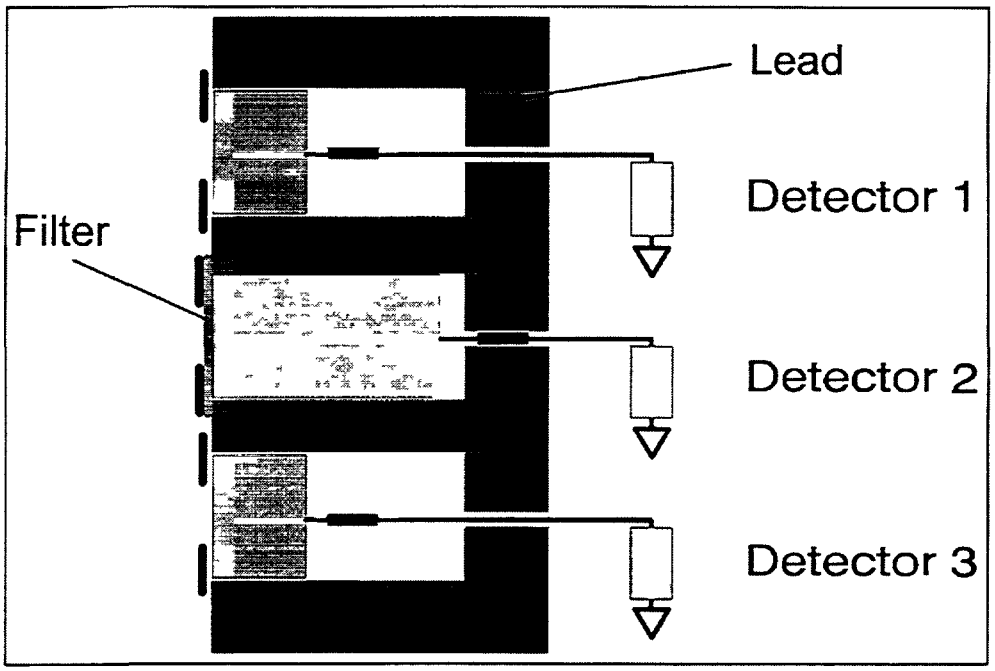

FIG. 4 Filtered Geiger Muller and angle spectrometer.

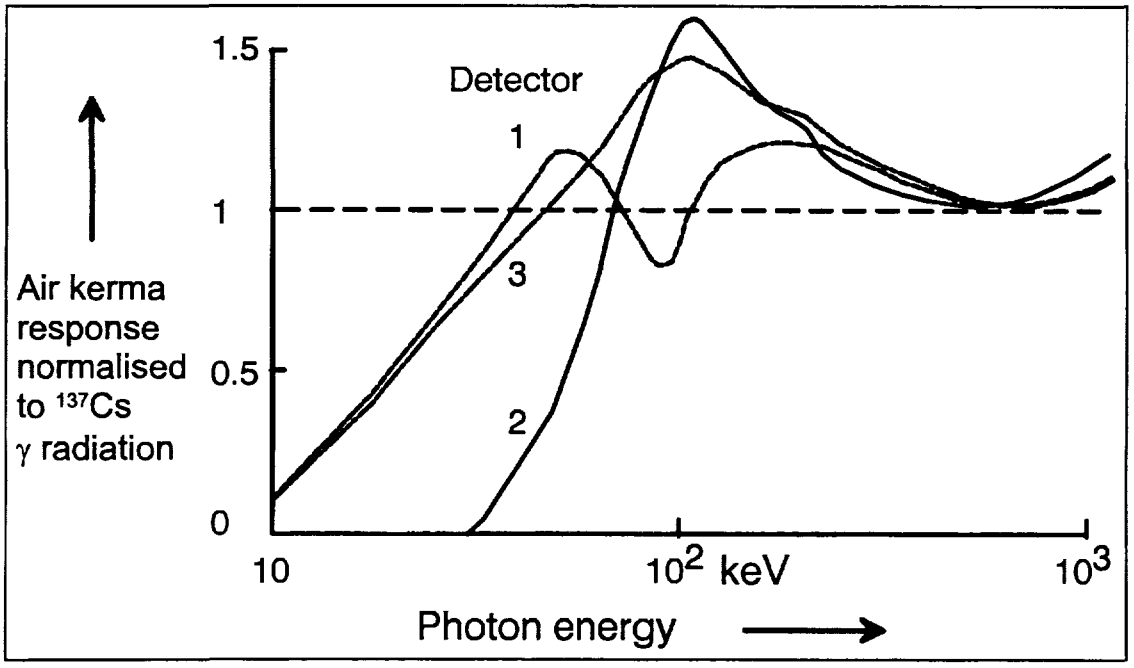

FIG. 5. Response of filtered Geiger Muller spectrometer.

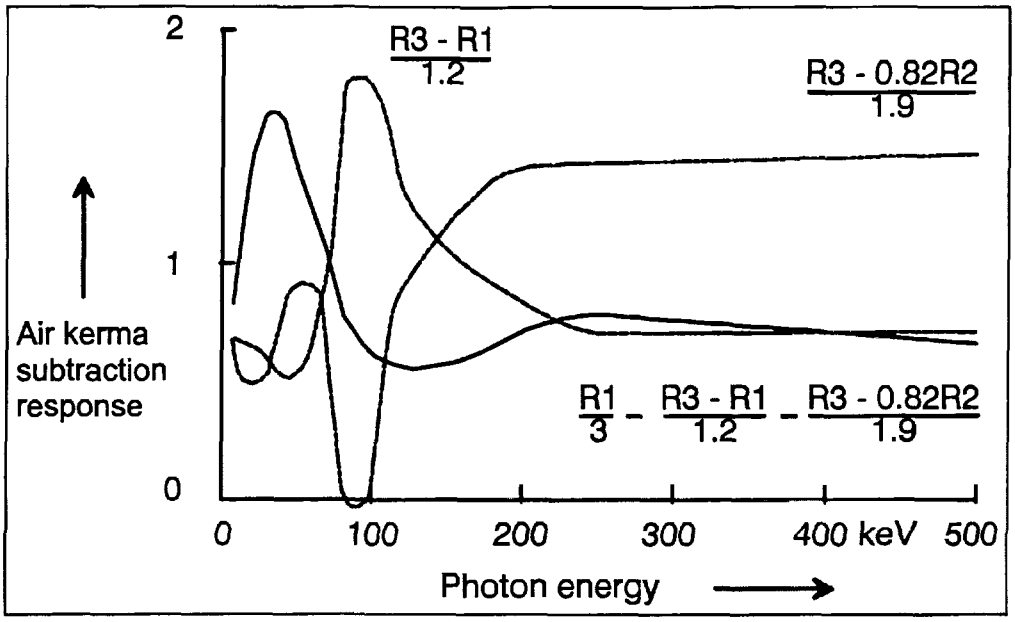

FIG. 6. Algorithm of Geiger Müller unit.

The design of the lead shielding was chosen to give, essentially, a 90° total viewing angle. In this way, 6 directions for each measurement position, could be chosen, 4 in the horizontal plane and, 2 in the vertical, making it possible to assess the radiation spectrum over the whole of the 4π solid angle. Additional information was provided for the dominant exposure direction by covering one of the detectors with an additional 6 mm thick lead filter. This produced a measure of the very penetrating component as the thickness of lead corresponds to the half value layer for 400 keV radiation.

The equipment was taken to a variety of establishments. These included:

- BNFL, Sellafield (Fuel manufacturer and reprocessing)
- Amersham International (Radiopharmaceuticals)
- David Brown Gears (Industrial radiography)
- Gloucester Royal Hospital (Hospital)

The method of use was to identify where a worker was likely to spend a reasonable fraction of the day in one position. A typical example is at a glove box where the worker would be working with material inside the glove box. The spectrometer head was positioned 1 m above the ground and the count rate was measured for each detector for each of the 6 directions. An additional measurement was made with the thick lead absorber in position for the dominant direction of irradiation.

An early observation was that radiation fields could be complicated in terms of their angular distribution, i.e. the worker was irradiated significantly from a variety of directions, some of which were unexpected, and also that, on some occasions, AP irradiation was not dominant. As an example one worker position was dominated not by radiation from the material on which he was working but on radiation incident from directly behind him which was coming in through the window from a building 20 metres away. In another example the radiation source, ^{60}Co, was in a well shielded enclosure and the main source of exposure was low energy radiation (~ 100 keV) from the maze entrance, which was at 90° to the source position.

A large number of measurements was performed with this equipment. One set is given as an example and is shown in Tables 1 to IV below. The following conclusions can be drawn:-

- $H_p(10)$ normally overestimates E (i.e. in about 90% of the measurements)
- $H_p(10)$ is normally within ± 25% of E (i.e. in about 78% of the measurements)
- The biggest influence on the ratio of $H_p(10)$ to E is the angular distribution, not the energy spectrum.

TABLE I. RESULTS FOR VARIOUS DOSE QUANTITIES : BNFL

Position	Worker orientation	Estimated values per unit air kerma, $Sv.Gy^{-1}$		
		E	$H^*(10)$	$H_p(10)$
1	AP	1.05	1.21	1.21
2	AP	1.09	1.25	1.23
3	LAT	0.67	1.25	0.95
4	AP, PA	0.90	1.27	0.79
5	AP, PA, LAT	0.92	1.26	0.73
6, 8, 10, 11, 13, 15	AP	1.07	1.21	1.21
9	ROT	0.82	1.21	0.80
12	AP, LAT, FH	0.89	1.21	1.07

TABLE II. RESULTS FOR VARIOUS DOSE QUANTITIES: AMERSHAM INTERNATIONAL

Position	Worker orientation	Estimated values per unit air kerma, $Sv\ Gy^{-1}$		
		E	H*(10)	$H_p(10)$
1	AP	1.11	1.25	1.25
2	AP	1.43	1.63	1.63
3	AP	1.07	1.21	1.21
4	AP	1.11	1.25	1.25
5	AP	1.32	1.50	1.50

TABLE III. RESULTS FOR VARIOUS DOSE QUANTITIES : DAVID BROWN GEARS

Position	Worker orientation	Estimated values per unit air kerma, $Sv.Gy^{-1}$		
		E	H*(10)	Hp(10)
1	ROT	0.55	1.24	0.57
2	ROT	0.84	1.27	0.80
3	ROT	0.86	1.34	0.80
4	ROT	0.90	1.46	0.80
5	ROT	0.89	1.42	0.80
6	ROT	0.92	1.50	0.80

TABLE IV. RESULTS FOR VARIOUS DOSE QUANTITIES : GLOUCESTER HOSPITAL

Position	Worker orientation	Estimated values per unit air kerma, $Sv.Gy^{-1}$		
		E	*H*(10)*	*Hp(10)*
1	AP	1.11	1.26	1.26

The original project created sufficient interest for the EC to sponsor a further contract starting in 1993 [7,8]. By this time the capability of laptop personal computers had increased considerably and their cost had reduced. Manufacturers had introduced a range of add on cards which were capable of driving sodium iodide scintillation detectors and performing pulse height analysis. We decided to take advantage of this by building a directional sodium iodide based spectrometer which could be used to generate more detailed spectra. The size of the unit was limited by the maximum acceptable weight, 15 kg, which, in turn, demanded a balance between detector size and thickness of the surrounding shielding and collimator. The final design is shown in Figure 7. The crystal was 19 mm in diameter and 25 mm long.

Again this unit was designed to give an approximately 90° viewing angle and was used in the same way i.e. 4 measurements made in the horizontal plane and 2 in the vertical. This method covers approximately 78 % of the 4π solid angle. Attempts were made to ensure that the obvious sources of radiation did not lie at angles of 45° to the reference orientations.

The data at each site were recorded as raw spectra which were then analysed by a spectrum stripping programme. This was based on Monte Carlo simulations of the complete detector, including the shielding, and generated a fluence spectrum incident on the detector from each of the 6 directions. Such a process is not perfect and the detector was, of necessity, rather small for measurements above 1 MeV. However when the detector was tested using collimated beams of known radiation spectra up to 1.25 MeV (^{60}Co) agreement was good.

Some examples of observed spectra are given in Figures 8, 9 and 10.

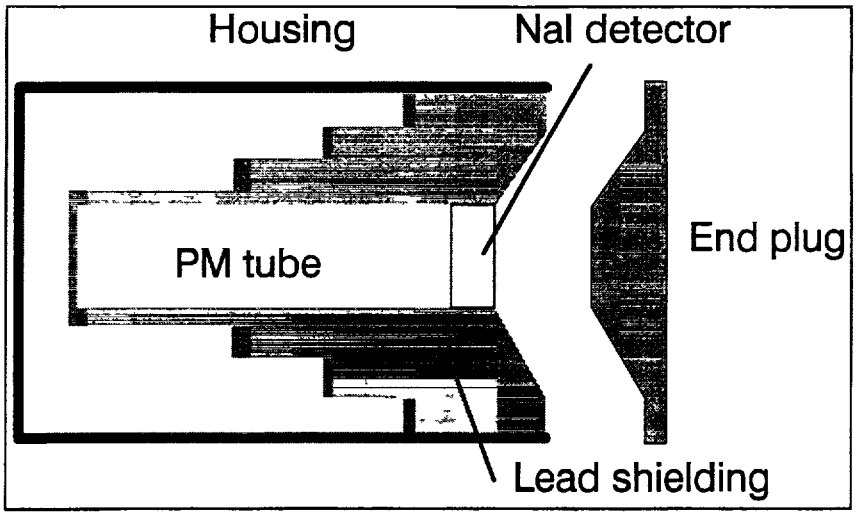

FIG. 7. Sodium iodide spectrometer.

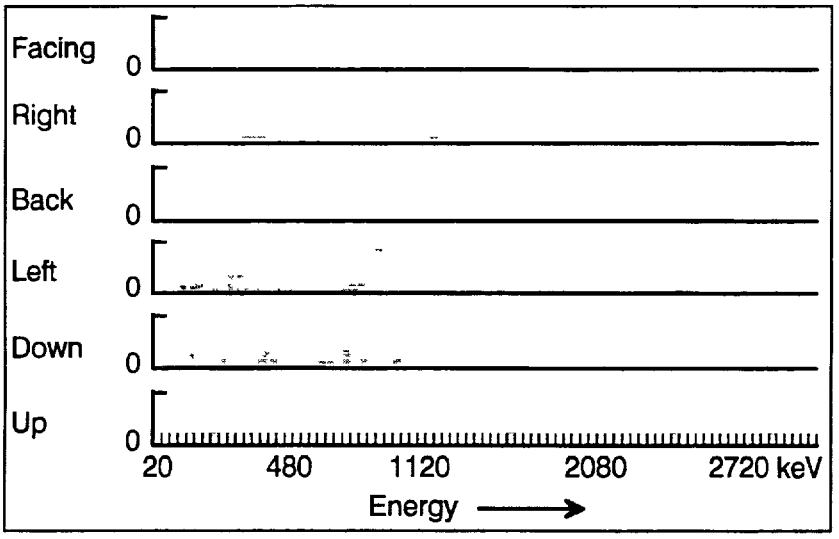

FIG. 8. Magnox reactor spectrum.

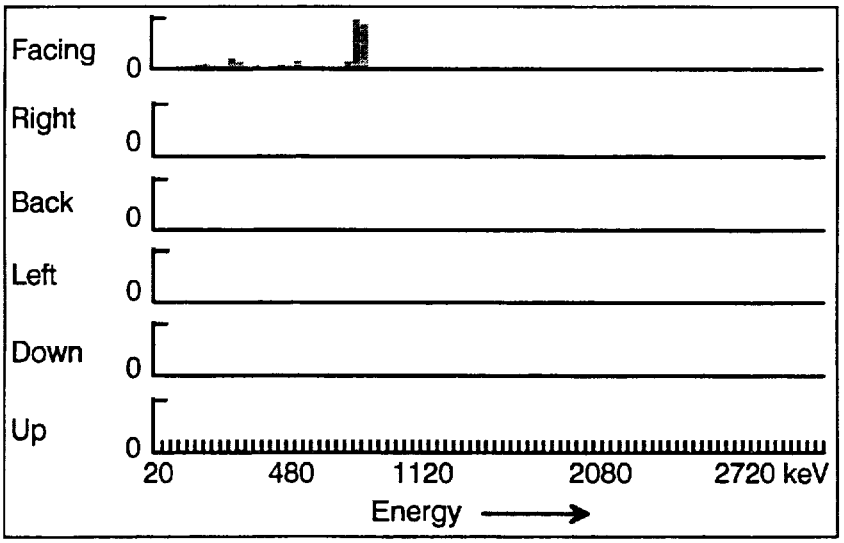

FIG. 9. ^{57}Co Source manufacture.

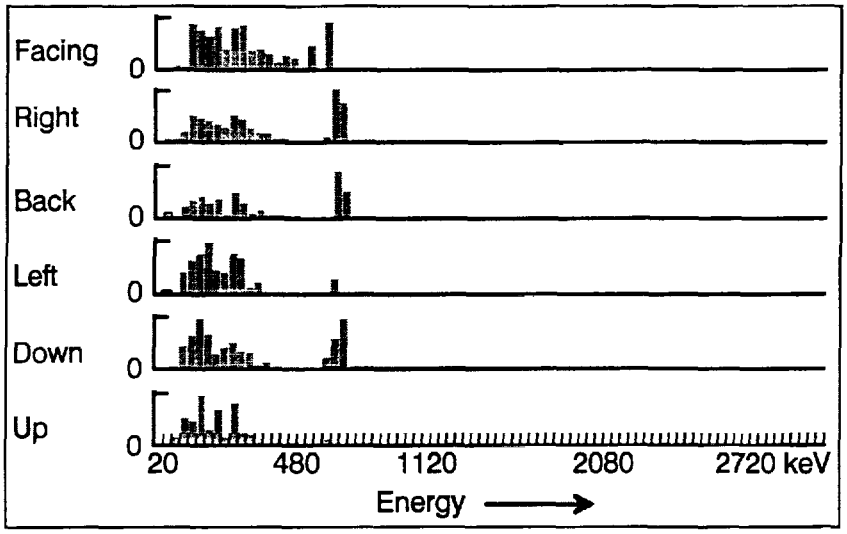

FIG. 10. ^{137}Cs contaminated waste.

These results were then combined with the appropriate conversion coefficients for fluence to E and $H_p(10)$ and a value of the ratio of $H_p(10)$ to E generated for each position. Some examples are shown in Table V.

TABLE V. VALUES OF $\dot{H}_p(10)$, $\dot{E}$ AND THEIR QUOTIENTS FOR 12 LOCATIONS

Location	Dose Rate $\dot{H}_p(10)$ in $\mu Sv.h^{-1}$	Dose Rate $\dot{E}$ in $\mu Sv.h^{-1}$	$\frac{\dot{H}_p(10)}{\dot{E}}$
i	7.02	6.57	1.07
ii	7.00	5.42	1.29
iii	5.82	5.08	1.15
iv	1.01	0.92	1.10
v	12.75	10.78	1.18
vi	3.03	2.66	1.14
vii	5.99	5.74	1.04
viii	4.50	4.03	1.12
ix	2.15	2.01	1.07
x	9.08	7.20	1.26
xi	5.12	4.65	1.10
xii	0.62	0.58	1.06

Again conclusions were similar to the previous exercise:

- $H_p(10)$ normally overestimates E, i.e. in 93 % of cases
- $H_p(10)$ is normally within ± 25% of E, i.e. in 90 % of cases
- Lowest ratio of $H_p(10)$ to E was 0.68

The biggest influence on the ratio of $H_p(10)$ to E is the angular distribution, not the energy spectrum. As an additional exercise, a much larger scintillator (127 mm × 102 mm) was taken to Hinkley Point A power station. This is a twin reactor steel pressure vessel CO_2 cooled Magnox reactor with heat exchangers outside the main shielding. Measurements of spectra indicated that a large fraction of the dose rate over a wide area of the site was 6 to 7 MeV γ radiation from the $^{16}O(n,p)^{16}N$ reaction. Similar fields will exist where the transit time of water from the core of a reactor to an accessible or less shielded area is less than approximately one minute.

3. SSI/EURADOS MEASUREMENTS

As part of a field investigation and comparison exercise at nuclear facilities in Sweden undertaken by Statens Strålskyddsinstitut (SSI) and EURADOS [9,10,11], measurements were made of the photon fields inside operating PWR and BWR containment vessels. Measurements were made with passive and electronic personal dosimeters mounted on all surfaces of slab phantoms, and with spectrometers. The results indicated a large contribution, in the workplace fields sampled, from the high energy (6 - 7 MeV) photons from the decay of the excited state of oxygen-16 (after beta decay of nitrogen-16). A measured spectrum is shown in Figure 11 and the data are also given in Table VI. Dose is dominated by photons of energy greater than 2 MeV, with a large fraction from photons of 6 - 7 MeV.

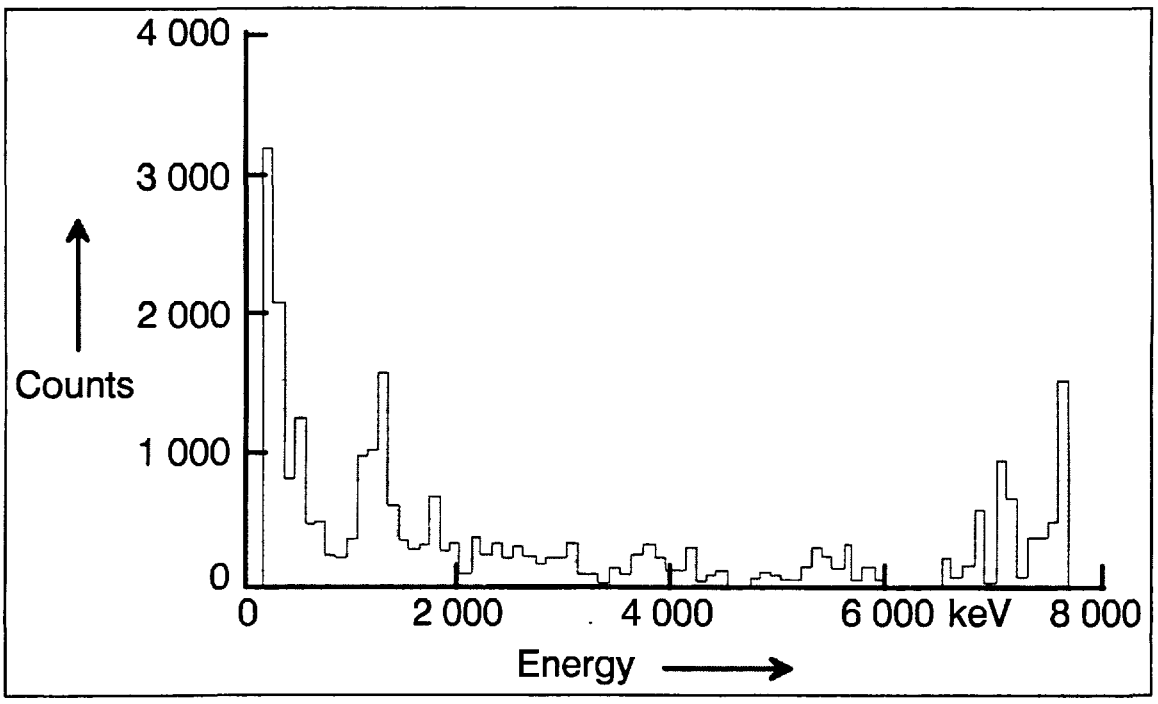

FIG. 11. SSI/EURADOS measurements in a PWR.

TABLE VI. SPECTRUM IN OPERATING PWR (LOCATION E)

	Energy Interval in keV			
	180-1000	1000-2000	2000-6000	6000-7000
Fluence proportion in %	33	24	15	28
Mean energy in keV	300	1300	3800	7200
$H^*(10)$ proportion in %	6	17	35	42

4. PTB INVESTIGATIONS

Existing German legislative requirements demand a good performance from a dosimeter only for angles of incidence from 0° to 45° to the normal. A programme of measurements [12,13] was undertaken to determine whether, in the workplace, the contribution to dose of radiation incident at more than 45° was large. The PTB investigations used equipment which was worn by a person. This, in some ways, makes for a more realistic measurement, but places more severe limitations on the weight and hence on the size of the detectors. Hemispherical CdTe detectors with an active volume of about 50 mm^3 and an integrated charge-sensitive preamplifier were therefore chosen as detectors. These detectors are sufficiently small, light and robust and can be operated without any cooling and their sensitivity and energy resolution are sufficient for this application [12]. The unit is shown being worn in Figure 12. The photon spectrometer contains of a stack of three hemispherical CdTe detectors, see Figure 13. Each detector is surrounded by a cylindrical shielding of lead and copper to allow the photon radiation incident on the wearer of the spectrometer to be measured from three different cylindrical segments of the solid angle. Figure 14 shows the measured polar response characteristics using 65 keV mean energy X radiation.

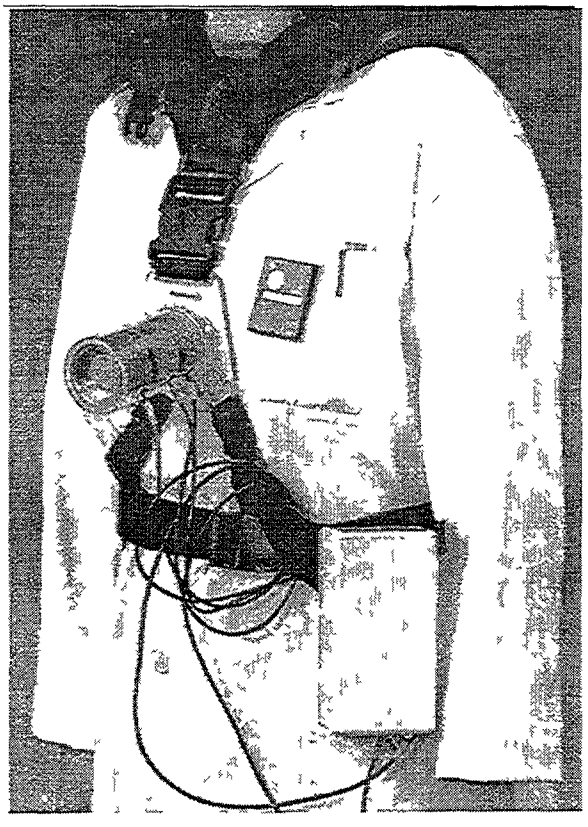

FIG. 12. PTB unit view.

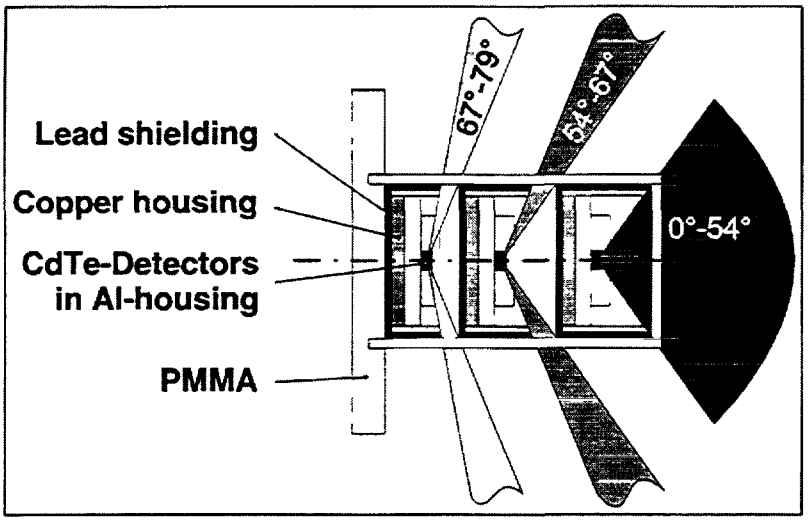

FIG. 13. PTB unit internal construction.

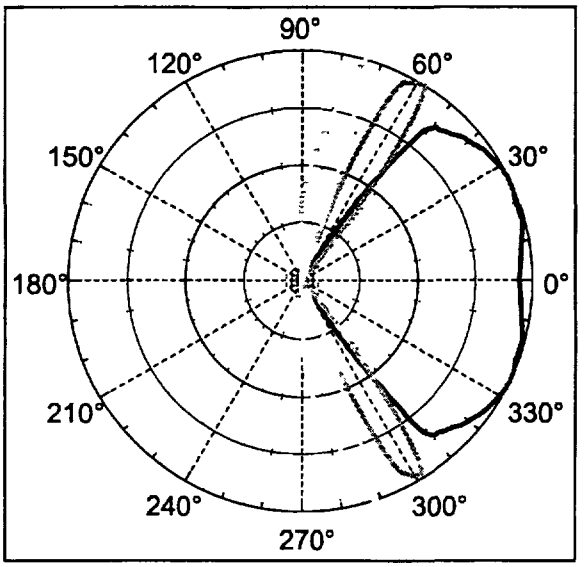

FIG. 14. PTB unit polar response.

A programme of measurements was undertaken

- at a cell used for processing ^{147}Pm,
- at a cell used for processing ^{131}I,
- at a cell for processing ^{137}Cs,
- in a despatch area for sources produced in the cells above,
- in a feedwater pump area in a BWR, and
- for work with X ray tubes.

Spectra are presented in Figure 15 for the source handling activities, Figure 16 for the reactor exposures and in Figure 17 for exposures to radiation from X ray tubes. Figure 18 gives data on the angular distribution at the position of the worker from the same sources. This clearly indicates that the contribution to dose of radiation incident at more than 45° was large.

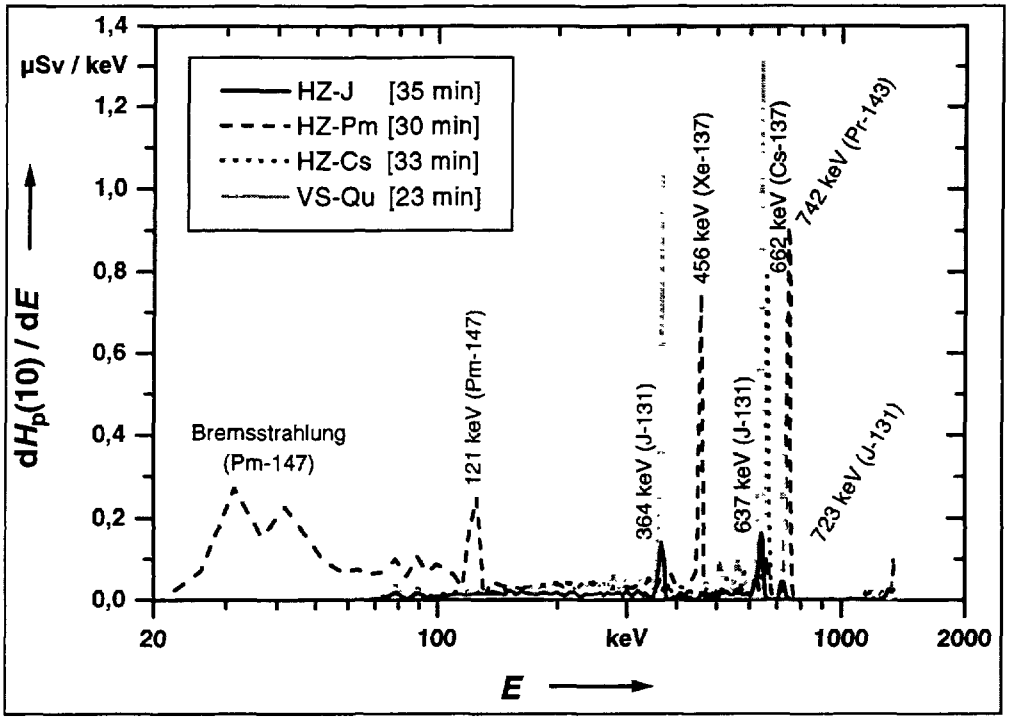

FIG. 15. PTB Unit Results for Source Handling.

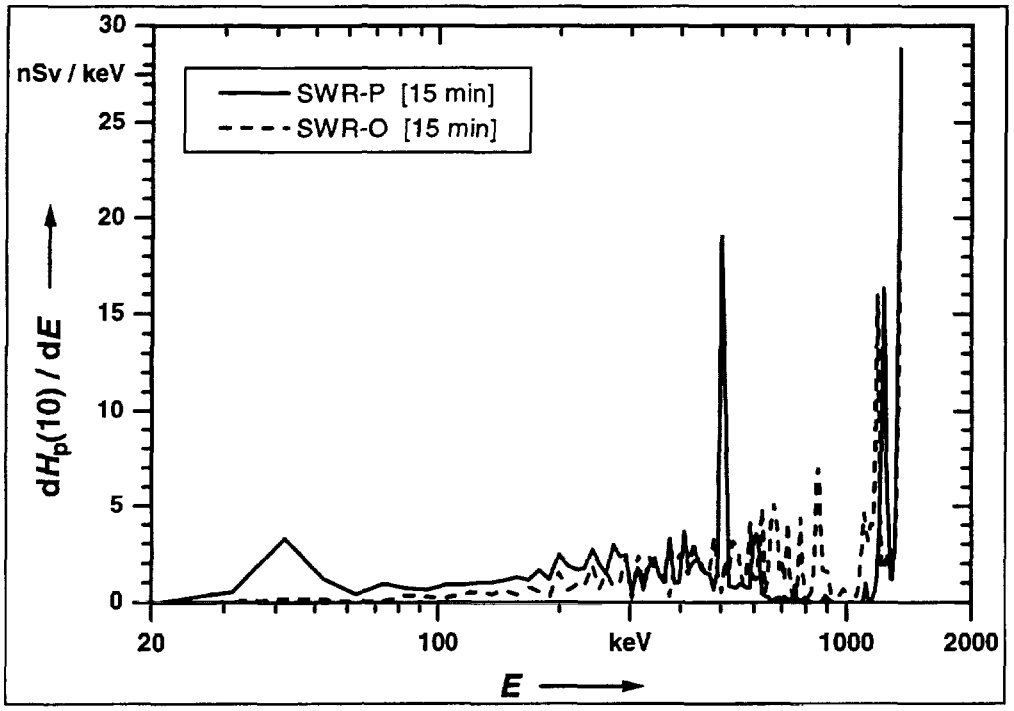

FIG. 16. PTB unit BWR results.

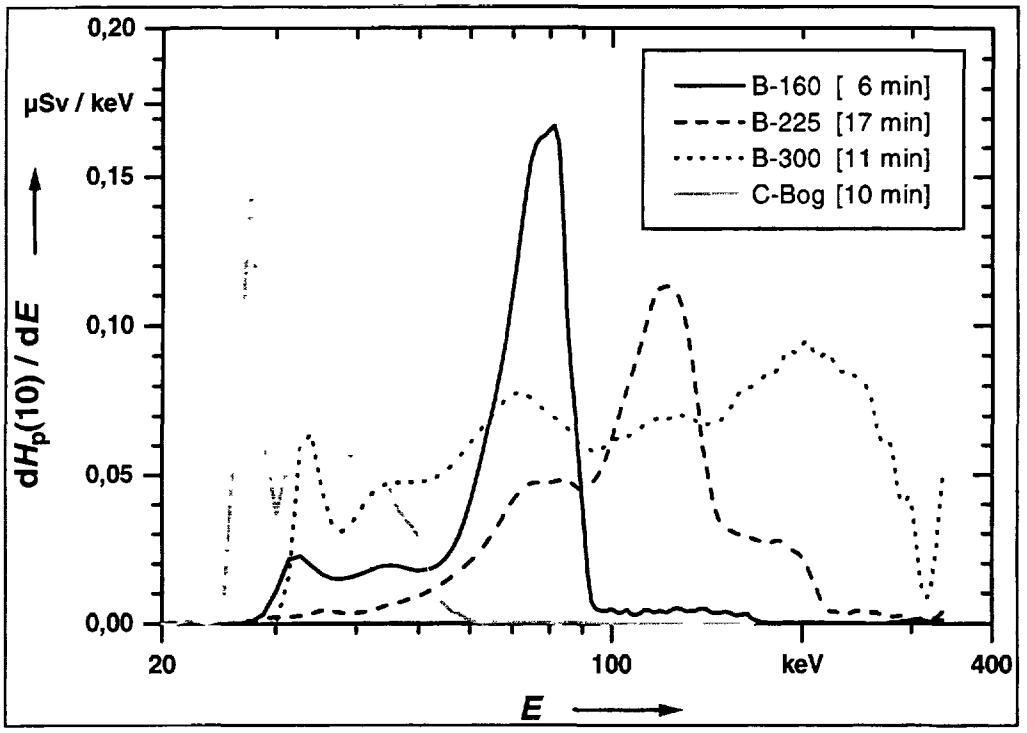

FIG. 17. PTB unit X ray field results.

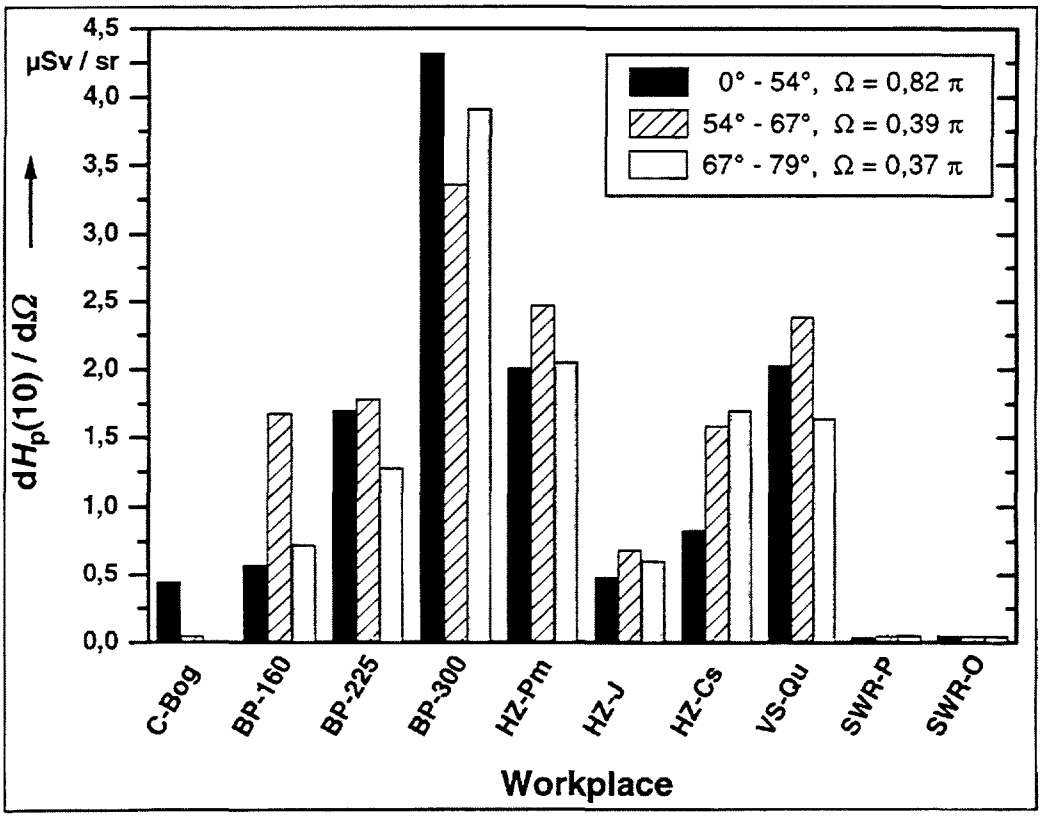

FIG. 18. PTB unit angular data.

One important aspect concerns the ^{147}Pm process, where the majority of the dose is from low energy bremsstrahlung. This is in an energy range where dosimeters tend to be less accurate and also where the ratio of E to $H_p(10)$ falls sharply. However it is normally possible to reduce exposure to direct radiation from such sources by simple shielding such as lead loaded glass or PMMA. Another important aspect is that in most of the circumstances most of the radiation was incident at large angles (> 54°) referred to normal incidence.

5. SUMMARY OF RESULTS OF THE INVESTIGATIONS INTO WORKPLACE FIELDS AND POTENTIAL IMPACT ON DOSIMETER DESIGNS AND ALGORITHMS

In a complicated situation with well shielded sources and multiple scattering it is not possible to predict either the energy spectrum or the angular distribution of radiation incident on the worker. Hence any dosimeter used in such situations has to be capable of responding correctly to photon radiations with energies from essentially the minimum relevant to the quantity, i.e. 10 to 15 keV for Hp(10), up to the maximum possible. If a dosimeter is available which does have satisfactory characteristics for the measurement of $H_p(10)$ then in the vast majority of circumstances it will provide an acceptable measurement of E, i.e., it will produce a result which is within ± 25% of E. The wide angular distribution of observed radiation fields demands that dosimeters operate acceptably out to very large angles of incidence. This is often difficult to achieve, especially with dosimeters using flat metal filters, and algorithms are normally developed to balance out the performance over the front 2π.

With some designs of dosimeter it is possible to ensure that the device is worn in the reference orientation, i.e. with one particular side always to the body. This is generally easy with dosimeters that are obviously asymmetrical. These dosimeters need not have a good low energy performance in the rear 2π, i.e. for radiation either backscattered from or transmitted through the body. The dosimeter can be designed to give the right response, i.e., to appear to respond to both incident and backscattered radiation, by over responding to the incident radiation and under responding to the backscattered radiation. This has the advantage that results are less susceptible to the dosimeter being off the body surface, on coveralls for example. The body is also a very effective attenuator of radiation incident from behind. For dosimeters which are essentially symmetrical, however, it is less easy to ensure that the dosimeter is worn in the correct orientation. In such cases it is prudent to design the dosimeter so that it responds correctly to backscattered radiation and hence will not be sensitive to being worn the wrong way round. This is the case in Germany. Unfortunately, practical considerations may well require a dosimeter which is less than perfect in terms of its ability to reproduce the quantity. What action should be taken in such cases? Measurement of the energy and angular distribution will give some information but the equipment is expensive, the analysis time consuming, and the results are difficult to apply to an individual worker. The most effective procedure is often an intercomparison on phantoms of dosimeters which reproduce the quantity and the preferred practical dosimeter. Overnight or over weekend exposures can often be employed to allow the accumulation of sufficient dose well above the measurement threshold. Multiple dosimeters can be used on the same phantom to mimic rotation of the worker. In some countries, e.g. Germany, such a 'field calibration' is not possible due to legal regulations. Other procedures can be used to identify areas where there is a strong low energy component which may lie below, for example, the threshold of an electronic personal dosimeter. Copper 1 mm thick has a transmission of essentially zero below 40 keV, 30 % at 60 keV and 73 % at 100 keV. A comparison of the indication of an ion chamber with and without a 1 mm thick copper cover will clearly identify situations where a

low energy component exists. In similar ways it is possible to search for radiation incident at unexpected angles, by using lead shielding around a Geiger Müller detector to collimate the response to a few tens of degrees. All these procedures must be performed in advance to any measurement to an individual worker and are only the second choice if no well suited dosimeter is available.

If a dosimeter has only one detector, then the measured value of this detector simply is the dose value of the dosimeter. If such a dosimeter is tested with narrow spectra (i.e. ISO N-Series) and shows good performance in the ranges of energy and angle of radiation incidence which cover the ranges measured in the field analysis, then the dosimeter will be appropriate to all fields, mixed and wide energy, within the range of photon energies investigated.

The situation is more complicated if a dosimeter has more than one detector. In such cases a dose calculating algorithm is required to combine the reading from each detector in order to produce a measured dose value. The simplest is the linear combination of the detector readings. The latest method uses linear programming, which has been in use in economics for more than 30 years. For these two linear methods the situation is almost as simple as for a dosimeter with one detector. A type test with narrow spectra covering the anticipated energy range is sufficient to establish whether the dosimeter is appropriate. Algorithms which rely on the ratio of readings from several of the detectors in the dosimeter are more difficult to test, particularly those that use branching programmes. Strictly, the performance of such dosimeters can only be assumed for the radiation qualities used in the testing process [14]. Performance in workplace fields may be disappointing, as the algorithm may have been designed, quite deliberately, to generate good results in established testing programmes rather than to operate well in environments with wide energy spectra and angles of incidence. Hence it is important to test such dosimeters using spectra and angular distributions typical of workplace fields using, for example, broad X ray spectra and multiple nuclide exposures.

The potential problems associated with the use of non-linear algorithms was clearly demonstrated by the experience of a dosimetry service in the United States. A particular multi element TLD was supplied by the manufacturer with an algorithm which had been optimised to meet the US DOELAP requirements. The algorithm computer program involved tests of element reading ratios before applying correction factors. The computer program in effect applied tests to recognise the performance test radiation quality before applying an appropriate correction factor. When the dosimetry service carried out performance tests with mixtures of fields used in the DOELAP test, the dosimeter estimates of dose equivalent (approximately the same as $H_p(10)$) were outside the DOELAP requirements and were not equal to the dosimeter estimates which would have been anticipated from a summation of its estimates for the components of the mixed field. These tests at this time were only of energy dependence of response. More difficulties can be anticipated with the use of non-linear algorithms/programs for the calculation of readings in fields of wide angle distributions.

REFERENCES

[1] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Pergamon Press, Oxford (1991).

[2] EURATOM, Council Directive 96/29/ of 13 May 1996 Laying Down the Basic Safety Standards for Protection of the Health of Workers and the General Public Against the Dangers Arising from Ionising Radiation, Official Journal of the European Communities **39**, L159 (29 June 1996).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY. International Basic Safety Standards for Protection Against Ionising Radiation and for the Safety of Radiation Sources, Safety Series N^0 115, IAEA, Vienna (1996).

[4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. General Principles of Monitoring for Radiation Protection of Workers. ICRP Publication 75. Pergamon Press, Oxford (1997).

[5] BURGESS, P. H., BARTLETT, D.T., MCCLURE, D.R. Field Measurement of Photon Energy and Angle Spectral Distributions; the Determination of Ambient Dose Equivalent, Individual Dose Equivalent Penetrating and Effective Dose Equivalent and their Comparison. Final Report of European Commission Directorate-General XII Contract B16-A-015-UK (1989).

[6] BURGESS, P.H., BARTLETT, D.T., MCCLURE, D.R. The Measurement of Practical Radiation Fields and Calculation of Ambient and Effective Dose Equivalent. Radiat. Prot. Dosim. **28**(2), (1989) 83–87.

[7] CLARK, M.J. in European Advances in Radiological Protection: CEC-NRPB Agreement of Association Project Co-ordinator Reports for 1993-1995, EUR 16951 NRPB, Chilton (1996).

[8] BRITCHER, A.R., BARTLETT, D.T., BURGESS, P.H.. The Measurement of Occupational Exposure to External Radiation: Principles and Practice. J. Radiol. Prot. **11**(3), (1991) 185–190.

[9] KLEIN, H., LINDBORG, L. Determination of Neutron and Photon Dose Equivalent at Work Places in Nuclear Facilities of Sweden. An SSI-EURADOS Comparison Exercise, Part I: Measurement and Data Analysis. SSI-report 95-15, SSI, Stockholm (1995).

[10] BARTLETT, D.T., DRAKE, P., KLEIN, H., LINDBORG, L., SCHMITZ, T., TICHY, M. Determination of Neutron and Photon Dose Equivalent at Work Places in Nuclear Facilities of Sweden. An SSI-EURADOS Comparison Exercise. Part II: Evaluation of the Results. SSI-report 95-16, SSI, Stockholm).

[11] LINDBORG, L., BARTLETT, D.T., DRAKE, P., KLEIN, H., SCHMITZ, T., TICHY, M. Determination of Neutron and Photon Dose Equivalent at Work Places in Nuclear Facilities of Sweden. A Joint SSI-EURADOS Comparison Exercise. Radiat. Prot. Dosim. **61**, (1995) 89–100.

[12] ALT, R., AMBROSI, P., BÖHM, J., HILGERS, G., JORDAN, M., RITZENHOFF, K-H. The Generation of the Response Matrix of Hemispherical CdTe Detectors. Nuclear Instruments and Methods in Physics Research **A353**, (1994) 71–75.

[13] AMBROSI, P., BÖHM, J., HILGERS, G., JORDAN, M., RITZENHOFF, K-H. A Photon Spectrometer to Investigate the Energy Spectrum and the Angular Distribution of Photon Radiation Incident on a Personal Dosimeter. Proceedings of the 9th International Congress on Radiation Protection, , **4**, Vienna, (1996) 263–265.

[14] KRAGH, P., RITZENHOFF, K-H., JORDAN, M., AMBROSI., BÖHM, J., HILGERS, G. The Evaluation of Multi-Element Personal Dosimeters using Linear Programming Method. Proceedings of the 9th International Congress on Radiation Protection, **4**, Vienna (1996) 272–274.

CALIBRATION OF PERSONAL DOSIMETERS FOR PHOTON RADIATION WITH RESPECT TO THE PERSONAL DOSE EQUIVALENT $H_P(10)$

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Abstract

The main steps of the calibration of personal dosimeters in terms of the personal dose equivalent $H_P(10)$ are described. Special consideration is given to ISO photon reference radiations, conversion coefficients from air kerma to $H_P(10)$, various calibration methods including an example of a routine calibration, and positioning of dosimeters for the calibration. In particular, radiation qualities used for measuring the response as a function of the photon energy and of the direction of the incident radiation in an intercomparison of a Co-ordinated Research Project of the IAEA are dealt with.

1. INTRODUCTION

This paper deals with the calibration of personal dosimeters for photon radiation to be worn on the trunk with respect to the measurand (quantity subject to measurement) personal dose equivalent $H_p(10)$. $H_p(10)$ is defined in the body and, for calibration purposes, also in the calibration phantom, a slab phantom. An ideal personal dosimeter for $H_p(10)$ should have a response with respect to $H_p(10)$ which does no vary with the energy and directional distribution of incident radiation. When personal dosimeters are calibrated with monodirectional radiation, the angle α between the direction of incidence of the (calibration) radiation and the reference direction of the personal dosimeter is of importance. In such calibrations, the quantity measured is denoted by $H_p(10;\alpha)$, or by $H_p(10;E,\alpha)$ if it is stressed that the quantity is valid only for the photon energy E (see Figure 1). More general information about calibration, the appertaining terminology and other dosimetric measurands can be found elsewhere [1-10].

In the past air kerma or photon dose equivalent on the front surface of a person was frequently used as the measurand for the dose to be determined for individual monitoring, the personal dose. When changing to the operational quantity personal dose equivalent $H_p(10)$, much will remain unaltered:

For example, radiation backscattered from the body contributed also to the values of the old measurands. If one compares the value of $H_p(10)$ with the value of air kerma, K_a, multiplied by the backscatter factor of the trunk at parallel incidence of the radiation from the front (see Figure 2), one can see that the quotient of these two values deviates from unity by less than 25 % above a photon energy of about 25 keV.

Moreover, the measurement point of the personal dose remains a location on the body surface representative of the radiation exposure. This is not even changed by the fact that, now as before, the dosimeter measures at the surface of a person's body while the measured value of $H_p(10)$ is related to a dose at 10 mm depth inside the person.

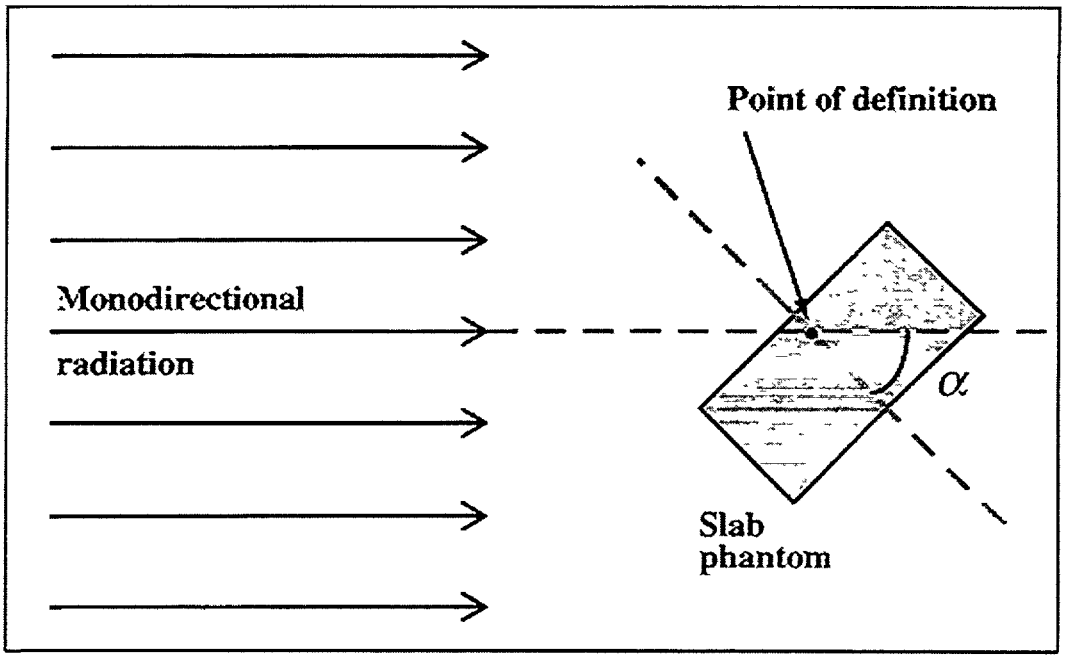


FIG. 1. Definition of $H_p(10; E, \alpha)$ for the photon energy E and the angle of incidence α in the slab phantom consisting of ICRU tissue.

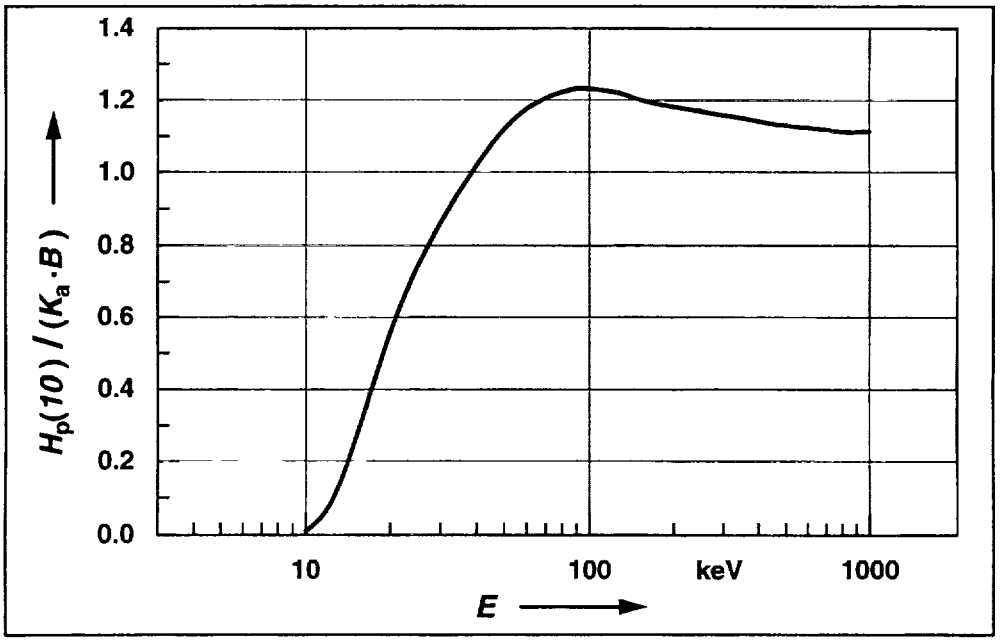


FIG. 2. Quotient $H_p(10; E, 0°)/(K_a \cdot B)$ for the ISO water slab phantom for monoenergetic photon radiation as a function of the photon energy E. B is the backscatter factor for the ISO water slab phantom [5].

The term *calibration* needs some clarification. *Calibration* is defined in the *International Vocabulary of Basic and General Terms in Metrology* [1]. If the text is applied to a dosimeter as a measuring instrument, the definition of calibration reads: "The set of operations that establish, under specified conditions, the relationship between the quantity indicated by a dosimeter and the corresponding value realised by standards." Three notes are added to the definition:

- The result of the calibration permits either the assignment of values of measurands to the indications or the determination of corrections with respect to indications.
- A calibration may also determine other metrological properties such as the effect of influence quantities.
- The result of a calibration may be recorded in a document, sometimes called a calibration certificate or a calibration report.

Attention has to be paid also to *routine calibration* because of its importance in practice. A *routine calibration* can be performed, under simplified conditions, either to check the calibration carried out by the manufacturer or to check whether the calibration factor is sufficiently stable during a continued long-term use of the dosimeter. In general, the methods of a routine calibration will be worked out on the basis of the results of a type test, or it may be one of the objectives of a type test to establish the procedures for a routine calibration in such a way that the result of a routine calibration approximates that of a calibration under standard test conditions as closely as possible. A routine calibration is often used to provide batch or individual calibration factors.

The calibration of personal dosimeters on a phantom, which is basically necessary, does not mean that regular routine calibrations cannot be carried out free in air when the performance characteristics of a personal dosimeter are known from a previous test (e.g. a pattern evaluation) which covered irradiations on a phantom and when the characteristics once determined are invariant. The calibration free in air must then be corrected for the influence of the phantom.

A calibration procedure in compliance with ISO standards [2,12] consists of the following steps:

1. Selection of the personal dosimeter to be calibrated. Examination of the dosimeter to confirm that it is in a good serviceable condition and free from radioactive contamination. The set-up procedure and the mode of operation of the dosimeter must be in accordance with its instruction manual.

2. Selection of the calibration conditions, including the radiation type and energy from the series of ISO reference radiations, and of the ISO water slab phantom orientation.

3. Selection of the actual radiation field and the point of test in this radiation field at which the conventional true value of the personal dose equivalent is known.

4. Selection of the calibration method, i.e. calibration against a reference instrument without any monitor or with a monitor; or calibration in a known radiation field.

5. If necessary, establishment of full secondary charged particle equilibrium by means of an additional layer of appropriate material in front of the dosimeter.

6. Positioning of the personal dosimeter with its reference point at the point of test, together with the ISO water slab phantom, both properly oriented in the desired direction, and irradiation of the dosimeter.

7. Computation of the dosimeter's calibration factor or response from the conventional true value of the personal dose equivalent and the value measured by the dosimeter.

This paper deals with the crucial features of the calibration procedure. The ISO photon reference radiations (see step 2) are described with special attention given to the narrow-spectrum series, radiations from radionuclide sources and high-energy photon radiations. These radiations are used in the present "type test" intercomparison of the IAEA. The conversion coefficients necessary to calculate the conventional true value of the personal dose equivalent at the point of test (step 3) are given. Three different methods of calibration (step 4) are explained, and an example of a routine calibration is given. The basic expressions are given for calculating a dosimeter's calibration factor based on an air kerma calibration of the user's reference instrument. Finally, a section is devoted to the positioning of the personal dosimeter at the point of test, including the establishment of secondary charged particle equilibrium (steps 5 and 6).

The term dosimeter is used as a generic term denoting any personal dose or dose rate meter. The term kerma is used to denote air kerma free in air. Detailed definitions of other dosimetric terms are given in a previous paper of the workshop [9].

2. FUNDAMENTALS OF CALIBRATION

2.1. Calibration factor (for reference conditions)

In radiation protection dosimetry the term *calibration factor* is frequently used in a restricted meaning. When assessing whether a particular dosimeter is adequate for its intended use and before it is used the first time, it is important to have access to reliable type test data of that dosimeter. Each dosimeter should be calibrated before its first use and then be recalibrated periodically. In some countries type test and periodic calibration are already prescribed by law. The calibration factor is determined under a controlled set of conditions which lie within a range of *standard test conditions* (e.g. photon energy, angle of radiation incidence, air pressure and temperature, see table in [3, 9]) and its value is corrected for *reference conditions* (frequently only for air pressure and temperature). This convention assigns unequivocally one calibration factor to a dosimeter, a significant simplification for routine monitoring.

To be consistent with international standards on personal dosimeters, the term *calibration factor* is defined only for reference conditions.

The calibration factor (for reference conditions), N, is the conventional true value of the quantity the dosimeter is intended to measure, $H_p(10)$, divided by the dosimeter's reading, the measured value M (corrected if necessary), under reference conditions. The calibration factor with respect to $H_p(10)$ is given by:

$$N = \frac{H_p(10)}{M} \tag{1}$$

The calibration factor refers to *reference conditions* and shall be determined under conditions which lie within the range of *standard test conditions* recommended in international standards. The conditions under which the determination of the calibration factor was actually carried out shall be specified in the calibration certificate.

To obtain the measured value M, as may be prescribed in the dosimeter's instruction manual, it may be necessary, for example, to correct the indicated value M_1 for the zero indication M_0 and other effects represented by the appropriate correction factors k_{ci}:

$$M = (M_1 - M_0) \prod_i k_{ci} \tag{2}$$

The factors k_{ci} are unity for *reference conditions*. The additional index c indicates that this correction factor is specific to the calibration. It should not be confused with other correction factors applied in practice, for example to correct the indicated value of a dosimeter in a well-known radiation field for the energy dependence of the response to obtain a more accurate result (in routine monitoring, however, such a correction is not necessary).

The calibration factor N is dimensionless when the instrument indicates the quantity to be measured. A dosimeter correctly indicating the conventional true value has a calibration factor of unity.

The value of the calibration factor may vary with the magnitude of the quantity to be measured. In such cases a dosimeter is said to have a non-linear response.

To supplement the definition of the calibration factor when determining other metrological properties such as the effect of influence quantities (e.g. photon energy E, angle of radiation incidence α), the term *response* has been introduced in several international standards. The reciprocal of the calibration factor is equal to the *response* under reference conditions. In contrast to the calibration factor which refers to the reference conditions only, the response refers to any conditions prevailing.

In practice, response divided by the value of the response for the reference radiation quality (*relative response*) is of particular importance. As an example, the relative response R of a phosphate glass dosimeter with regard to $H_p(10, 0°)$ as a function of the mean photon energy $\overline{E}$ is shown in Figure 3 [5]. In this case, the response is divided by the value of the response for ^{137}Cs gamma radiation, the reference radiation quality. The calibration factor is unity for this radiation quality.

The conventional true value of $H_p(10)$ is determined from air kerma (realised by standards) using conversion coefficients (see section 4); thus, $H_p(10)$ is not normally determined directly by means of primary standard measuring devices. The conversion coefficient refers to the slab phantom made of ICRU tissue. Calibrations of personal dosimeters shall be performed on the ISO water slab phantom described in the next chapter.

2.2. Phantoms

For calibrations of whole-body dosimeters, ICRU has extended the definition of $H_p(10)$ to a slab phantom made of ICRU tissue equivalent material (*ICRU tissue*), with the dimensions 300 mm × 300 mm × 150 mm [4].

As the ICRU tissue cannot be realized in practice, the personal dosimeters to be calibrated are to be irradiated on the ISO water slab phantom (substitute for the trunk). The ISO water slab phantom has the dimensions 300 mm × 300 mm × 150 mm. It is water filled, the walls are made of polymethyl-methacrylate (PMMA), the front side is 2.5 mm thick, the other sides are 10 mm thick. This phantom is recommended by ISO [2] and has only the function of a backscatter body. Figure 4 shows an example of such an ISO water slab phantom together with a personal dosimeter fastened in the center of the phantom's front surface by means of a holder. The holder consists of a minimum of material (PMMA) to avoid radiation being scattered from the holder into the dosimeter.

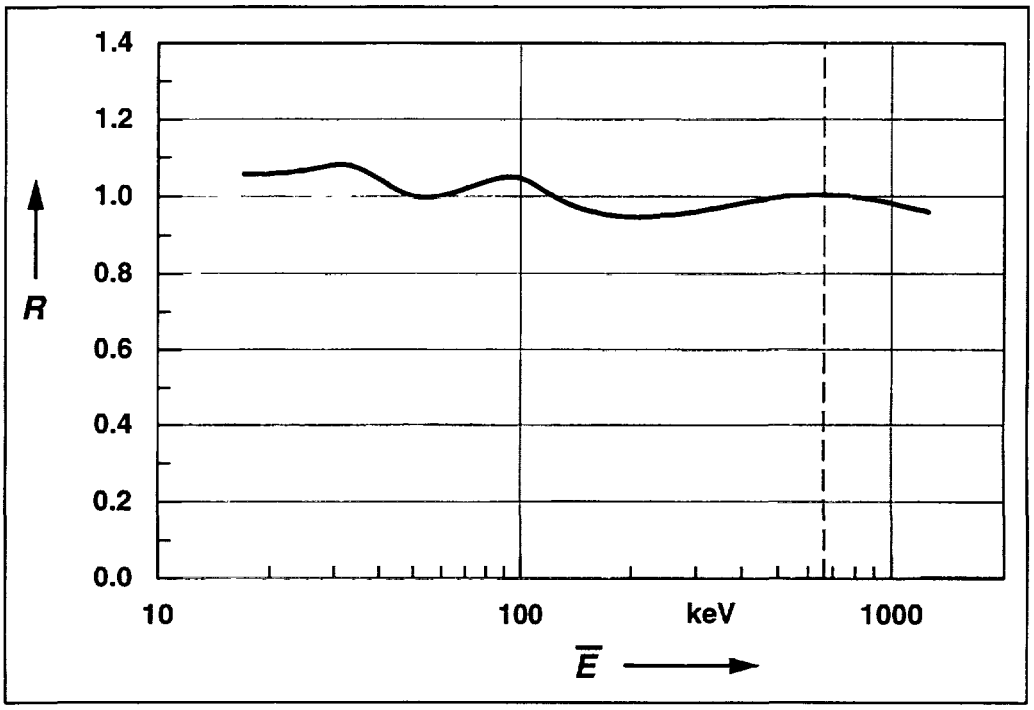


FIG. 3. Example of the relative response R with regard to $H_p(10, 0°)$ as a function of the mean photon energy $\overline{E}$ [5]. The response was normalized for ^{137}Cs gamma radiation, the reference radiation quality. The calibration factor is unity for the reference radiation quality.

In the past, dosimeter irradiations were frequently performed free in air with a typical diameter of the radiation field of about 10 cm; now the diameter of the radiation field on the ISO water slab phantom should be approximately 40 cm to irradiate the whole phantom. As a rule, an increase in the distance between dosimeter and radiation source will be necessary, resulting in a prolongation of the irradiation times by up to a factor 10.

The conversion coefficients for calibrations are calculated using phantoms made of ICRU tissue. For photon radiation, Figure 5 shows a comparison of the backscatter factors of the ISO water slab phantom and of the PMMA slab phantom originally favoured by ICRU, with the backscatter factors of the slab phantom made of ICRU tissue. The backscatter factor of the ISO water slab phantom is much closer to the backscatter factor of the ICRU tissue phantom than that of the PMMA phantom. When the ISO water slab phantom is employed as described

above, no correction factors shall be applied to the dosimeter reading for possible differences between the backscatter properties of the phantom and those of ICRU tissue.

3. PHOTON REFERENCE RADIATIONS

All photon reference radiations shall be chosen from and produced in accordance with ISO Standard 4037-1 [12]. In general, it will be useful to select an appropriate radiation quality, taking into account the specified energy and dose or dose rate range of the dosimeter to be calibrated. For reasons of brevity, short names have been introduced. For X radiation the letters F, L, N, W or H denote the radiation quality, i.e. the fluorescence, the low air-kerma rate, the narrow-spectrum, the wide-spectrum, the high air-kerma rate series, respectively, followed by the chemical symbol of the radiator for the fluorescence X radiation and the generating potential for filtered X radiation. Reference radiations produced by radioactive sources are denoted by the letter S combined with the chemical symbol of the radionuclide; reference radiations produced by nuclear reactions are denoted by the letter R followed by the chemical symbol of the element of the target responsible for the emission of the radiation. Table 1 states all radiation qualities recommended by ISO, together with their mean energies $\overline{E}$ averaged over the fluence spectrum.

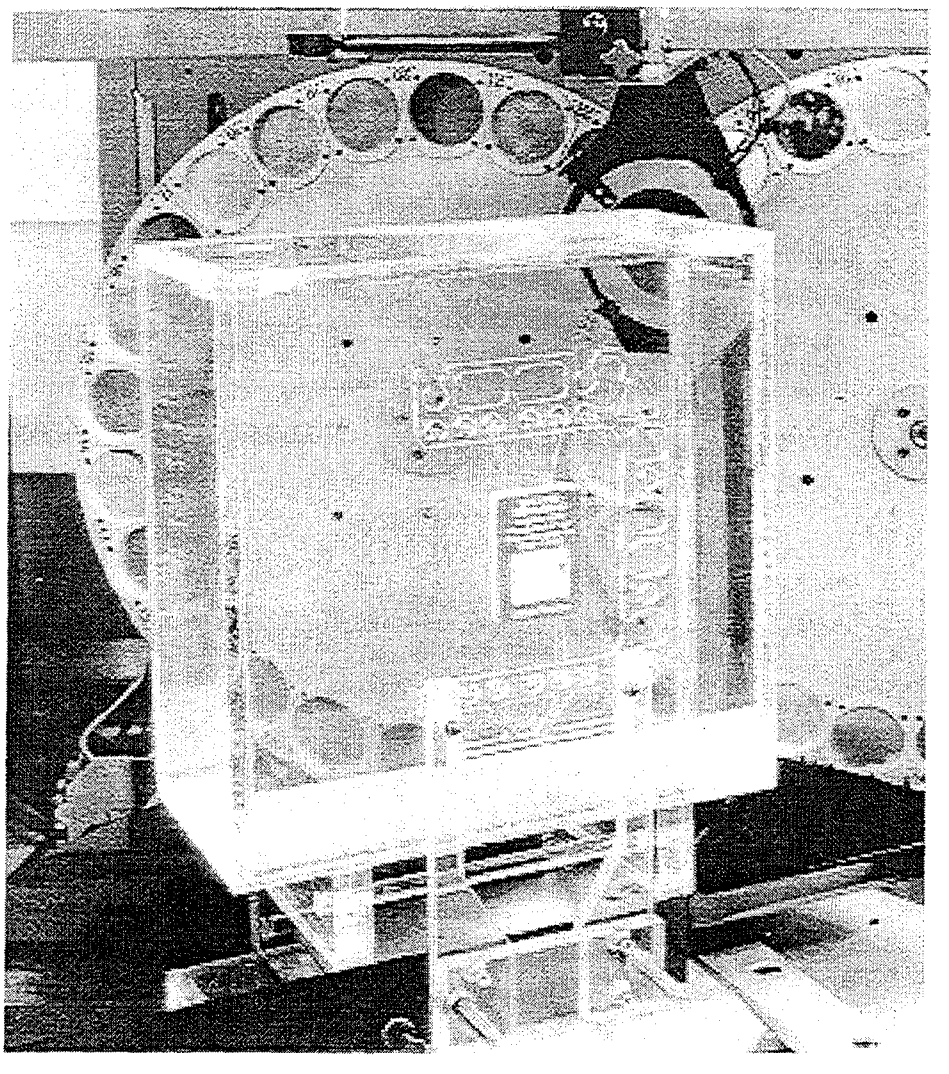


FIG. 4. Example of an ISO water slab phantom together with a personal dosimeter fastened in the center of the phantom's front surface.

Each series produces spectra of different resolutions and air-kerma rates. The spectral resolution, R_E (full width at half maximum), is the ratio, expressed as a percentage $(\Delta E / \overline{E}) \cdot 100$ where increment ΔE is the spectrum width corresponding to half the maximum ordinate of the spectrum. The low air-kerma rate series have the narrowest spectra and lowest air-kerma rates. The high air-kerma rate series produce very wide spectra and the highest air-kerma rates. The narrowest spectra should be used for measurements of the variation of the response of a detector with photon energy, provided that the dose equivalent rates of that series are consistent with the dose equivalent rate range of the instrument under test. The high air-kerma rate series is suitable for determining the overload characteristics of some instruments.

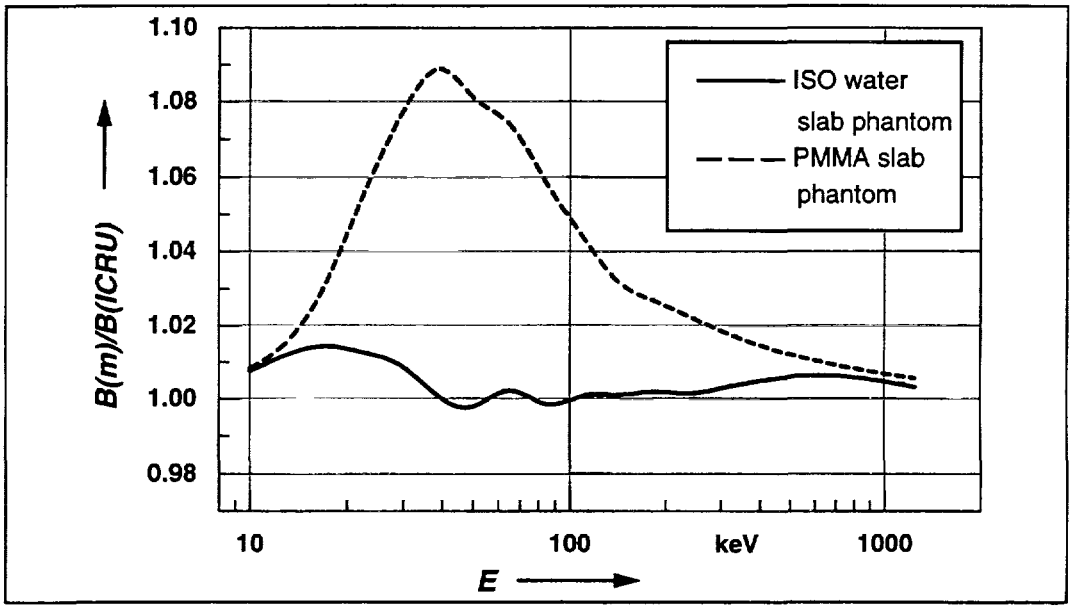


FIG. 5. Quotient of the backscatter factor for a slab phantom made of the material m, B(m), and that of a slab phantom made of ICRU tissue, B(ICRU). The phantom materials m are water with polymethyl-methacrylate (PMMA) walls (ISO water slab phantom: solid curve) and PMMA (dashed curve) [11]. E is the photon energy.

Typical differences between these ISO series can be recognized, for example, when comparing spectra produced at the same high voltage. Figure 6 shows spectra calculated for the high voltage of 100 kV [13]. The calculations were performed by the semi-empirical program described in [14], a program similar to the program XCOMP5R described in [16]. As no wide spectrum has been recommended by ISO for the high voltage of 100 kV, it is assumed that the filtration for the wide spectrum W-110 produced at 110 kV is adequate for the purpose of this comparison. Table 2 summarizes characteristics of these spectra. It can clearly be seen that dose equivalent rates (expressed by the spectral photon flux per solid angle and tube current, N_E) belonging to the spectra, the resolution and the relative contribution of the fluorescent radiation to the dose equivalent rate decrease from the high air-kerma rate spectrum to the low air-kerma rate spectrum. The maximum values of N_E for the narrow spectrum and the low air-kerma rate spectrum in the upper part of Figure 6 are so small that the spectra almost cannot be seen there and are, therefore, magnified in the lower

part of Figure 6 (both parts of the Figure have a linear scale). The decrease of the resolution of the spectra is accompanied by an increase of the mean energy $\overline{E}$.

The narrow-spectrum series and the reference radiations produced by radionuclide sources and high-energy photon radiations are of particular interest in the "type test" intercomparison of the co-ordinated research project of the IAEA. Their characteristics are given in Tables 3 and 4. The particular spectra used for the supplementary tests are shown in Figure 7.

Details of the operational conditions required to produce the filtered X radiations are also specified in the ISO Standard 4037-1. A typical calibration set-up for the calibration against a reference instrument and a monitor (see section 5.3) is shown schematically in Figure 8. How such a set-up may look in practice is shown in Figure 9. The wheels with the filters used for the computer controlled selection of the filtration of the X radiation can clearly be seen.

TABLE I. DESIGNATIONS OF THE RADIATION QUALITIES OF THE REFERENCE RADIATION SERIES RECOMMENDED BY ISO, TOGETHER WITH THEIR MEAN ENERGIES

Fluorescence Radiation Series		Low Air-Kerma Rate Series		Narrow-Spectrum Series		Wide-Spectrum Series		High Air-Kerma Rate Series	
Radiation Quality	Energy keV	Radiation Quality	$\overline{E}$ keV	Radiation Quality	$\overline{E}$ keV	Radiation Quality	$\overline{E}$ keV	Radiation Quality	$\overline{E}$ keV
F-Zn	8,6	L-10	8,5	N-10	8	W-60	45	H-10	7,5
F-Ge	9,9	L-20	17	N-15	12	W-80	57	H-20	12,9
F-Zr	15,8	L-30	26	N-20	16	W-110	79	H-30	19,7
F-Mo	17,5	L-35	30	N-25	20	W-150	104	H-60	37,3
F-Cd	23,2	L-55	48	N-30	24	W-200	137	H-100	57,4
F-Sn	25,3	L-70	60	N-40	33	W-250	173	H-200	102
F-Cs	31,0	L-100	87	N-60	48	W-300	208	H-250	122
F-Nd	37,4	L-125	109	N-80	65			H-280	146
F-Sm	40,1	L-170	149	N-100	83			H-300	147
F-Er	49,1	L-210	185	N-120	100				
F-W	59,3	L-240	211	N-150	118				
F-Au	68,8			N-200	164				
F-Pb	75,0			N-250	208				
F-U	98,4			N-300	250				

Radionuclide Series				High-Energy Photon Radiation Series		
Radiation Quality	Radio-nuclide	$\overline{E}$ keV		Radiation Quality	Reaction	$\overline{E}$ MeV
S-Am	^{241}Am	59,5		R-C	^{12}C (p,p'γ) ^{12}C	4,36*
S-Cs	^{137}Cs	662		R-F	^{19}F (p,αγ) ^{16}O	6,61*
S-Co	^{60}Co	1250		R-Ti	(n,γ) capture in Ti	5,14*
				R-Ni	(n,γ) capture in Ni	6,26*
				R-O	^{16}O (n,p) ^{16}N	6,61*

All mean energies except those for the high-energy photon radiation series are averaged over the fluence spectrum. the mean energies marked by * are averaged over the energy fluence spectrum. for the fluorescence radiation series the energy of the main line of the spectrum is given. under certain circumstances the use of the lowest energy fluorescence radiations must be avoided for calibrations owing to the effect of the higher energy primary beam radiations scattered from the radiator.

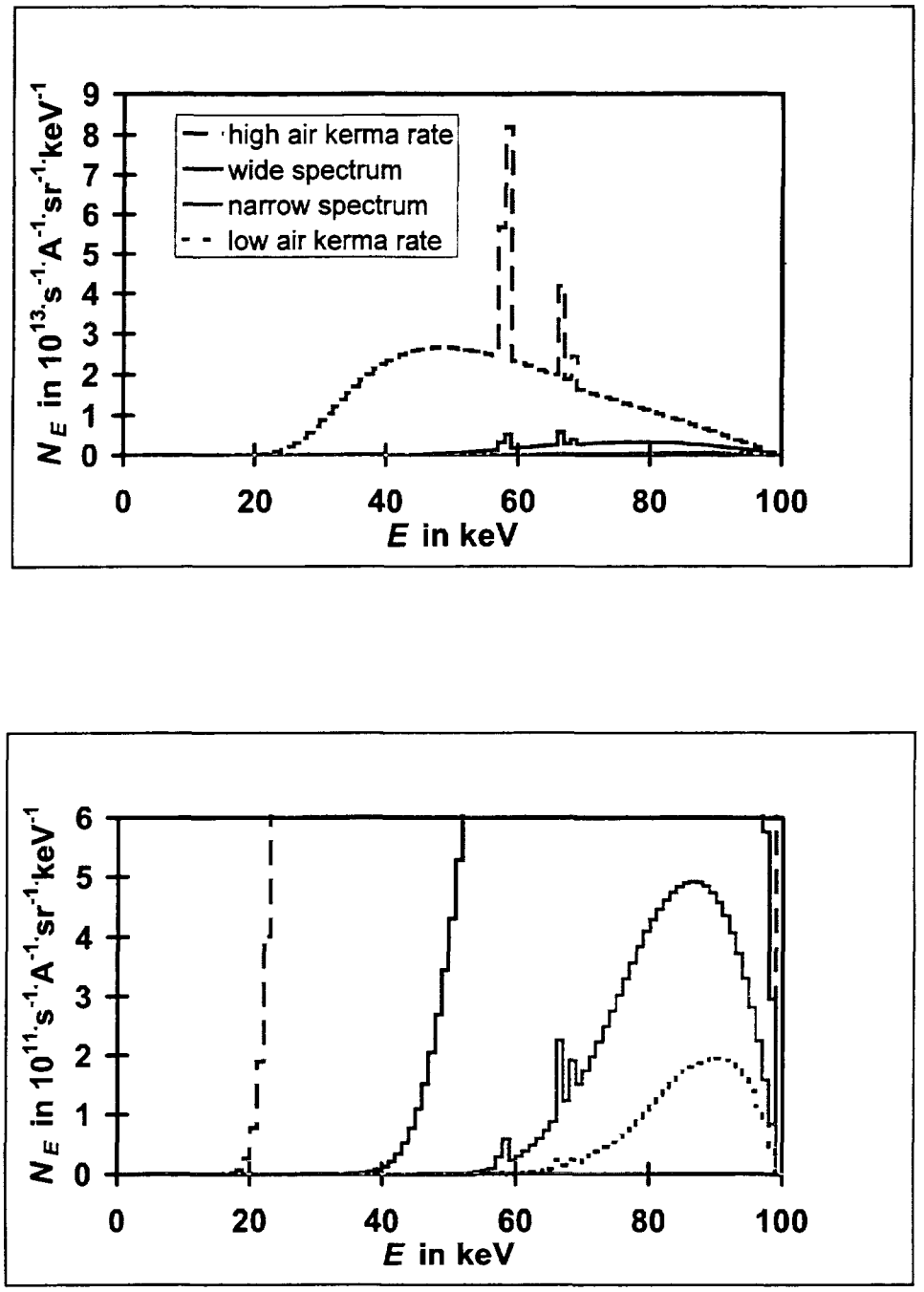


FIG. 6. Comparison of the calculated spectral photon flux per solid angle and tube current, N_E, of the low air-kerma rate spectrum L-100, the narrow spectrum N-100, the wide spectrum "W-100" and the high air-kerma rate spectrum H-100. The spectra are calculated for a distance of 2.5 m from a tube with a tungsten anode with an anode angle of 20°. The tube potential is 100 kV. The Figure is split in two parts to allow the four spectra to be presented with linear scales.
In the upper Figure the narrow spectrum and the low air-kerma rate spectrum cannot be seen because of their low N_E values

TABLE II. CHARACTERISTICS OF THE SPECTRA SHOWN IN FIGURE 5. (THE SPECTRAL PHOTON FLUX PER SOLID ANGLE AND TUBE CURRENT, N_E, IS CALCULATED FOR A DISTANCE OF 2.5 M FROM THE TUBE. $\overline{E}$ IS THE MEAN PHOTON ENERGY AVERAGED OVER THE FLUENCE SPECTRUM. THE FILTRATION OF BE IS THE INHERENT FILTRATION)

		Characteristic of Reference Radiation Radiation Quality			
		L-100	N-100	"W-100"	H-100
	Be	1.0	1.0	1.0	1.0
Filtration	Al	4.0	4.0	4.0	3.9
mm	Cu	0.5	5.0	2.0	0.15
	Sn	2.0	–	–	–
$\overline{E}$ in keV		87	83	75	57
Resolution in %		22	28	46	75
N_E (s^{-1} sr^{-1} A^{-1} keV^{-1})		$3.6\ 10^9$	$1.2\ 10^{10}$	$1.1\ 10^{11}$	$1.3\ 10^{12}$

TABLE III. CHARACTERISTICS OF THE NARROW-SPECTRUM SERIES. THE TUBE POTENTIAL IS MEASURED UNDER LOAD.

Radiation Quality	$\overline{E}$ keV	Resolution R_E %	Tube Potential kV	Additional Filtration (mm) Pb	Sn	Cu	Al	1st HVL mm	2nd HVL mm
N-10	8	28	10				0.1	0.047 Al	0.052 Al
N-15	12	33	15				0.5	0.14 Al	0.16 Al
N-20	16	34	20				1.0	0.32 Al	0.37 Al
N-25	20	33	25				2.0	0.66 Al	0.73 Al
N-30	24	32	30				4.0	1.15 Al	1.30 Al
N-40	33	30	40			0.21		0.084	0.091
N-60	48	36	60			0.6		Cu	Cu
N-80	65	32	80			2.0		0.24 Cu	0.26 Cu
N-100	83	28	100			5.0		0.58 Cu	0.62 Cu
N-120	100	27	120		1.0	5.0		1.11 Cu	1.17 Cu
N-150	118	37	150		2.5			1.71 Cu	1.77 Cu
N-200	164	30	200	1.0	3.0	2.0		2.36 Cu	2.47 Cu
N-250	208	28	250	3.0	2.0			3.99 Cu	4.05 Cu
N-300	250	27	300	5.0	3.0			5.19 Cu	5.23 Cu
								6.12 Cu	6.15 Cu

For the five lowest energies the recommended filtration is 1 mm be but other values may be used provided that the mean energy is within $\pm$ 5 % and the resolution is within $\pm$ 15 % of the values given in the table. for the higher energies (radiation qualities N-40 and above) the total filtration consists of the additional filtration plus the inherent filtration adjusted to 4 mm of aluminium. the minimum purity of the filters should be 99.9 %. the half value layers (hvls) are measured at a distance of 1 m from the focal spot.

TABLE IV. CHARACTERISTICS OF THE REFERENCE RADIATIONS PRODUCED BY RADIONUCLIDE SOURCES AND OF THE HIGH-ENERGY PHOTON RADIATIONS

Radiation Quality	Energy of the Radiation (MeV)	Half-Life (days)	Air-kerma Rate Constant $mGy\ h^{-1}.m^2.MBq^{-1}$
S-Co	1.1733 and 1.3325	1925.5	0.31
S-Cs	0.6616	11050	0.079
S-Am	0.05954	157788	0.0031
R-C	4.36		
R-F	6.13 to 7.12		
R-Ti	5.14		
R-Ni	6.26		
R-0	6.13 to 7.12		

The value of the air-kerma rate constant is valid only for an unshielded point radionuclide source. It is given only as a guide. Air-kerma rates at the exposure positions should be measured using a secondary ionisation chamber. Instead of using sources with different activities, the air-kerma rate may also be varied by means of lead attenuators for collimated beams of ^{137}Cs and ^{60}Co. The attenuators shall be placed in close vicinity to the diaphragm.

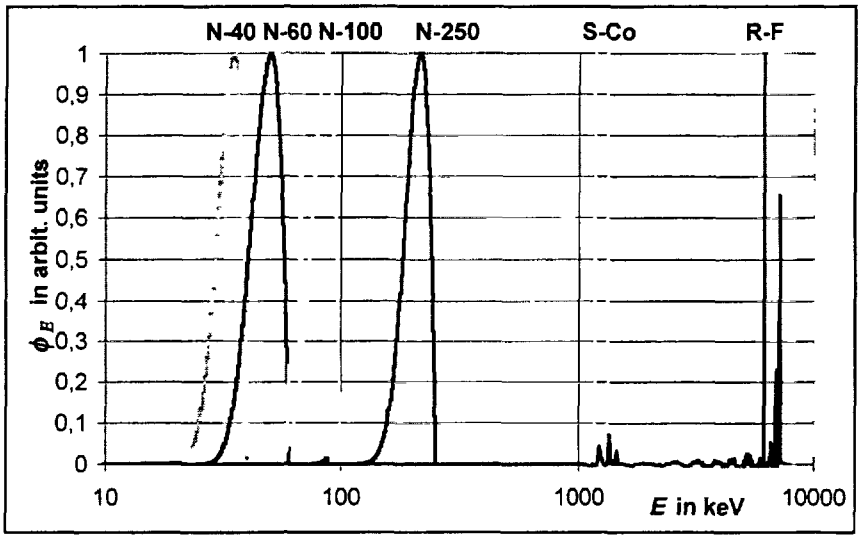


FIG. 7. Relative spectral photon fluence Φ_E of the reference photon radiations used in the "type test" intercomparison of the co-ordinated research project of the IAEA. The radiation qualities N-40, N-60, N-100 and N-250 belong to the narrow-spectrum series, the radiation quality S-Co to the radionuclide series and the radiation quality R-F to the high-energy photon radiation series. All spectra except the R-F spectrum are theoretical spectra. The R-F spectrum is an unfolded spectrum generated at 2.7 MeV proton energy [15]. In this spectrum the photon radiation generated by an annihilation reaction at 0.51 MeV is omitted for reasons of clarity.

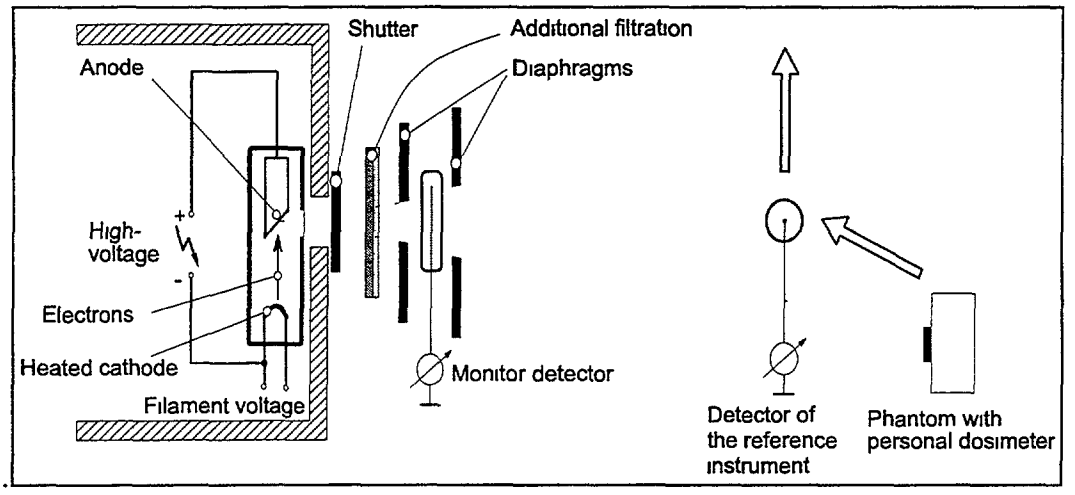


FIG 8 Scheme of a typical calibration set-up with X radiation for the calibration against a reference instrument and a monitor

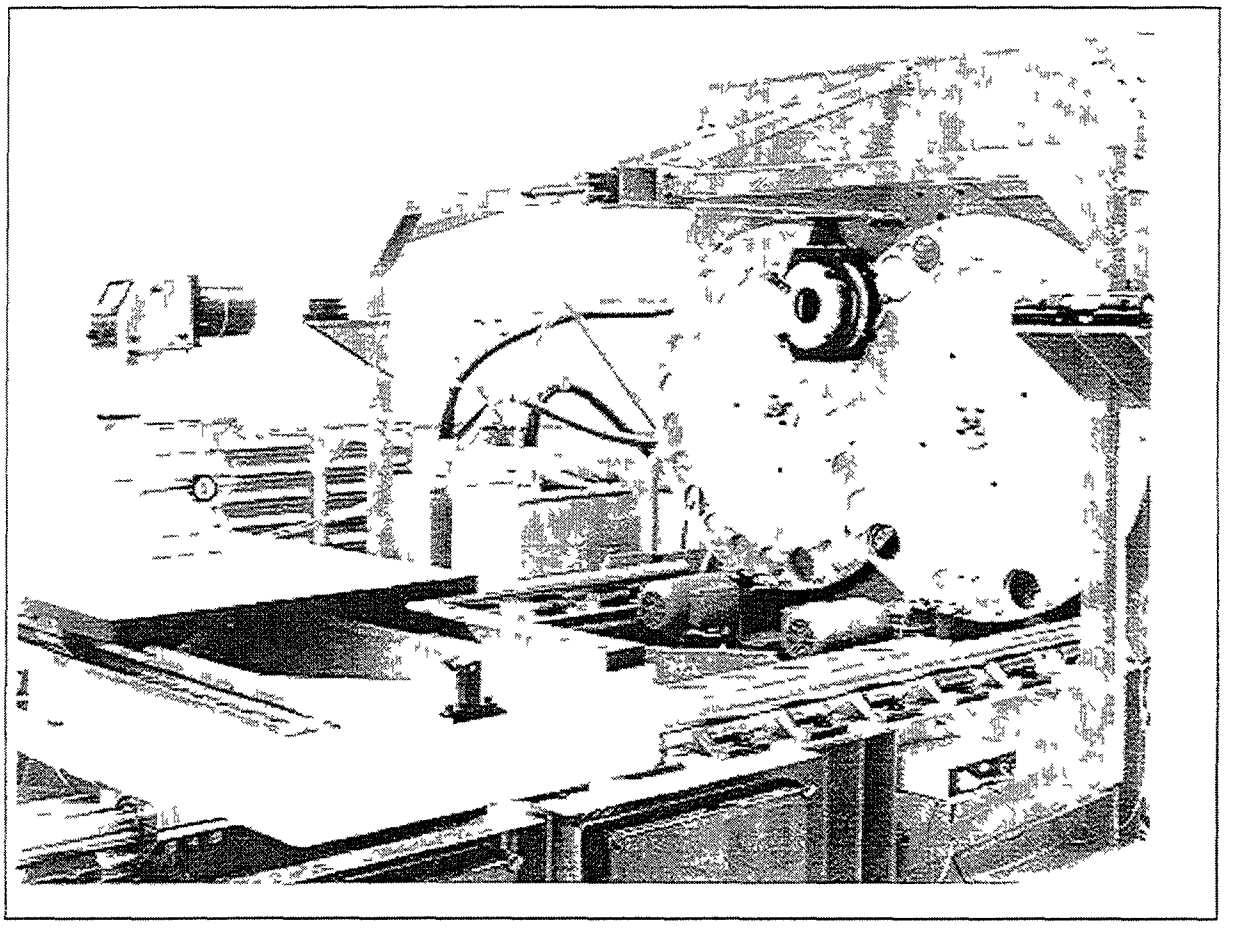


FIG 9 Example of a calibration set-up with X radiation for the calibration against a reference instrument and a monitor

4. CONVERSION COEFFICIENT FROM AIR KERMA TO $H_p(10)$ IN THE ICRU SLAB PHANTOM

In general reference instruments for photon radiation do not *directly* indicate $H_p(10;E,\alpha)$ but the air-kerma rate. $H_p(10;E,\alpha)$ is derived from air kerma K_a using appropriate conversion coefficients, $h_{pK}(10;E,\alpha)$, for photon radiation of energy E, with an angle α between the reference direction of the dosimeter and the direction of radiation incidence:

$$h_{pK}(10;E,\alpha) = H_p(10;E,\alpha) / K_a \tag{3}$$

Tabulated values for $h_{pK}(10;E,\alpha)$ presuppose the establishment of secondary charged particle equilibrium for the radiation field. An appropriate build-up layer may be required (see section 6.4) resulting in a substitution of $h_{pK}(10;E,\alpha)$ by $h_{pK}(10;E,\alpha)\cdot k_{PMMA}$ in eq. (3). If a reference instrument is used for calibration (denoted by subscript R in the following), as for the methods given in sections 5.2, 5.3 and 5.5, its calibration factor for air kerma, N_R, given in the calibration certificate can be used to determine the conventional true value of $H_p(10;E,\alpha)$ by means of the conversion coefficient $h_{pK}(10;E,\alpha)$ of eq. (3) and the measured (indicated) value M_R of the reference instrument (corrected for reference conditions):

$$H_p(10;E,\alpha) = h_{pK}(10;E,\alpha)\cdot N_R M_R \tag{4}$$

For radiation qualities of finite spectral width, the symbol E is replaced by the relevant letter according to Table I denoting a particular series of reference radiation, i.e. F, L, N, W, H, S or R.

Conversion coefficients $h_{pK}(10;E,\alpha)$ for monoenergetic radiation shall be treated as if they are not affected by an uncertainty. The conversion coefficients for the narrow-spectrum series, the radionuclide sources and the high-energy photon radiations given in Tables 5 and 6 shall be considered as being affected by a relative standard uncertainty of 2 % except those with an exclamation mark. The relative standard uncertainty of 2 % takes into account differences between the spectrum used for the calculation of the conversion coefficient [2,12] and that prevailing at the point of test.

The numerical values with an exclamation mark actually applicable to a given experimental set-up may differ by considerably more than 2 % from the given value. Such exclamations marks have to be considered only for tube voltages below about 30 kV when photons of low energies may strongly influence the numerical value of the conversion coefficients. Small differences in the energy distribution can result in significant changes in the numerical values of these conversion coefficients as the majority contribution to the air kerma originates from the low-energy part of the spectrum, while the majority contribution to $H_p(10)$ originates from the high-energy part of the spectrum. Differences between the experimental arrangements as regards the energy distribution may be due to a great number of factors, e.g. anode angle,

anode roughening, tungsten evaporated on the tube window, presence of a transmission monitor chamber in the beam, deviation of the thickness of filters from nominal values, length of the air path between focal spot and point of test, and atmospheric pressure at the time of measurement.

In practice, calibrations are always performed in divergent beams. This is taken into account by relating the conversion coefficients to a reference distance between radiation source and point of test. In cases where a reference distance is given together with an angle α of the direction of radiation incidence, α pertains to the angle between the reference and actual orientation of the dosimeter in the field.

TABLE V. CONVERSION COEFFICIENT $h_{pK}(10;N,\alpha)$ FROM AIR KERMA, K_a, TO THE DOSE EQUIVALENT $H_p(10;N,\alpha)$ FOR RADIATION QUALITIES GIVEN IN ISO 4037, PART 1 [12] AND THE SLAB PHANTOM, REFERENCE DISTANCE 2 m

Radiation	Irr. Dist.	d_F	$h_{pK}(10;N,\alpha)$ in Sv /Gy for Angle of Incidence of								
Quality	m	cm	0°	10°	20°	30°	40°	45°	50°	60°	70°
N-15 !	1,0 - 2,0	25	0,06	0,06	0,06	0,04	0,03	0,03	0,02	0,01	0,00
N-20 !	1,0 - 2,0	25	0,27	0,27	0,26	0,23	0,20	0,17	0,15	0,09	0,04
N-25 !	1,0 - 3,0	23	0,55	0,55	0,53	0,50	0,44	0,41	0,37	0,28	0,15
N-30	1,0 - 3,0	20	0,79	0,78	0,77	0,74	0,68	0,65	0,60	0,49	0,32
N-40	1,0 - 3,0	16	1,17	1,16	1,15	1,12	1,06	1,02	0,98	0,85	0,65
N-60	1,0 - 3,0	11	1,65	1,64	1,62	1,59	1,52	1,47	1,42	1,27	1,04
N- 80	1,0 - 3,0	11	1,88	1,87	1,86	1,83	1,76	1,71	1,66	1,50	1,26
N-100	1,0 - 3,0	11	1,88	1,88	1,86	1,82	1,76	1,73	1,68	1,53	1,31
N-120	1,0 - 3,0	11	1,81	1,80	1,79	1,76	1,71	1,68	1,64	1,51	1,28
N-150	1,0 - 3,0	11	1,73	1,72	1,71	1,68	1,64	1,61	1,58	1,46	1,26
N-200	1,0 - 3,0	12	1,57	1,56	1,56	1,55	1,51	1,49	1,46	1,38	1,23
N-250	1,0 - 3,0	13	1,48	1,48	1,48	1,47	1,44	1,42	1,40	1,33	1,21
N-300	1,0 - 3,0	15	1,42	1,42	1,42	1,41	1,40	1,38	1,36	1,30	1,19

The irradiation distance is measured from the focal spot of the x-ray tube to the point of test, at which the reference point of the dosimeter shall be located. The values of the conversion coefficients may be used without modification over the given range of irradiation distances. For radiation qualities with an exclamation mark, care needs to be taken as variations in energy distribution may have a strong influence on the numerical values of conversion coefficients. The meaning of the diameter d_F is explained in Section 6.

5. CALIBRATION METHODS

5.1. General

As stated in section 2, the calibration factor shall be determined under standard test conditions which implies that ISO reference radiations should be used. The first three methods described in this section presume the existence of such reference fields in the calibration laboratory.

However, some laboratories or services have only irradiation facilities differing from those recommended by ISO and, for the time being, have to use this *test field* for calibrations.

TABLE VI. CONVERSION COEFFICIENTS $h_{pK}(10;S,\alpha)$ AND $h_{pK}(10;R,\alpha)$ FROM AIR KERMA, K_a, TO THE DOSE EQUIVALENT $H_p(10;S,\alpha)$ AND $H_p(10;R,\alpha)$, RESPECTIVELY, FOR RADIATION QUALITIES GIVEN IN ISO 4037-1 [12] AND THE SLAB PHANTOM

Radiation Quality	Irr. dist. m	d_F cm	Build-up Layer mm	k_{PMMA}	$h_{pK}(10;S,\alpha)$ and $h_{pK}(10;R,\alpha)$ in Sv /Gy for Angle of Incidence of								
					0°	10°	20°	30°	40°	45°	50°	60°	70°
S-Am	2,0 - 3,0	11	-	-	1.89	1.88	1.86	1.83	1.77	1.72	1.66	1.50	1.25
S-Cs	1,5 - 4,0	15	1.5	1.00	1.21	1.22	1.22	1.22	1.22	1.22	1.22	1.19	1.14
S-Co	1,5 - 4,0	15	4	1.00	1.15	1.15	1.15	1.15	1.16	1.16	1.16	1.14	1.12
R-C	1,0 - 5,0	15	25	0.94	1.11	1.11	1.12	1.12	1.11	1.11	1.11	1.11	1.10
R-F	1,0 - 5,0	15	25	0.94	1.12	1.12	1.12	1.11	1.11	1.11	1.11	1.12	1.13
T-Ti	1,0 - 5,0	15	25	0.94	1.11	1.11	1.11	1.11	1.10	1.11	1.11	1.11	1.12
R-Ni	1,0 - 5,0	15	25	0.94	1.11	1.11	1.11	1.11	1.10	1.10	1.10	1.11	1.12
R-O	1,0 - 5,0	15	25	0.94	1.12	1.12	1.12	1.11	1.11	1.11	1.11	1.12	1.13

The irradiation distance is measured from the geometrical centre of the radionuclide source to the point of test, at which the reference point of the dosimeter shall be located. In the case of high-energy photon radiations, the irradiation distance shall be measured from the centre of the radiator or target surface from which the radiation emerges to the point of test. The values of the conversion coefficients may be used without modification over the given range of irradiation distances. The meanings of the diameter d_F, the build-up layer and the correction factor k_{PMMA} are explained in Section 6.

An example of such a test field is a photon radiation field generated by a ^{137}Cs source operated in a small room so that radiation scattered from the walls makes a remarkable contribution to the air-kerma rate at the reference point, say 20 %. The application of eq. (3) in section 4 using a value of the air-kerma rate measured by a reference instrument and the conversion coefficient from Table 6 would produce a faulty result as :

- the detector of the reference instrument for the air-kerma rate probably is an ionisation chamber with an almost isotropic angular response to air kerma measuring the air kerma not only of the collimated beam but also of the radiation scattered from all directions of the room, i.e. even of that backscattered radiation which does not contribute to the indication of a personal dosimeter fastened on a phantom because this scattered radiation is shielded by the phantom;

- the conversion coefficient from Table VI refers to pure ^{137}Cs radiation only, i.e. collimated beam conditions are presumed.

Another example of a test field is a field of high-energy beta radiation emitted by a beta source (e.g. of the radionuclide ^{90}Y). This radiation may not even be a type of radiation which the dosimeter is intended to measure.

It is essential that the correspondence of the dosimeter's reading in the test field to the reading of the dosimeter in a reference field is established, and that this correspondence, once determined in a type test, is invariant. In this case, a routine calibration with, of course, less than the highest metrological quality can be carried out in such a test field. Considering the importance such routine calibrations have in practice, it is shown in section 5.5 by an example how such a test field can be used.

5.2. Calibration with a reference instrument without any monitor

This procedure is appropriate if the value of the air-kerma rate is stable over a time period corresponding to the duration of the calibration so as to achieve results of the desired accuracy. The calibration is carried out under standard test conditions close to the reference conditions. The calibration set-up is shown schematically in the upper half of Figure 10. The reference points of the reference instrument and the dosimeter under calibration are subsequently positioned at the point of test in the radiation field for calibration in terms of $H_p(10;E,\alpha)$. The position of the point of test is determined by the intersection of the dashed lines in Figure 10.

Part (1) of the Figure: For the reference instrument (subscript R) one obtains the calibration factor N_R of the reference instrument (under reference conditions) from the measured (indicated) value M_R of the reference instrument corrected for reference conditions by means of eq. (4):

$$N_R = \frac{H_p(10;E,\alpha)}{h_{pK}(10;E,\alpha)\cdot M_R} \tag{5}$$

$h_{pK}(10;E,\alpha)$ is the coefficient to convert from air kerma measured by the reference instrument to $H_p(10;E,\alpha)$. Depending on the radiation quality used, the energy E has to be replaced in eq. (5), and consequently in the following equations, by F, L, N, W, H, S or R (see section 3).

Part (2) of the Figure: The dosimeter under calibration (subscript *I*) has an indication directly related to the dose equivalent quantity $H_p(10;E,\alpha)$. The dosimeter is positioned on the ISO water slab phantom with an angle α between the axis of the reference radiation field and the reference direction of the personal dosimeter; most frequently α = 0° will be chosen. The dosimeter's calibration factor (under reference conditions) N_I is obtained from the measured (indicated) value, corrected for reference conditions, M_I:

$$N_I = \frac{H_p(10;E,\alpha)}{M_I} \tag{6}$$

The combination of eqs. (5) and (6) results in the calibration factor N_I derived from N_R:

$$N_I = N_R \cdot \frac{h_{pK}(10;E,\alpha) \cdot M_R}{M_I} \tag{7}$$

5.3. Calibration with a reference instrument and with a monitor

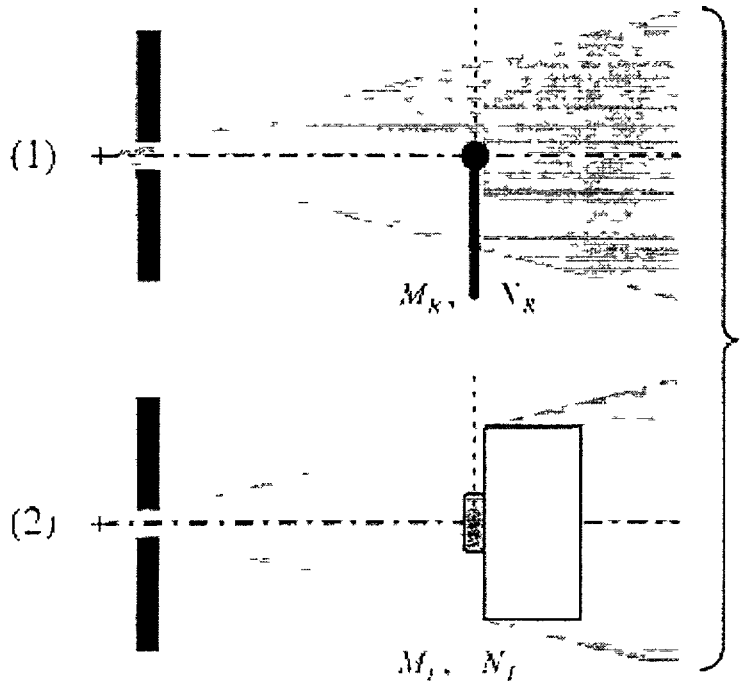
Moderate variations in the course of time in the physical quantities that characterize the dosimetric properties of the radiation field (e.g. air-kerma rate) can be corrected by using a monitor and by irradiating the reference instrument and the personal dosimeter under calibration sequentially. This technique is often employed with X-ray units in order to correct for variations in the air-kerma rate when reference instrument and dosimeter under calibration are alternately placed at the point of test. The calibration set-up is schematically shown in the lower part of Figure 10 in a way similar to that chosen for the calibration set-up in the previous chapter. The reference points of the reference instrument and the dosimeter under calibration are subsequently positioned at the point of test in the radiation field for calibration in terms of $H_p(10;E,\alpha)$. Its value at the point of test is related to the calibration factor of the monitor chamber, N_M, and its measured (indicated) value *m* by

$$N_M = \frac{H_p(10;E,\alpha)}{m} \tag{8}$$

Part (1) of the Figure: The calibration factor N_R of the reference instrument (under reference conditions) is

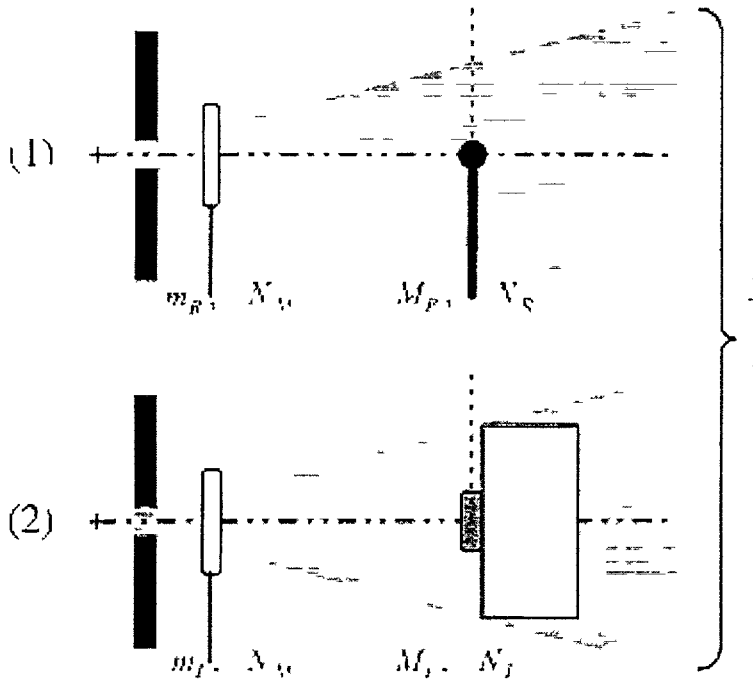
$$N_R = \frac{H_p(10;E,\alpha)}{h_{pK}(10;E,\alpha)\ M_R} \tag{9}$$

where M_R is the measured (indicated) value of the reference instrument corrected for reference conditions (i.e. indication multiplied by applicable correction factors, e.g. a correction factor considering differences in air density).



$$V_J = N_K \cdot \frac{h_{pK}(10, E, \alpha)}{M_J} \cdot M_R$$

Calibration with a reference instrument without any monitor



$$V_J = V_R \cdot \frac{h_{pK}(10; E, \alpha)}{m_R} \cdot M_R \cdot \frac{m_J}{M_J}$$

Calibration with a reference instrument and with a monitor

FIG 10 Calibration with a reference instrument (schematically)

Part (2) of the Figure: The corresponding equation for the calibration factor N_I of the dosimeter (under reference conditions) is:

$$N_I = \frac{H_p(10;E,\alpha)}{M_I} \tag{10}$$

M_I is the respective value of the dosimeter under calibration.

$H_p(10;E,\alpha)$ can be eliminated in eqs. (9) and (10) by means of eq. (8) if one introduces the measured values m_R and m_I of the monitor for the irradiation of the reference instrument and the dosimeter under calibration:

$$N_R = \frac{N_M \; m_R}{h_{pK}(10;E,\alpha) \; M_R} \tag{11}$$

$$N_I = \frac{N_M \; m_I}{M_I} \tag{12}$$

m_R is the measured (indicated) value of the monitor for the irradiation of the reference instrument, corrected for reference conditions (i.e. indication multiplied by applicable correction factors, e.g. differences in air density) and m_I the corresponding value of the monitor for the irradiation of the dosimeter.

By division of eqs. (11) and (12), the calibration factor N_M disappears and one obtains for the calibration factor of the dosimeter (under reference conditions) N_I:

$$N_I = N_R \left(\frac{h_{pK}(10;E,\alpha) \; M_R}{m_R} \right) \left(\frac{m_I}{M_I} \right) \tag{13}$$

In practice, if the irradiations of reference instrument and dosimeter to be calibrated are performed in brief succession, the ambient conditions of the radiation monitor remain the same and corrections of the indicated value of the monitor to reference conditions are unnecessary.

In cases where the monitor is of good long-term stability, it may serve as the reference instrument after having been calibrated against another reference instrument.

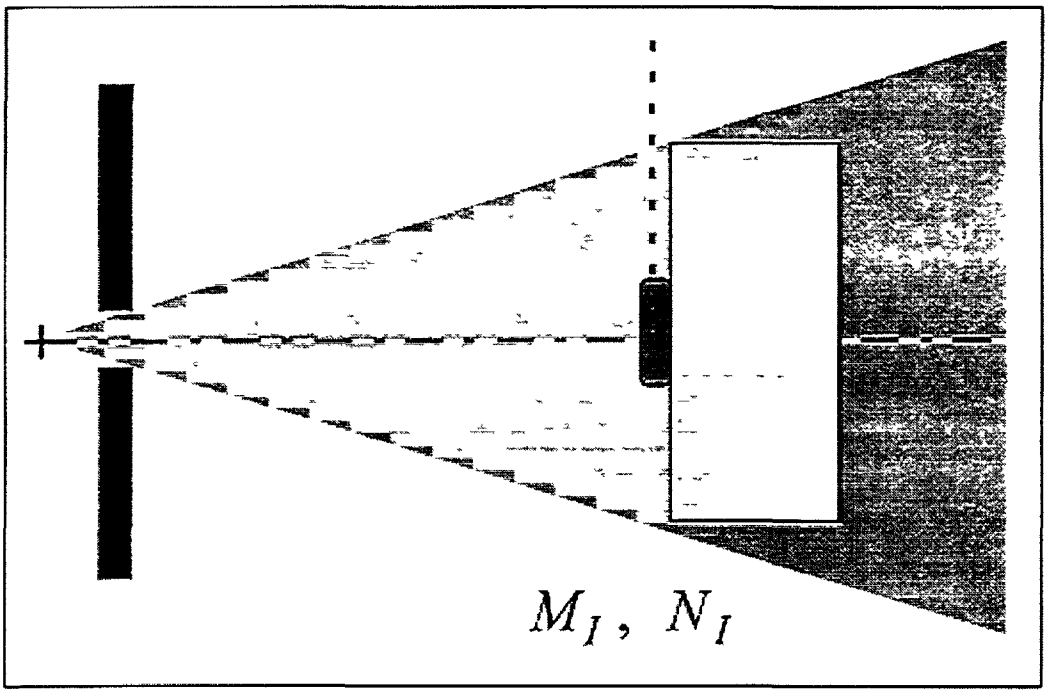


FIG. 11. Calibration in a known radiation field (schematically)

5.4. Calibration in a known radiation field

For a radiation field in which the conventional true value of $H_p(10;E,\alpha)$ at the point of test is directly known, the calibration factor N_I of the dosimeter is obtained from its measured value, corrected for reference conditions, M_I (see Figure 11):

$$N_I = \frac{H_p(10;E,\alpha)}{M_I} \tag{14}$$

5.5. Example of a routine calibration

It is assumed that a service has established a test field with a ^{137}Cs source for routine calibrations of dosimeters as described in section 5.1. This test field is used in connection with occasional calibrations in a reference field of a secondary standard laboratory. The correspondence must be established between the dosimeter's reading in the test field and the reading of the dosimeter in the reference field, and it must be shown that this correspondence is invariant. Routine calibrations will be needed for new batches of dosimeters and for routine checks of the reproducibility of the dosimeter evaluation. In this example, a three step procedure is followed by the service (see Figure 12).

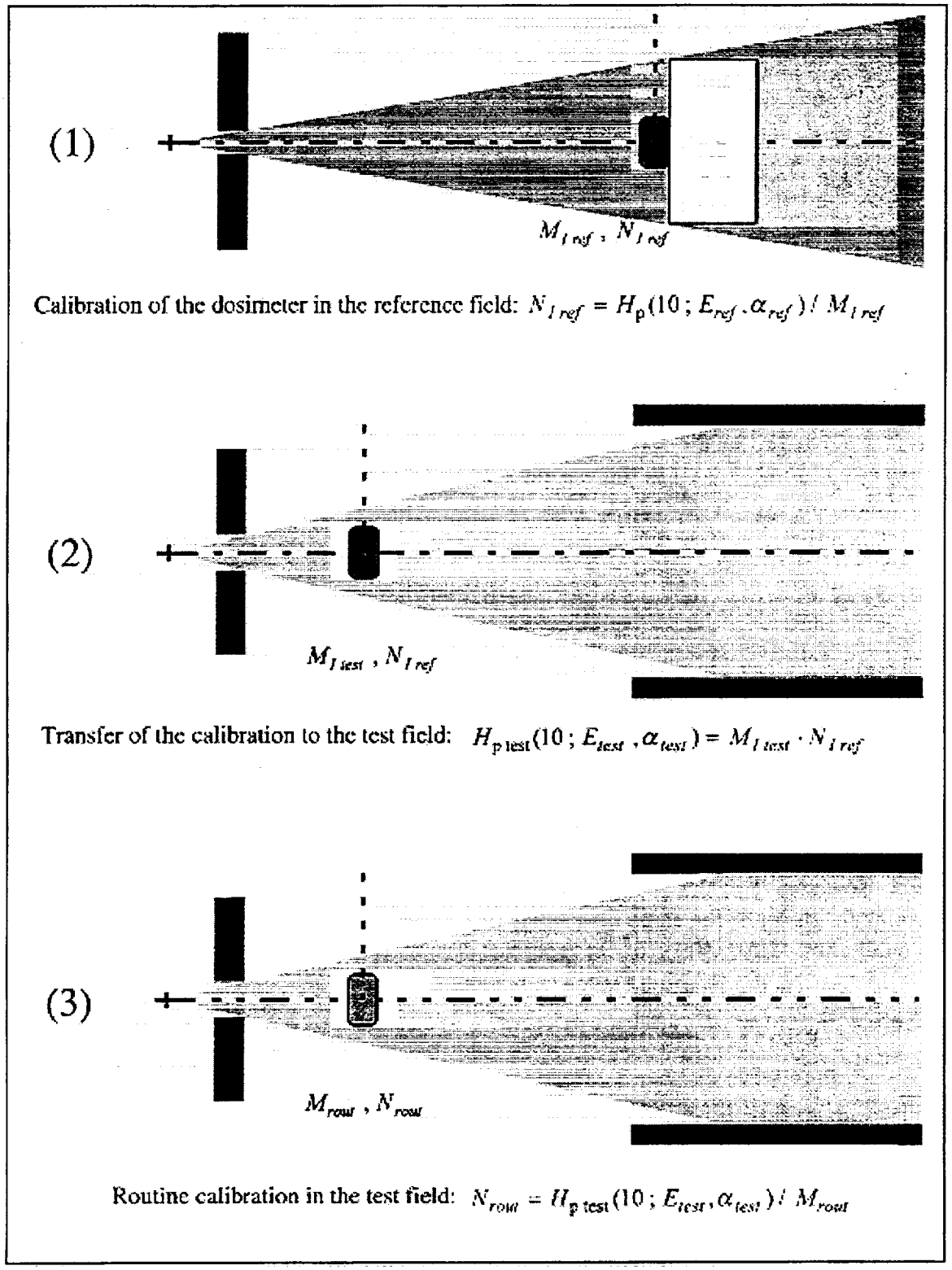


FIG. 12. Example of a routine calibration with three experimental set-ups (schematically).

Step 1. For simplicity it is assumed that one routine dosimeter is sent by the service to a secondary standard laboratory; if more dosimeters are sent in, appropriate mean values of the measured values have to be taken into account. In the secondary standard laboratory the irradiation is performed on an ISO water slab phantom in the reference field, for which the conventional true value of $H_{\mathrm{p\ ref}}(10; E_{ref}, \alpha_{ref})$ is known at the point of test. According to eq. (14), the calibration factor $N_{I\,ref}$ is obtained from the measured value, corrected for reference conditions, $M_{I\,ref}$:

$$N_{I\,ref} = \frac{H_{\mathrm{p\ ref}}(10; E_{ref}, \alpha_{ref})}{M_{I\,ref}} \tag{15}$$

Step 2. After return to the service, the calibrated dosimeter is irradiated homogeneously at a certain point (point of test) in the test field where the measured value, corrected for reference conditions, $M_{I\,test}$, is obtained. This can be formally associated with a dose equivalent $H_{\mathrm{p\ test}}(10; E_{test}, \alpha_{test})$ if one assumes the validity of the calibration factor of the reference field, $N_{I\,ref}$:

$$H_{\mathrm{p\ test}}(10; E_{test}, \alpha_{test}) = M_{I\,test} \cdot N_{I\,ref} \tag{16}$$

Here the routine dosimeter plays the role of a reference instrument. It links the quantity $H_{\mathrm{p\ test}}(10; E_{test}, \alpha_{test})$ of the test field with $H_{\mathrm{p\ ref}}(10; E_{ref}, \alpha_{ref})$ in the reference field even if the dosimeter is not irradiated on a phantom.

Step 3. This step 3 is the routine calibration in the true sense of the word. Subject is any (routine) dosimeter of the same type as the dosimeter calibrated in the reference field (*step 1*). The calibration factor N_{rout} of the (routine) dosimeter is obtained at the point of test in the test field from the the measured value, corrected for reference conditions, M_{rout}, and the dose equivalent $H_{\mathrm{p\ test}}(10; E_{test}, \alpha_{test})$ determined in *step 2*:

$$N_{rout} = \frac{H_{\mathrm{p\ test}}(10; E_{test}, \alpha_{test})}{M_{rout}} \tag{17}$$

It is obvious that this routine calibration is, in principle, of less metrological quality than a calibration based on one of the methods described in sections 5.2 to 5.4 because a routine dosimeter of inferior performance is used as a reference instrument in *step 1*. Moreover, the assumption that the calibration factor $N_{I\,ref}$ is valid for the *test field* has to be checked (compare eq. (16)). This assumption is questionable, for example, if the reading in the reference field is primarily generated by the backscatter of the phantom and the calibration in the test field is performed free in air.

6. POSITIONING OF THE PERSONAL DOSIMETER

6.1. Reference point and point of test

For the calibration the *reference point* of the dosimeter has to be placed at the so-called *point of test* in the radiation field at which the conventional true value of $H_p(10)$ is known. The reference point and the reference direction of the dosimeter should be stated by the manufacturer. The reference point should be marked on the outside of a dosimeter. If this proves impossible, the reference point should be indicated in the accompanying documents supplied with the dosimeter. All distances between the radiation source and the dosimeter shall be taken as the distance between the radiation source and the dosimeter's reference point.

In the absence of information on the reference point or on the reference direction of the dosimeter to be calibrated, these parameters shall be fixed by the calibrating laboratory. They shall be stated in the calibration certificate.

When the angular dependence of the response has to be measured, in a first step, the dosimeter is fastened on the phantom's front surface so that the dosimeter's reference direction coincides with the normal on the phantom's front surface (Figure 13). Then the dosimeter's reference point and the point of test in the radiation field are brought into coincidence and, finally, the *combination of dosimeter and phantom* is rotated about an axis passing through the reference point of the dosimeter so that the reference direction of the dosimeter and the direction of radiation incidence of the irradiation facility form the desired angle α.

The calibration factor is determined under conditions lying within the range of standard test conditions which usually means $\alpha = 0°$.

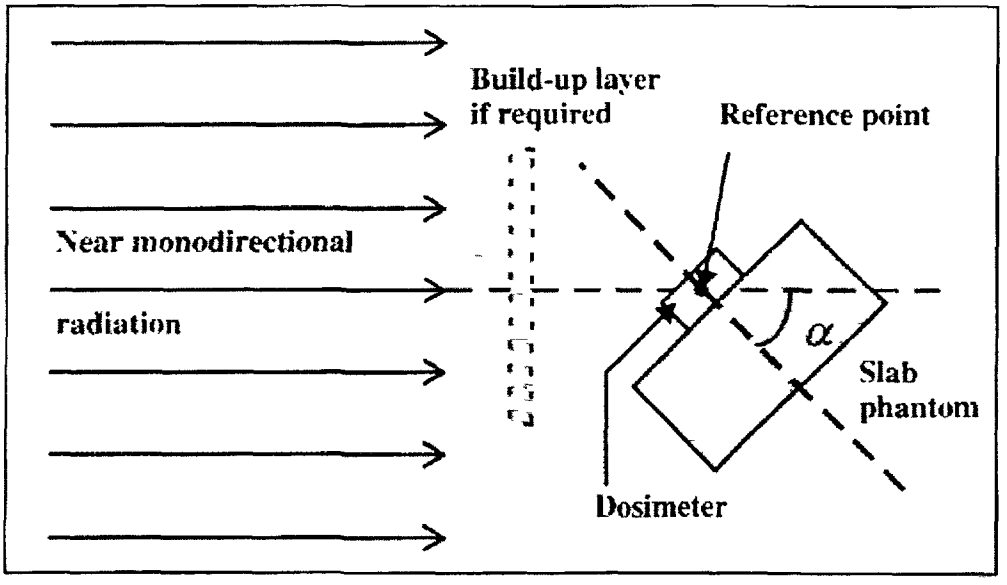


FIG. 13. Arrangement for the calibration and the measurement of the response of a personal dosimeter at the angle α.

6.2. Simultaneous irradiations of dosimeters

When several personal dosimeters are irradiated simultaneously on the front face of the slab phantom they shall not cover any phantom surface outside a circle of diameter d_F, given by the approximate locus of the 98 % isodose contour with respect to the dose in the centre of the phantom. The values of $h_{pK}(10; N, \alpha)$ depend on the radiation quality and they are given for some reference radiations in Tables V and VI. If irradiation distances smaller than those given in the Tables are used, the diameter d_F becomes smaller.

Two effects associated with this (simplified) procedure require additional attention:

- by positioning several dosimeters on the phantom surface the backscatter may be reduced due to the attenuation of the primary radiation passing through the dosimeters and
- possibly different distances of the reference points from the radiation source have to be considered.

Before such a practice is adopted it shall be verified that it leads to results identical to within 2 % to those obtained when only one dosimeter is irradiated in the centred position.

There may be certain types of dosimeters which respond very sensitively to small changes in the properties of the backscattered photon field. This may be due to the use of strongly energy-dependent detectors or possibly, to the properties of the algorithms used to arrive at the value of the dose equivalent from the detector signal. In such cases it may be advisable to have only one dosimeter mounted on the phantom surface for any calibration.

6.3. Misplacement and dosimeter supports

In the case of point sources and in the absence of scattered radiation and photon absorption, the dose rate changes with the inverse square of the distance R. A misplacement of the dosimeter's reference point in the beam by the amount of ΔR in the direction of the beam will lead to a relative error in the calibration factor of $2\Delta R/R$ at the distance R. Misalignment perpendicular to the beam axis by Δr causes a relative error of $(\Delta r/R)^2$. In the presence of scattered radiation and for sources of finite dimensions, the above approximations are limited to values of ΔR or Δr small in comparison with R.

The supports used for the dosimeter and the reference instrument, and the calibration source should introduce as little scattered radiation as possible. The effects of such scattered radiation on the indication of the instruments should be taken into account.

6.4. Effects associated with electron ranges

In some photon fields, effects associated with electron ranges have to be considered. For dosimeters being calibrated there is no secondary electronic equilibrium within the sensitive volume of their detectors. In some cases, the detector window or encapsulation is not sufficiently thick for dose build-up, one prerequisite for secondary electronic equilibrium. For those dosimeters one would obtain different indications in photon radiation fields with differing electronic equilibrium. By placing a layer in front of the detector, which together with the wall material and the cover of the detector gives a combined layer of a thickness larger than the range of the most energetic secondary electrons, one is able to obtain reproducible results. Experience has shown that one does not require any additional layers for photon energies below 250 keV; up to 0.66 MeV, a layer of PMMA 1.5 mm thick is

sufficient. For energies up to 1.33 MeV, a 4 mm PMMA layer is sufficient. The cross-sectional area of the plate shall be 30 cm x 30 cm.

The modification of the radiation field by introducing the PMMA plate shall be taken into account by multiplying the conversion coefficient by the correction factor k_{PMMA} (see Table 6).

For irradiations on a phantom it may be practical to position the PMMA plate at a certain distance away from the dosimeter or dosimeter-phantom combination so that it is not necessary to also rotate the plate when the variation of response with the direction of radiation incidence is examined.

REFERENCES

[1] DEUTSCHES INSTITUT FÜR NORMUNG E.V., International Vocabulary of Basic and General Terms in Metrology, ISBN 3-410-13086-1 (1994).

[2] INTERNATIONAL STANDARDS ORGANISATION, Reference Photon Radiations for Calibrating Dosemeters and Dose Ratemeters and for Determination of their Response as a Function of Photon Energy and Angle of Incidence, ISO/DIS 4037-3, Geneva (1996).

[3] INTERNATIONAL ELECTROTECHNICAL COMMISSION, Radiation Protection Instrumentation - Direct Reading Personal Dose Equivalent (Rate) Monitors - X, Gamma and High Energy Beta Radiation, International Standard IEC 1283 (1995).

[4] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Measurement of Dose Equivalents from External Photon and Electron Radiations. ICRU Report 47, Bethesda, (1992).

[5] ALBERTS, W.G., AMBROSI, P., BÖHM, J., DIETZE, G., HOHLFELD, K., WILL, W., New Dose Quantities in Radiation Protection. PTB Report PTB-Dos-23e, Braunschweig, (1995).

[6] BÖHM, J., THOMPSON, I.M.G., GRIFFITH, R., The New IAEA Recommendations on the Calibration of Radiation Protection Monitoring Instruments. 9th Int. Congress of IRPA, Vienna, 14-19 April 1996. Proc. Vol. 4, (1996) 186–188.

[7] BARTLETT, D.T., ALBERTS, W.G., Type Testing and Calibration of Personal Dosemeters. Radiat. Prot. Dosim. **54**, (1994) 259–266.

[8] BARTLETT, D.T., ILES, W.J., Calibration of Personal Dosemeters. NRPB Report NRPB-M520 (1994).

[9] ALEINIKOV, V., Calibration of Personal Dosimeters: Quantities and Terminology. This publication.

[10] GRIFFITH, R., Quantities and Units for External Dose Assessment. This publication.

[11] KRAMER, H.M., BÖHM, J., ILES, W.J., THOMPSON, I.M.G., On the Current Status of an ISO Working Document on the Calibration and Type-Testing of Radiation Protection Dosimeters for Photons. Radiat.Prot.Dosim. **54**, (1994) 267–272.

[12] INTERNATIONAL STANDARDS ORGANISATION, X and Gamma Reference Radiation for Calibrating Dosemeters and Doserate Meters and for Determining their Response as a Function of Photon Energy. Part 1: Radiation Characteristics and Production Methods, ISO 4037-1, Geneva (1996).

[13] BEHRENS, R., Physikalisch-Technische Bundesanstalt, Braunschweig, Personal Communication (1997).

[14] BEHRENS, R., Rechnergestützte Optimierung von Röntgenfluoreszenzanlagen, Diploma, Braunschweig (1995).

[15] BÜERMANN, L., Physikalisch-Technische Bundesanstalt, Braunschweig, Personal Communication (1997).

[16] NOWOTNY, R., HÖFER, A., Ein Programm für die Berechnung von diagnostischen Röntgenspektren. Fortschr. Röntgenstr. **142**, (1985) 685–689.

CALIBRATION OF A PERSONAL DOSIMETER IN THE FIELD OF A RADIONUCLIDE

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Abstract

An example of the practical implementation of the international standard ISO4037-3 for the calibration of an electronic dosimeter for $H_p(10)$ in the radiation field of a ^{137}Cs source for normal incidence of the radiation is given The set-up, the irradiation and the calculation of the results including the assessment of the uncertainties are described in detail

1. INTRODUCTION

This paper gives an introduction in the practical implementation of the international standard ISO4037-3 [1] for the calibration of an electronic dosimeter for $H_p(10)$ in the radiation field of a ^{137}Cs source for normal incidence of the radiation.

2. SOURCE AND BEAM

- Radionuclide: ^{137}Cs - Gamma source, encapsulated in steel.
- Material of the holder: Aluminium
- Nominal activity: $A_{act} = 65$ GBq
- The beam is collimated by an ISO-Collimator with 15° opening.
- The beam is measured and certified in terms of air-kerma rate.

For the calibration in a known radiation field in which the conventional true value of $H_p(10;E,\alpha)$ at the point of test is directly known, the calibration factor N_I of the dosimeter is obtained from its measured value, corrected for reference conditions, M_I (see eq. (14) in [2]):

$$N_I = \frac{H_p(10, S-Cs, 0^0)}{M_I} \tag{1}$$

whereby $H_p(10;E,\alpha)$ is obtained by (see eq.(3) in [2]:

$$H_p(10; S-Cs, 0^0) = h_{pK}(10; S-Cs, 0^0) \bullet k_{PMMA} \bullet K_a \tag{2}$$

$H_p(10,S\text{-}Cs,0°)$: Personal dose equivalent

$h_{pK}(10;S\text{-}Cs,0°)$: Conversion coefficient from air kerma to personal dose equivalent $H_p(10,S\text{-}Cs,0°)$

k_{PMMA} Correction factor for PMMA build-up plate

Number of certificate from Bundesamt für Eich- und Vermessungswesen (BEV): T 951091/6.

The value of $\dot{K}_{a,\,ref}$ in the certificate is given for the reference date. This value has to be reduced to the actual value as follows:

$$\dot{K}_a = \dot{K}_{a,ref} \cdot \exp\left(-\ln(2).\frac{\Delta t}{t_{\frac{1}{2}}}\right) \tag{3}$$

$\dot{K}_a$: Actual air-kerma rate (unit: μGy/h) at the point of test

$\dot{K}_{a,ref}$: Air-kerma rate at reference date (unit: μGy/h)

Δt: Time since reference date (unit: d)

$t_{1/2}$: Half-life of the source (unit: d)

3. DOSIMETER

- Type: Siemens electronic personal dosimeter EPD2
- Detector: Silicon diode
- Reference point: 5 mm behind mark
- Measuring quantity: $H_p(10)$
- Rated range of use 0 μSv to 15 Sv

The following accessory and documents are necessary:

- Manual
- Type test
- Batteries
-

4. SET-UP

The calibration will be done on the **ISO water slab phantom** [1].

Note: The irradiation conditions on the phantom should be similar to the practical wearing conditions on the body. Therefore a clip (if existing) must be used on the phantom.

The distance source-phantom should be sufficient, to assure that the whole phantom is within the beam.

The reference point of the dosimeter must be brought in the test point (in source-detector distance, SDD) and the phantom is used as a backscatter phantom. Reference point and centre of the phantom-surface are positioned in the main beam direction.

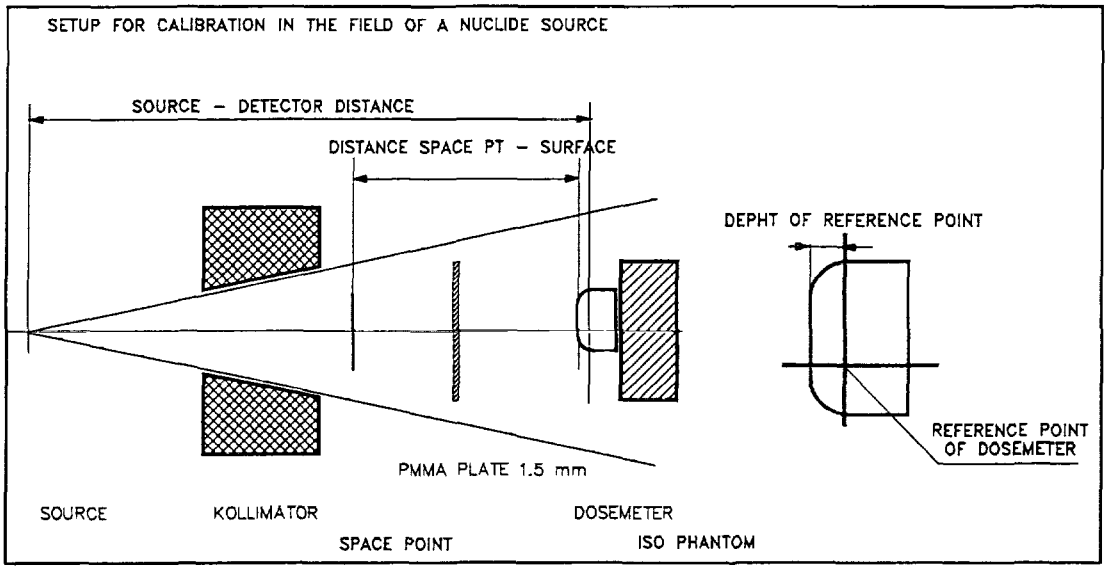

FIG 1. Set-up for the calibration of a dosimeter in a known radiation field.

5. IRRADIATION

The applied dose should be at least 100 times larger as the last digit of reading and also in a range where the background reading can be neglected. The irradiation time should be long enough to minimise uncertainties due to shutter time. The irradiation time t_i can be calculated as:

$$t_i = \frac{K_a}{\dot{K}_a} + \Delta t_s \tag{4}$$

t_i Indicated "Opening time" of shutter

Δt_S Delay of shutter time.

The delay time can be found in the certificate or has to be determined by the laboratory.

The indicated time t_i can be adjusted only in steps of seconds. The applied air kerma is therefore:

$$K_a = \dot{K}_a (t_i - \Delta t_s) \tag{5}$$

6. DETERMINATION OF THE CALIBRATION FACTOR

The calibration factor N_I is determined by combining equations (1) to (4):

$$N_I = \frac{h_{pk}(10; S-Cs,0^0) \cdot k_{PMMA} \cdot K_{a,ref} \cdot exp(-ln2 \cdot \frac{\Delta t}{t_{1/2}}) \cdot (t_i - \Delta t_s)}{M_I}$$

7. NUMERICAL VALUES FOR THE GIVEN EXAMPLE

7.1. Source

TABLE I. SOURCE AND RADIATION FIELD

SDD = 2500 mm	Beam diameter = 655 mm
Reference date: 1993 12 3	Calibration date: 1997 05 27
Δt = 1243d	$t_{1/2}$ = 11050 d
$\dot{K}_{a,ref}$ = 841 µGy/h	$\dot{K}_{a,act}$ = 777,9 µGy/h
h_{pK}(10: S-Cs,0°) = 1,21 Sv/Gy	k_{PMMA} = 1.0
$\dot{H}_p(10)$ = 941 µSv/h = 0,2161 µSv/s	

7.2. Set-up

Beam diameter = 650 mm which is more then the diagonal of phantom = 425 mm

(SPACE POINT ⇒ SURFACE) = 2500 - 458.8 - 5 = 2036,2 mm (see Figure 1)

7.3. Irradiation

Requested dose:	$H_p(10)$ = 100 µSv	⇒	K_a = 82,64 µGy
Irradiation time:	Δt_S = 2,1 s	t_i = 384,56 s	t_i* = 385 s (integer)
Applied dose:	K_a = 82,74 µGy	⇒	$H_p(10)_{appl}$ = 100,12 µSv

7.4. Calibration factor

M = 100,9 µSv	M	Meter reading as mean value of 10 readings
s = 1.1 µSv	s	Experimental standard deviation
N = 0,992	N	Calibration factor

8. UNCERTAINTIES OF THE CALIBRATION FACTOR

Uncertainties are evaluated according to the IAEA Technical Report Series No. 374 [3].

Due to the used formula **relative uncertainties (w)** are used.

- The coverage factor $k = 2$
- The uncertainty of the certified *Air-kerma rate* is stated with 1.5 % according to [3] and a coverage factor $k = 2$.
- The position of the reference point of the dosimeter is within s(R) = ± 1.5 mm. (Experience in Lab.)

  $$\frac{\Delta K_a}{K_a} = -2.\frac{\Delta R}{R} \Rightarrow w = 0.12\% \quad \text{(inverse square law} \Rightarrow \text{sensitivity factor = 2).}$$

- **Field inhomogeneity**: $(\Delta K_a/K_a) < 0{,}2$ **%.** (Measurement in laboratory). Values are upper and lower limits

  $$w^2 = (\Delta K_a/K_a)^2 / 3$$

  (rectangular probability distribution)
- The uncertainty of the **Conversion factor** h_{pK}**(10; S-Cs,0°)** is given in [1]:

  w = 2%.
- Meter reading M.:

  s = 1.1 µSv. $\quad s^2_{mean} = s^2 / n$

  s_{mean} experimental standard deviation of the mean
  n number of measurements

  $$w_{mean} = s_{mean} / M$$

- **Irradiation time**: Uncertainties are negligible

TABLE II. SUMMARY OF EVALUATION OF UNCERTAINTIES

Input Quantity			Uncertainty	Reference	w_i
Air-kerma rate	certified	K_a	$2w$ = 1.50 %	certificate BEV	0,75 %
Air-kerma rate	positioning	K_a	$s(R)$ = ± 1.5 mm	Lab	0,12 %
Air-kerma rate	field inhom.	K_a	$\Delta K_a/K_a$ < 0.2%	Lab	0,12 %
Conversion factor		$h_{p,K}(10)$	w = 2%	ISO4037-3	2,00 %
Meter reading		M	s = 1.1 µSv	measured value	0,35 %
Output Quantity					
Calibration factor		N			2,17 %

Uncertainty	$u = w(N) \cdot N$	$u = 0{,}022$
	$U = k \cdot u$	$U = 0{,}044$

U Associated expanded uncertainty to N

k coverage factor ($k = 2$)

The calibration factor can now be written as:

$$\underline{N = 0{,}99 \pm 0{,}04}$$

REFERENCES

[1] INTERNATIONAL STANDARDS ORGANISATION, Reference Photon Radiations for Calibrating Dosimeters and Dose Ratemeters and for Determination of their Response as a Function of Photon Energy and Angle of Incidence. ISO/DIS 4037-3, Geneva (1996).

[2] BÖHM, J., Calibration of personal dosimeters for photon radiation with respect to the personal dose equivalent Hp(10). Physikalisch-Technische Bundesanstalt, Braunschweig (1997).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Calibration of Dosimeters Used in Radiotherapy. Technical Report Series No. 374, IAEA, Vienna (1994).

DOSIMETER CHARACTERISTICS AND SERVICE PERFORMANCE REQUIREMENTS

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Abstract

The requirements for personal dosimeters and dosimetry services given by ICRP 26, ICRP 35, ICRP 60 and ICRP 75 are summarised and compared with the requirements given in relevant international standards. Most standards could be made more relevant to actual workplace conditions. In some standards, the required tests of energy and angular dependence of the response are not sufficient, or requirements on overall uncertainty are lacking.

1. INTRODUCTION

World-wide, there are many standards covering requirements for personal dosimeters and dosimetry services. This paper gives an overview of those standards which are either independent of the measurement quantity, or are written to be used with the new quantities $H_p(10)$ and $H_p(0,07)$. In the following only the new quantity $H_p(10)$ and photon radiation will be considered.

2. GENERAL RADIATION PROTECTION REQUIREMENTS

2.1. ICRP Recommendations 26, 35, 60 and 75

The basis for all requirements in the field of radiation protection is given by the International Commission on Radiation Protection (ICRP).

In Publication 26 [1] in paragraph (104) the Commission recommends a limit for the annual dose-equivalent [The remarks in square brackets are given by the authors.] :

(104) *For stochastic effects the Commission's recommended dose limitation is based on the principle that the risk should be equal whether the whole body is irradiated uniformly or whether there is non-uniform irradiation. This condition will be met if ... the recommended annual dose-equivalent limit for uniform irradiation of the whole body* ... [is] *50 mSv (5 rem).*

In Publication 35 [2] the concept of 'Recording Level' is introduced in paragraph (18) and the 'Accuracy Required in Routine Monitoring' is given in paragraph (109).

(18) The recording level is a formally defined value for dose equivalent or intake above which a result from a monitoring program is of sufficient interest to be worth keeping. The Commission has recommended that the recording level for individual monitoring should be based on one-tenth of that fraction of the annual limit corresponding to the period of time to which the individual monitoring measurement refers...

(109) The uncertainties acceptable in routine monitoring for external radiation should be somewhat less than the investigation level and can best be expressed in relation to the estimates of the annual deep and shallow dose-equivalent indices [now taken to be $H_p(10)$ and $H_p(0.07)$] *that are measured. The uncertainty in the measurement of the annual value of these quantities (or of the upper limits if a cautious interpretation is being conducted) should be reduced as far as reasonable achievable. If these quantities are of the order of the relevant annual limits, the uncertainties should not exceed a factor of 1.5 at the 95% confidence level. Where they amount to less than 10 mSv an uncertainty of a factor of 2 at the 95% confidence level is acceptable. This uncertainty includes errors due to variations in the dosimeters sensitivity with incident energy and direction of incidence as well as intrinsic errors in the dosimeter and its calibration. It does not include uncertainties in deriving tissue or organ dose equivalents from the dosimeter results.*

In Publication 60 [3] earlier concepts, relevant to matters of concern here, are mostly retained. In paragraph (257) the reference levels are explained and in paragraph (271) uncertainties are given. In paragraph (S25) the dose limits are summarised:

(257) *It is often helpful in the management of operations to establish values of measured quantities above which some specified action or decision should be taken. These values are generally called reference levels. They include recording levels, above which a result should be recorded, lower values being ignored; investigation levels, above which the cause or the implication of the result should be examined; and intervention levels, above which some remedial action should be considered. The use of these levels can avoid unnecessary or unproductive work and can help in the effective deployment of resources. If recording levels are used, the fact that no unrecorded results exceeded the recording level should be made clear.*

(271) In practice, it is usually possible without great difficulty to achieve an accuracy of about 10% at the 95% confidence level for measurements of radiation fields in good laboratory conditions. In the workplace, where the energy and the orientation of the radiation field are rarely known, uncertainties by a factor of 1.5 will not be unusual in the estimation of the annual doses from the external exposure of the individual workers. In view of the other uncertainties this factor is acceptable...

(S25) The Commission recommends a limit on effective dose of 20 mSv per year, averaged over 5 years (100 mSv in 5 years), with the further provision that the effective dose should not exceed 50 mSv in any single year. The 5-year period would have to be defined by the regulatory agency, e.g. as discrete 5-year calendar periods. The Commission would not expect the period to be introduced and then applied retrospectively. It is implicit in these recommended dose limits that the dose constraint for optimisation should not exceed 20 mSv in a year.

In Publication 75 [4], the revision of Publication 35, ICRP states in paragraphs (229), (230) Table 2, (232), and (233), and in (249), (250) and (251) the following:

The Use of Reference Levels

(229) Reference levels are values of measured quantities above which some specified action or decision should be taken. They include recording levels, above which a result should be recorded, lower values being ignored; investigation levels, above which the cause or the implications of the result should be examined; intervention levels, above which some remedial action should be considered; and, more generally, action levels above which some specified action should be taken. ...

(230) Table 2: [The] *Recording level* [is] *set by operating management or national authority,* [it] *allows records to exclude trivial information,* [it is] *advisory but should be applied consistently,* [it] *applies principally to occupational exposure with particular reference to monitoring of individuals and workplaces.*

(232) The Commission now considers that the recording level for individual monitoring should be derived from the duration of the monitoring period and an annual effective dose of no lower than 1 mSv or an annual equivalent dose of about 10% of the relevant dose limit. ...

(233) In practice, little use is made of recording levels in individual monitoring for external exposure because the measured dose is usually entered directly as a measure of the effective dose. The minimum level of detection should then be used as the recording level with results below that level being deemed to be zero. However, the recording level is useful in defining the low dose requirements of dosimeters; it can be used as the basis for defining performance requirements. ...

Accuracy

(249) The errors in the use of monitoring to provide estimates of individual doses and intakes lie partly in the measurement and partly in the models linking the measured and the required quantities. The errors contributing to the overall uncertainty may be regarded as falling into at least four broad categories:

(a) random errors in the measurement, e.g. counting statistics,

(b) systematic errors in the measurements, e.g. calibration errors,

(c) errors, mainly systematic, in dosimetric and metabolic models, ...

(d) errors ... in the use of the models, ...

(250) Individuals are usually exposed over an extended period and so assessments tend to be based on a number of measurements made over that period. The use of multiple measurements reduces the random errors. For most assessments, the systematic errors in modelling result in a bias towards over-estimation of the true dose.

(251) The Commission has noted that, in practice, it is usually possible to achieve an accuracy of about 10% at the 95% confidence level for measurements of radiation fields in good laboratory conditions (Paragraph 271, Publication 60). *In the workplace, where the energy spectrum and orientation of the radiation field are generally not well known, the uncertainties in a measurement made with an individual dosimeter will be significantly greater. ... The*

overall uncertainty at the 95% confidence level in the estimation of effective dose around the relevant dose limit may well be a factor of 1.5 in either direction for photons and may be substantially greater for neutrons of uncertain energy and for electrons. Greater uncertainties are also inevitable at low levels of effective dose for all qualities of radiation.

In the following these requirements are interpreted for the most important case of a monitoring period of one month. The factors given above mean that the value of the quotient H_m/H_t of the measured dose value, H_m, and the conventionally true value, H_t, has firstly to be smaller than or equal to the factors and secondly larger than or equal to the reciprocal of the factors. The 95% confidence level means that the given requirement must be fulfilled for 19 of 20 different measurements. In terms of uncertainties, the recording level is interpreted to allow a 100% relative uncertainty for a true dose value of the recording level itself. The recording level for individual monitoring should be derived from the duration of the monitoring period. For a monitoring period of one month the recording level is

50 mSv/(10·12) = **0.42 mSv**, according to ICRP 21/35,
20 mSv/(10·12) = **0.17 mSv**, according to ICRP 35/60,
not lower than 1 mSv/12 = **0.085 mSv** according to ICRP 60/75.

Thus the following two requirements are drawn from ICRP 26 to ICRP 75, see also Table 1 and the broad lines in Figure 1:

1. For a dose value equal to or approaching the annual dose limit, the relation $1.5 \geq H_m/H_t \geq 1/1.5$ must be fulfilled for 19 of 20 different measurements.

2. For a dose value less than or equal to H_r, the recording level for monthly monitoring, the relation $2.0 \geq H_m/H_t \geq 0.0$ must be fulfilled for 19 of 20 different measurements.

These two requirements are represented by the solid bars in Figure 1. They must be linked together in some way. This necessity is indicated by the straight dashed lines in that Figure 1.

TABLE I. REQUIREMENTS GIVEN BY ICRP 26 TO ICRP 75 AND THEIR INTERPRETATION WITH RESPECT TO UNCERTAINTY FOR MONTHLY MONITORING

Dose limit or level	Dose value according to			Requirements
	ICRP 26/35	ICRP 35/60	ICRP 60/75	
$H_m \geq H_a$ annual limit	$H_a = 50$ mSv	$\overline{H_a} = 20$ mSv	$\overline{H_a} = 20$ mSv	$1.5 \geq H_m/H_t \geq 1/1.5$ for 19 of 20 measurements
$H_m \leq H_r$ recording level	$H_r = 0.42$ mSv	$H_r = 0.17$ mSv	$H_r \geq 0.085$ mSv	$2.0 \geq H_m/H_t \geq 0.0$ for 19 of 20 measurements

2.2. Trumpet curves

The requirements of Table 1 can be met by so-called 'trumpet curves' [5,6]. They are used in many countries and are also incorporated in a number of standards. If H_0 is the equivalent to the recording level for monthly monitoring, e.g. 0.017 mSv according to ICRP 35/60 or not lower than 0.085 mSv according to ICRP 60/75, then the upper limit of the ratio H_m/H_t is given by

$$\left(\frac{H_m}{H_t}\right)_{\text{Upper Limit}} = 1.5\left(1+\frac{H_0}{2H_0+H_t}\right) \tag{1}$$

and the lower limit by

$$\left(\frac{H_m}{H_t}\right)_{\text{Lower Limit}} = \frac{1}{1.5}\left(1-\frac{2H_0}{H_0+H_t}\right) \tag{2}$$

These limits, the trumpet curves, are shown as dashed curves in Figure 1 for the two combinations ICRP 35/60 and ICRP 60/75 given above. They are the basic requirements for performance testing of dosimetry services and dosimeters. The methods for testing are given in the Section 3.

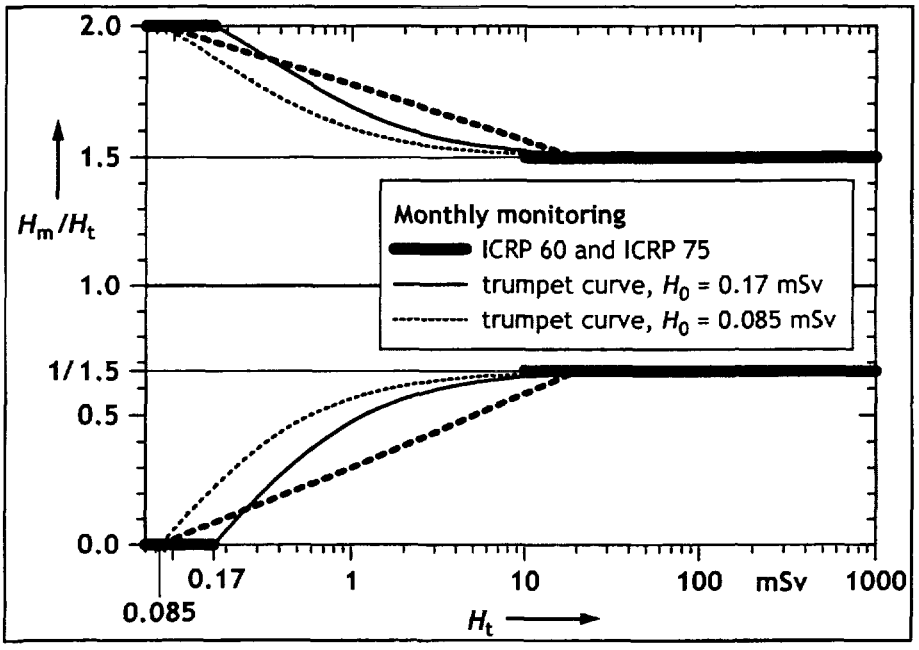

FIG. 1. Limits for the ratio H_m/H_t for monthly monitoring according to ICRP 60 and ICRP 75 and the trumpet curves for H_0 = 0.17 mSv and H_0 = 0.0.085 mSv. (H_m is the measured dose value and H_t, the conventionally true value. 95% of all measurements must be within the limits).

3. REQUIREMENTS FROM INTERNATIONAL STANDARDS

3.1. Relevant standards

Table II gives a list of those relevant international standards for personal monitoring which are either independent of the measuring quantity or are written to be used with the new quantities $H_p(10)$ and $H_p(0,07)$. In the following the requirements of these standards for $H_p(10)$ from photon radiation will be described and compared in detail with respect to requirements on overall accuracy, energy and directional dependence, linearity, coefficient of variation, environmental effects, electromagnetic fields and mechanical shock. There are of course additional influence quantities such as chemical vapours, and other types of radiation such as beta or neutron radiation, but these effects are not discussed here. Finally, we give our judgement on the relevance of these standards for actual conditions of use.

The *International Electrotechnical Commission* (IEC) issues a series of requirements, IEC 1283, IEC 1525 and IEC 1526 (draft), which are intended to be identical for the quantity $H_p(10)$ from X, gamma and high energy beta radiation and which should differ only in additional requirements, either in the validity for neutrons in the case of IEC 1525 or in the additional quantity $H_p(0,07)$ in the case of the draft of IEC 1526. There are in fact some marginal differences in the requirements for the quantity $H_p(10)$ from X, gamma and high energy beta radiation, but in the following all these requirements are referenced as IEC 1283 series. If in some cases the differences seem important then they are indicated in the text.

3.2. Overall uncertainty

Methods for calculating the overall uncertainty from component uncertainties measured, for example, in type tests are given in the 'ISO guide', by ISO and other international bodies [15]. It is not the aim of this paper to repeat details of these methods here. Table III gives an overview on the requirements on overall accuracy given in the relevant standards.

Comparing the different requirements three problems arise. Firstly, the requirements by ICRP (and consequently the trumpet curves) are asymmetrical (on a linear plot) with respect to the conventionally true value whereas the percentage deviation, which is used in nearly all cases where the overall uncertainty is calculated from component uncertainties measured in type tests, is symmetrical. Secondly, some requirements, for example those of ICRP are directed towards the final dose values assessed by a service which may include a calibration error or normalisation factor, whereas some requirements concentrate on the type test (performance) characteristics of a dosimeter and do not incorporate calibration errors, for example PTB 95. Thirdly, the confidence level (or the coverage factor according to [15]) is not the same for all standards. Some standards do not even give any requirement on the overall uncertainty. In these cases in Table 3 the overall uncertainty shown is calculated according to the ISO guide with a coverage factor of two.

The requirements by EUR 73, ISO 14146 draft and IAEA 97 draft essentially follow the ICRP 35/60 requirements with asymmetrical limits, the PTB 95 requirements with symmetrical limits. The trumpet curves were devised to be in accordance with the ICRP requirements. The requirements of IEC 1066 and IEC 1283 series permit much larger uncertainties than those of ICRP.

TABLE II. LIST OF RELEVANT INTERNATIONAL STANDARDS FOR PERSONAL MONITORING

Abbreviation	Standard or requirement
ICRP 35	ICRP: *General Principles of Monitoring for Radiation Protection of Workers.* Publication 35, 1982 [2]
ICRP 60	ICRP: *1990 Recommendations of the International Commission on Radiological Protection.* Publication 60, 1991 [3]
ICRP 75	ICRP: *General Principles for the Radiation Protection of Workers.* Written to update Publication 75, 1997, in press [4]
EUR 73	European Commission: *Technical recommendations for monitoring individuals occupationally exposed to external radiation.* EUR 14852 EN, 1994 [7]
ISO 14146 d	ISO/DIS 14146: *Criteria and performance limits for periodic testing of external individual dosimetry for X and gamma radiations.* ISO/TC 85/SC 2 N 518, Draft 1996 [8]
IEC 1066	IEC 1066: *Thermoluminescence dosimetry systems for personal and environmental monitoring.* 1991 [9]
IEC 1283 ser.	IEC 1283: Radiation protection instrumentation – *Direct reading personal dose equivalent (rate) monitors - X, gamma and high energy beta radiation.* 1995 [10] IEC 1525: Radiation protection instrumentation – *X, gamma, high energy beta and neutron radiations – Direct reading personal dose equivalent and/or dose equivalent rate monitors.* 1996 [11] IEC 45B/162/CDV: *Direct reading personal dose equivalent and/or dose equivalent rate monitors for the measurement of personal dose equivalent $H_p(10)$ and $H_p(0.07)$ for X, gamma and beta radiation.* Draft of IEC 1526, 1996 [12]
IAEA 97 d	IAEA Safety Series: *Draft Safety Guide: Assessment of occupational exposures to external radiation.* NENS-12. Revised 6 February, 1997 [13]
PTB 95	PTB requirements: Measuring instruments for use in radiation protection: *Individual dosimeters for the measurement of personal dose equivalent $H_p(10)$ and $H_p(0.07)$,* November 1995 [14]

TABLE III. REQUIREMENTS OF RELEVANT INTERNATIONAL STANDARDS ON OVERALL ACCURACY FOR MONTHLY MONITORING

Standard	Requirements on overall accuracy
ICRP 35	95% level: $1.5 \geq H_m/H_t \geq 1/1.5$ for $H_t \approx H_a$ (H_a = 50 mSv [ICRP 26]) ($\overline{H_a}$ = 20 mSv [ICRP 60]) $2.0 \geq H_m/H_t \geq 0.5$ for $H_t \leq 10$ mSv [ICRP 26] $2.0 \geq H_m/H_t \geq 0$ for $H_t = H_r$, $H_r = H_a/120$
ICRP 60	$1.5 \geq H_m/H_t \geq 1/1.5$ for $H_t \approx H_a = 20$ mSv
ICRP 75	95% level: $1.5 \geq H_m/H_t \geq 1/1.5$ for $H_t \approx H_a$ ($\overline{H_a}$ = 20 mSv [ICRP 60]) $2.0 \geq H_m/H_t \geq 0$ for $H_t = H_r$, $H_r \geq 0.085$ mSv
EUR 73	95% level: trumpet curve with $H_0 = H_l/10$ ($2.0 \geq H_m/H_t \geq 0$ for $H_t = H_0$) (H_0 is lowest dose required to be measured) H_a = 20 mSv as given by ICRP 60 • H_0 = 0.17 mSv for monthly monitoring period, H_l =20 mSv/12 • H_0 = 0.08 mSv for two-weekly monitoring period, H_l =20 mSv/24
ISO 14146 d	90% level: trumpet curve ($H_0 \geq 0.2$ mSv is the lower limit of the dose range specified in the type test)
IEC 1066	no requirement *(95% level: $1.77 \geq H_m/H_t \geq 0.33$ Calculated according to ISO guide)*
IEC 1283 ser.	no requirement *(95% level: $2.1 \geq H_m/H_t \geq 0.0$ Calculated according to ISO guide)*
IAEA 97 d	as EUR 73
PTB 95	92% level: $1 + 0.4 \cdot t(H_t) \geq H_m/H_{m,ref} \geq 1 - 0.4 \cdot t(H_t)$, $H_0 \leq 0.2$ mSv
Definitions:	H_m := measured dose value for the period considered $H_{m,ref}$:= measured dose value under reference conditions H_t := conventional true value of the dose H_a := dose limit for the period of one year H_r := recording level for the period of one month H_l := dose limit for the period considered U_{95} := absolute uncertainty of H_m on 95% level trumpet curve: $\frac{1}{1.5}\left(1-\frac{2H_0}{H_0+H_t}\right) \leq \frac{H_m}{H_t} \leq 1.5\left(1+\frac{H_0}{2H_0+H_t}\right)$ trumpet function: $t(H_t) = 1+\frac{20}{9}\frac{H_0}{H_0+H_t}$, H_0 := lowest dose for which trumpet curve can be used

3.3. Energy and directional dependence

Table IV shows the requirements on energy and directional dependence. There are significant differences between these requirements.

TABLE IV. REQUIREMENTS OF RELEVANT INTERNATIONAL STANDARD ON ENERGY AND DIRECTIONAL DEPENDENCE

Standard	Requirements on acceptable uncertainty due to energy and directional dependence
ICRP 35 **ICRP 60** **ICRP 75**	No specific requirements, they are included in total overall uncertainty of a factor of 1.5 at or near dose limits
EUR 73	$\left\lvert\left[0.25\left(R_{E,0^o} + R_{E,20^0} + R_{E,40^0} + R_{E,60^0}\right)\right] - 1\right\rvert \le 1.96 \cdot \Delta \quad (\Delta \approx 0.16)$ E : ISO narrow spectrum series is preferred, no mixtures Δ : calculated to fulfill overall uncertainty requirement
ISO 14146 d	No specific requirements, included in overall uncertainty E, α : all values from rated range of use, even mixtures
IEC 1066	$\lvert R_{E,0^0} - 1\rvert \le 0.3 - I$ (I := confidence interval $\approx$ 0.03) E : 15.8 keV, 30 - 40 keV, 80 - 100 keV, ^{137}Cs or ^{60}Co no other energies, no mixtures $\lvert R_{60keV,\alpha} / R_{60keV,0^0} - 1\rvert \le 0.15 - I$ (I := confidence interval » 0.03) α : 20°, 40°, 60°; no other energies, no mixtures
IEC 1283 ser.	$\lvert R_{E,0^0} / R_{Cs-137,0^0} - 1\rvert \le 0.30$, E : ISO narrow spectrum series 50 keV to 1.5 MeV, no mixtures (IEC 1526 draft: 20 keV to 1.5 MeV) $\lvert R_{60keV,\alpha} / R_{60keV,0^0} - 1\rvert \le 0.50$ and $\lvert R_{Cs-137,\alpha} / R_{Cs-137,0^0} - 1\rvert \le 0.20$ α : 15°, 30°, 45°, 60°, 75°; no other energies, no mixtures (IEC 1526 draft: without 75°)
IAEA 97d	as EUR 73, but all ISO series can be used
PTB 95	$\lvert R_{E,\alpha} / R_{ref} - 1\rvert \le 0.35$ and G(Ht) < 0.4·t(Ht) E, α : all values from rated range of use, even mixtures
Definitions: H_m : = measured dose value H_t : = conventional true dose value R : = response, $R = H_m / H_t$ $R_{E,\alpha}$: = response at mean energy E and incident angle α $G(H_t)$: = overall uncertainty at the 92% level for the true dose H_t Trumpet function $t(H_t) = 1 + \frac{20}{9}\frac{H_0}{H_0 + H_t}$,	

The ICRP and ISO 14146 draft have no specific requirements, only the requirement on the overall uncertainty.

In EUR 73 and IAEA 97 draft, the requirements on energy and directional dependence are combined. For every radiation quality used for the test the directional dependence is considered by calculating the mean value of the response at 0°, 20°, 40° and 60°. The deviation of this mean value from unity is limited by a parameter Δ, which is calculated such that the overall uncertainty (for all influence quantities and other parameters like coefficient of variation) does not exceed the limits given by the trumpet curves. Δ is of the order of 0.16. For the tests, ISO (EUR 73: narrow only specified) spectrum series are preferred, no mixtures are allowed. Due to the use of the mean value of the response the overall uncertainty can exceed the limits given by the trumpet curves, if the directional dependence of the response is large and the monitored person is irradiated mainly from one direction. The limits can also be exceeded by mixed radiation fields or even broad spectra, if an evaluation procedure using non-linear algorithms is optimised only for the test radiation fields (see paper on 'Workplace Fields" [15]).

In IEC 1066, in order to take into account the statistical uncertainty in a test result, the confidence interval, I, for the test is specified (from experience I is of the order of 0.03). IEC 1066 has separate requirements for the energy dependence of the response and the directional dependence of the response. For the first the deviation from unity must not exceed $0.3 - I$ for 4 test energies: 15.8 keV, 30 - 40 keV, 80 - 100 keV and ^{137}Cs or ^{60}Co. No other energies and no mixtures are used. The directional dependence of the response is only tested at one energy and four angles: 60 keV and 0°, 20°, 40° and 60°. The deviation of the response for 20°, 40° and 60° must not deviate from that at 0° by more than $0.15 - I$. Due to the limited extent of the tests the overall uncertainty can exceed the limits given by the trumpet curves. The probability to exceed the limits is larger than for the EUR 73 requirements.

The IEC 1283 series requirements have similarities with the IEC 1066 requirements. Again, separate requirements for the energy dependence of the response and the directional dependence of the response are given. For the energy dependence the deviation from unity must not exceed 0.3 for all 8 (IEC 1526 draft: 11) test energies of the ISO series. No mixtures are used. The directional dependence of the response is tested at two energies and six (IEC 1526 draft: five) angles: 60 keV plus ^{137}Cs and 0°, 15°, 30°, 45°, 60° and 75° (IEC 1526 draft: without 75°). The deviation of the response for oblique incidence must not deviate from that at 0° by more than 0.5 for 60 keV and 0.20 for ^{137}Cs. For use in the vicinity of nuclear reactor installations the response at 6 MeV must be between -50% and +100%. Also for the IEC 1283 series requirement the overall uncertainty can exceed the limits given by the trumpet curves.

The PTB 95 requirements on energy and directional dependence are combined. The response for every energy and direction of incidence, even any mixture, must not deviate from that at reference conditions by more than about 0.35. This factor depends slightly on the other performance characteristics and is adjusted so that the overall uncertainty calculated according to the ISO guide with a coverage factor of $\sqrt{3}$ does not exceed $0.4 \cdot t(H_V)$. This procedure is similar to that in EUR 73. The function $t(H_V)$ is given in Table 3. It produces a symmetrical trumpet curve.

3.4. Linearity and coefficient of variation

Table 5 shows the requirements on linearity and Table 6 those on coefficient of variation. Most standards have no specific requirements, only the requirement on the overall uncertainty. For those standards having specific requirements the differences are not very large.

TABLE V. REQUIREMENTS OF RELEVANT INTERNATIONAL STANDARDS ON LINEARITY

Standard	Requirements on Linearity
ICRP 35 **ICRP 60** **ICRP 75** **EUR 73**	No specific requirements, included in overall uncertainty
ISO 14146 d	No specific requirements, included in overall uncertainty The range $H_0 \leq H_t \leq 1$ Sv should be tested
IEC 1066	$\lvert R(H_t) - 1 \rvert \leq 0.1 - I$ (I := confidence interval ≈ 0.03) for 0.1 mSv $\leq H_t \leq 1$ Sv
IEC 1283 ser.	$\lvert R(H_t) - 1 \rvert \leq 0.15$ for the 'value of the relative intrinsic error over the effective range of measurement'
IAEA 97 d	No specific requirements, included in overall uncertainty. No rated range of use
PTB 95	$\frac{R_{max} - R_{min}}{R_{max} + R_{min}} \leq 0.15$ for 0.2 mSv $\leq H_t \leq 1$ Sv (For larger dose values a ratio of 0.25 is allowed)
Definitions:	H_m := measured dose value H_t := conventional true dose value $R(H_t)$:= response, $R = H_m / H_t$ R_{max} := maximum value of the response in the specified range R_{min} := minimum value of the response in the specified range

The IEC 1066 requires for linearity, that the deviation of the response from unity must not exceed 0.1 - I for the range $H_0 < H_t < 1$ Sv. The requirement for the coefficient of variation is that it must not exceed 0.075 - I for both, a sample of n dosimeters and 10 repeated measurements with the same dosimeter. Again, I is the confidence interval for the test.

The IEC 1283 series have a combined requirement for linearity and coefficient of variation, called 'relative intrinsic error'. The deviation of the response from unity must not exceed 0.15 for the 'effective range of measurement' for any single measurement.

The PTB 95 requires that the nonlinearity, calculated according to the formula given in Table V, must not exceed 0.15 in the range 0.2 mSv < H_t < 1 Sv. For larger dose values a value of 0.25 is allowed. For the coefficient of variation a test procedure is given to calculate this coefficient in such a way that it incorporates the uncertainty due to differences in batch manufacturing, in build-up or fading due to the time of exposure in the given measuring period and its dose dependence. The requirement itself is included in the overall uncertainty.

TABLE VI. REQUIREMENTS OF RELEVANT INTERNATIONAL STANDARDS FOR COEFFICIENT OF VARIATION

Standard	Requirements for coefficient of variation
ICRP 35 **ICRP 60** **ICRP 75** **EUR 73** **ISO 14146d**	No specific requirements, included in overall uncertainty
IEC 1066	$v(10\ \text{mSv}) \leq 0.075 - I$ (I := confidence interval ≈ 0.03) for a) a sample of n dosimeters or b) 10 repeated measurements with the same dosimeter
IEC 1283 ser.	No specific requirements, included in the requirement on linearity
IAEA 97 d	No specific requirements, included in overall uncertainty
PTB 95	$v(H_t)$ must be measured over the whole dose range for a sample of dosimeters stored up to the maximum wear period and fulfill overall uncertainty requirement
Definitions:	Hm := measured dose value H_t := conventional true dose value $v(Ht)$:= coefficient of variation, $v(H_t) = s(H_m) / \overline{H_m}$

3.5. Environmental effects, electromagnetic fields and mechanical shock

The requirements on climatic effects, light exposure, electromagnetic fields and mechanical shock dependence are shown in Tables VI to X.

Explicit requirements for these influence quantities are only given by three standards, IEC 1066, IEC 1283 series and PTB 95, all others have included the requirements in the overall uncertainty.

In IEC 1066 three tests on climatic dependence are prescribed, one at normal temperature (20 °C) and elevated relative humidity (90%), and a second at elevated temperature (50 °C) and normal relative humidity (65%). In both cases the storage time is 30 days and the requirement is that the deviation of the response from unity must not exceed 0.2 - I. The third test is at standard test conditions (18-20 degree C, 50-60% RH), for which the deviation of the response must not exceed 5% after 30 days storage, or 10% after 90 days. For the light dependence one test at bright sunlight (1000 W/m^2 with the spectral distribution at sea level, normal incidence and clear sky) is given. The duration is 168 h (7 days) and the requirement is that the deviation of the response from unity must not exceed 0.1 - I.

The UV part especially of the spectral distribution must be carefully monitored during the test. For the shock dependence one test is given. After a drop of 1.0 m height on concrete surface the deviation of the response from unity must not exceed 0.1 - *I*. As before, *I* is the confidence interval.

TABLE VII. REQUIREMENTS OF RELEVANT INTERNATIONAL STANDARDS FOR EFFECTS OF CLIMATIC CONDITIONS

Standard	Requirements given for effects due to climatic conditions
ICRP 35 **ICRP 60** **ICRP 75** **EUR 73**	No specific requirements, included in overall uncertainty
ISO 14146 d	Not tested, see type test results
IEC 1066	$\lvert R_{T,r} - 1 \rvert \le 0.2 - I$ (I := confidence interval ≈ 0.03) for a) 30 days storage at $T = 20$ °C and $r = 90\%$ rel. humidity b) 30 days storage at $T = 50$ °C and $r = 65\%$ rel. humidity
IEC 1283 ser.	$\lvert R_{T,65\%} / R_{20^oC,65\%} - 1 \rvert \le 0.2$ for - 10 °C ≤ T ≤ 40 °C $\lvert R_{T,65\%} / R_{20^oC,65\%} - 1 \rvert \le 0.5$ for - 20 °C ≤ T ≤ 50 °C (only IEC 1283: -25 °C) $\lvert R_{T,35\%} / R_{35^oC,65\%} - 1 \rvert \le 0.1$ for 40% ≤ r ≤ 90%
IAEA 97 d	No specific requirements, included in overall uncertainty
PTB 95	$\lvert R_{T,r} / R_{20^oC,60\%} - 1 \rvert \le 0.2$ for 48 h storage at any combination of - 10 °C ≤ T ≤ 40 °C and 10% ≤ r ≤ 90% ($\rho_w \le 30$ g.m^{-3})
Definitions: H_m := measured dose value H_t := conventional true dose value R := response, $R = H_m / H_t$ $R_{T,r}$:= response at temperature T and relative humidity r ρ_w := water vapour density	

In IEC 1283 series the temperature dependence and the relative humidity dependence are tested separately. For the temperature two rated ranges of use are given, one from -10°C to 40°C with a maximum change of the response of 20% and a second lager one from -20°C (only IEC 1283: -25°C) to 50°C with a maximum change of the response of 50%. For relative humidity the rated range of use is from 40% to 90% and a maximum change of the response of 10%. For light dependence no test and no requirement is given. The required electromagnetic field immunity is that for the range of values shown (Table IX), the response must not change by more than 10%. Similarly, the response must not change by more than 10% if a mechanical shock, a 1.5 m drop on hard wood surface, is applied. Additional vibration tests are prescribed.

The PTB 95 combines temperature dependence and the humidity dependence and requires that the response must not change by more the 20% for any combination out of the two rated ranges of use, for temperature from -10°C to 40°C and for relative humidity from 40% to

90%. The absolute humidity in these tests is limited to 30 $g.m^{-3}$ (equivalent at 40°C to a relative humidity of about 60%). The light dependence is limited to a change of the response of 10% after 48 h storage at bright sunlight of the same spectral distribution as given by IEC 1066. The electromagnetic field immunity requirements are shown in Table IX. There are two sets of tests in PTB 95, one following an IEC recommendation (IEC 1000-4-2/3/4/5/6/8/11) and the other set designed to simulate the fields produced by portable digital telephones. For both sets of tests, the requirement is that the response must not change by more than 10%. For mechanical shock the requirement is that after a sinusoidal shock of 1 ms duration and 4900 m/s^2 amplitude the response must not change by more than 10%. This shock is equivalent to a drop of 0.5 m on a concrete surface.

4. RELEVANCE/APPLICABILITY TO WORKPLACE CONDITIONS

The aim of all the relevant standards should be to determine whether the performance of an individual dosimeter or dosimetry service is good, or at least adequate, in normal routine use. The requirements of the standards should be relevant for actual workplace conditions. Any standard is a compromise of the views of the originators, influenced by their professional experience, and the state of the art of the dosimeters to which the standard should be applied. We give in Table XI our opinion as to the relevance of these standards for workplace conditions.

The ICRP publications serve as general guidelines and have, therefore, a large relevance, but they do not give any detailed requirements or test procedures.

The EUR 73 recommendations give much information on the measurement quantities and give some detailed test procedures, but the requirements for the most important influence quantities, the energy and radiation incidence direction, are not complete (see paragraph 3.3) and for many influence quantities, none are given. The relevance/applicability to workplace conditions is only medium. However, together with IAEA 97, these recommendations include requirements for many operational aspects of dosimetry services

The ISO 14146 draft is intended for the routine testing of dosimeters in use by dosimetry services, and therefore the relevance/applicability to normal conditions of use is large, but a type test should also be specified.

The IEC 1066 is a good standard, in general, which addresses both detectors and readers, but specifies only four energies for the assessment of the energy response characteristics and the dependence of response on radiation incidence direction is only required to be investigated at one energy. Two dosimeters with the same test results, may have quite different performance in realistic workplace conditions. Therefore, the relevance/applicability to such conditions is considered small.

The IEC 1283 series have more energy values than IEC 1066 for testing the influence quantity radiation energy, and specifies at least two energy values for testing radiation incidence direction, but has much the same deficiencies. We conclude that IEC 1283 series have medium relevance/applicability to realistic workplace conditions, and note that the required value for the overall uncertainty is rather large.

The IAEA 97 Draft has many similarities to EUR 73, and therefore similar relevance/applicability (medium) to actual conditions of use, but note the useful requirements given for operational aspects of dosimetry services

TABLE VIII. REQUIREMENTS OF RELEVANT INTERNATIONAL STANDARDS FOR SENSITIVITY TO LIGHT

Standard	Requirements for sensitivity to light
ICRP 35 **ICRP 60** **ICRP 75** **EUR 73**	No specific requirements, included in overall uncertainty
ISO 14146 d	Not tested, see type test results
IEC 1066	$\left\lvert R_{Light}/R_{Dark} - 1\right\rvert \leq 0.1 - I$ (I := confidence interval ≈ 0.03) for 168 h storage at bright sunlight (1000 W.m^{-2} at sea level)
IEC 1283 ser.	No test, no requirement
IAEA 97 d	No specific requirements, included in overall uncertainty
PTB 95	$\left\lvert R_{Light}/R_{Dark} - 1\right\rvert \leq 0.1$ for 48 h storage at bright sunlight (1000 W.m^{-2} at sea level)
Definitions:	H_m := measured dose value H_t := conventional true dose value R := response, $R = H_m/H_t$ R_{Light} := response after specified light exposure R_{Dark} := response after storage in darkness

The PTB 95 requirements give detailed test procedures for almost all influence quantities and place most importance on satisfying the requirements on overall uncertainty. We consider that the relevance/applicability to actual workplace conditions is large.

4.1. List of methods

The best method of performance testing is one which allows the assessment of the performance of the service for routine measurements in workplace conditions. The service must not do any special treatment to the dosimeters to avoid unrepresentative results. Three methods for performance testing will be explained in the following, the 'blind' test, the 'surprise' test and the 'announced' test. According to the legal and local circumstances, other approaches may be acceptable.

In a **'blind' test** the service is not aware of the tests and cannot use selected dosimeters or special evaluation procedures for the tests. One approach is the invention of a 'dummy customer' and controlled irradiation of the dosimeters by a control institute. Normally, any dose above a certain threshold leads to an alert to the authorities, this alert needs to be blocked for these tests. The largest Netherlands and UK services use a dummy customer for quality assurance purposes [17]. Another approach is to issue the same person, identified as someone who gets a non-zero dose, with several (perhaps electronic) dosimeters. In this case the measurement is done in a real radiation field under workplace conditions, but the value of H_t is unknown.

TABLE IX. REQUIREMENTS OF RELEVANT INTERNATIONAL STANDARDS FOR ELECTROMAGNETIC FIELD IMMUNITY

Standard	Requirements given for effects due to electromagnetic fields
ICRP 35 **ICRP 60** **ICRP 75** **EUR 73**	No specific requirements (included in overall uncertainty)
ISO 14146 d	Not tested, see type test results
IEC 1066	No requirements
IEC 1283 ser.	Warning if influenced by electromagnetic fields If manufacturer claims insensitivity: $\lvert R_{field}/R_{ref} - 1 \rvert \leq 0.1$ for 10 V/m 100 kHz to 500 MHz CW-field 1 V/m 500 MHz to 1 GHz CW-E-field 60 A/m 50 Hz CW-field 6 kV discharge (IEC 1526 draft: 8 keV)
IAEA 97 d	No requirements
PTB 95	$\lvert R_{field}/R_{ref} - 1 \rvert \leq 0.1$ for the total of all tests, • tests according to IEC1000-4-2/3/4/5/6/8/11 (8 kV discharge, 10 V/m 80 kHz to 1 GHz fields, ±2 kV transients , ±4 kV bursts, 10 V 150 kHz to 80 MHz line voltage, 30 A/m 50 Hz field) • 20 V/m 0.9 GHz 100% AM/200 Hz/50% and 15 V/m 1.8 GHz 100% AM/200 Hz/50% (equivalent to Handy at 30 cm distance)
Definitions:	H_m := measured dose value H_t := conventional true dose value R := response, $R = H_m/H_t$ R_{field} := response after exposure to specified field R_{Ref} := response after storage without shock

In a **'surprise' test** the service is aware of the tests but does not know the actual test date in advance (e.g. once a year). The service may use selected dosimeters but cannot use special evaluation procedures. The control institute receives regularly a fixed number of dosimeters. The dosimeters are irradiated. Without prior notice, an official of the verification office submits, in person, the irradiated dosimeters to the service. The official observes the evaluation, which should follow written quality assured procedures, and passes the results back to the control institute. This method avoids the high dose alert to the authorities.

In an **'announced' test** the service is aware of the tests and may use selected dosimeters and special evaluation procedures. The control institute asks the service to send the dosimeters to it and irradiates them. Then the dosimeters are sent back to the service for evaluation. The UK regulatory body (HSE) and many international (including IAEA) intercomparisons are of this type.

TABLE X. REQUIREMENTS OF RELEVANT INTERNATIONAL STANDARDS FOR EFFECTS OF MECHANICAL SHOCK

Standard	Requirements given for effects of mechanical shock
ICRP 35	No specific requirements, included in overall uncertainty
ICRP 60	
ICRP 75	
EUR 73	
ISO 14146 d	Not tested, see type test results
IEC 1066	$\lvert R_{Shock}/R_{Ref} - 1\rvert \leq 0.1 - I$ (I := confidence interval ≈ 0.03) after 1.0 m drop on concrete surface
IEC 1283 ser.	$\lvert R_{Shock}/R_{Ref} - 1\rvert \leq 0.1$ after 1.5 m drop on hard wood surface (additional vibration test)
IAEA 97 d	No specific requirements, included in overall uncertainty
PTB 95	$\lvert R_{Shock}/R_{Ref} - 1\rvert \leq 0.1$ after sinusoidal shocks, 1 ms, 4900 m/s^2 (equivalent to 0.5 m drop on concrete surface)
Definitions:	H_m := measured dose value H_t := conventional true dose value R := response, $R = H_m/H_t$ R_{Shock} := response after specified shock exposure R_{Ref} := response after storage without shock

TABLE XI. CONDITIONS OF USE OF DOSIMETERS AND DOSIMETRY SERVICES

Standard	Relevance/applicability of the standard to workplace conditions
ICRP 35 **ICRP 60** **ICRP 75**	**Large:** General guidance, no test procedures given
EUR 73	**Medium:** Dependent on evaluation procedure and angular dependence of the response. Operational aspects of service included.
ISO 14146 d	**Large:** But 10 tested dosimeters per year are only sufficient if a type test has been performed in advance
IEC 1066	**Small:** No overall uncertainty, only 4 test energies, the angular dependence is tested at only one energy, strongly dependent on evaluation procedure
IEC 1283 ser.	**Medium:** No overall uncertainty, no mixture of test energies, the angular dependence is tested at only 2 energies, strongly dependent on evaluation procedure. Required overall uncertainty large
IAEA 97 d	**Medium:** Dependent on evaluation procedure and angular dependence of the response. Operational aspects of service included.
PTB 95	**Large:** Detailed test procedures given

5. METHODS OF PERFORMANCE TESTING

5.1. Example

The German performance tests are of the surprise test type. The method of the performance test is illustrated in Figure 2. Every service is tested once a year with all its types of dosimeters. The Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig is the control institute. Therefore, the PTB irradiates every year about 200 dosimeters of the 6 German services for this test. The dose varies from 0.2 mSv to 10 Sv, the radiation mean energy from 20 keV to 1250 keV and the angle of radiation incidence from 0° to ± 45°. Mixtures of radiation qualities and angles of radiation incidence are frequently used.

The results for the years 1990 to 1995 are shown in Figure 3. All services fulfilled the requirements. The difference in performance between film, TL and RPL dosimeters is minimal. Similar results have been obtained in other countries [6]. All these results indicate that the ICRP requirements are practical and can be fulfilled in routine monitoring.

6. OVERVIEW OF SERVICE PERFORMANCE REQUIREMENTS

Some service performance requirements are given by the ICRP, more requirements are only given in two standards, EUR 73 and IAEA 97 draft. Both give a lot of requirements and recommendations which are similar in many aspects. In this overview it is only possible to list some headlines of these two standards; this is done in Table XII.

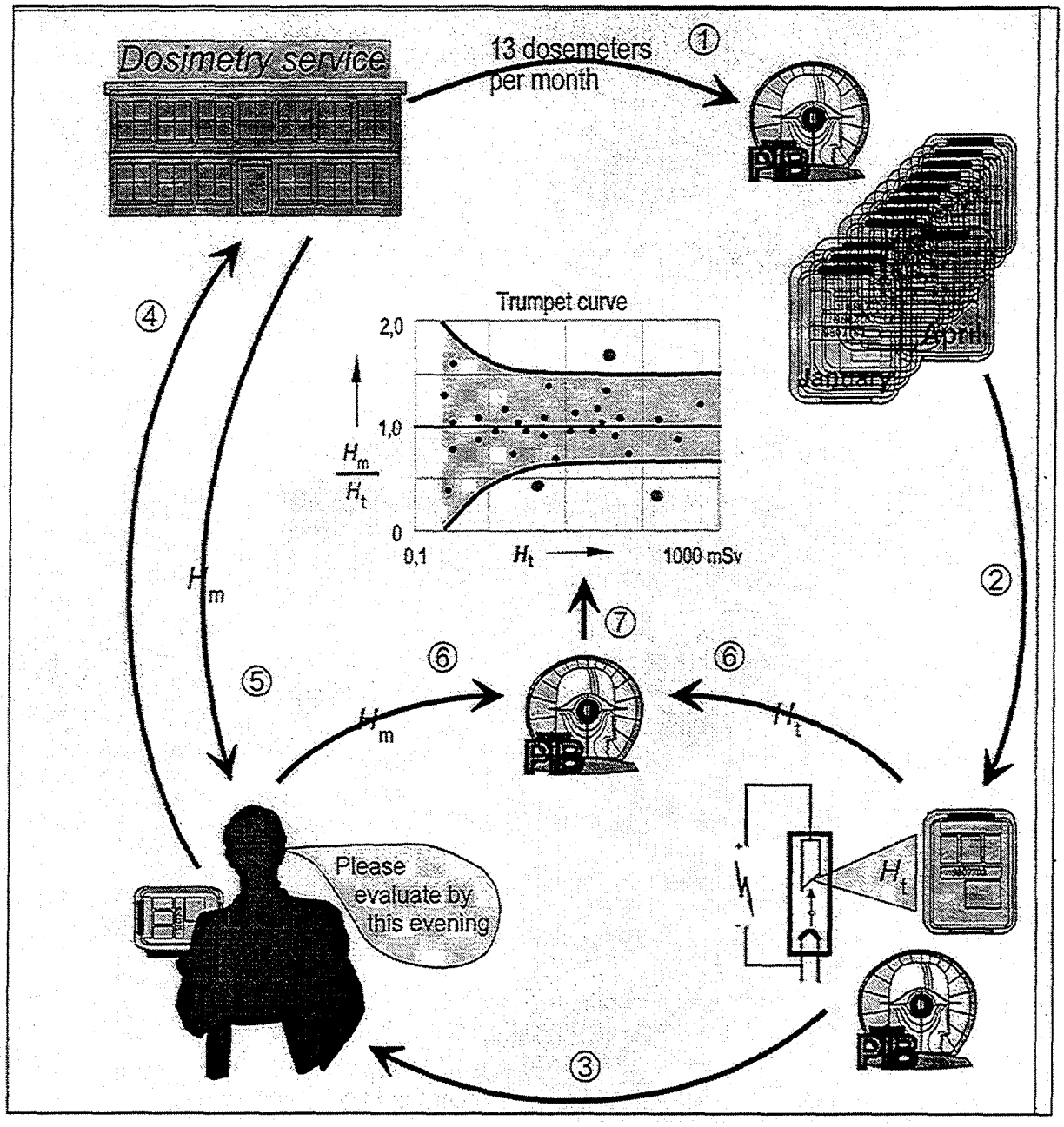

FIG. 2. Method of the regular surprise tests conducted in Germany. See text for details.

TABLE XII. SERVICE PERFORMANCE REQUIREMENTS AND RECOMMENDATIONS IN EUR 73 AND IAEA 97 DRAFT

Standard	Requirements given for
EUR 73	• Dose record data • Recording and reporting levels • Reporting of dose information • Setting up a dose record and information system • Organisational structure and personnel • Laboratory accommodation and environment • Scientific research • Quality assurance
IAEA 97 d	• Dose record keeping for individual monitoring • Record keeping for workplace monitoring • Quality assurance requirements • Documentation of methods, procedures and test results • Quality awareness and training of personnel • Acceptance testing of newly supplied materials • The laboratory accommodation and environment • Maintenance and testing of equipment, materials and processes • Verification of calibration facilities • Testing the overall performance of the system

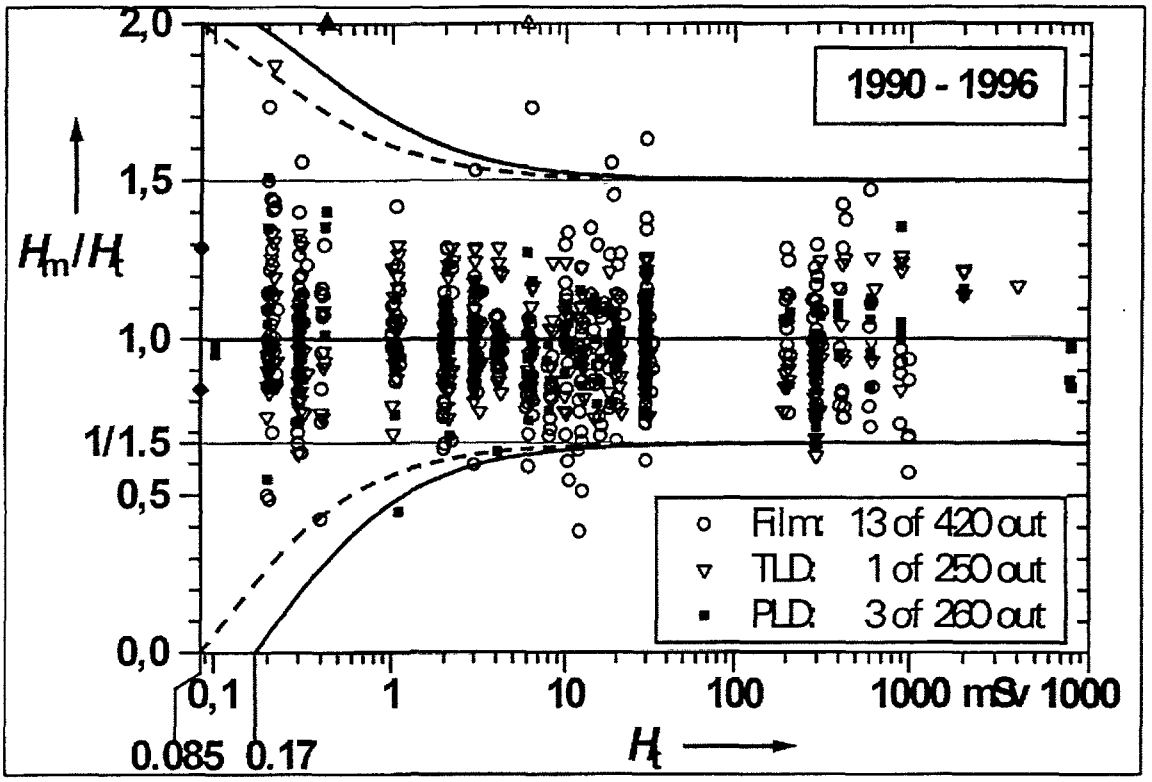

FIG. 3. Results of the regular surprise tests conducted in Germany for film, TL and RPL dosimeters of the years 1990 to 1995. The solid lines are the trumpet curves for H_0 = 0.17 mSv, the dashed ones those for H_0 = 0.085 mSv. H_m is the measured dose value and H_t, the conventionally true value. 95% of all measurements must be within the limits

REFERENCES

[1] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. Recommendations of the International Commission on Radiological Protection. ICRP Publication 26, Pergamon Press, Oxford (1977).

[2] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. General Principles of Monitoring for Radiation Protection of Workers. ICRP Publication 35, Annals of ICRP **9**, Nr.4, Pergamon Press, Oxford (1982).

[3] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60, Annals of ICRP **21**, Nr.1-3, Pergamon Press, Oxford (1991).

[4] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION. General Principles for the Radiation Protection of Workers. ICRP Publication 75, written to update and replace ICRP Publication 35 [2], (1997).

[5] BÖHM, J., AMBROSI, P., Mandatory Type Tests of Solid State Dosimetry Systems as an Appropriate Aid to Quality Assurance in Individual Monitoring. Rad. Prot. Dosim. **34**, 1990, 123-126.

[6] BÖHM, J., LEBEDEV, V. N., MCDONALD, J. C., Performance testing of Dosimetry Services and its Regulatory Aspects. Rad. Prot. Dosim., **54**, 1994, S. 311-319.

[7] EUROPEAN COMMISSION, Technical recommendations for monitoring individuals occupationally exposed to external radiation. EUR 14852 EN, (1994).

[8] ISO/DIS 14146, Criteria and performance limits for periodic testing of external individual dosimetry for X and gamma radiations. ISO/TC 85/SC 2 N 518, (1996).

[9] INTERNATIONAL ELECTROTECHNICAL COMMISSION, Thermoluminescence dosimetry systems for personal and environmental monitoring. IEC 1066, 1991–12.

[10] INTERNATIONAL ELECTROTECHNICAL COMMISSION, Radiation protection instrumentation – Direct reading personal dose equivalent (rate) monitors - X, gamma and high energy beta radiation. IEC 1283,1995-02.

[11] INTERNATIONAL ELECTROTECHNICAL COMMISSION, Radiation protection instrumentation – X, gamma, high energy beta and neutron radiations – Direct reading personal dose equivalent and/or dose equivalent rate monitors. IEC 1525, 1996-09

[12] INTERNATIONAL ELECTROTECHNICAL COMMISSION, Direct reading personal dose equivalent and/or dose equivalent rate monitors for the measurement of personal dose equivalent $H_p(10)$ and $H_p(0.07)$ for X, gamma and beta radiation. 45B/162/CDV Draft of IEC 1526, 1996.

[13] INTERNATIONAL ATOMIC ENERGY AGENCY, Assessment of Occupational Exposures to External Radiation. Safety Series, Draft Safety Guide, NENS-12, Revised 6 February, Vienna, 1997.

[14] PHYSIKALISCH-TECHNISCHE BUNDESANSTALT, Measuring instruments for use in radiation protection, Individual dosimeters for the measurement of personal dose equivalent $H_p(10)$ and $H_p(0.07)$, November 1995. (an unofficial English translation is available from Physikalisch-Technische Bundesanstalt, Fachlabor 6.51, Bundesallee 100, D-38116 Braunschweig).

[15] INTERNATIONAL ORGANISATION FOR STANDARDISATION, Guide to the Expression of Uncertainty in Measurement, ISO, Geneva, (1993).

[16] BURGESS P., BARTLETT D., AMBROSI P., Workplace fields, this publication.

[17] VAN DIJK, T. W E., JULIUS, H. W., Dose thresholds and quality assessment by statistical analysis of routine individual monitoring TLD data. Rad. Prot. Dosim., **66**, (1994), 17–22.

CHARACTERISTICS OF PERSONAL DOSIMETERS TO MEASURE $H_p(10)$ FOR PHOTONS

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Abstract

This paper explains how the calibration of dosimeters free-in-air in terms of air kerma (or exposure) or tissue kerma, can be related to an on-phantom calibration in terms of $H_p(10)$, and discusses the characteristics of some simple designs of dosimeter.

1. INTRODUCTION

Many photon personal dosimeters in current use were designed to measure exposure or air kerma at the surface of the body. In some cases the free-in-air calibration in terms of exposure or air kerma has been related to tissue kerma, and estimates made of tissue dose at the surface of the body. The relationship of tissue dose at the surface of the body to dose in organs of the body was discussed by the International Commission on Radiological Protection (ICRP) in Publication 21 [1]. Alternatively the use of filters over the sensitive volume of the detector (or part thereof) enables the estimation of dose to tissue at a depth in the body either using a free-in-air calibration or calibration on a phantom in terms of dose at a depth in the phantom [2]. Following the introduction by the International Commission on Radiation Units and Measurements (ICRU) of the operational quantity personal dose equivalent, $H_p(10)$ [3,4], and its adoption by the ICRP [5] and their incorporation into the IAEA Basic Safety Standards [6] and the European Union Basic Safety Standards Directive [7], personal dosimeters are, in general, characterized and calibrated in terms of this quantity.

2. CALIBRATION PROCEDURES: FREE-IN-AIR VERSUS PHANTOM CALIBRATION QUANTITIES

Figure 1 shows the ratio of tissue kerma to air kerma as a function of photon energy calculated using the mass energy absorption coefficients (to a good approximation equal to the mass energy transfer coefficients) tabulated by Hubbell [8]. It can be seen that a dosimeter whose reading is proportional to air kerma, when calibrated in terms of air kerma will give a good estimate of tissue kerma or tissue dose (to within about 10%).

The radiation field of the surface of the body is the sum of two components, the incident and the backscattered radiation. The ratio of the total tissue dose at the surface of the ICRU slab phantom (30 x 30 x 15 cm of ICRU 4-element tissue) [4] to the incident component is shown in Figure 2 (data for $H_{p,slab}(10)$ conversion coefficients and for $H_{p,slab}(10)$ have been taken from references [9,10,11,12].

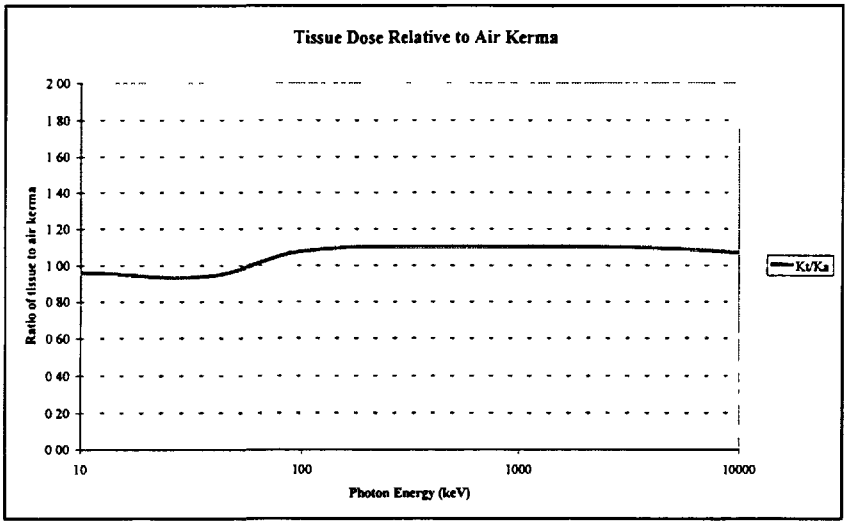

FIG. 1. Tissue dose relative top air kerma.

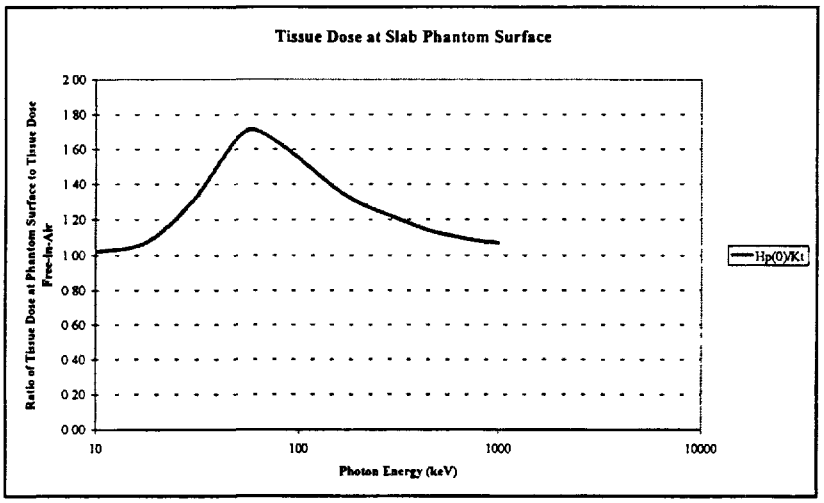

FIG. 2. Tissue dose at slab phantom surface.

If the reading of a dosimeter is proportional to dose to tissue more-or-less independent of energy and if it responds to both the incident and backscattered radiation, the dosimeter reading will be proportional to the total dose at the surface of the body, and no explicit account need be taken of the backscattered component. (but see discussion below).

For a dosimeter whose reading is to be taken as an estimate of $H_p(10)$ in the body when worn, the accepted procedure is to characterize and calibrate the dosimeter in terms of $H_p(10)$ in the ICRU slab phantom. The ratio of $H_{p,slab}(10)$ to tissue dose at the surface (at the point at which it may be assumed the dosimeter is positioned) is shown in Figure 3. To take account of the drop-off in $H_{p,slab}(10)$ at lower photon energies, if it is required to measure $H_p(10)$ in this energy region, a suitable filter must be incorporated in the dosimeter. In simple terms, a dosimeter with a tissue-equivalent detector would need a 10 mm thick filter of tissue equivalent material. For such a dosimeter, good response characteristics when calibrated free-in-air in terms of air kerma would translate into good response characteristics when characterized on the ICRU slab in terms of $H_{p,slab}(10)$.

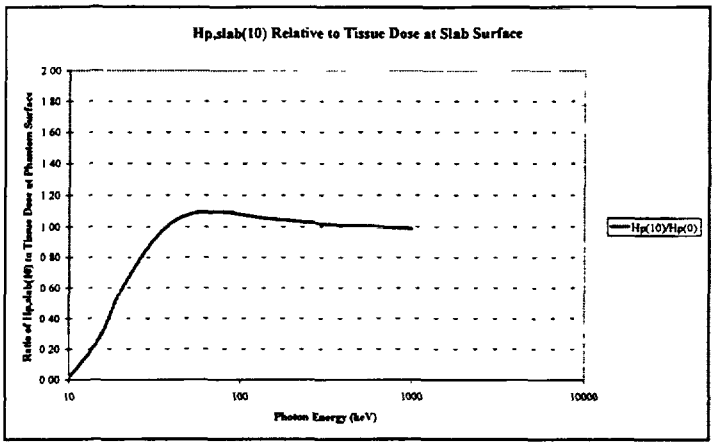

FIG. 3. $H_{p,slab}(10)$ relative to tissue dose at slab surface.

3. DOSIMETER CHARACTERISTICS

In general, the detectors in personal dosimeters are not fully tissue equivalent. The ratio of detector material kerma to tissue kerma is shown in Figure 4 for a number of common thermoluminescent detector materials. For lithium fluoride (LiF:Mg,Ti) for example, the ratio of response at 30 keV to that at 662 keV (^{137}Cs) is 1.5. (Note that the choice of detector material may be made for reasons other than its energy dependence of response).

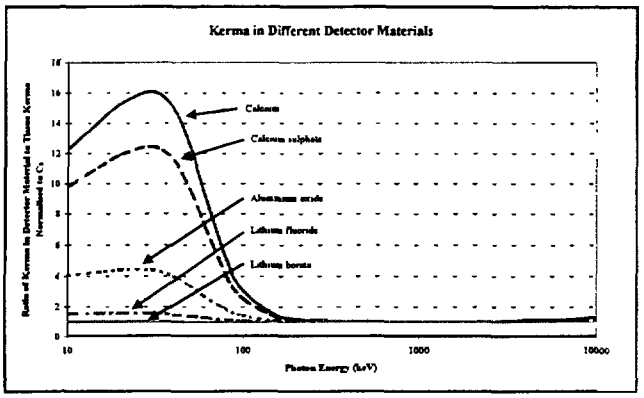

FIG. 4. Kerma in different detector materials.

The overresponse of dosimeters with these detectors can be compensated for by the use of filters. The filters may also be chosen such that the required drop-off in $H_p(10)$ relative to tissue dose at the surface of the body is also obtained. This is illustrated in Figure 5 in the case of a dosimeter with a lithium fluoride detector (LiF:Mg,Ti).

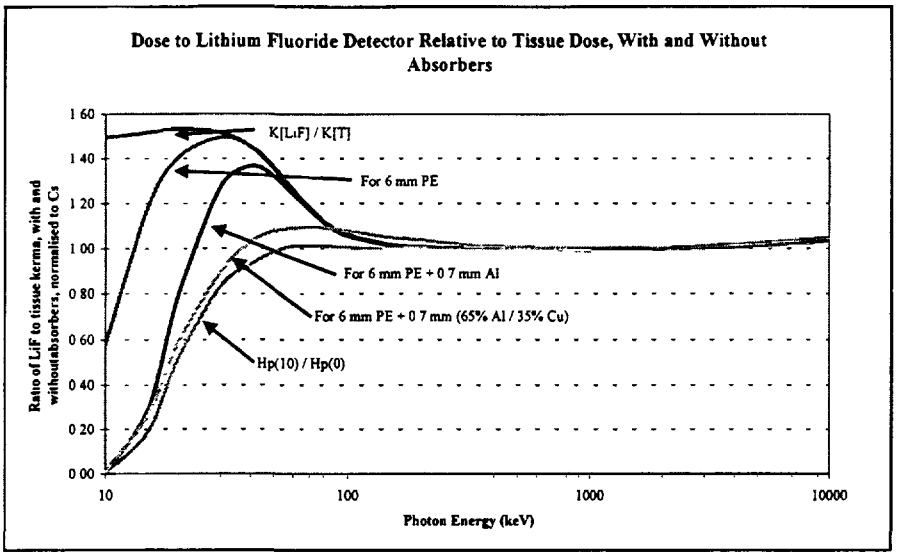

FIG. 5. Dose to lithium fluoride detector relative to tissue dose, with and without absorbers.

With suitable choice of filter, an adequate (6 mm polyethylene plus 0.7 mm aluminium) or good (6 mm polyethylene plus 0.7 mm aluminium/copper filter) approximation to the $H_{p,slab}(10)/H_{p,slab}(10)$ ratio can be obtained. As well as the energy dependence of response for normal incidence, personal dosimeters need to match the angle dependence of $H_p(10)$. The dependence of $H_{p,slab}(10)$ on the direction of incident radiation is shown in Figure 6.

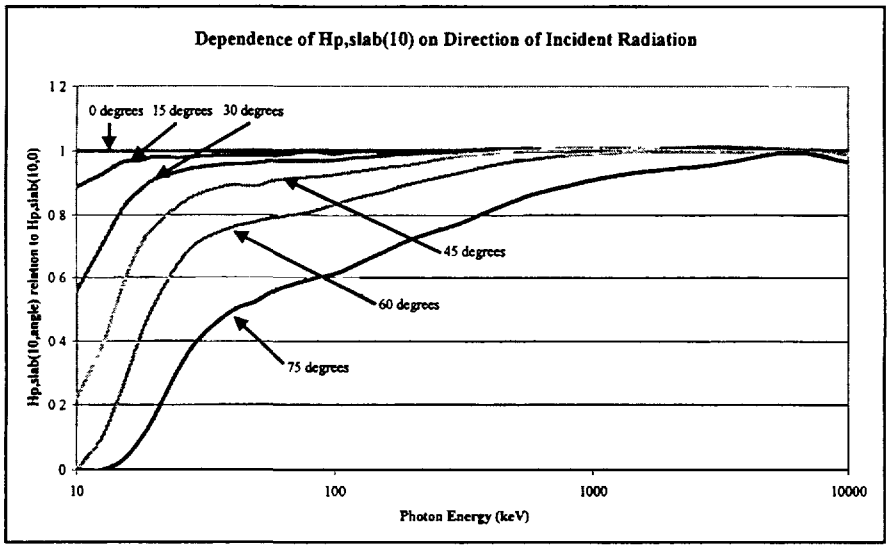

FIG. 6. Dependence of $H_{p,slab}(10)$ on direction of incident radiation.

Where a filter is used to both produce the required drop-off in response at lower photon energy to match the $H_{p,slab}(10)/H_{p,slab}(0)$ ratio and also any over-response of the detector material relative to tissue, it will not generally be possible to additionally match the

angle dependence of response. The response characteristics of some simple designs of thermoluminescence dosimeters are shown in Figure 7.

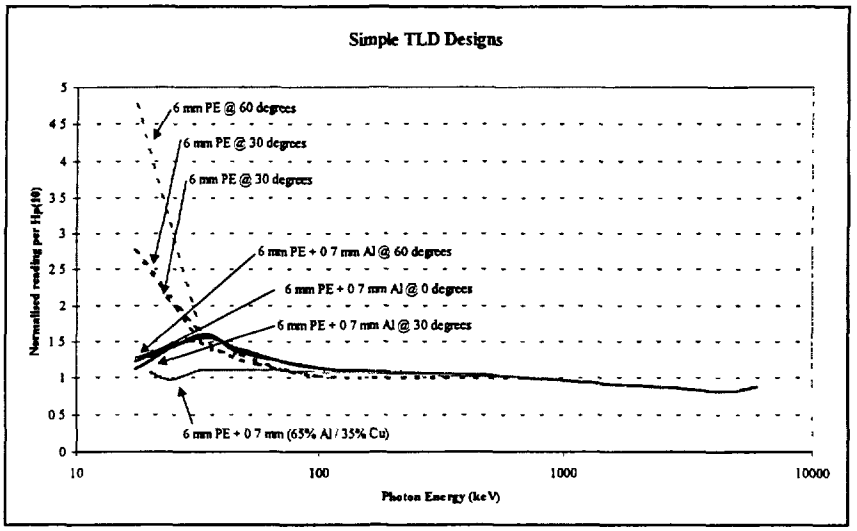

FIG. 7. Simple TLD design.

The principles which have been illustrated in the foregoing for thermoluminescent detectors apply, of course, to film badge dosimeters, but here the detector over-response of lower photon energies relative to tissue is more pronounced, see Figure 8.

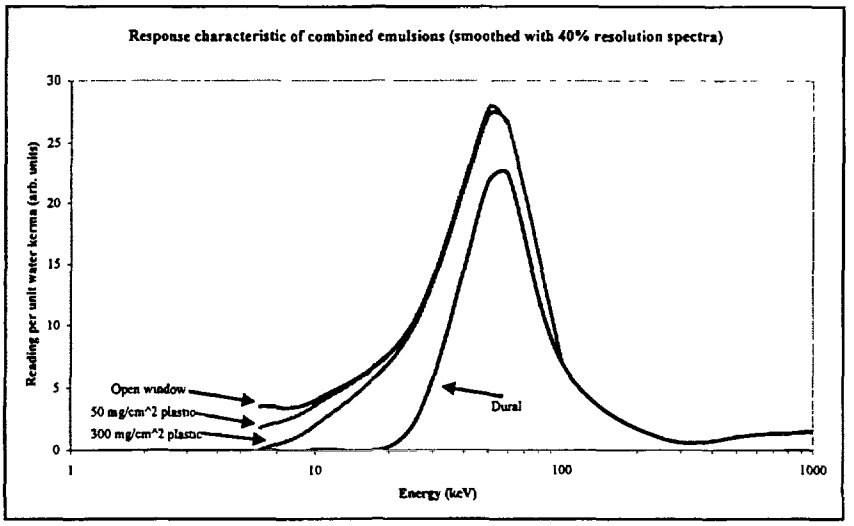

FIG. 8. Response characteristics of combined emulsions (smoothed with 40% resolution spectra).

A reasonable $H_p(10)$ response characteristic can be obtained with a single filter (Figure 9), and full, acceptable characteristics with, essentially, just two filters and linear algorithm can be seen from the data shown in Figure 10 [13].

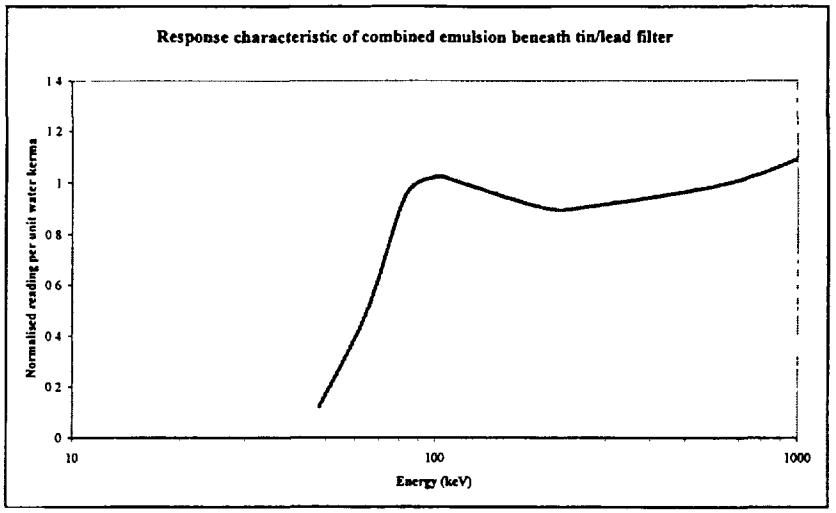

FIG. 9. Response characteristics of combined emulsion beneath tin/lead filter.

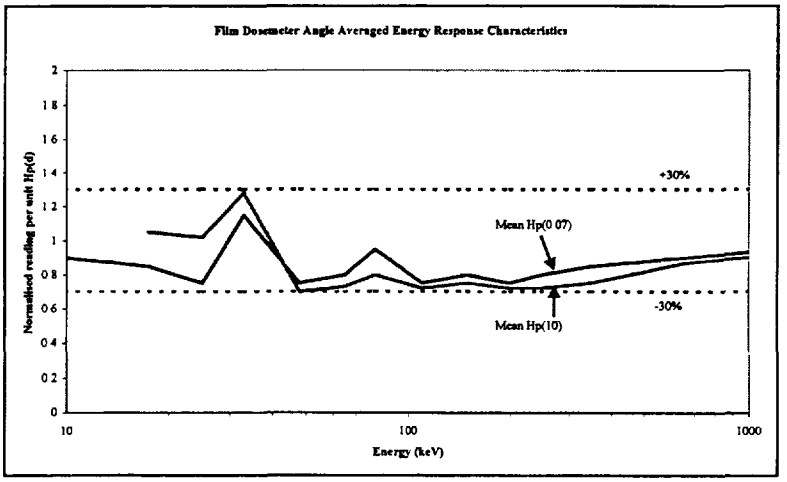

FIG. 10. Film dosimeter angle averaged energy response characteristics.

4. BACKSCATTERED RADIATION FIELD

To be able to provide a good estimate of $H_p(10)$ over the energy range from 10 or 20 keV to a few MeV, a personal dosimeter must either be able to respond fully, or partly to the backscattered radiation, or by other means must incorporate the contribution of the backscatter to the radiation field at the position of the dosimeter (Figure 11).

The first approach has been assumed in this paper. It should be noted that the backscatter field decreases with increasing dosimeter - body separation (Figure 12), varies in magnitude and angle distribution across the face of a calibration phantom (Figure 13).

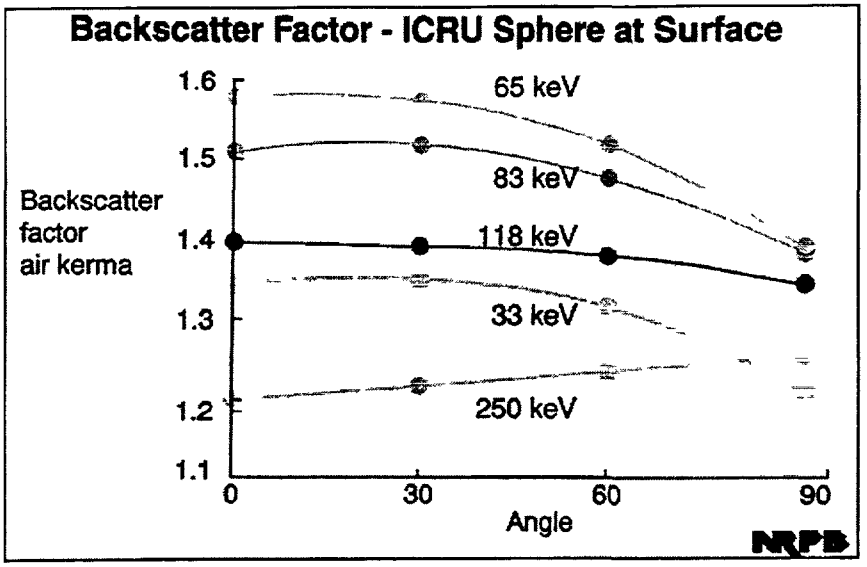

FIG. 11. Backscatter factor - ICRU sphere at surface.

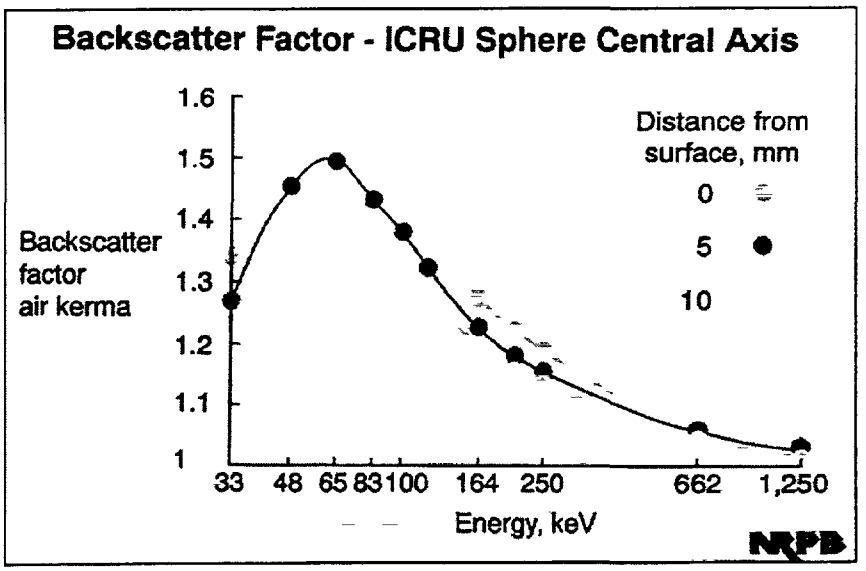

FIG 12. Backscatter factor - ICRU sphere central axis.

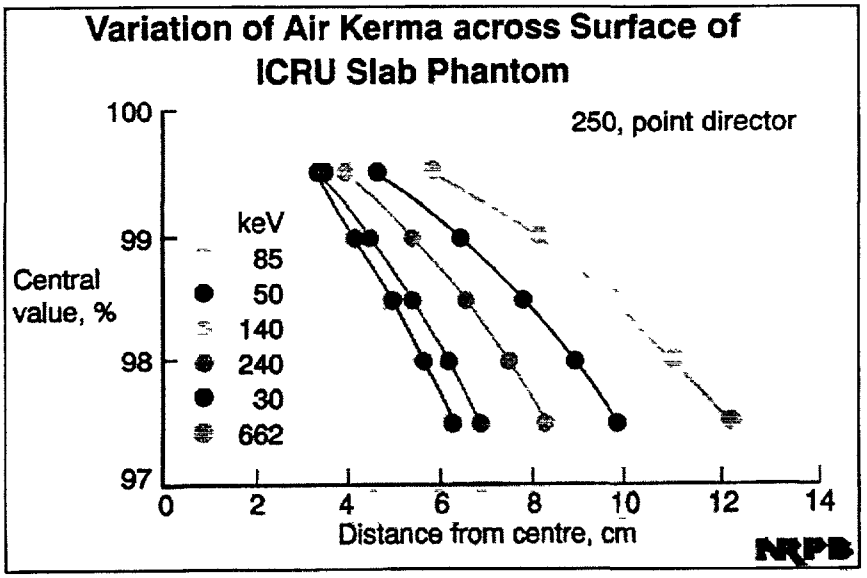

FIG 13. Variation of air kerma across surface of ICRU slab phantom.

The energy of the backscattered field, in general, has a different spectrum to the incident field (Figures 14–15 and references 14 to 18).

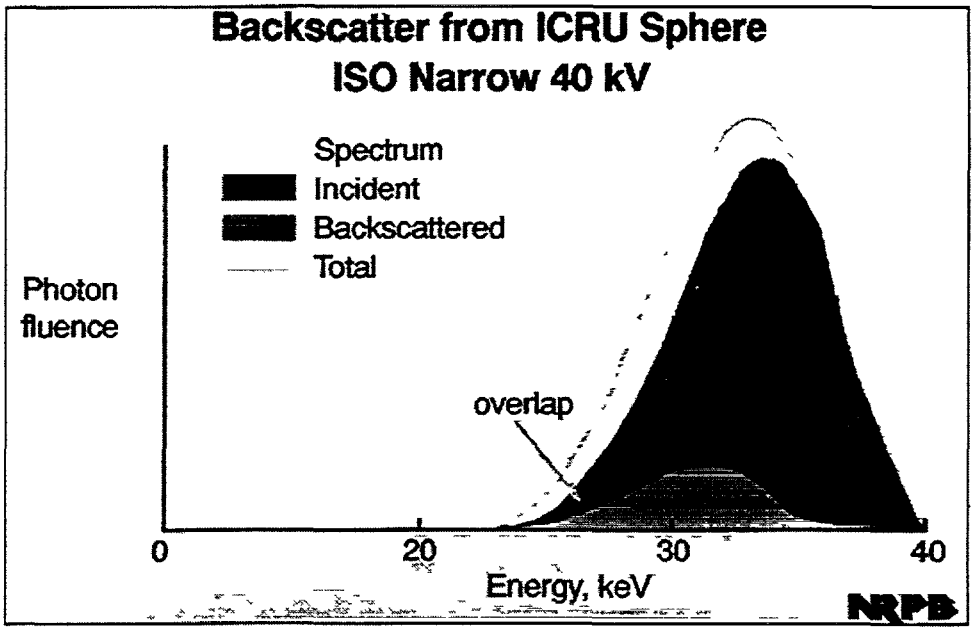

FIG 14 Backscatter from ICRU sphere ISO narrow 40 kV

The backscattered field is dependent on the shape and material (see Figure 16) and this has led to the recommended ISO calibration phantom which closely matches the backscatter from a phantom of ICRU 4-element tissue [12].

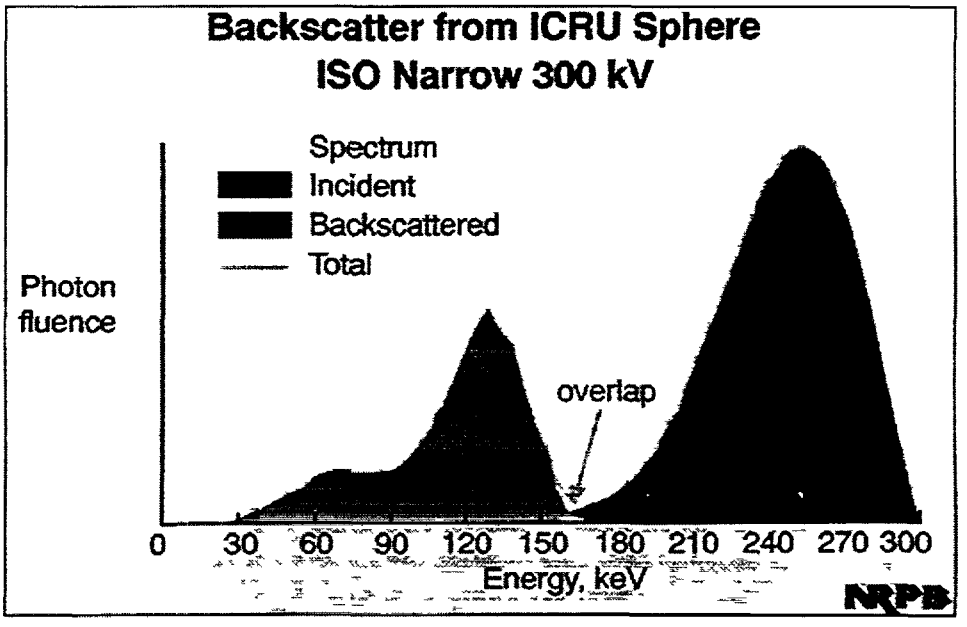

FIG 15 Backscatter from ICRU sphere. ISO narrow 300 kV

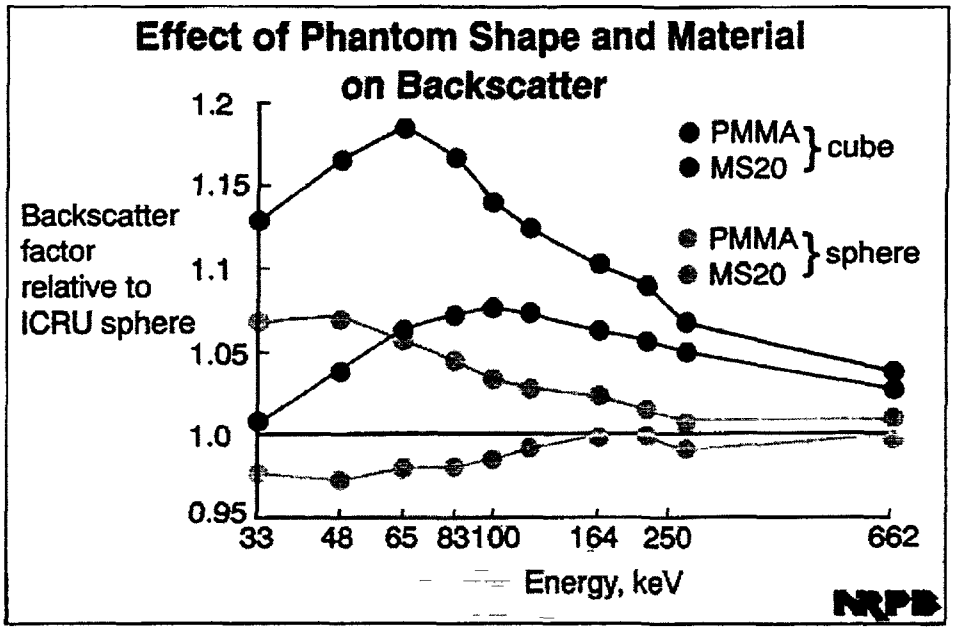

FIG. 16. Effect of phantom shape and material on backscatter.

REFERENCES

[1] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Data for Protection against Ionising radiation for External Sources: Supplement to ICRP Publication 15, ICRP Publication 21, Pergamon Press, Oxford (1971).

[2] SHAW, K. B., WALL, B. F., Performance Tests on the NRPB Thermoluminescent Dosemeter. National Radiological Protection Board, NRPB-R65, Chilton, UK, (1977).

[3] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Quantities and Units in Radiation Protection Dosimetry. ICRU Report 51, ICRU, Bethesda (1997).

[4] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Measurement of Dose Equivalents from External Photon and Electron Radiations. ICRU Report 47, ICRU, Bethesda (1992).

[5] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection Publication 60, Pergamon Press, Oxford, UK (1991).

[6] INTERNATIONAL ATOMIC ENERGY AGENCY, International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996).

[7] EUROPEAN COMMISSION, Council Directive 96/29/EURATOM of 13 May 1996 laying down basic safety standards for the protection of the health of workers and the general public against the dangers arising from ionizing radiation. Official Journal of the L159, Vol. **39**, 29 June 1996.

[8] HUBBELL, J.H., SELTZER, S.M. Tables of X-Ray Mass Attenuation Coefficients and Mass Energy-Absorption Coefficients 1 keV to 20 MeV for Elements Z=1 to 92 and 48 Additional Substances of Dosimetric Interest, National Institute of Standards and Technology Reports NISTIR 5632, Gaithersburg, USA (1995).

[9] GROSSWENDT, B. The Angular Dependence and Irradiation Geometry Factor for the Dose Equivalent for Photons in PMMA Slab Phantoms and Tissue Equivalent Material Radiat. Prot. Dosim. **35** (1991) 221–235

[10] DIMBYLOW, P.J., FRANCIS, T.M., BARTLETT, D.T. Calibration of Photon Personal Dosemeters in Terms of the ICRU Operational Quantities: Calculations of Phantom Backscatter and Depth Dose Distributions. National Radiological Protection Board Report, NRPB-R230, Chilton, (1990).

[11] INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS, Conversion Coefficients for Use in Radiological Protection against External Radiation. ICRU Report 57, Bethesda, (1998).

[12] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, X and Gamma Reference Radiations for Calibrating Dosemeters and Dose Ratemeters and for Determining their Response on a Function of Photon Energy – Part 3: Calibration of Area and Personal Dosemeters, and the Measurement of their Response as a Function of Energy and Angle of Incidence, ISO DIS 4037-3, ISO, Geneva, (1998).

[13] ILES, W.J., MILTON, M.I.L., BARTLETT, D.T., BURGESS, P.H., HILL, C.E. Type Testing of the NRPB/AERE Film Badge Dosemeter in Terms of the New ICRU Secondary Quantities – Part 1: Photons Over the Energy Range 10 keV to 1250 keV. National Radiological Protection Board Report, NRPB-R236, NRPB, Chilton, (1990).

[14] KRAMER, H.M., GROSSWENDT, B., HOHLFELD, K., SELBACH, H.J. An Investigation of Tissue Equivalent Materials of Determining Their Backscatter Factor. Proc. 6th Int. Congress IRPA Berlin, May 7-12, 1987, Ed. Kaul, A., Neider, R., Pesko, J., Stieve, F.E., and Brunner, H. (Jülich : Fachverband für Strahlenschutz e.v.) (1984).

[15] KRAMER, H.M. Personal Communication (1997).

[16] GUALDRINI, G.F. Field Parameters and Operational Quantities for the ICRU Sphere with Reference Photon, Part 1: Monte Carlo Calculations of Angular Distribution of Backscatter Factors. Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, ENEA Report RT/AMB/92/12, ENEA, Bologna, (1992).

[17] GUALDRINI, G.F., MORELLI, B. Studies on the Homogeneity of Photon Fields for Contemporary Calibration of Personal Dosimeters on Slab Phantoms. Ente per le Nuove Tecnologie, l'Energia e l'Ambiente RT/AMB/96/22, ENEA, Bologna, (1996).

[18] GUALDRINI, G.F., PADOANI, F., MORELLI, B. Field Parameters and Operational Quantities for the ICRU Sphere with Reference Photon Beams – Part 2: Monte Carlo Calculations of Backscattered Spectrum and Backscattered Mean Energy Angular Distribution, Ente per le Nuove Tecnologie, l'Energia e l'Ambiente, ENEA Report RT/AMB/92/13, ENEA, Bologna, (1992).

PASSIVE DOSIMETER CHARACTERISTICS AND NEW DEVELOPMENTS

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Abstract

The characteristics of the various personal dosimeters presently used by the national dosimetry services are reviewed. Recent developments in this field are also presented, including the Direct Ion Storage technique.

1. GENERAL REQUIREMENTS

Individual monitoring enables individual control of exposure in order to ensure that exposure limits are not exceeded and to support reduction of exposures ever further below these limits. The dose limit for occupational exposure has been reduced to 20 $mSv.y^{-1}$ averaged over 5 consecutive years with a maximum of 50 mSv within one year (ICRP 60). For a working period of 1800 $h.y^{-1}$, 20 mSv results in a mean dose rate of about 11 $\mu Sv.h^{-1}$ or a mean dose per month of 1.7 mSv. If we take into account the ICRP 35/60 recommendations an individual dosimeter used for monthly recording of doses should be able to register about 10% of this dose at least, so that the lowest measurable dose (recording level) should be about 0.17 mSv. The new recommendation ICRP 75 which is at the printers (the revision of ICRP 35) considers that the recording level for individual monitoring should be derived from the duration of the monitoring period and an annual effective dose of no lower than 1 mSv or an annual equivalent dose of about 10% of the relevant dose limit. For the monitoring period of one month the recording level is in this case not lower than 1 mSv/12=0.085 mSv.

In personal dosimetry the maximum error in the measurement of a dose at the level of the annual dose limit should not exceed a factor of 1.5 at the 95% confidence level. This means that the measured dose should be within the interval from - 33% to + 50% of the conventional true value of the quantity of interest which for individual monitoring is personal dose equivalent Hp(l0).

The highest measurable dose for a personal dosimeter is not given by the ICRP recommendations, as for the gamma radiation. This value should be at least several Gy, and, in some control areas the accident dosimeter is recommended.

The overall accuracy of a dosimetry system is determined from the combined effect of a number of systematic and random errors [l-5]. The following sources are usually considered to cause systematic uncertainties:

(1) energy dependence

(2) directional dependence

(3) fading

(4) non linearity of the response

(5) effects from exposure to light

(6) effects from exposure to types of ionising radiation not intended to be measured by the dosimeter

(7) effect from a mechanical shock

(8) calibration errors

(9) variation in local natural background

(10) effect of dose rate.

Typical sources of random uncertainties are inhomogeneity of detector sensitivity and zero dose for the batch of dosimeters used and fluctuations in reading parameters, including reader sensitivity and background.

The combined uncertainty may be expressed in the form of a standard deviation $S=\sqrt{\delta_r^2+\delta_s^2}$ where δ_r and δ_s are the resultant random and systematic standard deviations. It is convenient to differentiate between the systematic uncertainty component related to the energy and angular responses and to all other systematic errors.

2. STATE OF THE ART

From the practical point of view personal dosimeters can be divided into four categories (ICRP 60):

Basic whole body dosimeter which is worn to estimate the operational quantities Hp(10) and Hp(0.07). It is not required to provide any other information. Examples of this category are two-element thermoluminescent dosimeters and radiophotoluminescent dosimeters.

Discriminating whole body dosimeter which provides information on the radiation conditions, for example:

- the type, energy and direction of the radiation having caused the exposure, and
- contamination of the dosimeter.

This kind of information can help to estimate effective dose following accidental exposure, or, in situations where workers may regularly receive doses approaching the dose limits in complex radiation fields.

A typical example of a discriminating dosimeter is the film badge type which may be capable of providing a great deal of information on the circumstances of the exposure.

A multi-element thermoluminescent dosimeter with different filters and thickness can also give information on the type and energy of the radiation.

Extremity Dosimeters

An extremity dosimeter is such a one which is worn on an extremity, i.e. hand, fore-arm, foot or ankle, when the extremity may become the limiting organ or tissue. These dosimeters are usually worn in addition to a whole-body dosimeter.

Thermoluminescent dosimeters are mostly used for extremity dosimetry. Radiophotoluminescent dosimeters are also used for this purpose.

3. THE CHARACTERISTICS OF PERSONAL DOSIMETERS PRESENTLY USED ON NATIONAL SCALE

3.1. Film Dosimeter

Film dosimeters are used for determining individual exposure to photon, beta and thermal neutron radiations. For individual monitoring, the photographic films are commonly placed inside suitable holders. Such assemblies are often referred to as film badges [1,18, 20].

The emulsion of the film is made of silver bromide crystals which are suspended in a gelatinous medium. A thin layer of this emulsion is coated uniformly on a thin plastic base, mostly on both sides. After exposure to ionizing radiation, the latent image is developed, and, the optical density is measured by a densitometer.

The optical density depends on the:

- film type
- developing process (temperature and time)
- type and energy of radiation
- time after exposure (fading).

The optical density does not vary linearly with the dose. The complicating factor, important in practical photon dosimetry, is the energy dependence of the film response relative to human tissue. Compensation of this effect is achieved by using one or more filters, either with a different atomic number, or of various thickness.

Selection of films

Various films for individual dosimetry are on the market now. Those mostly used are Agfa or Kodak and, in the Czech Republic, Foma. Two films – one of high and one of low sensitivity – are packed in a plastic cover. For film evaluation, the following criteria should be taken into account:

- sensitivity and dose range
- energy response
- fading
- homogeneity

When selecting the sensitivity range of films which can be influenced by the type of developer and temperature and time of developing, the lower limit as well as the upper one of the dose must be considered. Taking into account the general requirements (ICRP 60), for monthly recording of doses the range of doses should be at present from about 0.17 mSv (-50% +100%) to at least 100 mSv (-33% +50%). The new ICRP 75 Publication which is at present at the printers requires the recording level for one month monitoring period 0.085 mSv.

Dosimetric Analysis and Interpretation of Results

The non-linearity of the dose-density dependence is simply overcome by the calibration process. In this some films are irradiated in a relevant range of doses (~0.2 mSv ~ 1 Sv) by ^{137}Cs or ^{60}Co sources and/or X rays at maximum sensitivity (~ 45 keV). The set of calibrated films is then developed together with films to be evaluated. A new type test calibration is necessary when a new type of film is used or changes are made to the developing process.

The energy dependence is often compensated, either by using one filter with a higher atomic number (Pb or Cd), or by a filtration analysis. While the single filter method is suitable for photon energies higher than about 0.1 MeV, for the lower range of energies, filtration analysis is inevitable. In this case, the energy of incident radiation can be estimated from the ratio of responses behind different filters, and, thus the correction factor for the response of the unscreened part of the film can be found.

For the practical application a linear combination method is often used. In this case, each filter element as well as open window can be regarded as an individual dosimeter with its own individual dose measurement value. In general, the individual dose values of one dosimeter vary according to the exposure conditions, i.e. the energy and angle of incidence of the radiation. The final dose value of the personal dosimeter is calculated by means of the linear combination of individual dose values under each element, the evaluation algorithm must be found experimentaly. Recently the linear programming method was proposed [21].

Computers are generally used for dose calculation. A fading correction can be simply made by appropriate time of calibration with regard to the monitoring period.

The dependence of $H_p(10)$ on the photon energy for film under the open window is given in Figure 1. The curve is normalized to ^{137}Cs radiation. For the dose calculation by means of filtration analysis and filters 0.05; 0.5; 1.6 mm Cu; 0.5 mm Pb and open window the second curve on Figure 1 is obtained. The ratio of measured Hp(10), and irradiated Hp(10) lies within ± 10% for narrow photon spectra in the range of 15 keV and 6 MeV. For mixed photon energies and routine conditions the accuracy is worse (up to ± 25%). The linear combination method gives similar results for narrow photon spectra, but for mixed photon energies the results are generally worse.

From the practical point of view, the filtration analysis method gives additional information about the spectrum of photons, while the linear combination method gives additional information concerning the uncertainty of the evaluated dose.

The film badge characteristics, including desirable and undesirable features, are summarized in Table I. There has been a big discussion whether to substitute this technique with another (TLD or RPL). One view is that in countries with extreme weather conditions (high temperature and humidity), latent image fading and higher fogging of film are the reasons for replacing the film badge technique with TLD.

TABLE I. FILM BADGE CHARACTERISTICS IN INDIVIDUAL DOSIMETRY OF PHOTONS

Influence quantity	Character
Dose - density dependence	Non linear, calibration is unavoidable
Dose range covered	~ 0,2 mSv - ~ 3 Sv (two films in one package)
Type of radiation covered	Photons - greater than 15 keV electrons - greater than 200 keV thermal neutrons
Energy dependence	Yes sensitivity ratio 45 keV ~15 ^{137}Cs
Compensation of energy dependence	Unavoidable, by one filter method (E>0.1 MeV) or filtration analysis (E<0.1 MeV)
Fading	Less than about 15% in 90 days for high sensitive film and less than about 20% for low sensitive film both for temperature range up to 30 °C and humidity up to 60%
Fading compensation	Simple by computer program or time of calibration
Developing process	Time consuming, special equipment with temperature and time held constant. Whole process must be in a dark room
Light sensitivity	Yes, must be protected from exposure by light
Dependence upon the incidence	Yes, can be compensated to some extent angle of photons
Information on radiation conditions	Yes, provides information about the type and energy of radiation angle of incidence, contamination etc.
Stability of background density (fog)	Not stable, changes with time, temperature and humidity, the higher the sensitivity - the higher is the increase of fog with time and temperature
Permanent record of received dose	Yes
Cost of dosimeter	Not expensive
Effect of dose rate	None

3.2. Thermoluminescent dosimeter

The application of the phenomenon of thermoluminescence to dosimetry is based on the fact that the amount of the light released during heating is directly related to the dose initially received by the material. The luminescent light output vs. temperature is called the "glow curve". The glow curve and the area below it depend on the number of lattice defects, on the type and amount of impurities present, as well as on the thermal history and treatment of the material. The response of most thermoluminescent materials as a function of absorbed dose is linear over a wide dose range.

In the higher dose range superlinearity may appear until saturation occurs. The decrease of the response after irradiation - fading - depends on the type of detector and environmental conditions (temperature, humidity). Energy dependence changes with Z_{eff}, some phosphors (LiF) have a very low energy dependence, while some others ($CaSO_4$:Dy) cannot be used without compensation of energy dependence.

Compensation for energy dependence can be realized either by filtration analysis or by linear combination method. Both these methods are described in the previous chapter. For the energy dependence compensation of TL dosimeters one filter with a higher atomic number (Pb, Cd) can be also used, where only part of the detector is screened. Practical application is enabled by using a cross-shaped filter compensating also the directional dependence, especially when the photon energies below about 0.1 MeV are present [19].

Thermoluminescent materials

To date more than hundred phosphors have been described. Some common characteristics of phosphors vary greatly from one to another. So far some ten different phosphors have been used in radiation dosimetry and about four of them are suitable for personal monitoring purposes. These phosphors are LiF, CaF_2, aluminophosphate glass and $CaSO_4$. The other phosphors have not been fully accepted for personnel monitoring, though few of them, which are being studied, are showing a considerable promise. General characteristics of some commercially available TL dosimeters are summarised in Table II.

Lithium fluoride

More commonly used phosphor because of its low energy dependence (maximum + 30%) and wide range of doses (0.2 - 10^2 Gy). Fading after a special annealing process is negligible. Higher doses produce radiation damage and the sensitivity of the phosphor decreases. It is preferable that the phosphor is recalibrated after each processing. Using phosphors of different compositions (^{6}LiF; ^{7}LiF) one can discriminate gamma radiation from thermal and epithermal neutrons.

Calcium fluoride

The natural mineral and the synthetic monocrystal CaF_2 activated with Mn are widely used in TLD. The dose response is strictly linear over a very wide dose range (0.02 - 10^3 Gy) with a little superlinearity above about 10^2 Gy. Energy dependence must be compensated.

Aluminophosphate glass

Glass is a clean, inert, insoluble and non-toxic material and can be produced cheaply in different shapes [18], The energy dependence must be compensated, fading is about 15% in a three months period. The dose range covered is wide (0.2 ~ 10^2 Gy), higher doses are measurable using the colorization effect. Annealing after use is important, reusability without a change in sensitivity is a valuable feature.

Calcium sulfate

This phosphor is available in two forms - one activated with Mn and the other with Tm or Dy. $CaSO_4$:Mn is the most sensitive phosphor but its fading is very high. Activation by Dy or Tm or Sm gives high sensitivity, and fading is within tolerable limits. Energy dependence must be compensated.

Reading Instruments

The irradiated phosphor must be heated to release luminescence emission. This must be measured by a suitable detector. All TLD reading instruments consist of the following basic components:

- Heating and temperature control unit
- Mechanical arrangement for positioning the phosphor on a heating pan or into the heating circuit in a dark chamber
- Luminescent detector with optical filters
- Power supplies
- Read out.

The heating unit must produce temperatures at the maxima of the glow curve as rapidly as possible without the infrared background. If the peak height is used for dose evaluation, the heating cycle must be sufficiently reproducible.

The mechanical part of the reader must allow quick placement of the dosimeters one after another in a light-tight chamber and their connection with the heating circuit.

As a luminescence detector a photomultiplier tube is used. The selection of the photomultiplier must be done with regard to the emission spectrum of the phosphor and the spectral sensitivity of the cathode.

The characteristics of TL dosimeters strongly depend on the reading instrument and method of measurement. A number of reading instruments for manual or automatic processing is available on the market at acceptable prices. TLD is increasingly accepted for radiation protection dosimetry for the following reasons:

- the existence of nearly tissue equivalent TL dosimeters where energy dependence compensation is not necessary
- sufficiently high sensitivity and accuracy
- number of TL materials in different type and shape are commercially produced on a large scale
- commercial availability of reading equipment semi automatic or fully automatic produced by Harshaw, Teledyne, Risø-Alnor, NE Technology etc. makes routine service very simple and economical
- suitability for extremity dosimetry
- excellent long term stability under varying environmental conditions
- reusability of detectors after annealing process.

Today TLD is a commonly used dosimetric method for routine individual dosimetry, environmental monitoring and clinical radiation dosimetry. In many countries the film badge method was replaced by TLD not only in nuclear power stations but also in national personal dosimetry services. Mostly both methods, film badge and TLD, are used for personal dosimetry because if the dose evaluation process is kept under appropriate control then the accuracy of both methods fulfills the general requirements for individual monitoring. The regular testing of the whole process is the basic requirement which must be fulfilled in every authorized service.

TABLE II. GENERAL CHARACTERISTICS OF SOME COMMERCIALLY AVAILABLE TL DOSIMETERS

TLD type	Z_{eff}	Main peak (°C)	Emission maximum (nm)	Relative sensitivity	Fading (at 25°C)
LiF:Ti,Mg	8.3	200	400	1	5%/year *
LiF:Na,Mg	8.3	200	400	1	5%/year *
LiF:Mg,Cu,P	8.3	210	400	25	5%/year
$Li_2B_4O_7$:Mn	7.3	220	605	0.20**	4%/lm
$Li_2B_4O_7$:Cu	7.3	205	368	2**	10%/2m *
MgB_4O_7:Dy	8.4	190	490	10**	4%/1m *
BeO	7.1	190	200-400	0.20**	8%/2m
$CaSO_4$:Dy	14.5	220	480-570	30**	1%/2m
$CaSO_4$:Tm	14.5	220	452	30**	1-2%/2m
CaF_2:Mn	1	260	500	5**	16%/2w
CaF_2 (natural)	16.3	260	380	23	very slight
CaF_2:Dy	16.3	215	480-570	15**	8%/2m
AIP glass	12.3	280	560	2	7%/1 m

* Fading in the dark (after using a post-irradiation annealing of 15 min at 100°C) related to 1 day storage
** Light sensitive

3.3. Radiophotoluminescent Dosimeter

Photon individual dosimeters based on the phosphate radiophotoluminescent (RPL) glasses have been known for many years [1]. They have been developed in Japan, France, and for many years also in Germany, where they are also approved for routine individual monitoring [2]. Their basic properties as personal dosimeters have been recently summarized and can be briefly presented as follows:

Energy and angular dependence

As far as the energy response is concerned, for $H_p(10)$ it is within ± 15% in the energy range from 10 keV to 8 MeV when an appropriate compensating Sn filter is used. The uncertainty mentioned slightly increases (to about ± 25%) when incidence angle interval is enlarged up to 90°. The typical data on energy and angular responses are presented in Figure 2.

Lowest detectable dose and linearity

Due to the pulsed UV laser excitation the pre-dose of previous types of RPL glasses has been largely suppressed, and can be measured individually. The typical mean value of pre-dose found is about 30 μSv with a standard deviation of about 1 to 2 μSv. According to the pattern approval specification the lowest detectable dose is 0.03 mSv, and the coefficient of variation at 0.1 mSv is estimated to be about ± 3%. At higher doses it decreases to about ± 1%. The response is linear with dose equivalent up to about 10 Sv.

Long term stability

It is known that the RPL signal builds up with time immediately after the exposure, the maximum value at 20 °C is achieved about 10 days after irradiation. When preheating at 35 °C for 24 hours is applied, the long term stability can be characterized by a standard deviation about ± 0.4% over a period of nearly one year. The specific ability of repeated readouts should also be noted.

Sensitivity to other types of radiation

RPL glasses can be used as dosimeters also for other penetrating low LET radiation (electrons, high energy charged particles, etc.). Their response per unit absorbed decreases, as for the most of solid state detectors, with the LET of particles depositing the energy in a glass. As far as neutrons are concerned, the energy deposited in RPL glasses is much lower than the energy deposited in tissue. As a result, their relative response to neutrons is much lower than 1.0 even in terms of kerma [4], obviously much lower in terms of dose equivalent. Typical values of responses in terms of tissue kerma relative to gamma radiation response at E_N ~ 10 MeV are less than 0.01.

Some remarks on routine experience

The basic characteristics mentioned above have been also confirmed in some larger scale tests, both at nuclear power plants as well as during some intercomparisons. As an example, Figure 3 shows the results obtained with the RPL personal dosimeter during two year tests performed at PTB Braunschweig. The standard deviation of the glass reading (5.6%) was better than for TLD systems tested at the same time. The RPL characteristics are summarised in Table III. The cost of the RPL method, and the availability of reading equipment is worse in comparison with TLD.

4. NEW DEVELOPMENTS

4.1. Progress in the systems already used

Film badge methods:

- production of new dosimeter films with higher sensitivity and/or better homogeneity of emulsion (fog value, density - dose slope, fading)
- production of densitometers with higher density range (0-6)
- production of developing equipment with better parameters for large scale developing (fixing of temperature, time and mixing of developer)
- densitometer on line with computer
- improvements in dose calculation process
    a) calibration curves calculated by a computer program from density of films which are sumultaneously developed with every group of films issued
    b) energy correction curves introduced into the dose computation programme regular testing of the quality of films and whole evaluation process.

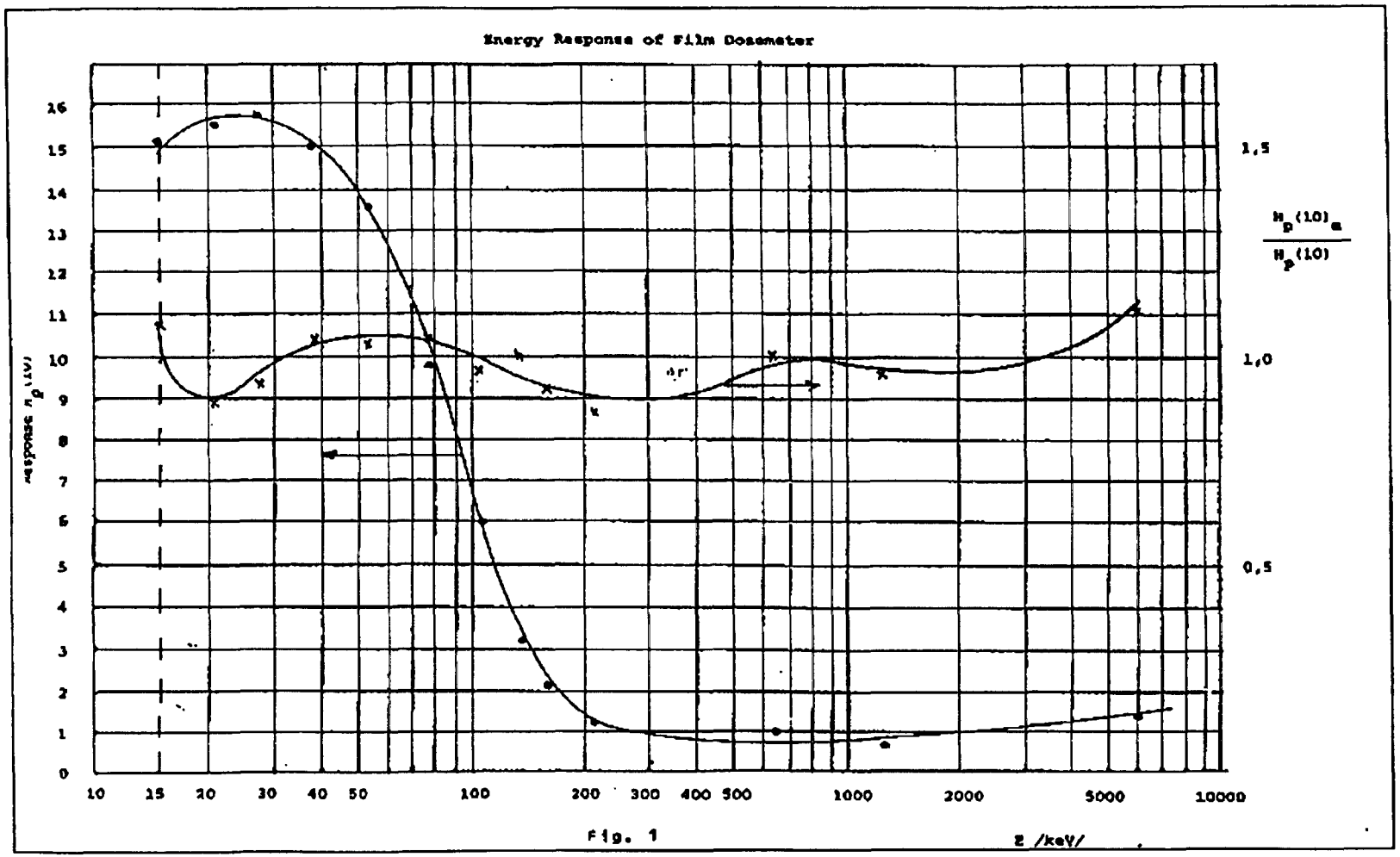

FIG 1. Energy response of film dosimeter.

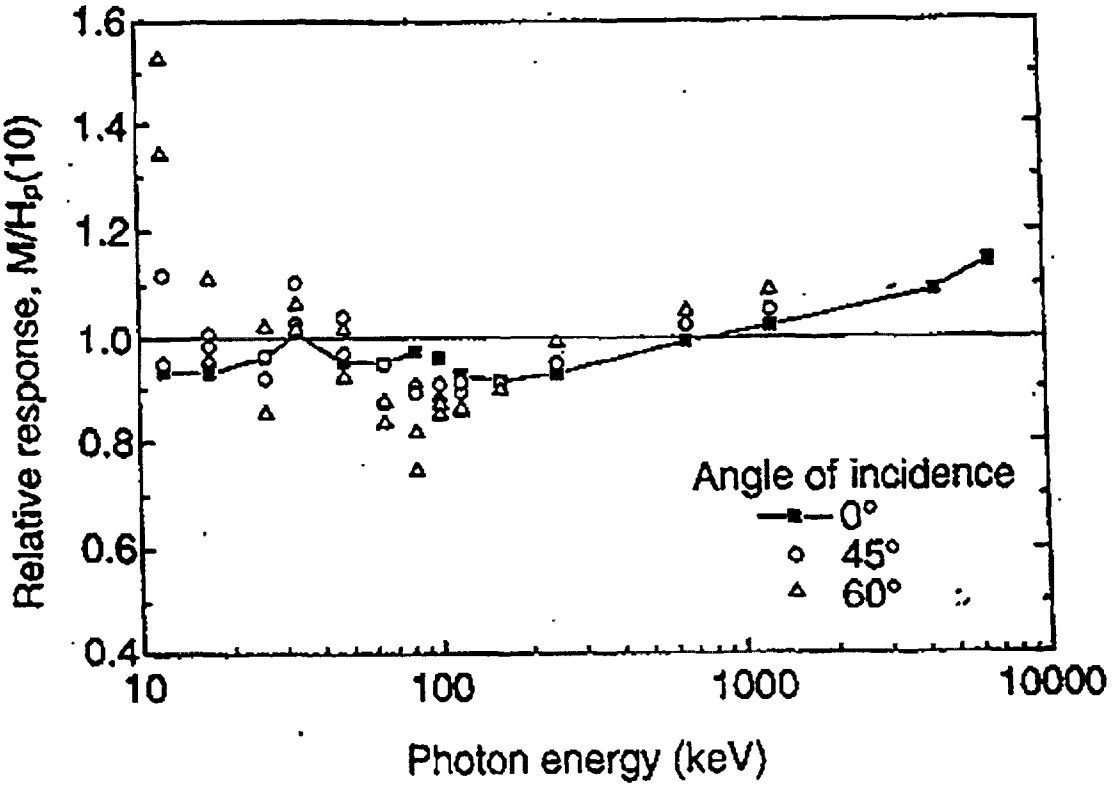

FIG 2. Energy and angular depends of the RPL glass (FKZ) dosimeter for the measurements of Hp(10).

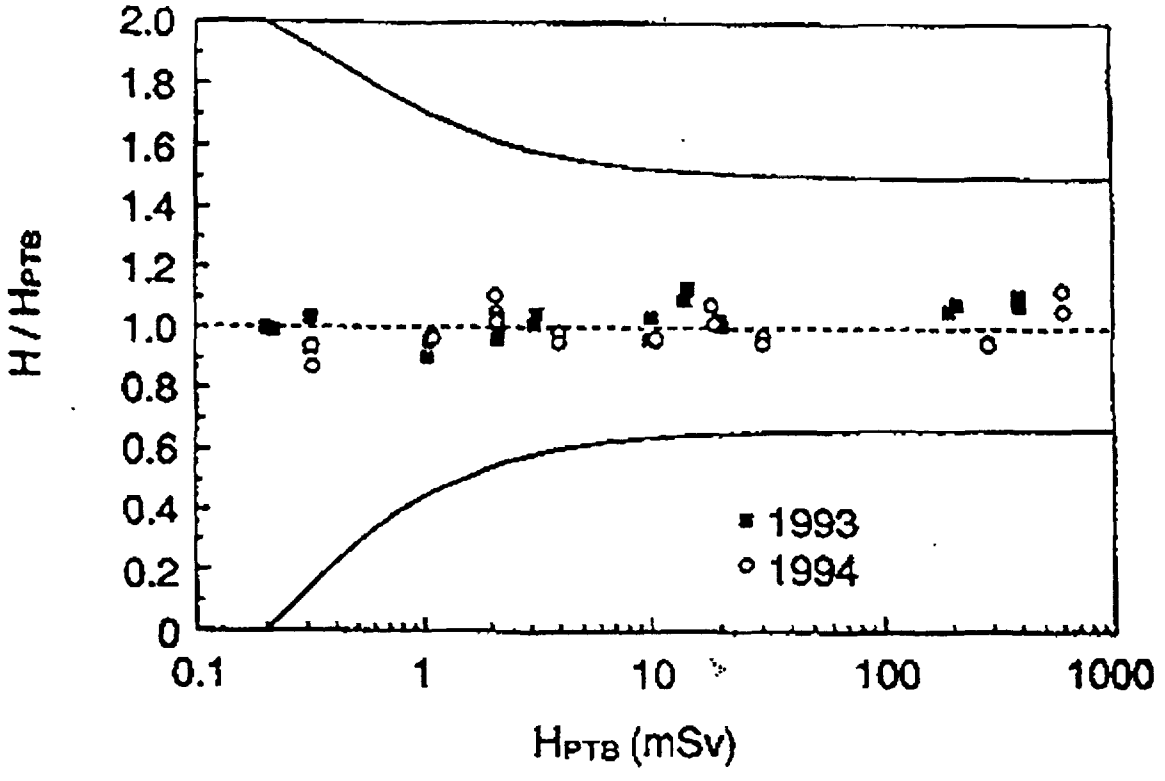

FIG 3. FZK results of the glass dosimeter relative to the PTB reference dose in terms of H for the annual PTB irradiations

TABLE III. RADIOPHOTOLUMINESCENT CHARACTERISTICS IN INDIVIDUAL DOSIMETRY OF PHOTONS

Influence quantity	Character
Type of detector	Phosphate glass activated with Ag commercially available
Dose - density dependence	Linear up to several Gy
Type of radiation covered	Photons: greater than ~ 20 keV Electrons: greater than about 1 MeV Thermal neutrons - over sensitivity should be reduced
Dose range covered	0.1 mSv - ~ 1 0 Sv (with pre-dose suppressed)
Energy dependence	Yes, sensitivity ratio 45 keV/^{137}Cs ~ 8
Compensation of energy dependence	Unavoidable, by one filter method from ~ 80 keV with perforated filter from ~ 40 keV
Fading	Buildup, max 10% in about 1 day, fading less than about 10 % in 1 year
Fading compensation	Not necessary
Build up compensation after exposure	Response measurement after ~ 1 day
Light sensitivity	Must be protected from ultra-violet light
Dependence upon the incidence angle of photons	Yes, can be compensated to some extent, by the shape of perforated filter
Effect of temperature	During irradiation ± 3% in the temperature range 0 - 40°C during storage - up to 40°C negligible
Evaluation equipment	Commercially available but expensive
Evaluation process	The dosimeter glass must be completely clean (the process is time consuming)
Information on radiation conditions	None
Stability of background	After evaluation an annealing process (400°C for 20 min) is unavoidable, the pre-dose increases after total exposure of about tens of mGy
Reusability	Yes, after annealing (400°C for 20 min)
Repeated measurement of exposed glass	Possible with negligible decrease of response
Permanent record of received dose	Not possible
Effect of dose rate	None

New thermoluminescent materials

Two very sensitive thermoluminescent materials have appeared recently: LiF:Mg,Cu,P [5] and Al_2O_3:C [6]. Their sensitivities to gamma radiation are about 30 times higher, relatively to well known TLD 700 [7]. Their properties have been extensively studied over several years as well as the possibility of their use in different applications. One application could be individual dosimetry. Principal properties of both mentioned TL materials and TLD 700 are presented in Table IV. One can see there that they should mainly improve the overall sensitivity of individual monitoring. As far as other properties are concerned:

- the energy and angular dependence, as well as fading, of 7 LiF:Mg,Cu,P should be better than to TLD 700;
- Al_2O_3:C will overestimate photons below 100 keV up to a factor about 5 at 60 keV; it should be easily compensated by proper filtration;
- the relative response of both hypersensitive TL materials decreases with LET more rapidly than for other TL materials [8]; their relative response to neutrons is therefore also much lower [7,8].

TABLE IV. BASIC CHARACTERISTICS OF TLD700, ^{7}LIF:MG,CU,P AND AL_2O_3:C

Property	TLD 700 (^{7}LiF:Mg,Ti)	^{7}LiF:Mg,Cu,P	Al_2O_3:C
Relative gamma sensitivity	1	~ 30	~ 25
Maximum heating temperature, [^oC]	400	240	400
Glow curve maximum [K]	463	510	440/570
Lowest detectable dose [μSv]	30	1	1
Linearity up to [Sv]	100	10	10

4.2. Other passive detectors

The use of thermally (or optically) stimulated exoelectron emission (TSEE) has been studied for many years. Up to now, however, no detectors based on these effects have been introduced in routine individual dosimetry. One of the reasons could be the toxicity of the best known TSEE material, BeO. Another could be related to more complicated reading procedure in comparison with, for example, TLD. Nevertheless, studies are still continuing. One of the last contribution was presented at the 11th International Conference on Solid State Dosimetry in Budapest, July 1995 [9]. It was reported that the response of thin BeO on the ISO phantom, correlates well with personal dose equivalent, independent of photon energy. The studies on the correlation between TL and TSEE mechanisms are also continuing [10].

Lyoluminescence is one of other methods which has been studied for special emergency situations. Organic materials, after irradiation, emit light when dissolved in water. The advantage of lyoluminescence dosimetry is in the fact that some lyoluminescence phosphors may closely approximate the chemical composition of tissue. The minimum detectable dose is about 0.1 Sv, and, therefore, the applications are in radiobiological, radiotherapeutic and criticality dosimetry.

A new technique, direct ion storage (DIS), was also presented during the same conference as a possible new alternative for individual photon dosimetry (both passive and active) [11,12]. Its principle is described in few sentences [13]: "A method for detecting ionising radiation by allowing the radiation to affect the surface of the floating gate of the MOSFET transistor through on air or gas space. For this purpose an uncovered area is formed on the surface of the floating gate of the MOSFET transistor forming the detector. The MOSFET transistor is used so that a charge is formed on its floating gate, the charge changing as a result of the ionising radiation the transistor is exposed to. The radiation dose is determined by the change which takes place in the charge of the gate". This new personal dosimeter has been compared with a TLD (Harshaw TLD 100) on the base of the IEC standard 1066 [4]. The results of such comparison are shown in Table 5. One can see there that the properties of DIS do not fulfill some requirements, on a personal photon dosimeters (energy response, equivalent dose range). Nevertheless, some technological improvements are possible, and the reading procedure promises to be an advantage.

TABLE V. COMPARISON OF TLD AND DIS ON THE BASE OF IEC 1066 PERFORMANCE CRITERIA [13]

Test	**Results**(1)	
	TLD	DIS
Batch homogeneity	7%	20%
Reproducibility	≤ 1.1 % separately ≤ 1.1 % collectively	< 4.5 % -
Linearity(2)	≤ 26 %	≤ 20%
Stability(3)	≤ 19%	≤ 1%
Energy response(4) to photons	≤ 12%	≤ 80%
Isotropy(5)	≤ 11%	≤ 12%

(1) within 95% confidence interval
(2) TLD: 0.1 mSv - 1 Sv; DIS: 0.5 mSv - 50 mSv
(3) 30 days at 20 °C, 90% RH
(4) $E_{phot} \in$ < 1 5 keV; 3. 0 MeV>
(5) Mean value of the responses at the angle of incidence of 20°, 40° and 60° from normal

REFERENCES

[1] BECKER K. Solid State Dosimetry, CRC Press, Cleveland, OH (1975).

[2] PIESCH E., BURGHARDT B., VILGIS M. Progress in Phosphate Glass Dosimetry: Experience and Routine Monitoring With a Modern Dosimetry System. Radiat. Prot. Dosim, **47**, (1993) 403 – 414.

[3] BURGHARDT B., UGI S., VILGIS M, PIESCH E. Experience with Phosphate Glass Dosimeters in Personal and Area Monitoring. Radiat. Prot. Dosim. **66**, (1996) 83 – 88

[4] SPURNY F. Methods of External Dosimetry and Their Use. DSc thesis (in Czech), Prague, (July 1984).

[5] WANG S., CHEN G., WU F., LI Y., ZHA Z., ZHU J.. Newly Developed Highly Sensitive LiF:Mg,Cu,P TL Chips with High Signal-to-noise Ratio. Radiat. Prot. Dosim. **14**, (1986) 223 – 229.

[6] AKSELROD M.S., KORTOV V.S. Thermoluminescent and Exoemission Properties of New High-Sensitivity TLD α-Al_2O_3:C Crystals. Radiat. Prot. Dosim. **33**, (1990) 123 – 126.

[7] KLEMIC G.A., AZZIZ N., MARINO S.A. The Neutron Response of Al_2O_3:C, ^{7}LiF:Mg,CuP and ^{7}LiF:Mg,Ti TLDs. Radiat. Prot. Dosim. **65**, (1996) 221 – 226.

[8] SPUNY F, VOTOCKOVÁ I. Response of some TLD to Alpha Particles with Energies from 2.5 to 5 MeV. Radiat. Prot. Dosim. **48**, (1993) 355 – 358.

[9] BURKHARDT W., KRIEGSEIS W., PETEL M., REGULLA D., SCHÄM M., SCHARMAN A. TSEE Response of BeO thin Film Detectors Irradiated on ISO Rod Phantoms to Photons and Beta Radiation. Radiat. Prot. Dosim. **66**, (1996) 13 – 16.

[10] MILMAN I.I., SJURDO A.I., KORTOV V.S., LESZ JA. TSEE and TL of Non Stoichiometric BeO-TiO2 Ceramics. Radiat. Prot. Dosim. **65**, (1996) 401 – 404.

[11] WEMII C. Dosimetric Characteristics of a Novel Personal Dosimeter Based on Direct Ion Storage (DIS). Radiat. Prot. Dosimetry, **66**, (1996) 23 – 28.

[12] KOSUNEN A., VARTIAINEN E., HYVÖNEN H., RANTANEN E., KAHILAINEN J. Testing of a TLD and a Direct Ion Storage (DIS) Dosimeter for use as a Personal Dosemeter Radiat. Prot. Dosimetry **66**, (1996) 29 – 32.

[13] KAHILAINEN J. RADOS Technology Oy, Finland, International Patent Publication Number WO 95/12134, 4 May 1995, World Intellectual Property Organization (WIPO).

[14] INTERNATIONAL ELECTORTECHNICAL COMMISSION. International Standard Thermoluminescence Systems for Personal and Environmental Monitoring. CEC/IEC 1066 (1991).

[15] CHRISTENSEN P., JULIUS H.W., MARSHALL T.O.: Technical Recommendations for monitoring individuals occupationally exposed to external radiation. EUR 14852 (1994).

[16] PHYSIKALISCH-TECHNICHE BUNDESANSTALT Intercomparison for individual Monitoring, PTB-Bericht Dos-20, Braunschweig (1991).

[17] TROUSIL J., STRBA J., PLICHTA J. The Personnel Computer Application for Hs(0.07) and Hp(10) Measurement in the National Personnel Dosimetry Service in Czechoslovakia. Kernenergie 34, (1991) 94 – 97.

[18] TROUSIL J., ET AL., Basic Dosimetric Characteristics of the Czechoslovak Thermoluminescent and Neutron Dosimeter. Kernenergie **27**, (1984) 246 – 254.

[19] TROUSIL J., KOKTA L. Compensation for the Energy and Directional Dependence of a Thermoluminescent Dosemeter. Rad. Prot. Dosim. Vol.2, **31**, (1982) 69 – 174.

[20] INTERNATIONAL ATOMIC ENERGY AGENCY. Personnel Dosimetry Systems for External Radiation Exposures. Technical Reports Series No. 109. IAEA, Vienna, (1970).

[21] KRAGH P. ET AL. The Evaluation of Multi-Element Personal Dosimeters using the Linear Programming Method. Proc. of IRPA9. International Congress on Radiation Protection, Vienna (1996)

ELECTRONIC DOSIMETER CHARACTERISTICS AND NEW DEVELOPMENTS

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Abstract

Electronic dosimeters are very much more versatile than existing passive dosimeters such as TLDs and film badges which have previously been the only type of dosimeters approved by national authorities for the legal measurement of doses to occupationally exposed workers. Requirements for the specifications and testing of electronic dosimeters are given in the standards produced by the International Electrotechnical Commission Working Group IEC SC45B/B8. A description is given of these standards and the use of electronic dosimeters as legal dosimeters is discussed.

1. INTRODUCTION

Electronic personal dosimeters (EPDs) have for at least the past 25 years been used as secondary dosimetry for occupationally exposed workers and because they are easy to read and incorporate alarm capability they have almost replaced pocket ion chambers (commonly called pen dosimeters) for this application. As the size of EPDs have diminished and their capabilities have increased with improvements in electronics, they are being considered for primary dosimetry in place of the commonly used film badges and thermoluminescent dosimeters (TLDs). It has long been predicted [1] and [2] that such devices may replace films and TLDs for use as primary dosimeters in personal dosimetry services approved by their national authorities for occupationally exposed workers. However, as with all innovations the EPD brings with it some of the problems of instruments which are not seen with traditional dosimeters. Before EPDs are accepted as primary dosimeters the radiation protection community has to reassure itself that their costs, reliability and accuracy of the data are comparable to traditional methods.

The International Electrotechnical Commission (IEC) in 1984 set up a working group, IEC SC45B/WGB8, to produce standards on electronic dosimeters.

This report describes the standards being produced by this IEC working group and discusses the role of electronic dosimeters in radiation protection monitoring.

2. IEC STANDARDS

2.1. Discussion

IEC Working Group TC45/SC45B/B8 terms of reference are to prepare draft standards on pocket active electronic direct reading and warning dose equipment rate monitors for use with photon and neutron radiations. It is served by 24 experts from 11 different countries. It has produced four separate standards for equipment to measure the personal dose equivalent $H_p(10)$ from penetrating radiation. These standards are titled:

IEC 1283, radiation protection instrumentation - direct reading personal dose equivalent (rate) monitors - X, gamma and high energy beta radiations.

IEC 1323, radiation protection instrumentation - neutron radiation - direct reading personal dose equivalent and/or dose equivalent rate monitors.

IEC 1525, radiation protection instrumentation - X, gamma, high energy beta and neutron radiations - direct reading personal dose equivalent and/or dose equivalent rate monitors.

IEC 1344, radiation protection instrumentation, monitoring equipment - personal warning devices for X and gamma radiations.

This last standard is for simple warning equipment, frequently known as a bleeper. It provides an audible and/or visual alarm and does not quantify the dose received since it has no recording or digital indication of the accumulated dose.

In addition to these four standards, a standard IEC 1526: (45B/162/CDV) has just been approved for registrations as a FDIS.

IEC 1526, radiation protection instrumentation - direct reading personal dose equivalent and/or dose equivalent rate dosimeter for the measurement of personal dose equivalent $H_p(10)$ and $H_p(0.07)$ for X, gamma and beta radiations.

Since all the standards are for measurement of the same quantity, namely the personal dose equivalent, great care has been taken to ensure that the relevant specifications and test methods of all the standards are consistent. Therefore to illustrate the specifications to be found in all these standards those for this last standard for the measurement of $H_p(10)$ and $H_p(0.07)$ are described.

2.2. Requirements of Standard

2.2.1. RADIATION PERFORMANCE SPECIFICATIONS

The scope of the standard is for dosimeters worn on the trunk of the body which measure the personal dose equivalents (rate) $H_p(10)$ and $H_p(0.07)$ from X and gamma radiations of energies 20 keV to 1.5 MeV, and from beta radiation of mean energy >0.06 MeV. Where the dosimeters are to be worn by individuals in the location of nuclear reactor installations where 6 MeV photon radiation is present then testing is required at photon energies above 4 MeV. The required specifications for the dosimeter are given in Table I. These requirements are applicable for both the measurement of $H_p(10)$ and of $H_p(0.07)$. For the determination at the relative intrinsic error ^{137}Cs is to be used for $H_p(10)$ and $^{90}Sr/^{90}Y$ for $H_p(0.07)$.

For the variation of the response with radiation energy, tests are required for both beta and photon radiations. For the beta tests the ISO radiations from $^{147}Pm(E_{max}$ = 0.225 MeV), $^{204}Tl(E_{max}$ = 0.78 MeV), and $^{106}Rh(E_{max}$ = 3.5 MeV) are used to test that the $H_p(0.07)$ response is within ± 30% of the $^{90}Sr/^{90}Y$ response. For the photon tests the use of the ISO filtered X-radiation, low air kerma rate series, at 17,26,30, 48 60(or ^{241}Am), 87, 109, 148 and 211 keV and ^{60}Co shall be used to demonstrate that the response over the energy region 20 keV to 1.5 MeV is within ± 30% of the $H_p(10)$ response to ^{137}Cs, whilst at 6 MeV the response has to be within -50% to +100%. If, for the design of the dosimeter, the air kerma rates from the ISO Low Air Kerma Rate Series are insufficient to perform the test conveniently then the follwing energies of the ISO Narrow Series shall be used (20,24,33,48,65,83,100,164 and 208 keV).

TABLE I. TESTS PERFORMED WITH VARIATIONS OF INFLUENCE QUALITIES

Characteristic under test or influence quantity	**Range of values of influence quantity**	**Limits of variation of indication**
Relative intrinsic error	Effective range of measurement	Dose equivalent: ± 15% Dose equivalent : ± 20%
Response time	5 s	< ± 10%
Accuracy of alarm levels	All settings	± 15% ± 20%
Radiation energy Beta Photon	 $>E_{max}$ = 0.78 MeV 20 keV to 1.5 MeV 6 MeV	 ± 30% ± 30% -50% to +100%
Angle of incidence Beta Photon	 0° to ± 60° 0° to ± 60°	 ± 30% for $^{90}Sr/^{90}Y$ ± 20% for ^{137}Cs ± 50% for ^{241}Am
Retention of reading Class I and 2 dosimeters Class I dosimeters only	 8 hours 24 hours after loss of principal power supply	 ± 5% ± 5%
Dose equivalent rate dependence	Up to 1 $Sv.h^{-1}$	< ± 20%
Overload	10 times range maxima	Indication > full scale
Power supply voltage Primary batteries Secondary batteries	 After 100 h continuous use After 10 h continuous use	 ± 15% ± 15%
Drop tests	1.5 metres	+ 10%
Vibration test	$2g_n$ over frequencies 10 to 33 Hz	±15%
Microphony	10 cm	spurious dose <1 μSv
Ambient Temperature 3) Temperature shock	- 10°C to 40°C - 20°C to 50°C - 10°C to 50°C	± 20% ± 50% ± 15% relative to +20°C
Relative humidity Electromagnetic field of external origin Magnetic field of external origin	40% to 90% at +35°C 100 Vm^{-1} at 100 kHz to 600 MHz and I V m^{-1} at 500 MHz to 1 GHz 60 A m^{-1} at 50 to 60 Hz	± 10% ± 10% ± 10% ± 10%
Electrostatic	6 kV, 2mJ	± 10%

The specifications of the variation of response with angle of incidence of beta and photon radiation is made for two planes, one horizontal and one vertical through the front face of the dosimeter. For the $^{90}Sr/^{90}Y$ beta radiation the ratio of the dosimeter reading $H_p(0.07)$ at 0° relative to the reading at α = 0° for angles at 0°, 20°, 40° and 60° shall be within ± 30% of the ratios given in Table 2. For the photon radiations two energies are used and at 60 keV from 0° to 60° the ratios in Table III shall be within ± 50% and for 662 keV from 0° to 60° the ratios in Table III shall be within ± 20%.

It should be noted that all the IEC SC45B standards on electronic dosimeters specify that all the radiation tests shall be performed with the electronic dosimeter mounted on the ISO water phantom of 30 cm x 30 cm x 15 cm.

TABLE II. CONVERSION FACTORS FOR A TISSUE EQUIVALENT SLAB PHANTOM FOR $H_P(0.07)$ FOR BETA RAYS (EMITTED BY STANDARD SOURCES AND EXTENDED AREA SOURCES) AT ANGLES OF 0^0, 20^0, 40^0 AND 60^0, NORMALISED TO 0^0 (SEE NOTE)

Nuclide	Data normalised to zero degrees				
	Distance (cm)	0°	20°	40°	60°
Data (extended area sources)					
Strontium-90/Yttrium-90	20.0	1.00	1.03	1.10	1.14
Strontium-90/Yttrium-90	30.0	1.00	1.02	1.08	1.09
Thallium-204	20.0	1.00	1.02	1.00	1.82
Thallium-204	30.0	1.00	1.01	0.97	0.80
Promethium-147	15.0	1.00	1.87	1.7	0.48
Data (PTB standards)*		1.00			
Strontium-90/Yttrium-90					
Type 1	30.0	1.00	1.02	1.10	1.15
Type 2	30.0	1.00	1.02	1.10	1.19
Thallium-204	30.0	1.00	0.97	0.93	0.73
Promethium 147	20.0	1.00	0.95	0.71	

* Type 1: With beam flattening filter.
Type 2: Without beam flattening filter

* In compliance with ISO series 1 reference radiations [11]

Note: For beta irradiations it is only necessary to use factors to convert from normal incidence of the radiation to different angles of incidence as the calibration beams of the secondary standard beta units are normally calibrated in units of Hp(0.07) in tissue.

The electrical, mechanical and environmental performance requirements are summarised in Table I. Of these the most practically important are the performance of the dosimeter with variations in power supply, to temperature shock and the ability of the dosimeter not to respond to RF fields. This latter requirement is particularly important since in an emergency situation the wearer may also be operating a portable radio transmitter.

TABLE III. REQUIRED VARIATION OF THE RATIO OF READING AT α^0 FOR PHOTON RELATIVE TO THE READING AT $\alpha = 0^0$ FOR MONITORS USED TO MEASURE PERSONAL DOSE EQUIVALENT (RATE), $H_P(10)$

		Ratio = reading α^0/Reading at 0°				
Radiation source	Photon energy	$\alpha = 15°$	$\alpha = 30°$	$\alpha = 45°$	$\alpha = 60°$	$\alpha = 75°$
^{241}Am (or filtered X-radiation)	59.5 keV (or 60 keV)	0.99	0.97	0.90	0.77	0.51
^{137}Cs	662 keV	1.0	1.0	0.98	0.95	0.80

The required mechanical characteristics of the dosimeter are as follows:

2.2.2. SIZE

The dimensions shall not exceed 15 cm length, 3 cm depth, 8 cm width, excluding any clip or retaining device but in addition the volume shall not exceed 250 cm^3 excluding the clip or other fixing arrangement.

2.2.3. MASS

The mass shall not exceed 200 g.

2.2.4. CASE

The case should be smooth, rigid, shock resistant, dust and shower proof

The dosimeter shall be able to withstand dropping onto a hard floor from 1.5 m.

Means shall be provided for fixing the dosimeter to clothing, e.g. a strong clip or a ring or a lanyard. Due regard should be given to the necessary orientation of the detector and alarm indicators.

2.2.5. SWITCH

If external switches are provided these shall be adequately protected from accidental or unauthorised operation. Operation of any switches provided shall not interfere with the integrating function of the dosimeter. Switches should be operable through a plastic bag if used for contamination control and with gloved hands.

In the near future there are likely to be significant advances in the design of electronic dosimeters. They are almost certain to replace some dosimetry systems based upon passive detectors and in a few cases already have. It is therefore fortunate that the IEC standards on electronic dosimeters are already well developed and will provide the basis for manufacturers to design and test as well as for users to evaluate the dosimeter's potential performance against the standard criteria.

3. DISCUSSIONS

EPDs are obviously more complex than passive dosimeters, and in particular compared to TLDs. The degree of complexity that is required can to some extent be reduced by the specific needs of the operators and some of these are discussed in a US report [3] which deals with the adoption of EPDs as legal dosimeters.

(1) Users of EPDs have noted the tendency of workers to use the EPD as a survey meter. This will invalidate the results from the EPD and lead to recording of excessively high exposures. They therefore recommend that two steps should be taken to eliminate the tendency to use the EPD as a survey meter. First, display of dose rate should be eliminated and replaced by a single resetting alarm. If additional dose rate information is needed, survey meters or supplemental EPDs should be used. Second, administrative controls should be used, including worker training on the use of EPDs and worker reprimands for misuse of EPDs.

(2) Permanence of record is an issue with the EPD since electronic failure could lead to loss of data. Many EPDs periodically write the dose data to a nonvolatile EPROM memory. Transfer of data should occur at short intervals. Any EPD used as a primary dosimeter should have a non-volatile memory with dose data written to memory at least every 15 minutes. Documented procedures for recovery of the information from the nonvolatile memory must exist.

(3) EPDs can be susceptible to electromagnetic interference (e.g. RF emissions). This susceptibility, particularly in the case of EPDs designed to measure $H_p(0.07)$, may be virtually impossible to eliminate in intense fields such as pulsed radar or radio/TV transmitters. Therefore all EPDs should pass the test criteria given in the IEC standard. Manufacturers should have a quality control program that tests each EPD for susceptibility. Users should eliminate use of EPDs in high RF emission areas or areas with intense magnetic fields and should institute worker training programs.

(4) Many commercial EPDs have a poor low energy photon response. However, this may not be a severe problem in most environments. Studies in America, [4] and [5], have shown that significant beta or low energy photon exposures are rare in nuclear power plants. Below 50 keV, the value of $H_p(10)$ per air kerma decreases rapidly as a function of decreasing energy, down to zero at 10 keV, while that for $H_p(0.07)$ decreases by only 20% down to 10 keV. Thus, below 50 keV, it is the personal dose equivalent $H_p(0.07)$ that is more restricting. Also, the data produced by ICRU and ICRP show that below 100 keV, the measurement of $H_p(10)$ significantly overestimates the effective dose equivalent as well as the dose to most individual organs. Hence, it can be argued that the dosimeter's $H_p(10)$ response can fall significantly at low energies to compensate for this overestimation. Alternatively, there is no need to establish a requirement for measurements below 50 keV.

(5) Many commercial EPDs do not measure $H_p(0.07)$. Also, neutron dose is not easily measured by using EPDs. Users should therefore review workers' exposure data to determine the need to measure $H_p(0.07)$ since it is generally not a concern and $H_p(0.07)$ and neutron dose could be handled by supplemental dosimetry or workplace studies.

The conventional dosimeter is worn on the trunk placed on top of clothing. Usually, such workers wear a shirt or blouse and a coverall. With the thinnest shirt being about 30 $mg.cm^{-2}$, it is obvious that the worker's body is never receiving a dose equivalent at a depth of 0.07 mm (7-$mg.cm^{-2}$). It is also questionable that the shallow dose recorded should be assumed to be received by the wearer's extremities. The spatial dose-rate distribution from weakly penetrating radiations is frequently very variable and usually so inhomogeneous that the values measured on the trunk provide only little information on the actual exposure situation of the person to be monitored [6]. It would therefore seem more prudent to monitor the dose at the location where the dose is accumulated, namely by the issue of conventional extremity and skin dosimeters. For example Thind [7] observed that in radiation source fields near the hands of operators the dose gradient between the wrist and the tips of the fingers could vary by factors of up to 30. Thus, requirements for neutron measurements and measurements of $H_p(0.07)$ with EPDs may not be justifiable in many cases and are probably handled better with conventional dosimeters.

(6) Alarms are often difficult to hear and, in the case of multiple alarms may be difficult to distinguish particularly in noisy environments. It is therefore recommended that manufacturers are aware of the alarm problem and the use of earphones, vibrators, etc., should eliminate the audibility problem. Reduction of dose-rate alarms and other alarms should reduce the problems with multiple alarms. Dose, dose overload, battery failure, and dosimeter failure should trigger audible alarms; combining the three latter alarms would be practical since they indicate a need to leave the area and check the dosimeter for condition. Actual alarm condition could be displayed. Thus, one dose, one dose-rate, and one "failure" alarm would need to be available.

4. CONCLUSIONS

In summary the advantages of using electronic dosimeters over passive dosimeters are:

- no specialised processing laboratory is required to read out the doses
- they can be readily linked to entry and exit controls
- they can alarm to warn the wearer, or his controller, that pre-set dose or dose rate levels have been exceeded.

Disadvantages are:

- the cost of the dosimeter is significantly higher than films or TLDs
- their size and weight is much greater
- they need batteries to operate the dosimeter. Such batteries should be standard IEC batteries which are readily available in the country of use and also present no safety problems. It should be noted that the most recent commercial EPD operates without any batteries [8].

Some manufacturers claim that electronic dosimeters are more sensitive than TLDs and so will enable lower doses to be measured. Typically electronic dosimeters integrate in units of 1μSv. A European Commission (EC) environmental intercomparison [9] showed that even the most simple EPDs could, after correction for its inherent response and cosmic response, measure accurately environmental doses (Figure 1).

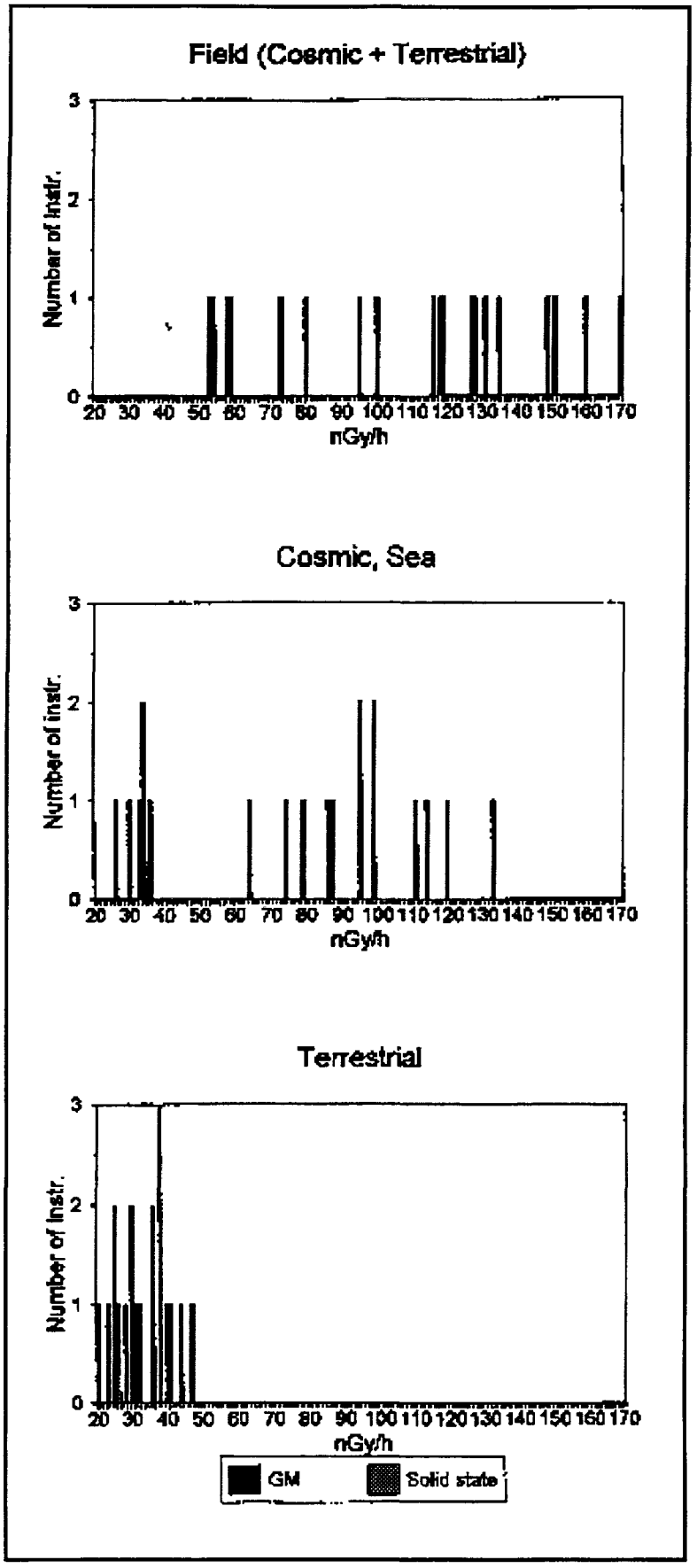
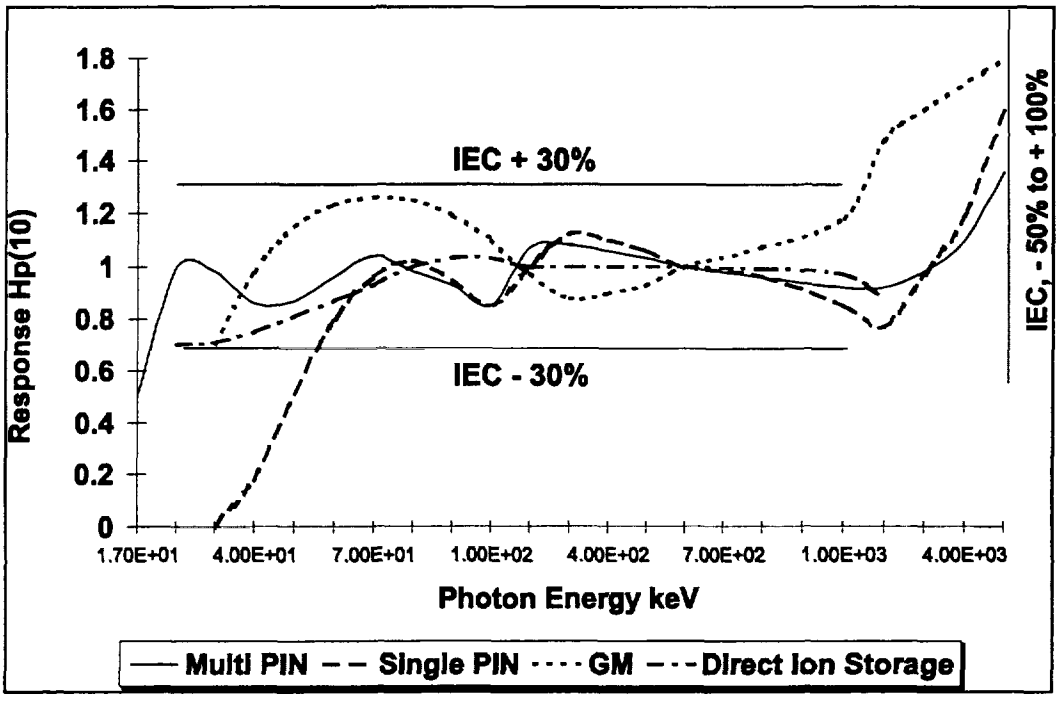


FIG. 1. Measurement of environmental doses with EPD.

These environmental measurements with TLDs and electronic dosimeters were made at a standard field station where the air kerma rate was about 75 $nGy.h^{-1}$ (approximately 0.07 $\mu Sv.h^{-1}$). The electronic dosimeter with 1 μSv sensitivity would have to be in this field for 14 hours before the first digit was displayed. However, with the more sensitive TLD materials now available and using glow curve analysis the TLDs were accurately reading, within ± 20%, the dose after only 6 hours exposure. To achieve a response as good as these TLDs the electronic dosimeter would have to have a 0.1 μSv sensitivity.



REFERENCES

[1] THOMPSON, I. M. G., Society for Radiological Protection, Scientific Meeting on Personal Dosimetry, London, (1972).

[2] SWINTH, K. L., Radiation Measurements, IEEE, Trans. Nuc. Sci. **35** (1988) 941.

[3] SWINTH, K. L., McDONALD, J. C., SISK, D. R., THOMPSON, I. M. G., PIPER, R. K. Performance Testing of Electronic Personal Dosimeters, NUREG/CR-634, PNL-10560, US Nuclear Regulatory Commission, Washington, DC (1995).

[4] ROBERTSON, P. L., ENDRES, G. W. R., FOX, R. A., HAGGARD, D. L., HOLBROOK, D. L., RATHBUN, L. A. Spectral and Dosimetric Measurements of Photon Fields at Commercial Nuclear Sites, NUREG/CR-3569, US Nuclear Regulatory Commission, Washington DC, (1984).

[5] SORBER, R. E., TWIGGS, J. A., NEI, N. H., Estimating Low Energy Photon Fractions at Nuclear Power Stations, Rad. Prot. Management, 5:8.59 (1988).

[6] ALBERTS,W.G., AMBROSI, P., BOHM, J., DIETZ, G., HOHLFELD, K., WILL, W. New Dose Quantities in Radiation Protection, PTB-Dos23e, Physikalisch-Technische Bundesanstalt, Braunschweig (1995).

[7] THIND, K.S. Extremity Dose: Its Definition, Standards and Regulatory Limits, Radiological Significance, Measurement and Practical Considerations, Health Physics, 161, 52, No. 6 (1987) 695-705.

[8] KAHILAINEN, J. The Direct Storage Dosemeter, Solid State Dosimetry International Conference, Budapest , Rad . Prot. Dosim., **66**, 1-4, (1996).

[9] BOTTER-JENSEN, l., THOMPSON, I. M.G. An International Intercomparison of Passive Dosemeters, Electronic Dosemeters and Dose-rate Meters used for Environmental Radiation Measurements, Rad. Prot. Dosim., Vol. 60, No. 3 pp. (1995), 201-211.

RESULTS OF THE 1996–1998 IAEA CO-ORDINATED RESEARCH PROJECT ON INTERCOMPARISON FOR INDIVIDUAL MONITORING OF EXTERNAL EXPOSURE TO PHOTON RADIATION

RESULTS OF THE 1996–1998 IAEA CO-ORDINATED RESEARCH PROJECT ON INTERCOMPARISON FOR INDIVIDUAL MONITORING OF EXTERNAL EXPOSURE TO PHOTON RADIATION

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Abstract

This paper presents the conclusions drawn at the end of the intercomparison, the purpose of which was to examine the performance of the dosimetry systems in radiation fields similar to those encountered in practical routine monitoring. These fields included, for a range of doses, mixed normally incident and wide angle fields of simulated direct source and room scatter radiation for some typical energy distributions and high-energy photons (6-7 MeV) with and without secondary electron equilibrium. Almost all of the participating services satisfied the evaluation criteria on overall accuracy for all fields.

1. INTRODUCTION

The results reported here stem from the Phase III of the IAEA Co-ordinated Research Project. Phase II was concluded in June 1998 with a Research Co-ordination Meeting (RCM) in Braunschweig, Germany.

The results are presented here in a form allowing conclusions to be drawn, while preserving the anonymity of the participants. The whole evaluation procedure was computer-assisted.

2. CHARACTERIZATION OF THE PARTICIPANTS' DOSIMETRY SYSTEMS

Before the irradiations, participants received a questionnaire to be filled in to provide information on their dosimetry system. The data obtained were used to prepare a table with all relevant details. Participants were given the opportunity to amend this table during the RCM in Braunschweig. The corrected data are summarized in the Appendix.

Sixteen participants used only thermoluminescence (TL) detectors, four participants used only films, and three participants used a film-TL detector combination. The TL materials are LiF:Mg,Ti - LiF-N:Mg,Ti - $Li_2B_4O_7$, Si - LiF_7 - LiF_6 - CaF_2 - Al_2O_3. The films are from different manufacturers.

3. EVALUATION OF THE SUBMITTED DATA

The dosimeters of each participant's dosimetry system were irradiated according to the irradiation plan described in this TECDOC.

For every irradiation, the participant was informed of the irradiation date, but no information was provided about the radiation quality or the angle of incidence.

As the dosimeters of every participant had to be divided into groups to enable dosimeter irradiation to be carried out at three different institutes, three dosimeters from each group were preserved unirradiated for background corrections.

Each group was composed of 4 dosimeters, for irradiations at different radiation qualities and/or different dose levels. In total, 12 results had to be reported by each participant.

Participants were requested to report their results on a prepared data-sheet, according to the following instructions:

- all results corrected for background,
- dose values given in term of $H_p(10)$
- mean energy and angle of incidence to be completed, if the dosimetry system permits to provide such data.

An example of an individual result sheet is given in Table I.

Seven participants provided mean energy and angle of incidence, one participant provided the mean energy only, 15 participants did not provide any additional information besides the dose values.

Details of the irradiation conditions are given in Table II of [1]

TABLE I. EXAMPLE OF INDIVIDUAL DATA SHEET

Results for the Individual Dosimetry System 1 - Film

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9 83	23/7/98	±80	400	9 05	0°	ROT	0 92
2	Ir-192	9 99	28/7/98	0 (50%) ±80 (50%)	400	9 66	0°	ROT	0 97
3	Ir-192	1 00	16/7/98	0	400	1 05	0°	AP	1 05
4	Ir-192	41	6/7/98	0	400	39	0°	AP	0 95
8	S-Co+W-80	3 09	17/7/98	0 (50%) ±80 (50%)	100	3 08	0°	ROT	1 00
9	S-Co+W-80	80 35	20/7/98	0 (20%) ±80 (80%)	200	83 3	0°	ROT	1 04
10	S-Co+W-80	1 52	15/7/98	0 (80%) ±80 (20%)	130	1 55	0°	ROT	1 02
11	W-80	0 43	16/7/98	±80	60	0 4	0°	ROT	0 94
15	R-F+W-300	7 25	22/06/98 + 14/07/98	0 (50%) ±80 (50%)	600	7 71	0°	ROT	1 06
16	R-F+W-300	1 1	22/06/98 +15/07/98	0 (50%) ±80 (50%)	1000	1 15	0°	ROT	1 05
17	R-F	1 03	22/06/98	0	6000	0 99	0°	AP	0 96
18	R-F (*)	1 29	23/06/98	0	6000	1 27	0°	AP	0 98

(*) Without electronic equilibrium

4. GRAPHICAL REPRESENTATION OF THE RESULTS OF EVERY PARTICIPANT

The results of each participant are arranged in a set of two diagrams aiming to facilitate comparison of the data sets of the participants. The data-sheet table is given together with these two diagrams in the Appendix, for every participant.

The first diagram illustrates the values of the response in the various radiation fields. The response is the quotient of measured value and the conventionally true value of $H_p(10)$.

The second diagram shows the location of the response values in relation to the "trumpet".

Details of the diagrams

In the diagram of Figure 1, where the participant is identified by the laboratory number and the type of dosimeter used is indicated, each of the 12 response values is represented by a box providing a visual indication as to whether the assessment by the dosimetry system is an overestimate or an underestimate. All Q values in the range of 2.0 are indicated.

For each radiation quality, the Q value is the mean of the values reported by the participant.

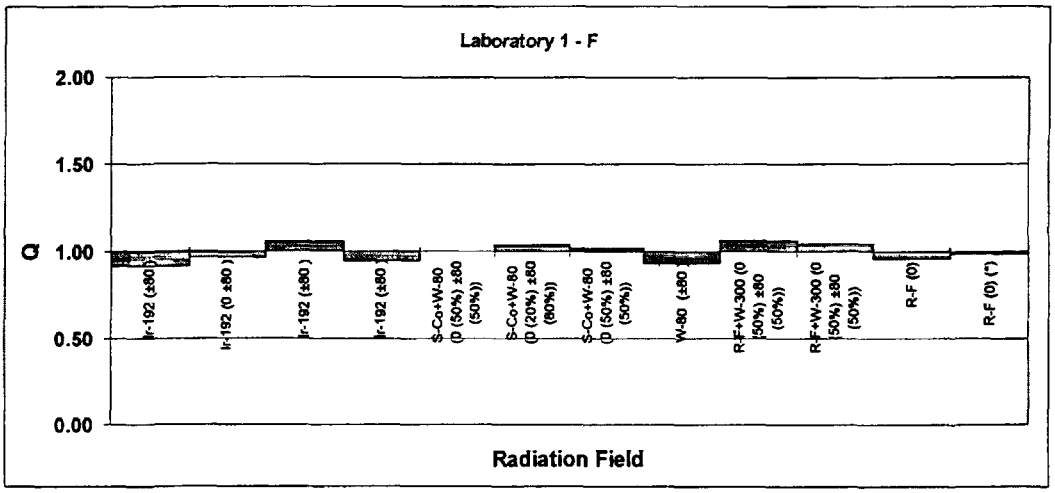


FIG. 1. Response (Q) in various fields (here the Laboratory 1, with a film dosimetry system).

In the second diagram (Figure 2) also identified by the laboratory number and the type of dosimeter, each response value in the range of 0 to 2 is indicated by a dot, together with so-called trumpet curves as given in [2]:

$$\text{high} : H_{ul} = 1.5[1 + H_o/2Ho + H_l)]$$

$$\text{low} : H_{ll} = (1/1.5)[1\text{-}2H_o/(H_0 + H_l)]$$

with H_0 taken as equal to 0.08 mSv.

Q values above 2.0 are separately indicated.

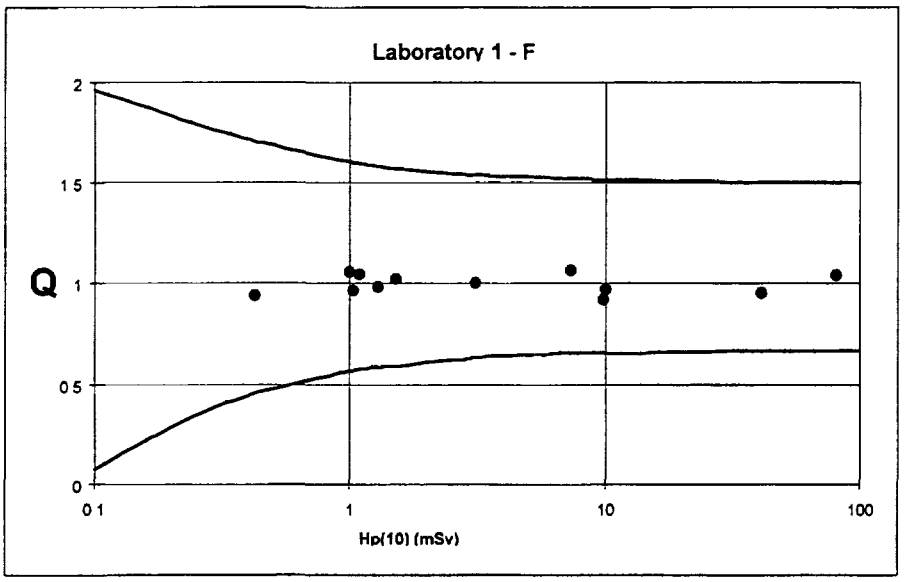


FIG. 2. Example of trumpet curve.

5. GENERAL SURVEY OF THE RESULTS FOR ALL DOSIMETRY SYSTEMS

Table 2 compiles the results obtained with all the participants' dosimetry systems, giving the following data:

- mean value R of all responses Q

- standard deviation, υ, belonging to R

- numbers of outliers *O*, i.e. the number of quotients which lie outside the ICRP interval.

The table is sub-divided into film dosimetry systems, TL dosimetry systems and others (film + TLD, phosphate dosimetry systems), and the results in every subsection are arranged according to the value of υ for $H_p(10)$ beginning with the smallest value. The number of outliers (*O*) outside the trumpet is given in the last column. Table II illustrates the great variety of the results reflecting the different performances of the dosimetry systems for the measurand $H_p(10)$.

6. FREQUENCY DISTRIBUTIONS OF THE Q VALUES AND OF THE VARIATION COEFFICIENT

The frequency distribution of all Q values is given in Figure 4.

TABLE II. GENERAL SURVEY OF THE RESULTS FOR ALL DOSIMETRY SYSTEMS

System Type	R	v in %	O
Film	0.99	5	0
	0.97	11	0
	1.23	28	0
	1.30	40	4
TLD	0.99	7	0
	1.16	8	0
	1.05	10	0
	0.99	15	0
	0.99	15	0
	1.05	16	0
	0.98	17	0
	0.93	18	0
	1.01	18	0
	1.08	20	0
	1.16	21	1
	0.94	23	0
	1.21	29	2
	1.25	29	2
	1.14	34	1
Other	1.11	15	1
	1.11	15	1
	1.08	20	0
	1.14	24	0
	1.20	43	4

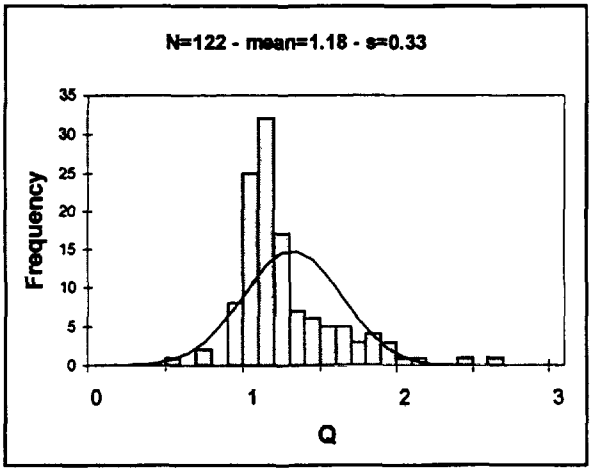


FIG. 4. Frequency distribution of all Q values.

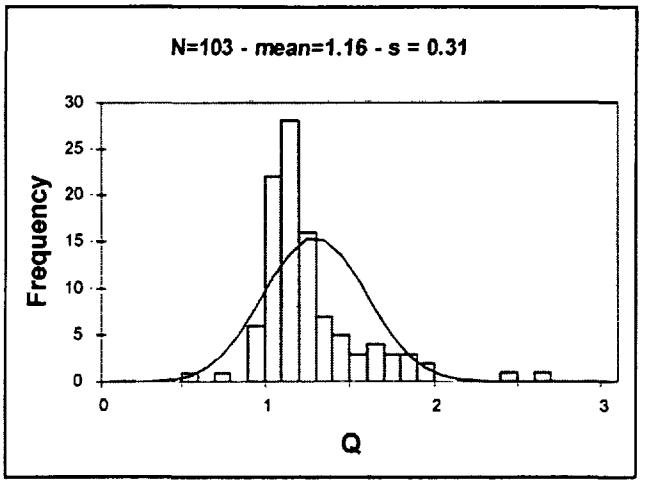


FIG. 5. Frequency distribution of Q values without dosimeter 18 (R-F without electronic equilibrium).

The frequency distribution of the variation coefficient υ is given in Figure 6.

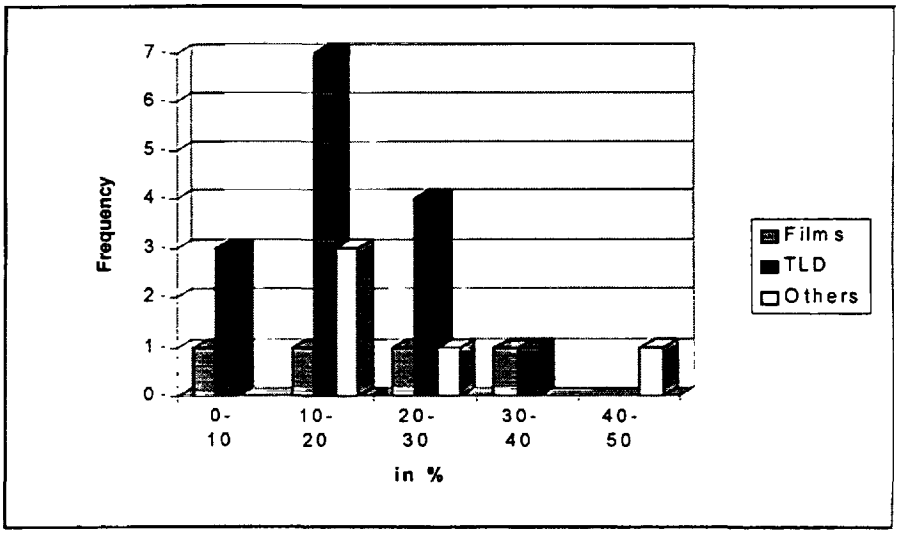


FIG. 6. Frequency distribution of all the υ values.

7. FREQUENCY DISTRIBUTION OF THE OUTLIERS

An impression of the irradiation conditions under which the doses have been most difficult to measure can be obtained from the frequency of the outliers for the various irradiations.

Figure 7 shows the frequency distribution for all the dosimetry systems for the measurand Hp(10). The radiation qualities given in the abscisse are the same as in Figure 1.

From this diagram, one can see that the radiation qualities Ir-192, S-Co+W-80 and R-F can be measured quite well by all the participants. But for W-80, R-F+W-300, R-F at low level and R-F without electronic equilibrium, there are, respectively, 3, 2, 5 and 6 outliers.

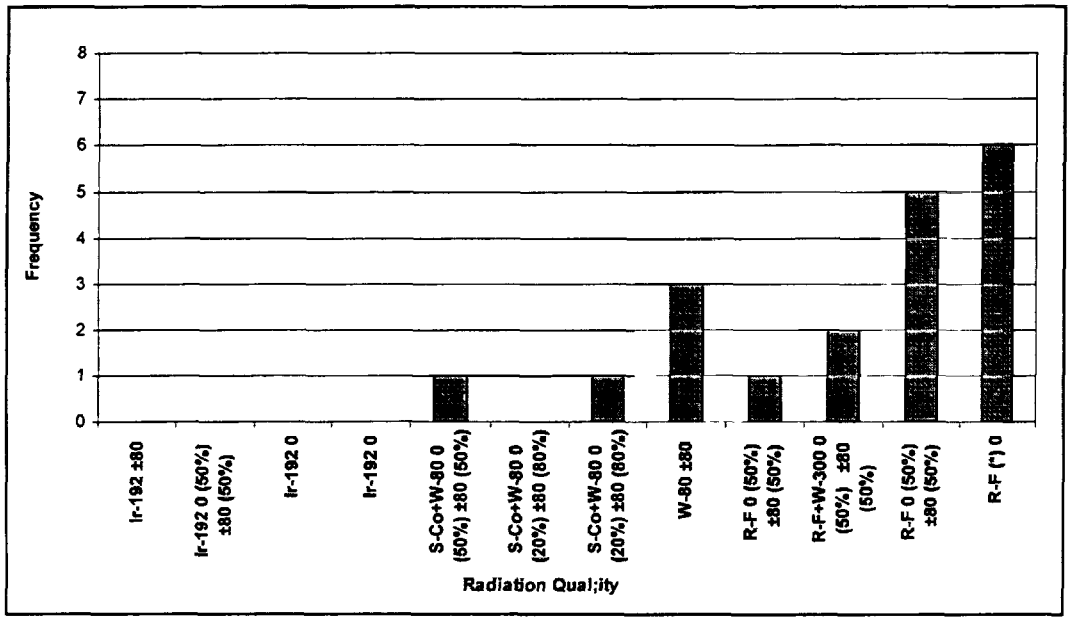


FIG. 7. Frequency distribution of all the outliers for all dosimetry systems.

Another question is how many dosimetry systems in this intercomparison fulfill the ICRP requirement, that is results for which at most one quotient lies within the trumpet curves. This is answered in Table III.

TABLE III. RELATIVE NUMBER OF DOSIMETRY SYSTEMS FOR WHICH AT MOST ONE QUOTIENT LIES BETWEEN 1/1.5 AND 1.5.

Dosimetry system	Percentage
TLD	62.5 %
Film	75 %
Others	100 %

8. CONCLUSIONS

The overall objective of the IAEA Occupational Protection Programme is to promote an internationally harmonized approach for optimizing occupational radiation protection through the development of standards and the provision for the application of these standards. This Co-ordinated Research Project had the aim to further both these objectives. In particular, this CRP gave participating dosimetry services from IAEA Member States in Eastern Europe, the opportunity to assess the recommendation of the IAEA to use the operational quantity personal dose equivalent, $H_p(10)$, and to evaluate the performance of their dosimetry systems. The intercomparison of systems was limited to whole body photon dosimeters in this instance, and examined the performance in simulated workplace fields. The use of such fields was to allow the assessment of the dosimetry systems under actual working conditions, at least in part.

The Workshop, attended by all the participants, gave information on the philosophy underlying the development and adoption of the operational quantities; on calibration procedures; on photon workplace fields energy and angle distributions; and on dosimeter characteristics. The participants were actively involved in the discussions and gave details of their services and dosimeters.

The "mini type test" enabled the participants to adjust, where necessary, their energy and angle response characteristic data, calibration and normalization factors to be in terms of personal dose equivalent. The discussion meeting which followed, clarified many aspects of the use of the new quantities. The "mini type test" had the second purpose of assisting in the harmonization of procedures at secondary standards laboratories in Eastern European States to type test in terms of $H_p(10)$. In addition a check was carried out of the dosimetry of the participating irradiating laboratories including PTB, ARCS and NRPB. The check demonstrated the agreement of the irradiation facilities in providing a given magnitude of $H_p(10)$, on phantom, within about 3%.

The intercomparison had 23 participating dosimetry services. The purpose of the intercomparison was to examine the performance of the dosimetry systems in radiation fields which were similar to those encountered in practical routine monitoring. These fields included, for a range of doses, mixed normally incident and wide angle fields of simulated direct source and room scatter radiation for some typical energy distributions and high-energy photons (6-7 MeV) with and without secondary electron equilibrium. Almost all of the services satisfied the evaluation criteria on overall accuracy for all fields.

The CRP was carried out successfully in every regard. Furthermore, the participating dosimetry services demonstrated a satisfactory proficiency to assess personal dose equivalent, $H_p(10)$, the quantity recommended by the IAEA to assess the occupational whole body exposure to photons.

REFERENCES

[1] V.E. ALEINIKOV, P. AMBROSI, D. BARTLETT, L. BÜERMANN, D.R. MCLURE, I. CSETE, V. FOMINYKH, H. STADTMANN. Dosimeter Irradiations for the IAEA 1996-1998 Co-ordinated Research Project on Intercomparison of Individual Monitoring (This TECDOC)

[2] P. AMBROSI, D. BARTLETT. Dosimeter characteristics and service performance requirements (this TECDOC)

APPENDIX

List of participants' dosimetry systems

Note : The participants are responsible for the technical information given.

Parti. Number	Quantity routinely measured	Photon energy range (keV)	Nominal dose range	Detector	Filter front		Filter back		Pre-irradiation procedure	Post-irradiation procedure	Read-out procedure
					Material	Thickness ($mg.cm^{-2}$)	Material	Thickness ($mg.cm^{-2}$)			
1	Hp(10)	50 - 1500	0.1 mSv - 1 Sv	Film	Plastic Cu Cu Sn (437) + Pb (227) Cd	150 45 715 664 690	Plastic Cu Cu Sn (437) + Pb (227) Cd	150 45 715 664 690	None	Single development	Densitometer Melico
2		50 - 3000	0.1 - 50 mSv	Film	Cu Pb Cu Cu Forsan	 150	Cu Pb Cu CU Forsan	 150	None		Densitometer TRD 04
3	Hp	10 - 1250	0.5 mSv - 2 Sv	F + TLD	Plastic Plastic Cu Cu Cu Sn + Pb Plastic Plastic	50 300 45 446 1338 436.8/340. 2 10 500	Plastic Plastic Cu Cu Cu Sn + Pb Plastic Plastic	50 300 45 446 1338 436.8/340. 2 600 100	Film: none TLD: anneal at 400°C for 1 h followed by 100 °C for 2h	Film TLD: anneal at 100 °C for 20 min	Film: manual optical density measurement with Victoreen 07-440 TLD: Harshaw 2000 AB
4	Exposure	15 - 1300	0.1 mSv - 1 Sv	TLD	Al	214	Plastic Plastic	106 130	80 °C for 1 h	Time annealing	Radose RF-1
5	Exposure	30 - 3000	5 μR - 1000 R	TLD	Plastic	480			Annealing 400 °C for 5-7 min	Li2B4O7: preheating for 1.5 s and heating for 10.5 s at 300 °C LiF: Pre-heating for 1.5 s and heating for 8 s at 300 °C	RADOS

Parti. Number	Quantity routinely measured	Photon energy range (keV)	Nominal dose range	Detector	Filter front		Filter back		Pre-irradiation procedure	Post-irradiation procedure	Read-out procedure
					Material	Thickness ($mg.cm^{-2}$)	Material	Thickness ($mg.cm^{-2}$)			
6	Hp	20 - 10000	0.01 mSv - 10 Sv	TLD	Al (241) Plastic (130) Al (241) Plastic (130) Al (241) Plastic (130) Mylar	371 371 371	Plastic Plastic Plastic Plastic	306 306 306 306	Annealing 300 °C for 12 s	24 h waiting time	RADOS
7	Exposure	30 - 1250	0.1 mSv - 1 Sv	TLD	Dural (230) Plastic (800)	1030	Plastic	30	Annealing	None	DTU-01
8	Hp	20 - 10000	0.05 mSv - 20 Sv	TLD	ABS (242) + Cu (91) ABS + PTFE Mylar ABS	333 1000 13 300	Plastic Plastic Plastic Plastic	50 50 50			
9	Hp(10) Hp(0.07) HE	15 - 6000	0.15 mSv - 2 Sv	Film	Cu Cu Cu Pb Plastic	45 445 1427 565 150	Plastic Cu Cu Cu Pb Plastic	300 45 445 1427 565 150			Densitometer
10	Absorbed dose i n air	20 - 1300	0.04 mGy - 6 Gy	Film + TLD	Plastic Plastic Dural Sn + Pb + Cd In Plastic + PFTE Mylar	50 300	Plastic Dural Sn + Pb + Cd Plastic Plastic	50	Film : none TLD: automated internal annealing	Film TLD heating 150 °C for 15 s	Film: densitometer Parry DR 1105 TLD: Harshaw 6600
11	Hp(10)	40 - 1256	0.1 mSv - 10 Sv	TLD	PVC (18) ABS (242) Cu (91) PTFE (7) PVC (18) Teflon (1000) PTFE (7) PVC (18) Mylar (17) PTFE (7) PVC (18) ABS (300) PTFE (7)	358 1025 42 345	PVC (18) ABS (166) PTFE (7) PVC (18) ABS (166) PTFE PVC (18) ABS (166) PTFE PVC (18) ABS (166) PTFE	191 184 184 184	None	Pre-heating 150 °C for 10 s	Harshaw 6600
12	Exposure	50 - 1500	0.2 mSv - 5 mSv	TLD	Open Al (214) Plastic (130)	374	BPO (106) Plastic (130) BPO (106) Plastic (130)	236 236	Annealing at 320 °C	Time annealing for 24 h	RADOS

Parti. Number	Quantity routinely measured	Photon energy range (keV)	Nominal dose range	Detector	Filter front		Filter back		Pre-irradiation procedure	Post-irradiation procedure	Read-out procedure
					Material	Thickness ($mg.cm^{-2}$)	Material	Thickness ($mg.cm^{-2}$)			
14	Hp	50 - 1300	0.01 mSv - 1 Sv	TLD	Plastic	75	Plastic	75	Annealing 30 mn at 350 °C	None	Home built
15	Hp(10)	100-3000	0.1 mSv - 1 Sv	TLD	ABS (242) Cu (91) ABS () PTE (1000) Mylar ABS	333 1000 17 300	ABS ABS ABS ABS	173 173 173 173	None	None	Harshaw 8800
16	Hp(10)	50 - 1300	0.1 mSv - 1 Sv	TLD	ABS	1000	Plastic	50	Annealing 1 h at 400 °C followed by 2 h at 100 °C	0.5 h at 100 °C	Harshaw 6600
18	Exposure	60 - 1250	0.01 R - 1000 R	TLD	Plastic	254	Plastic	413	Annealing 15 mn at 400 °C (if dose > 15 R)	15 s at 115 °C - 25 s at 220 °C - 20 s at 270 °C	KDT-02M
19	Exposure	20 - 1250	2 mR - 200 R	TLD	Sn Al Al Al	2 mm 1 mm 1 mm 10	Al Al Al Al	1 mm 1 mm 1 mm 1 mm	Annealing 10 min at 350 °C	None	PROTECTA
20	Dose equivalent	50 - 1500	0.1 mSv - 0. 1 Sv	Film	Open window Cu Cu Cu Pb	 0.05 mm 0.5 mm 1.5 mm 1.0 mm	Open window Cu Cu Cu Pb	 0.05 mm 0.5 mm 1.5 mm 1.0 mm	None	Manual development	VICTOREEN 07-440
23	Hp(10) Hp(0.07)	15 - 10000	0.05 mSv - 3 Sv	TLD	Open window Polypropylene Al	 6 mm 0.7 mm	Polypropylene Polypropylene	2 mm 2 mm	Annealing 2 h 300°C + 16 h 80°C		Vinten 802
24	Exposure	50 - 2000	5 - 200 mrem	Pen	Al	0.8 mm					

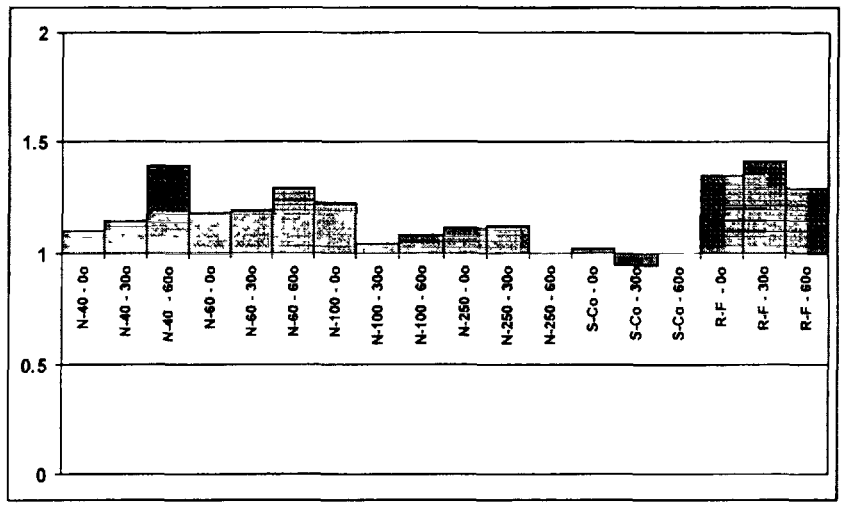
Annex

GRAPHIC REPRESENTATION OF RESULTS

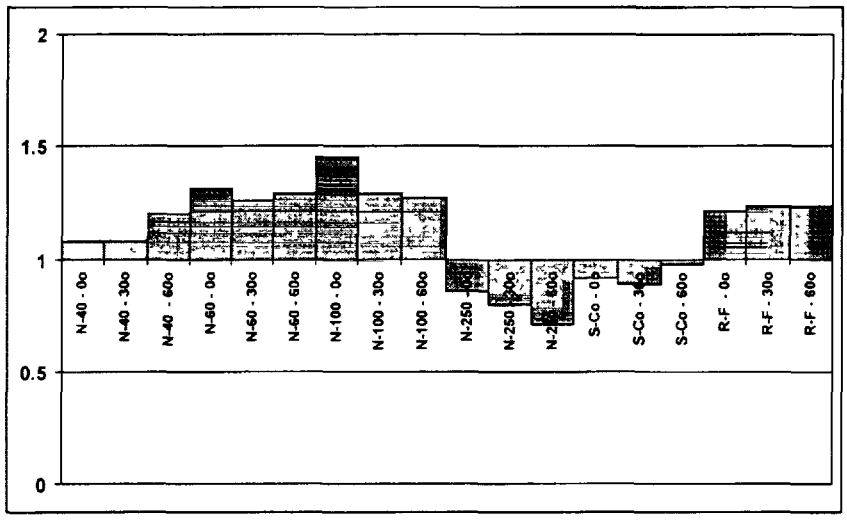
PHASE II RESULTS

(Note: because participants may have adapted their dosimetry systems after the meeting in Braunschweig, the following graphs may not necessarily represent the status of the dosimetry services at the time of Phase III.)

Laboratory 1



Laboratory 2



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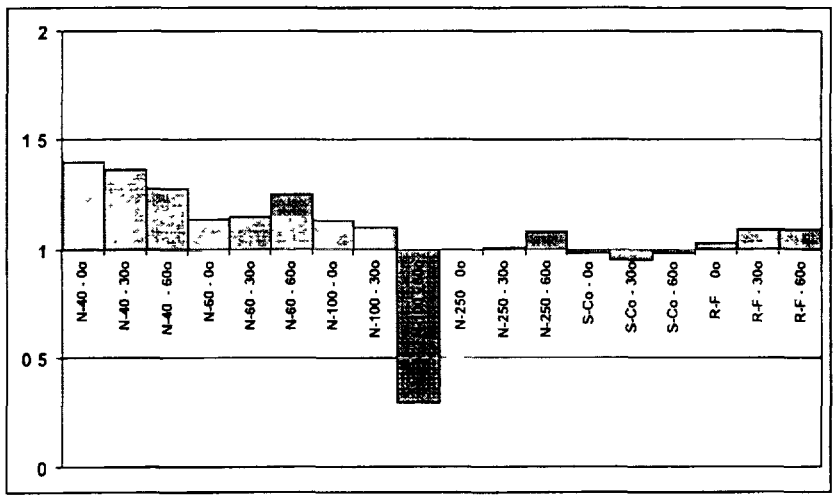
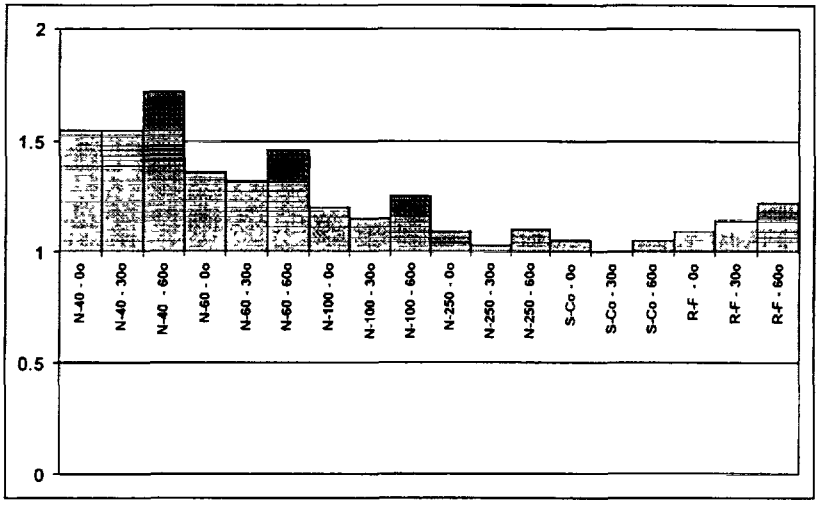


Laboratory 4



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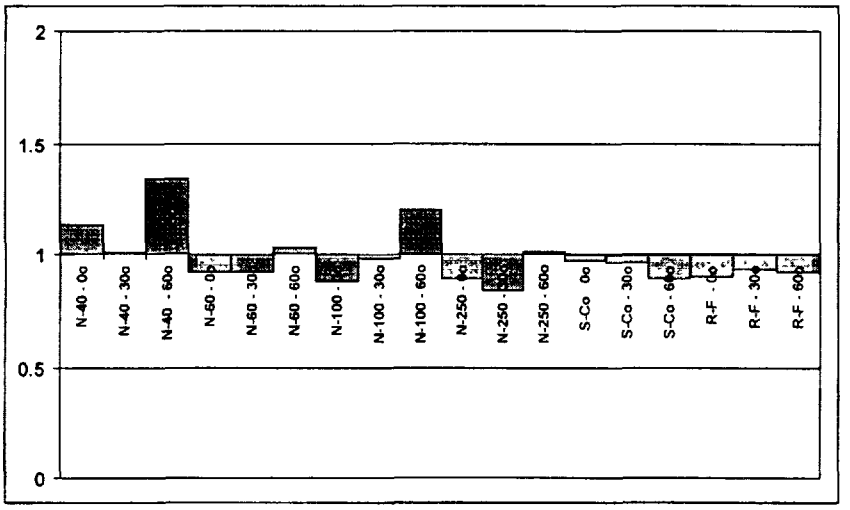
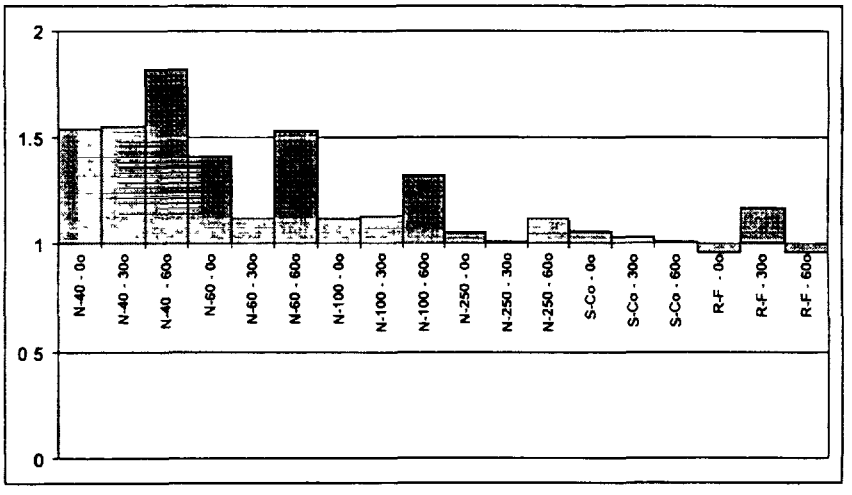
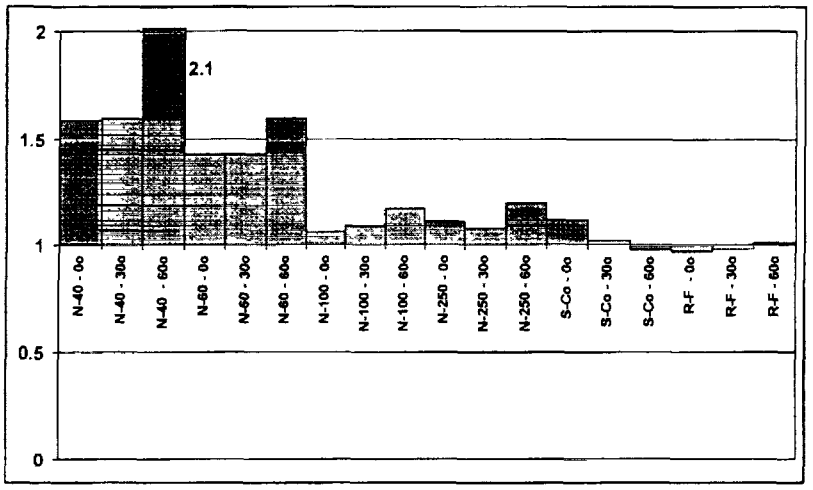


Laboratory 6



Laboratory 7



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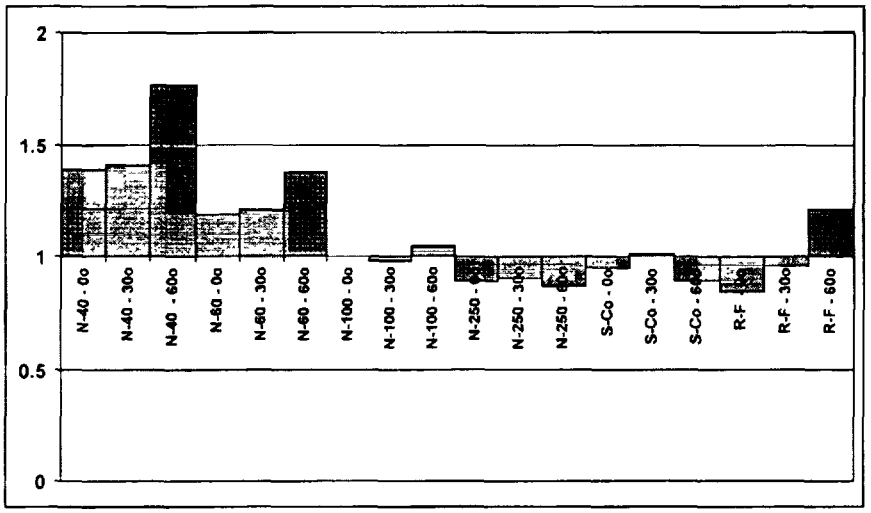

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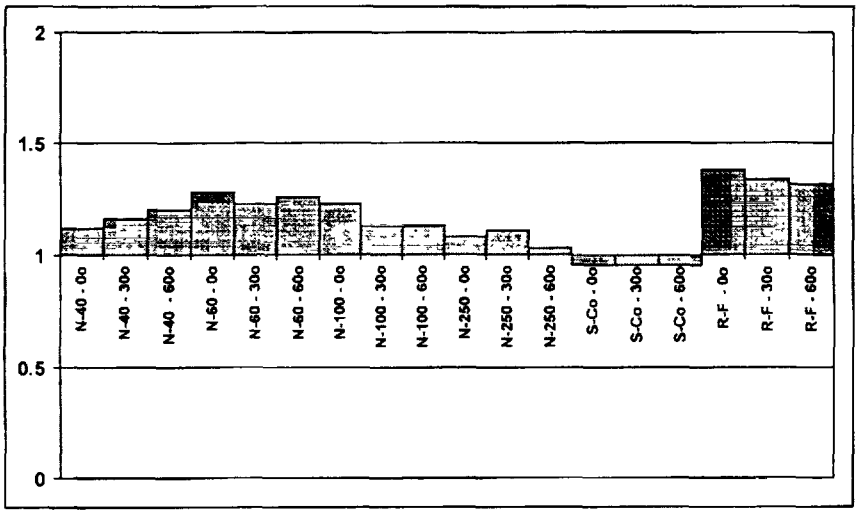
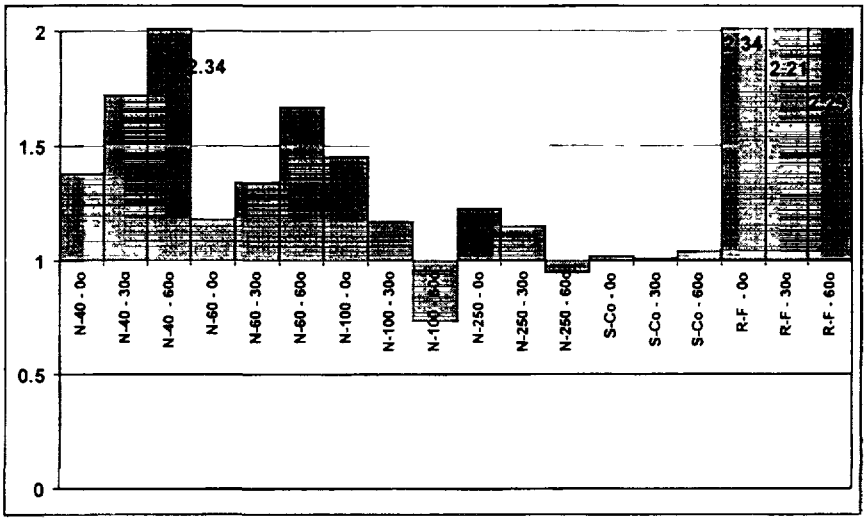


Laboratory 10



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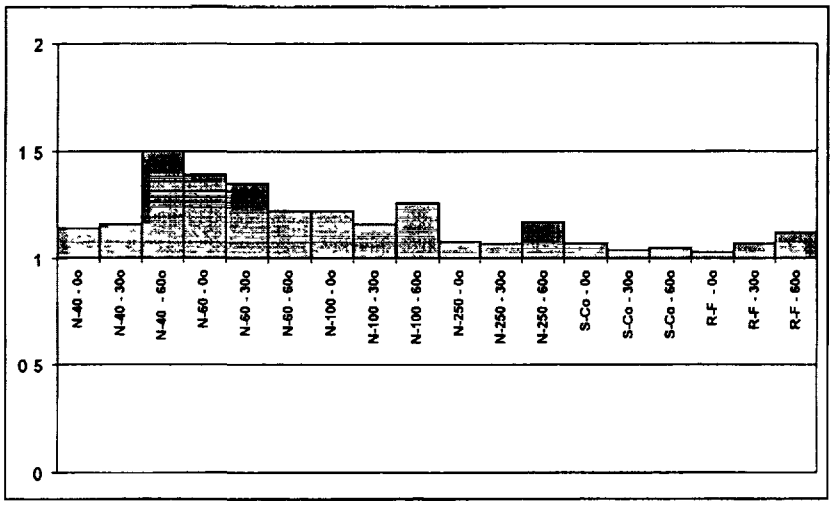
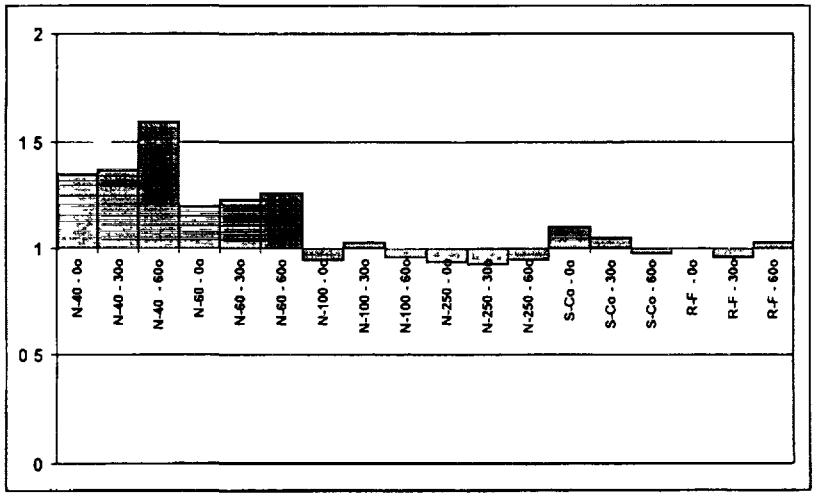


Laboratory 12



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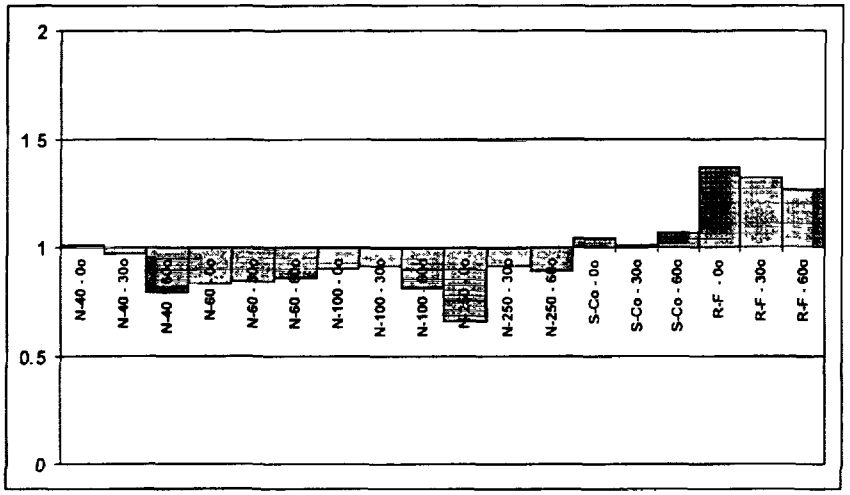

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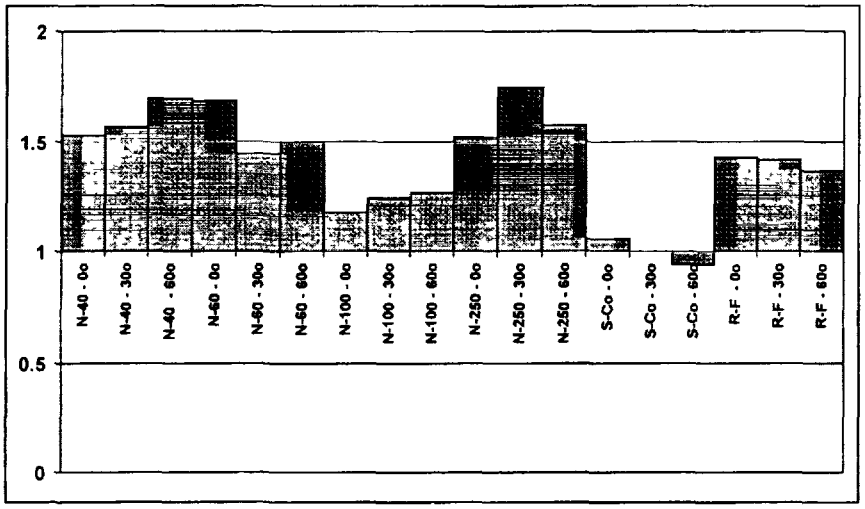
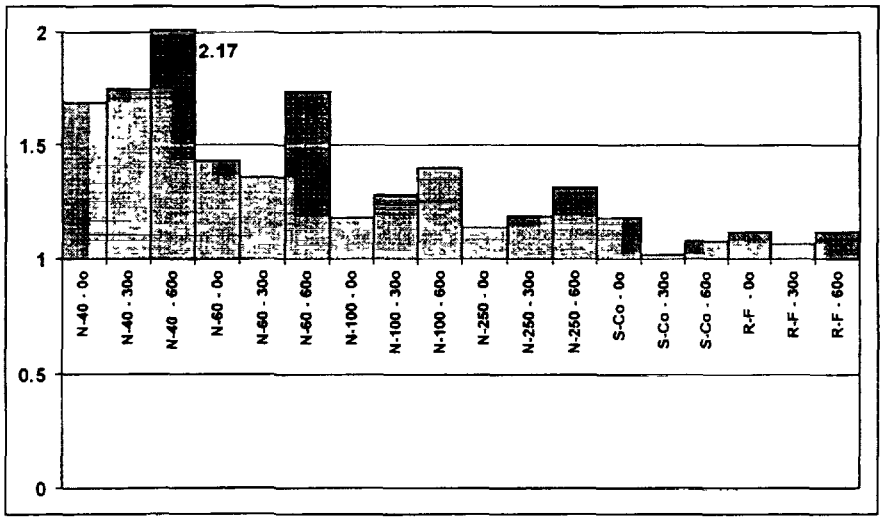
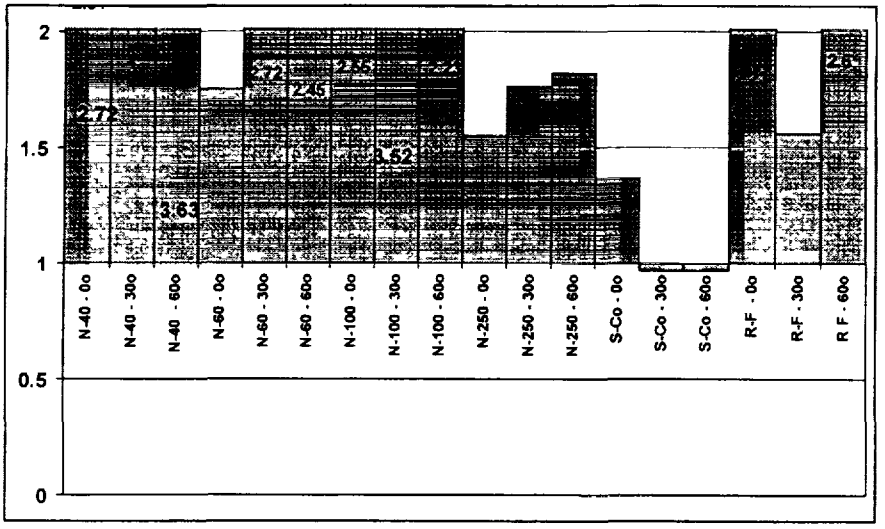


Laboratory 15



Laboratory 16

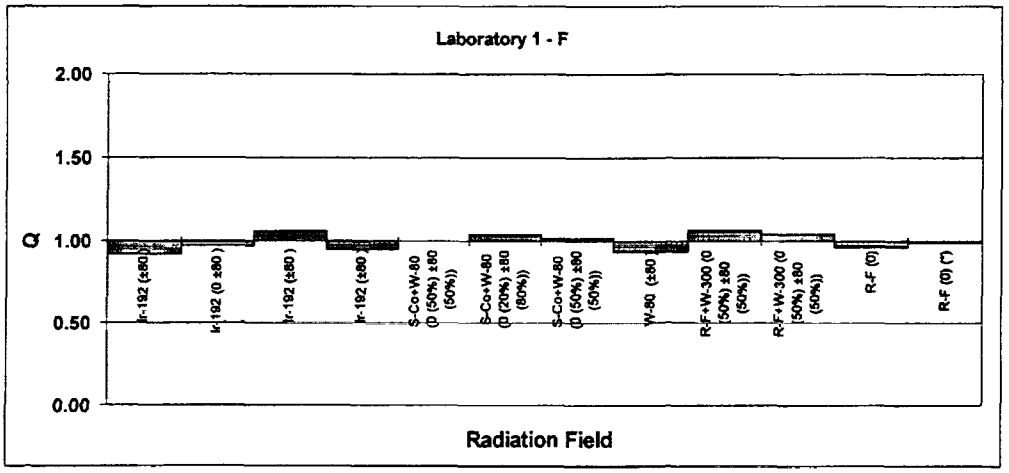


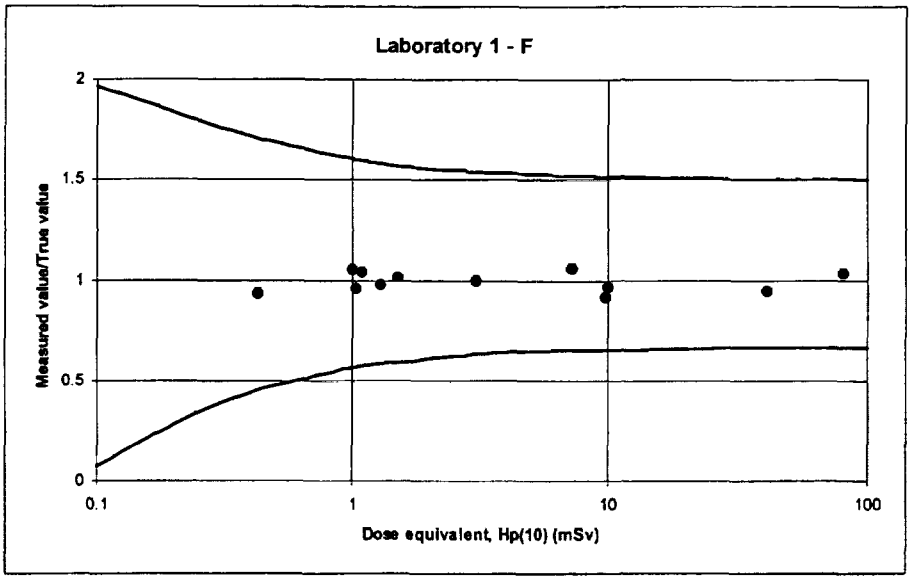
PHASE III RESULTS
(per laboratory)

Results for the Individual Dosimetry System 1 - Film

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.83	23/7/98	±80	400	9.05	0°	ROT	0.92
2	Ir-192	9.99	28/7/98	0 (50%) ±80 (50%)	400	9.66	0°	ROT	0.97
3	Ir-192	1.00	16/7/98	0	400	1.05	0°	AP	1.05
4	Ir-192	41	6/7/98	0	400	39	0°	AP	0.95
8	S-Co+W-80	3.09	17/7/98	0 (50%) ±80 (50%)	100	3.08	0°	ROT	1.00
9	S-Co+W-80	80.35	20/7/98	0 (20%) ±80 (80%)	200	83.3	0°	ROT	1.04
10	S-Co+W-80	1.52	15/7/98	0 (80%) ±80 (20%)	130	1.55	0°	ROT	1.02
11	W-80	0.43	16/7/98	±80	60	0.4	0°	ROT	0.94
15	R-F+W-300	7.25	22/06/98 + 14/07/98	0 (50%) ±80 (50%)	600	7.71	0°	ROT	1.06
16	R-F+W-300	1.1	22/06/98 +15/07/98	0 (50%) ±80 (50%)	1000	1.15	0°	ROT	1.05
17	R-F	1.03	22/06/98	0	6000	0.99	0°	AP	0.96
18	R-F (*)	1.29	23/06/98	0	6000	1.27	0°	AP	0.98

(*) Without electronic equilibrium

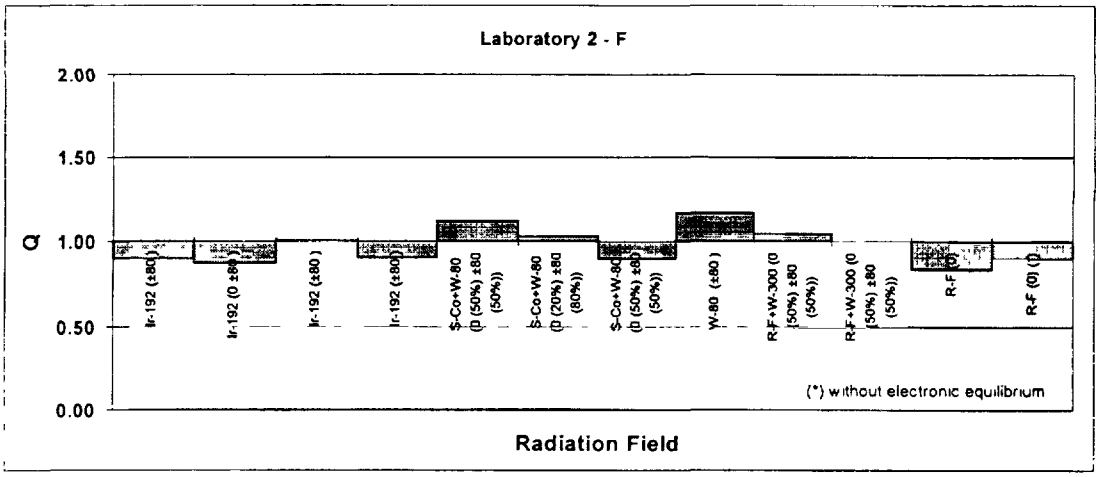


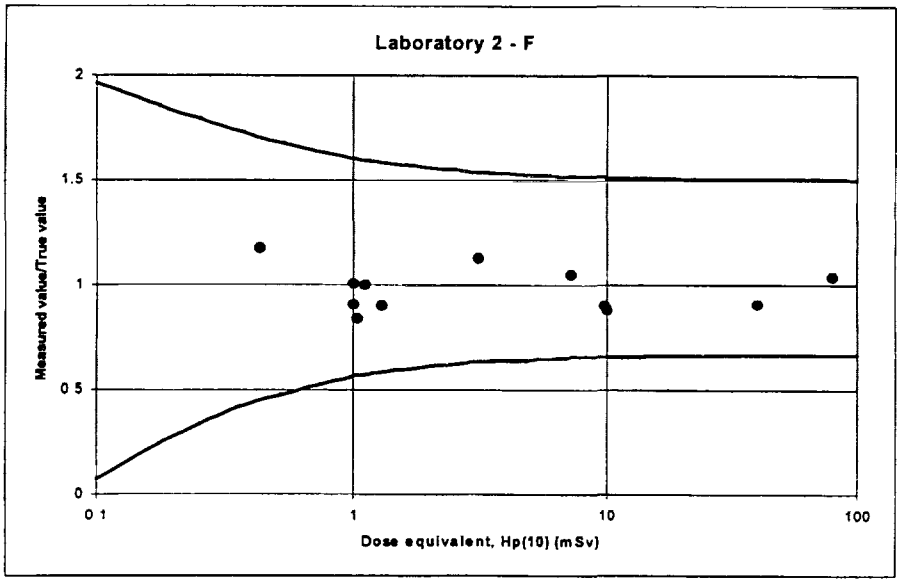


Results for the Individual Dosimetry System 2 - Film

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.84	23/7/98	±80	400	8.84	0°		0.90
2	Ir-192	9.99	28/7/98	0 (50%) ±80 (50%)	400	8.75	0°		0.88
3	Ir-192	0.996	16/7/98	0	400	1	0°		1.00
4	Ir-192	41	6/7/98	0	400	37.1	0°		0.90
8	S-Co+W-80	3.071	17/7/98	0 (50%) ±80 (50%)	100	3.45	0°	ROT	1.12
9	S-Co+W-80	80.272	20/7/98	0 (20%) ±80 (80%)	200	82.83	0°	ROT	1.03
10	S-Co+W-80	0.999	21/7/98	0 (80%) ±80 (20%)	130	0.9	0°	ROT	0.90
11	W-80	0.426	16/7/98	±80	60	0.5	0°	ROT	1.17
15	R-F	7.23	22/06/98 + 14/07/98	0 (50%) ±80 (50%)	600	7.56	0°	ROT	1.05
16	R-F+W-300	1.1	22/06/98 +15/07/98	0 (50%) ±80 (50%)	1000	1 1	0°		1.00
17	R-F	1.03	22/06/98	0	6000	0.86	0°		0.83
18	R-F (*)	1.29	23/06/98	0	6000	1.16	0°		0.90

(*) Without electronic equilibrium

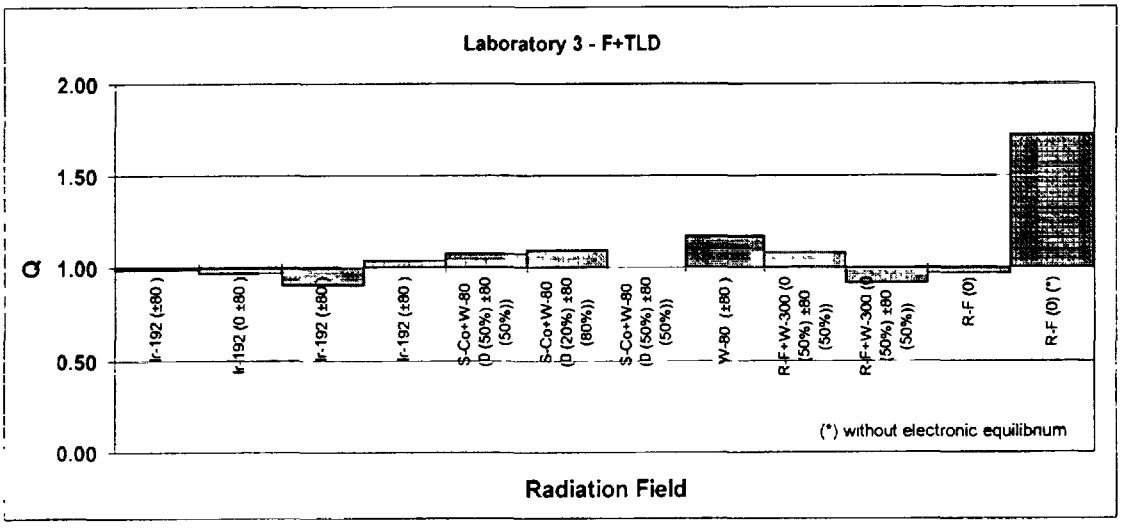


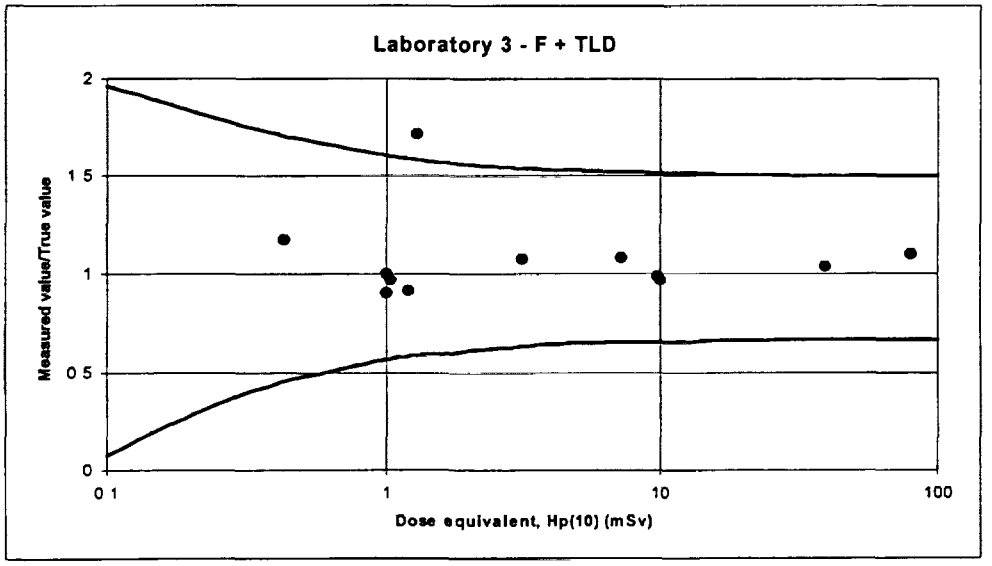


Results for the Individual Dosimetry System 3 - Film + TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.83	23/7/98	±80	400	9.7			0.99
2	Ir-192	9 99	28/7/98	0 (50%) ±80 (50%)	400	9 7			0.97
3	Ir-192	0 996	16/7/98	0	400	0.9			0 90
4	Ir-192	40	10/7/98	0	400	41.6			1.04
8	S-Co+W-80	3 07	17/7/98	0 (50%) ±80 (50%)	100	3.3			1.07
9	S-Co+W-80	80 358	20/7/98	0 (20%) ±80 (80%)	200	88.1			1.10
10	S-Co+W-80	0.999	21/7/98	0 (80%) ±80 (20%)	130	1			1.00
11	W-80	0.426	16/7/98	±80	60	0.5			1.17
15	R-F	7.21	22/06/98 + 14/07/98	0 (50%) ±80 (50%)	600	7.8			1.08
16	R-F+W-300	1.2	22/06/98 +15/07/98	0 (50%) ±80 (50%)	1000	1 1			0.92
17	R-F	1 03	22/06/98	0	6000	1			0 97
18	R-F (*)	1 28	23/06/98	0	6000	2.2			1.72

(*) Without electronic equilibrium

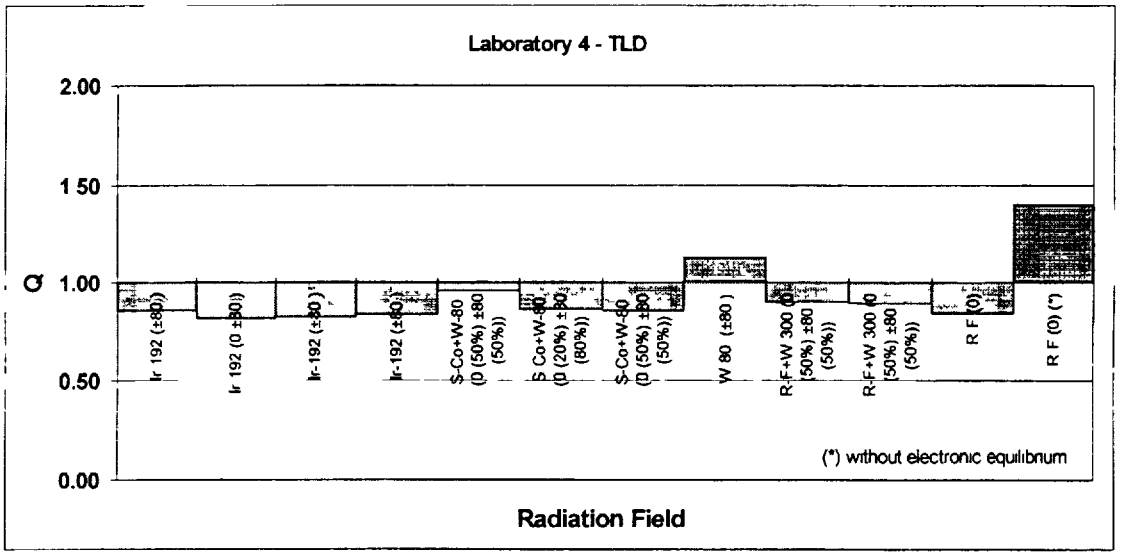


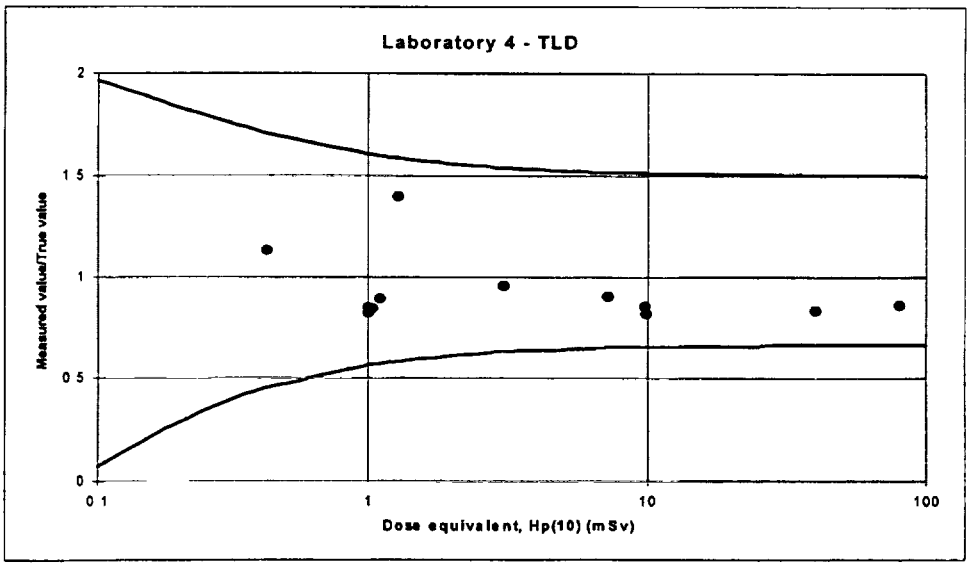


Results for the Individual Dosimetry System 4 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9 77	24/7/98	±80		8 36			0 86
2	Ir 192	9 98	28/7/98	0 (50%) ±80 (50%)		8 15			0 82
3	Ir-192	0 996	16/7/98	0		0 82			0 82
4	Ir-192	40 1	13/7/98	0		33 45			0 83
8	S-Co+W-80	3 071	17/7/98	0 (50%) ±80 (50%)		2 94			0 96
9	S-Co+W-80	80 386	20/7/98	0 (20%) ±80 (80%)		69 27			0 86
10	S-Co+W-80	0 998	21/7/98	0 (80%) ±80 (20%)		0 85			0 85
11	W-80	0 425	16/7/98	±80		0 48			1 13
15	R F	7 2	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		6 48			0 90
16	R-F+W-300	1 1	22/06/98 +15/07/98	0 (50%) ±80 (50%)		0 98			0 89
17	R-F	1 03	22/06/98	0		0 87			0 84
18	R-F (*)	1 28	23/06/98	0		1 79			1 40

(*) Without electronic equilibrium

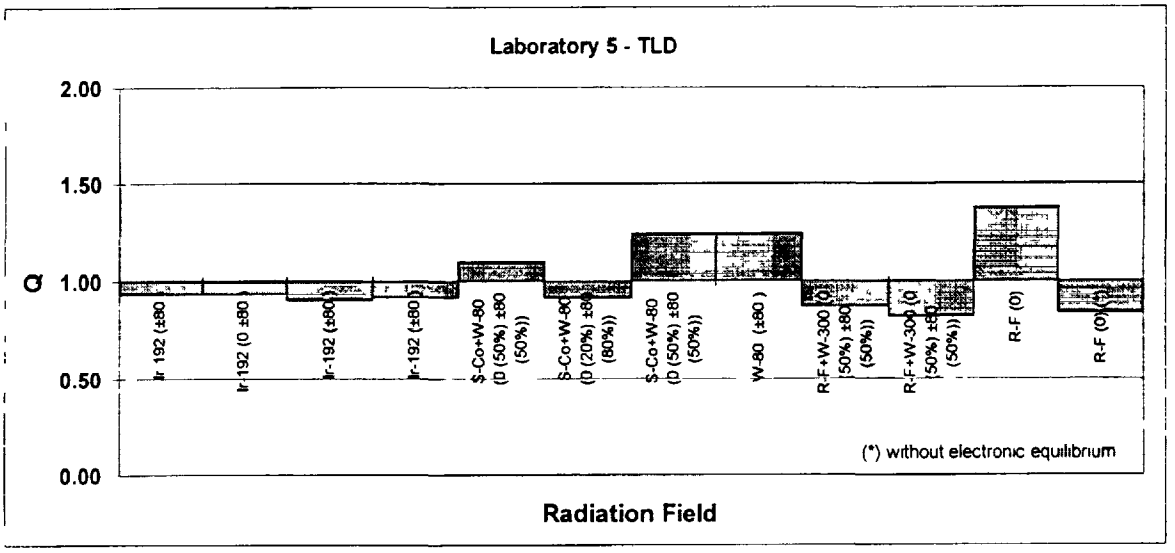


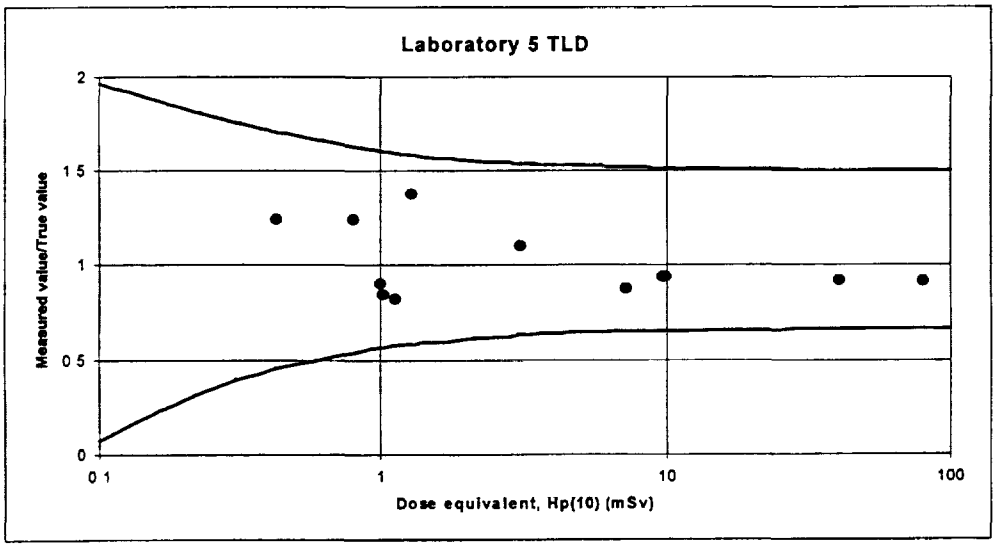


Results for the Individual Dosimetry System 5 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9 76	24/7/98	±80		9 13			0 94
2	Ir-192	9 98	28/7/98	0 (50%) ±80 (50%)		9 37			0 94
3	Ir-192	0 996	16/7/98	0		0 9			0 90
4	Ir-192	40 1	12/7/98	0		36 89			0 92
8	S-Co+W-80	3 071	17/7/98	0 (50%) ±80 (50%)		3 37			1 10
9	S-Co+W-80	80 376	20/7/98	0 (20%) ±80 (80%)		73 51			0 91
10	S-Co+W-80	0 799	21/7/98	0 (80%) ±80 (20%)		0 99			1 24
11	W-80	0 425	16/7/98	±80		0 527			1 24
15	R-F	7 2	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		6 31			0 88
16	R-F+W-300	1 13	22/06/98 +15/07/98	0 (50%) ±80 (50%)		0 93			0 82
17	R-F	1 28	22/06/98	0		1 76			1 38
18	R-F (*)	1 02	23/06/98	0		0 86			0 84

(*) Without electronic equilibrium

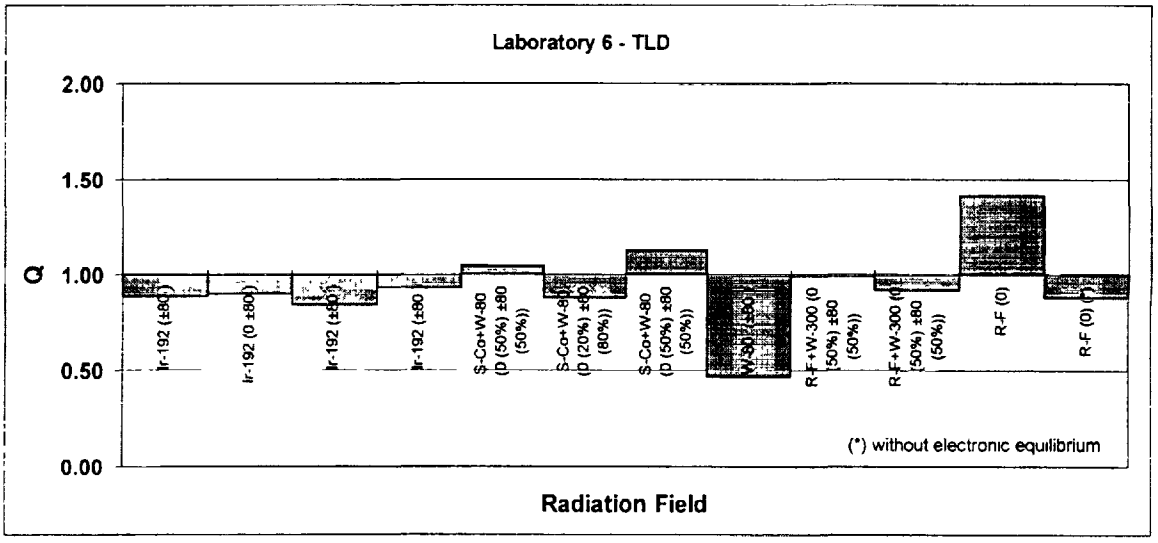


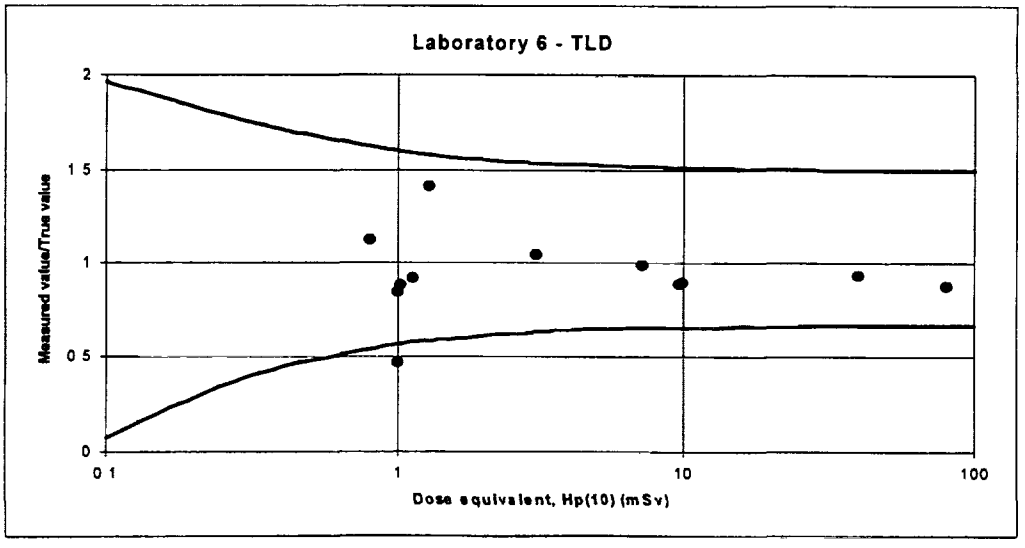


Results for the Individual Dosimetry System 6 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.76	24/7/98	±80		8 67			0.89
2	Ir-192	9.98	28/7/98	0 (50%) ±80 (50%)		8.95			0.90
3	Ir-192	0.996	16/7/98	0		0.84			0.84
4	Ir-192	40	12/7/98	0		37.32			0.93
8	S-Co+W-80	3.071	17/7/98	0 (50%) ±80 (50%)		3.2			1.04
9	S-Co+W-80	80.348	20/7/98	0 (20%) ±80 (80%)		70.61			0.88
10	S-Co+W-80	0.799	21/7/98	0 (80%) ±80 (20%)		0.9			1.13
11	W-80	0.998	16/7/98	±80		0.47			0.47
15	R-F	7.2	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		7.13			0.99
16	R-F+W-300	1.13	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1.04			0.92
17	R-F	1.28	22/06/98	0		1.81			1.41
18	R-F (*)	1.02	23/06/98	0		0.9			0.88

(*) Without electronic equilibrium

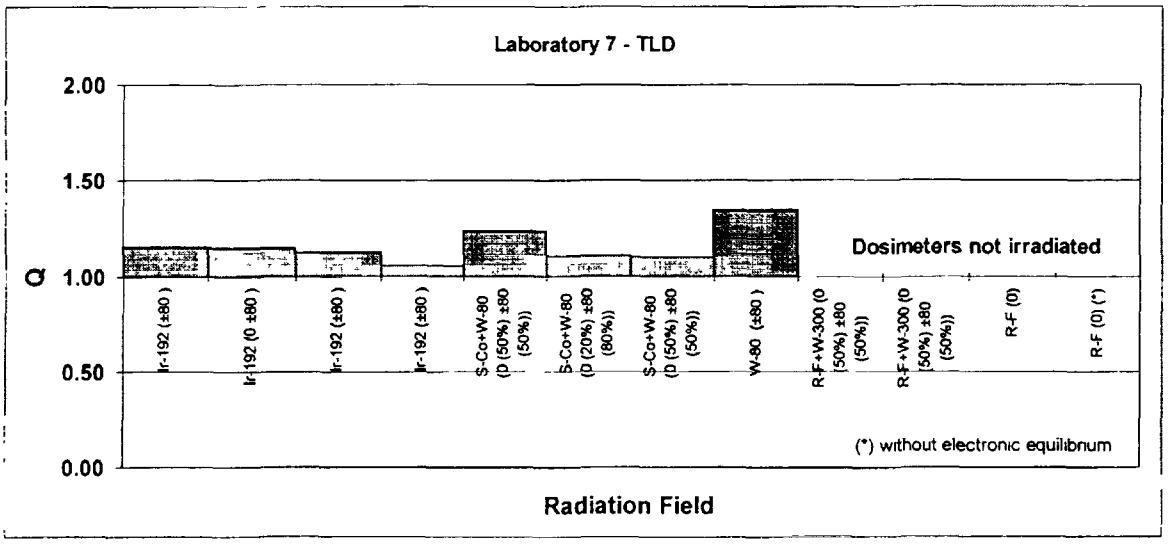


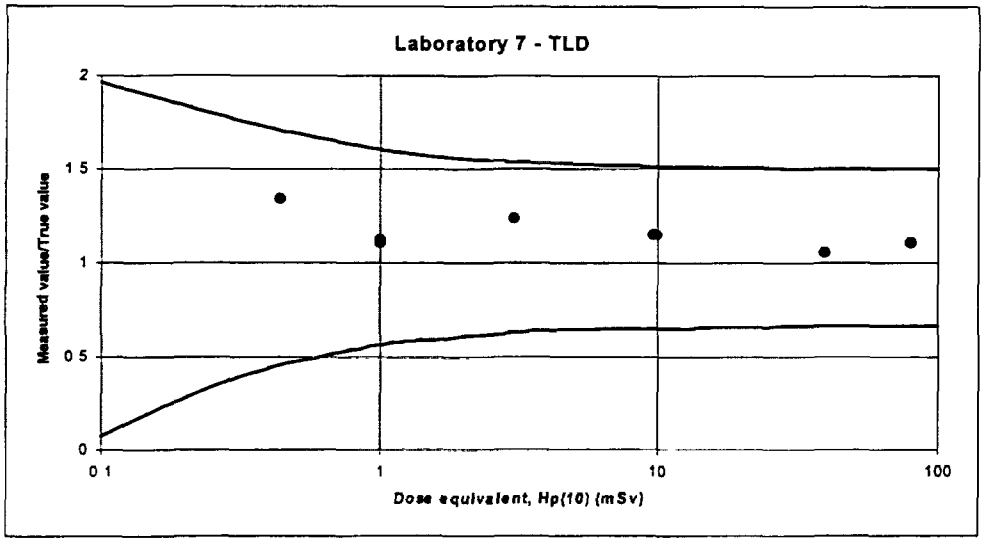


Results for the Individual Dosimetry System 7 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.76	24/7/98	±80		11.23			1.15
2	Ir-192	9 98	28/7/98	0 (50%) ±80 (50%)		11.44			1 15
3	Ir-192	0.995	16/7/98	0		1 12			1 13
4	Ir-192	40	12/7/98	0		42.23			1.06
8	S-Co+W-80	3.072	17/7/98	0 (50%) ±80 (50%)		3 8			1 24
9	S-Co+W-80	80.33	20/7/98	0 (20%) ±80 (80%)		88.8			1.11
10	S-Co+W-80	0.998	21/7/98	0 (80%) ±80 (20%)		1 1			1.10
11	W-80	0.425	16/7/98	±80		0 57			1.34
15	R-F	0	1/0/00	0 (50%) ±80 (50%)		0			
16	R-F+W-300	0	1/0/00	0 (50%) ±80 (50%)		0			
17	R-F	0	1/0/00	0		0			
18	R-F (*)	0	1/0/00	0		0			

(*) Without electronic equilibrium

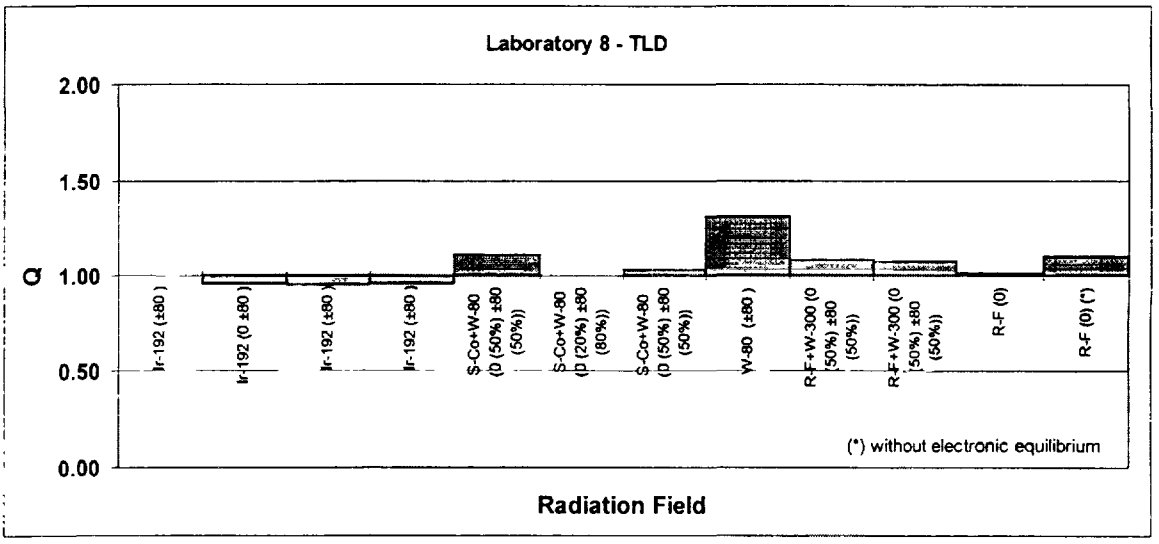


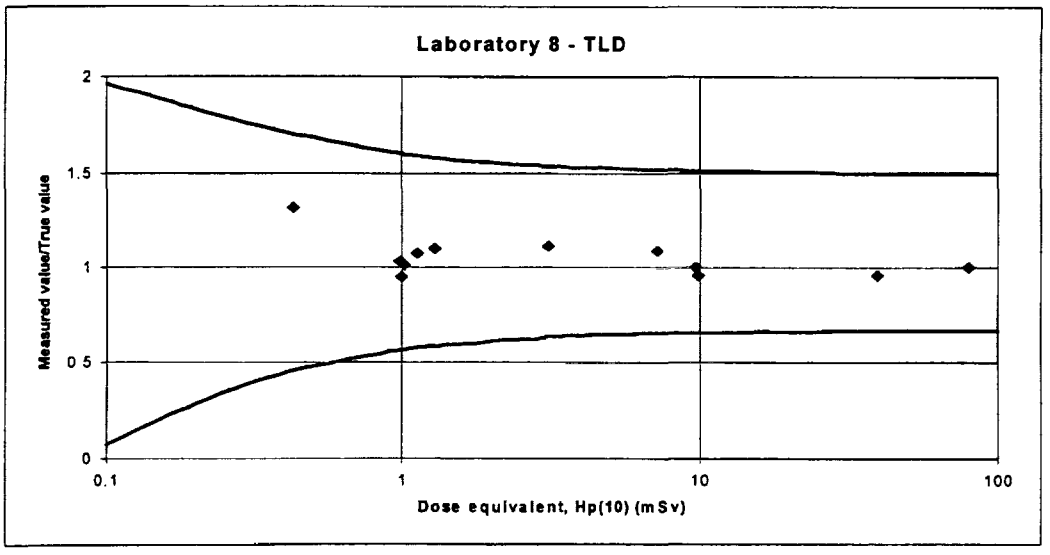


Results for the Individual Dosimetry System 8 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.76	24/7/98	±80		9.74			1.00
2	Ir-192	9.98	28/7/98	0 (50%) ±80 (50%)		9.56			0.96
3	Ir-192	0.995	16/7/98	0		0.943			0.95
4	Ir-192	40	12/7/98	0		38.15			0.95
8	S-Co+W-80	3 072	17/7/98	0 (50%) ±80 (50%)		3.406			1.11
9	S-Co+W-80	80.311	20/7/98	0 (20%) ±80 (80%)		80.44			1.00
10	S-Co+W-80	0.99	21/7/98	0 (80%) ±80 (20%)		1.022			1.03
11	W-80	0 425	16/7/98	±80		0.558			1.31
15	R-F	7.21	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		7.817			1.08
16	R-F+W-300	1.12	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1.203			1.07
17	R-F	1.02	22/06/98	0		1.035			1 01
18	R-F (*)	1.28	23/06/98	0		1.407			1 10

(*) Without electronic equilibrium

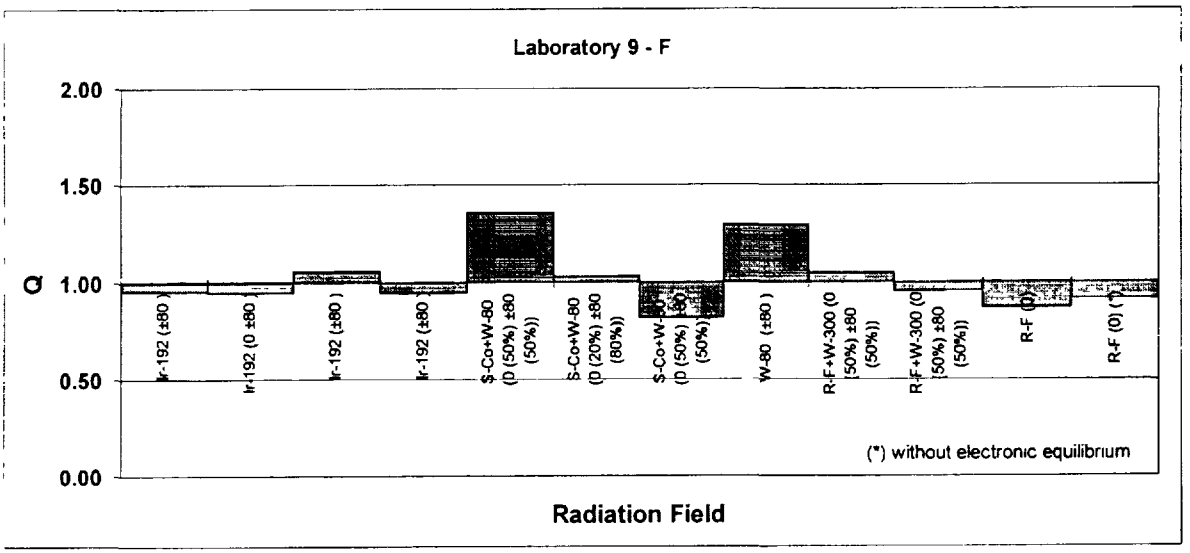


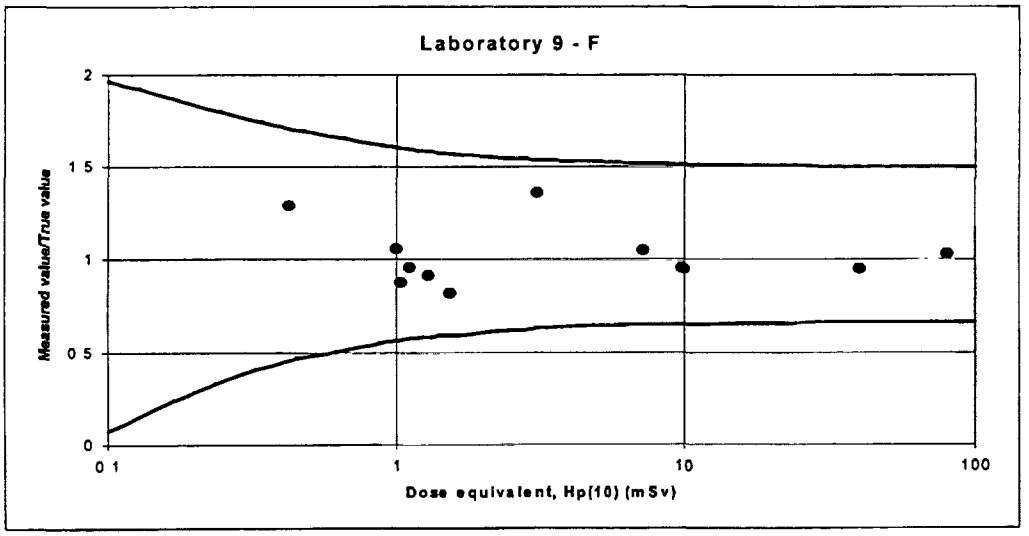


Results for the Individual Dosimetry System 9 - Film

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.83	23/7/98	±80	320	9.38	0°		0.95
2	Ir-192	9.99	28/7/98	0 (50%) ±80 (50%)	320	9.5	0°		0.95
3	Ir-192	0.996	16/7/98	0	320	1.05	0°		1.05
4	Ir-192	41	6/7/98	0	320	38.91	0°		0 95
8	S-Co+W-80	3.073	17/7/98	0 (50%) ±80 (50%)	80	4.17	0°	ROT	1.36
9	S-Co+W-80	80.352	20/7/98	0 (20%) ±80 (80%)	250	83	0°	ROT	1.03
10	S-Co+W-80	1.522	21/7/98	0 (80%) ±80 (20%)	100	1.25	0°	ROT	0.82
11	W-80	0 426	16/7/98	±80	55	0.55	0°	ROT	1.29
15	R-F	7.23	22/06/98 + 14/07/98	0 (50%) ±80 (50%)	600	7.6	0°	ROT	1.05
16	R-F+W-300	1.1	22/06/98 +15/07/98	0 (50%) ±80 (50%)	1000	1 05	0°		0.95
17	R-F	1.03	22/06/98	0	6000	0.9	0°		0.87
18	R-F (*)	1 29	23/06/98	0	600	1.18	0°		0.91

(*) Without electronic equilibrium

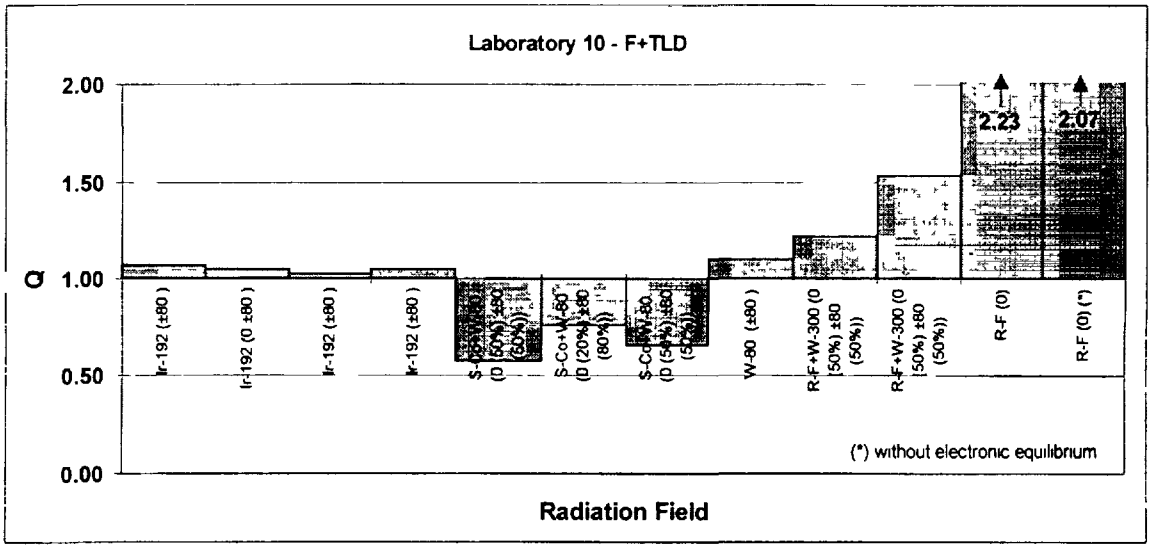


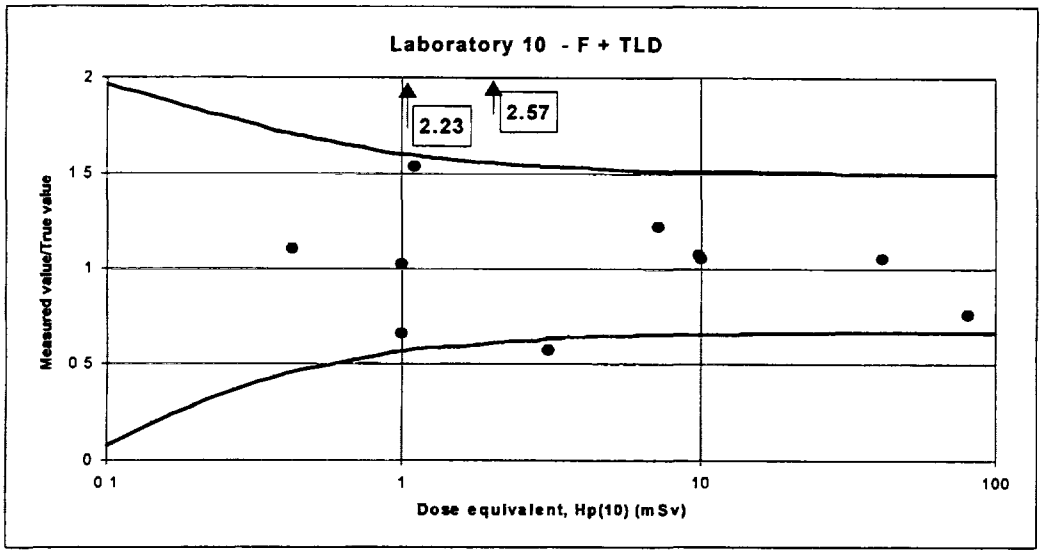


Results for the Individual Dosimetry System 10 - Film + TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9 83	23/7/98	±80		10 51			1 07
2	Ir-192	9 99	28/7/98	0 (50%) ±80 (50%)		10 52			1 05
3	Ir-192	0 996	16/7/98	0		1 02			1 02
4	Ir-192	40 9	6/7/98	0		43 1			1 05
8	S-Co+W-80	3 071	17/7/98	0 (50%) ±80 (50%)		1 76			0 57
9	S-Co+W-80	80 372	20/7/98	0 (20%) ±80 (80%)		60 93			0 76
10	S-Co+W-80	0 998	21/7/98	0 (80%) ±80 (20%)		0 66			0 66
11	W-80	0 426	16/7/98	±80		0 47			1 10
15	R-F	7 21	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		8 81			1 22
16	R-F+W-300	1 1	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1 69			1 54
17	R-F	1 03	22/06/98	0		2 3			2 23
18	R-F (*)	1 28	23/06/98	0		2 65			2 07

(*) Without electronic equilibrium

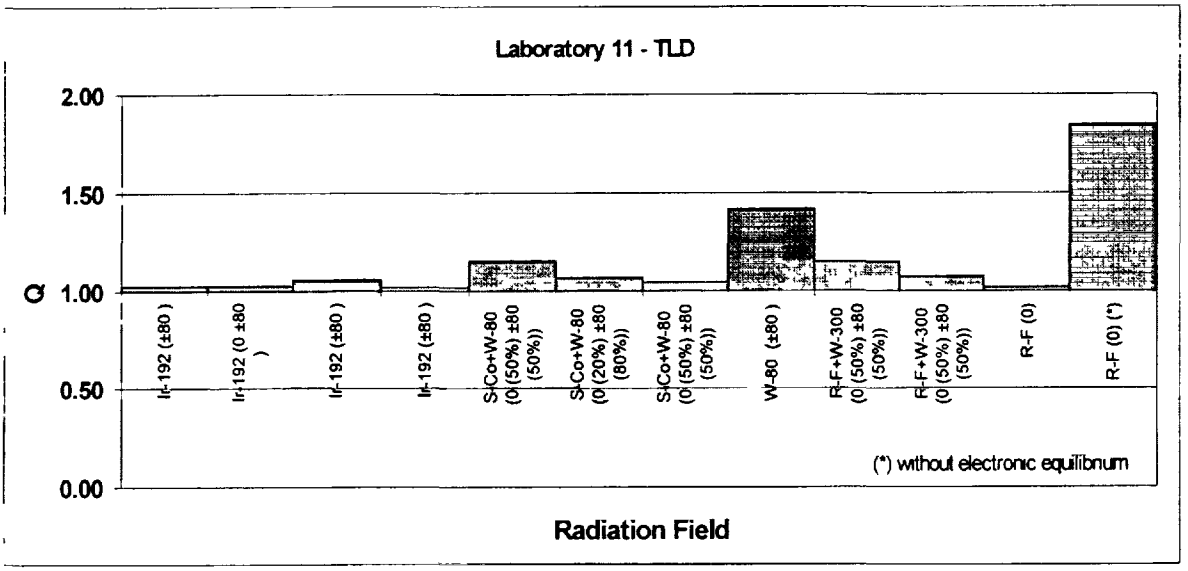


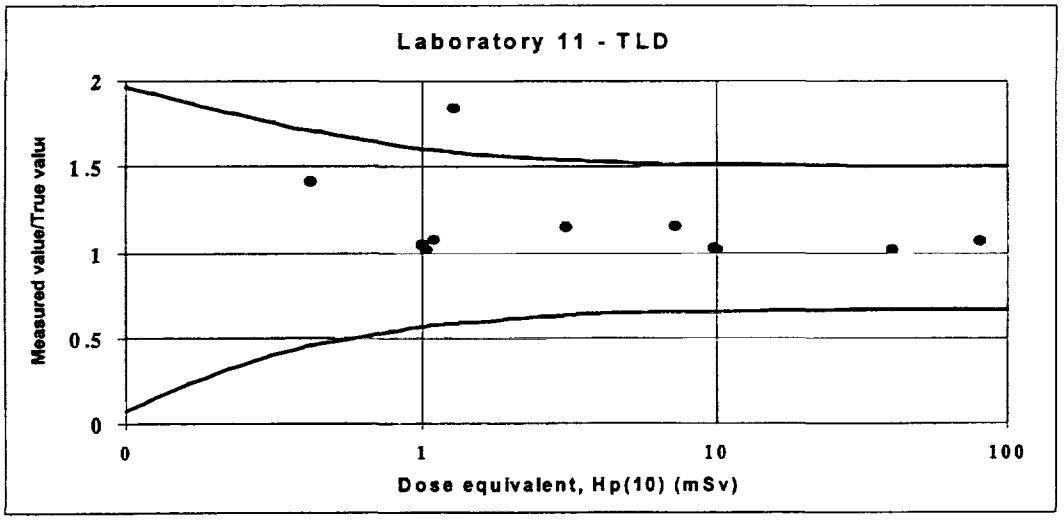


Results for the Individual Dosimetry System 11 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quobent
1	Ir-192	9 77	24/7/98	±80		10 072			1 03
2	Ir-192	9 99	28/7/98	0 (50%) ±80 (50%)		10 233			1 02
3	Ir-192	0 996	16/7/98	0		1 05			1 05
4	Ir-192	40 1	12/7/98	0		40 932			1 02
8	S-Co+W-80	3 07	17/7/98	0 (50%) ±80 (50%)		3 539			1 15
9	S-Co+W-80	80 381	20/7/98	0 (20%) ±80 (80%)		85 919			1 07
10	S-Co+W-80	0 999	21/7/98	0 (80%) ±80 (20%)		1 046			1 05
11	W-80	0 425	16/7/98	±80		0 601			1 41
15	R-F	7 2	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		8 325			1 16
16	R-F+W-300	1 1	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1 183			1 08
17	R-F	1 03	22/06/98	0		1 05			1 02
18	R-F (*)	1 28	23/06/98	0		2 353			1 84

(*) Without electronic equilibnum

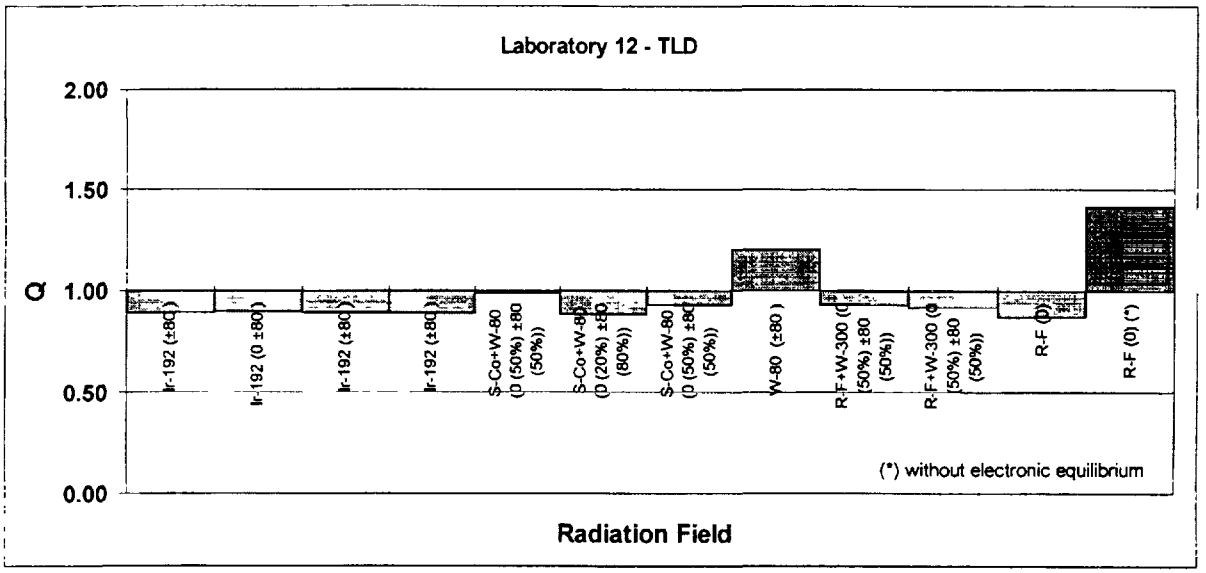


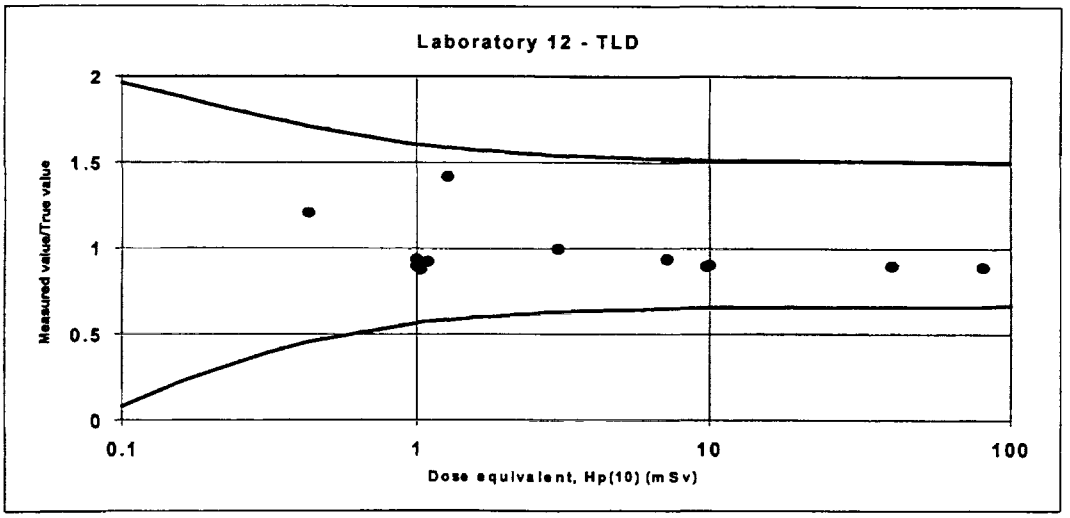


Results for the Individual Dosimetry System 12 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.77	24/7/98	±80		8.71			0.89
2	Ir-192	9.98	28/7/98	0 (50%) ±80 (50%)		9			0.90
3	Ir-192	0.996	16/7/98	0		0.89			0.89
4	Ir-192	40 1	12/7/98	0		35.9			0.90
8	S-Co+W-80	3.071	17/7/98	0 (50%) ±80 (50%)		3.04			0.99
9	S-Co+W-80	80 376	20/7/98	0 (20%) ±80 (80%)		71.4			0.89
10	S-Co+W-80	0.998	21/7/98	0 (80%) ±80 (20%)		0.93			0.93
11	W-80	0.425	16/7/98	±80		0.51			1.20
15	R-F	7.2	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		6.72			0.93
16	R-F+W-300	1.1	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1.01			0.92
17	R-F	1.03	22/06/98	0		0.9			0.87
18	R-F (*)	1.28	23/06/98	0		1.81			1.41

(*) Without electronic equilibrium

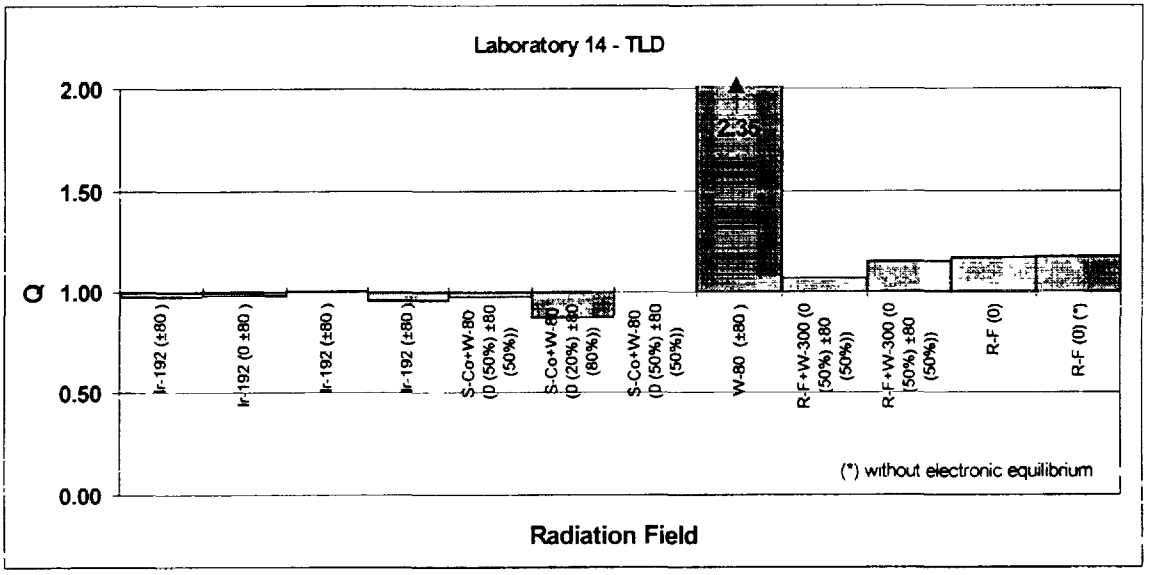


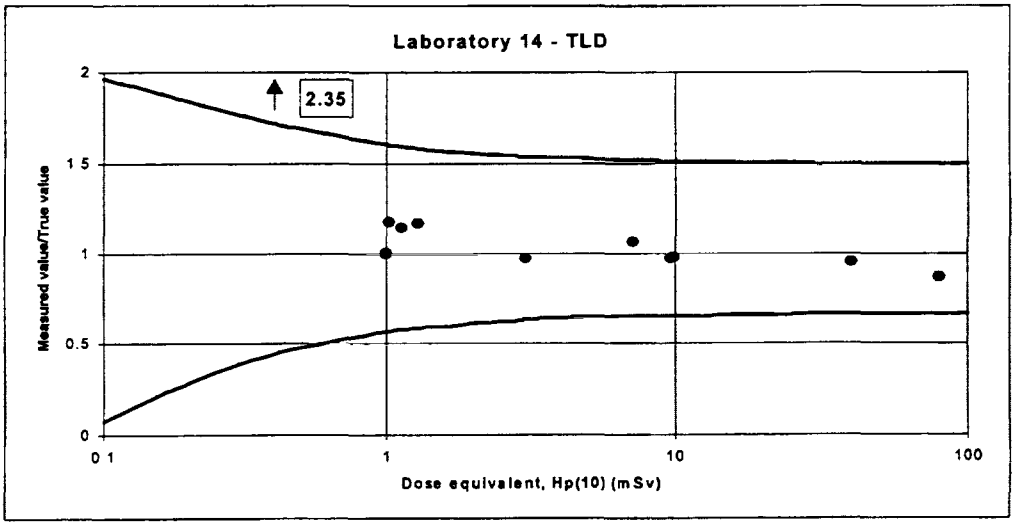


Results for the Individual Dosimetry System 14 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.76	24/7/98	±80		9.5			0.97
2	Ir-192	9.98	28/7/98	0 (50%) ±80 (50%)		9.8			0.98
3	Ir-192	0.995	16/7/98	0		1			1.01
4	Ir-192	40.1	13/7/98	0		38.4			0.96
8	S-Co+W-80	3 072	17/7/98	0 (50%) ±80 (50%)		3			0.98
9	S-Co+W-80	80.339	20/7/98	0 (20%) ±80 (80%)		70			0.87
10	S-Co+W-80	0.998	21/7/98	0 (80%) ±80 (20%)		1			1.00
11	W-80	0 426	16/7/98	±80		1			2.35
15	R-F	7.2	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		7.7			1.07
16	R-F+W-300	1.13	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1.3			1.15
17	R-F	1.28	22/06/98	0		1.5			1.17
18	R-F (*)	1 02	23/06/98	0		1.2			1.18

(*) Without electronic equilibrium

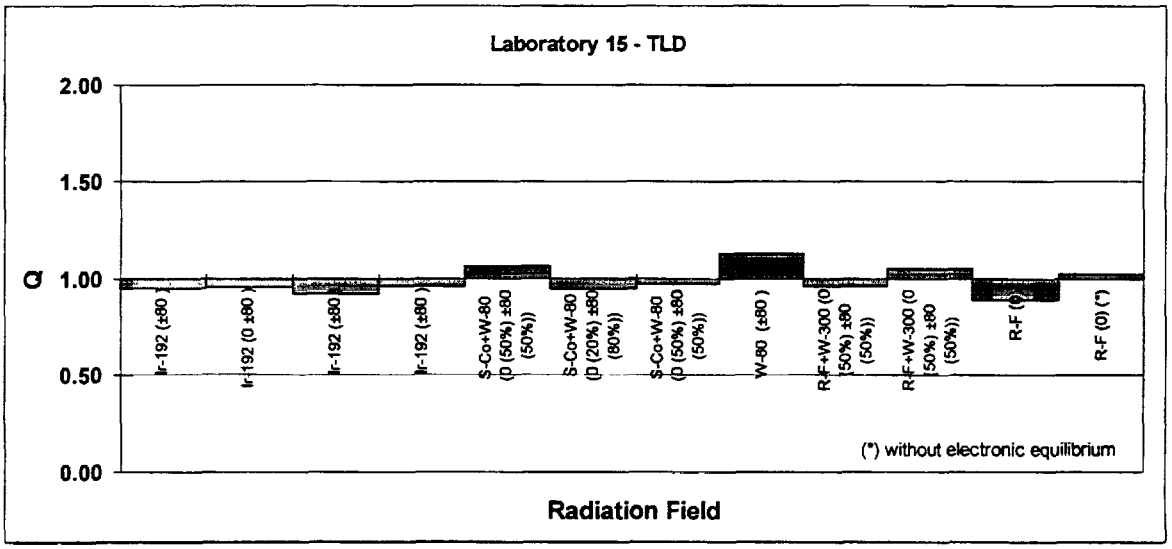


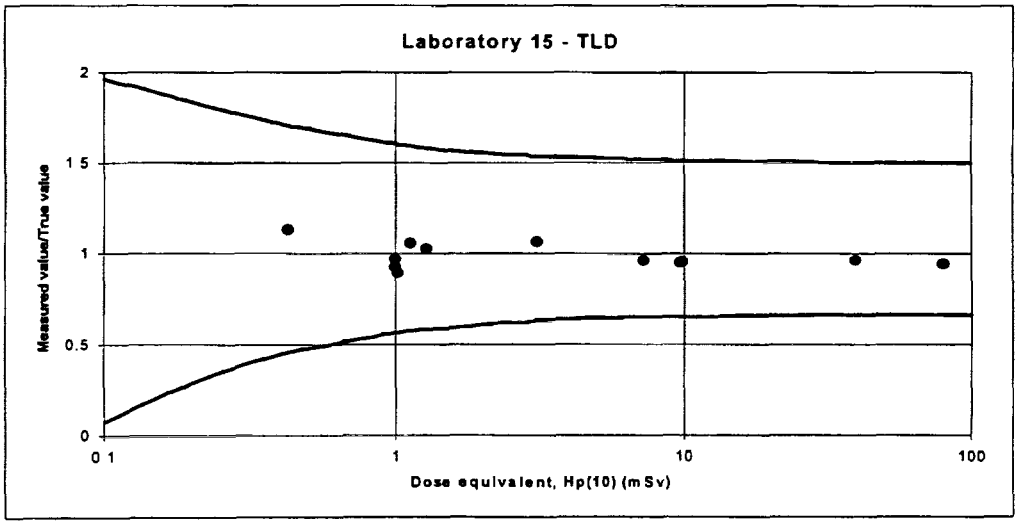


Results for the Individual Dosimetry System 15 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.76	24/7/98	±80		9.26			0.95
2	Ir-192	9.98	28/7/98	0 (50%) ±80 (50%)		9.55			0.96
3	Ir-192	0.995	16/7/98	0		0.92			0.92
4	Ir-192	40.2	12/7/98	0		38.65			0.96
8	S-Co+W-80	3.072	17/7/98	0 (50%) ±80 (50%)		3.27			1 06
9	S-Co+W-80	80.32	20/7/98	0 (20%) ±80 (80%)		76.05			0.95
10	S-Co+W-80	0.998	21/7/98	0 (80%) ±80 (20%)		0.97			0.97
11	W-80	0.425	16/7/98	±80		0.48			1.13
15	R-F	7.21	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		6.95			0.96
16	R-F+W-300	1.12	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1.18			1.05
17	R-F	1.02	22/06/98	0		0.91			0.89
18	R-F (*)	1.28	23/06/98	0		1.31			1.02

(*) Without electronic equilibrium

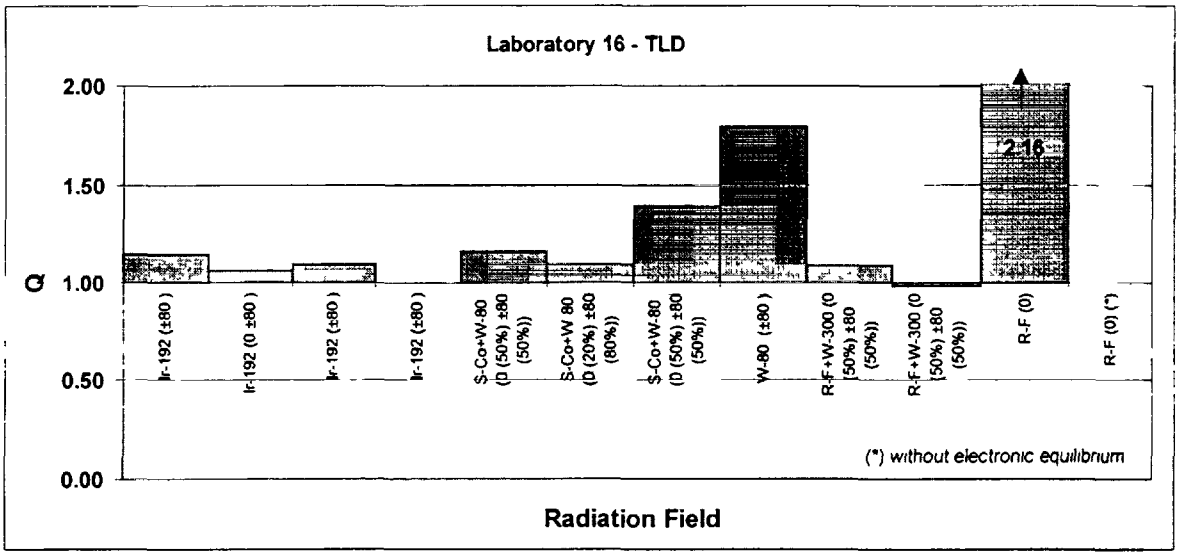


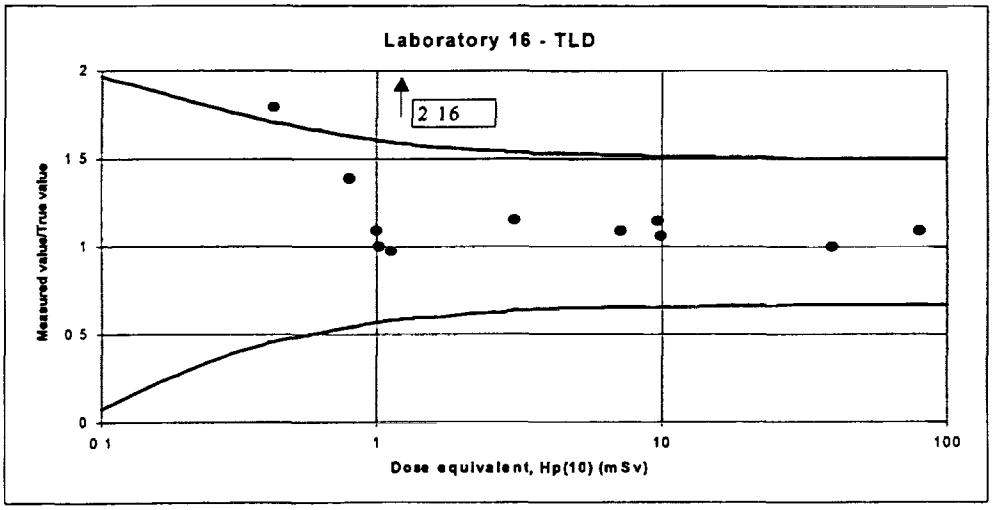


Results for the Individual Dosimetry System 16 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9 76	24/7/98	±80		11 211			1 15
2	Ir-192	9 98	28/7/98	0 (50%) ±80 (50%)		10 581			1 06
3	Ir-192	0 996	16/7/98	0		1 09			1 09
4	Ir-192	40 1	13/7/98	0		40 042			1 00
8	S-Co+W-80	3 071	17/7/98	0 (50%) ±80 (50%)		3 554			1 16
9	S-Co+W-80	80 367	20/7/98	0 (20%) ±80 (80%)		88 032			1 10
10	S-Co+W-80	0 799	21/7/98	0 (80%) ±80 (20%)		1 112			1 39
11	W-80	0 425	16/7/98	±80		0 76			1 79
15	R-F	7 2	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		7 852			1 09
16	R-F+W-300	1 13	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1 105			0 98
17	R-F	1 28	22/06/98	0		2 767			2 16
18	R-F (*)	1 02	23/06/98	0		1 023			1 00

(*) Without electronic equilibrium

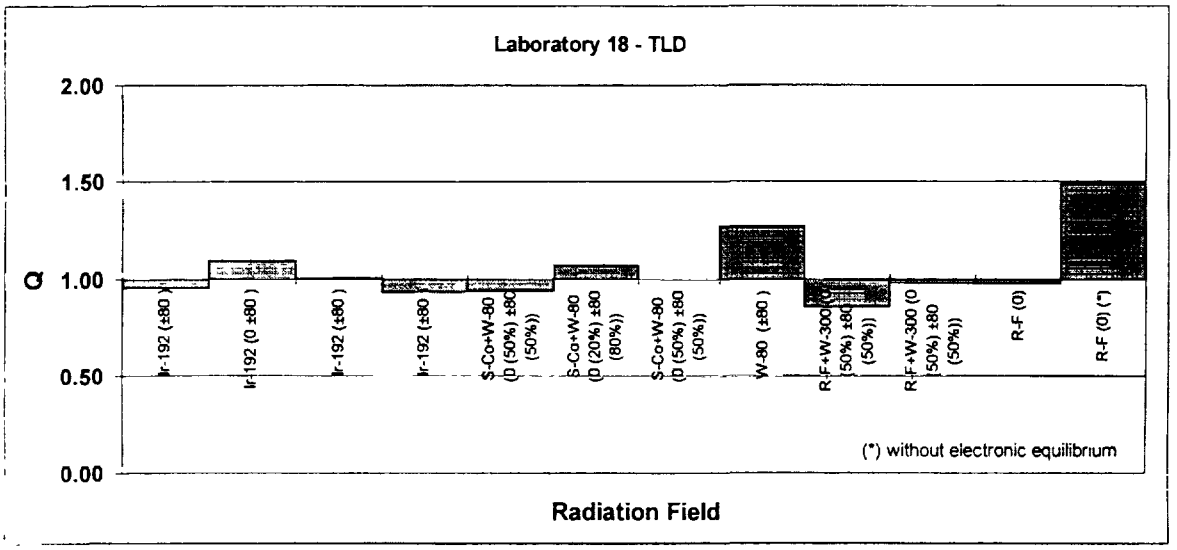


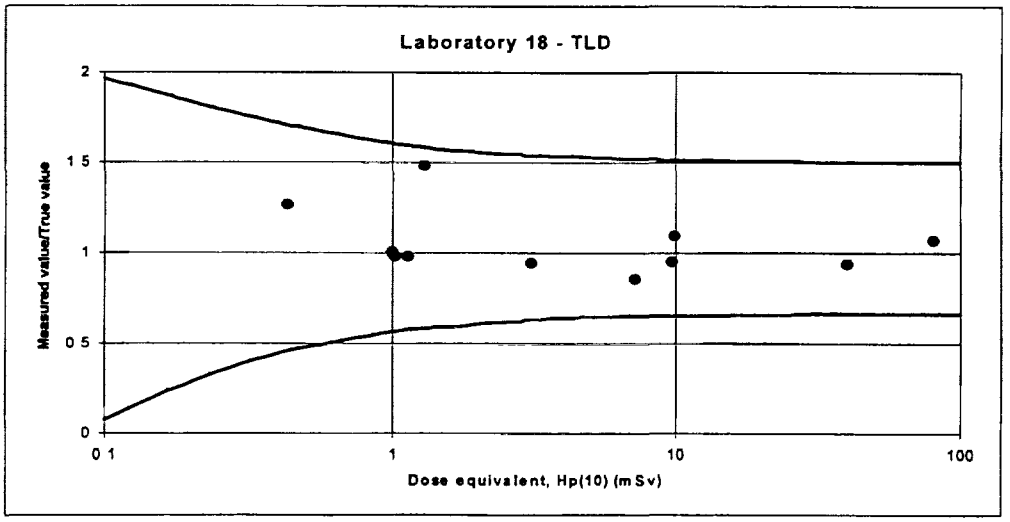


Results for the Individual Dosimetry System 18 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.76	24/7/98	±80		9.3			0.95
2	Ir-192	9.98	28/7/98	0 (50%) ±80 (50%)		10.9			1.09
3	Ir-192	0.995	16/7/98	0		1			1.01
4	Ir-192	40.1	13/7/98	0		37.6			0.94
8	S-Co+W-80	3.072	17/7/98	0 (50%) ±80 (50%)		2.9			0.94
9	S-Co+W-80	80.339	20/7/98	0 (20%) ±80 (80%)		85.8			1.07
10	S-Co+W-80	0.998	21/7/98	0 (80%) ±80 (20%)		1			1.00
11	W-80	0.426	16/7/98	±80		0.54			1.27
15	R-F	7.21	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		6.2			0.86
16	R-F+W-300	1.12	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1.1			0.98
17	R-F	1 02	22/06/98	0		1			0.98
18	R-F (*)	1 28	23/06/98	0		1.9			1 48

(*) Without electronic equilibrium

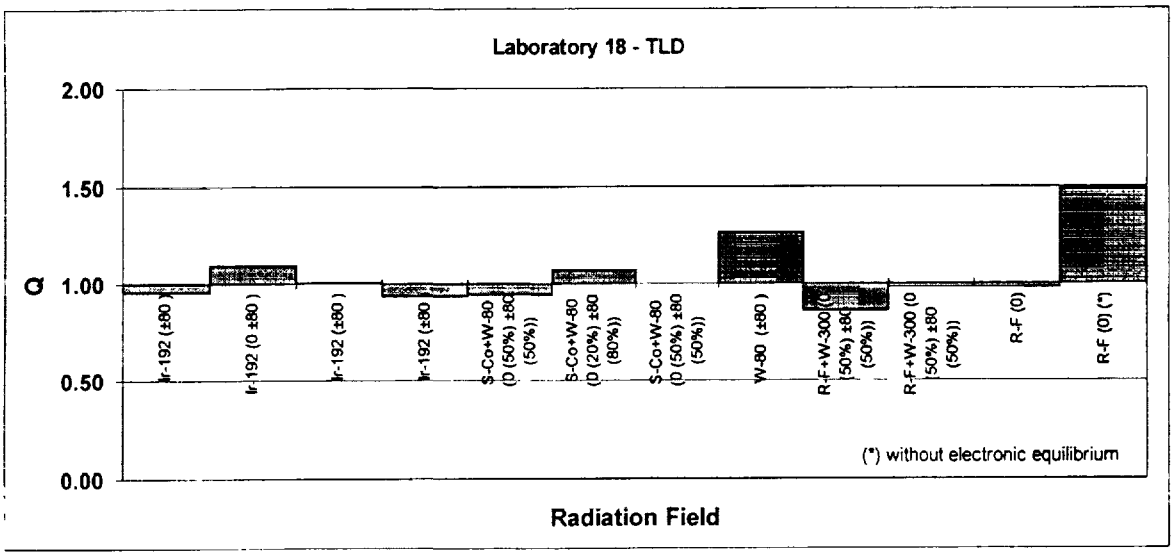


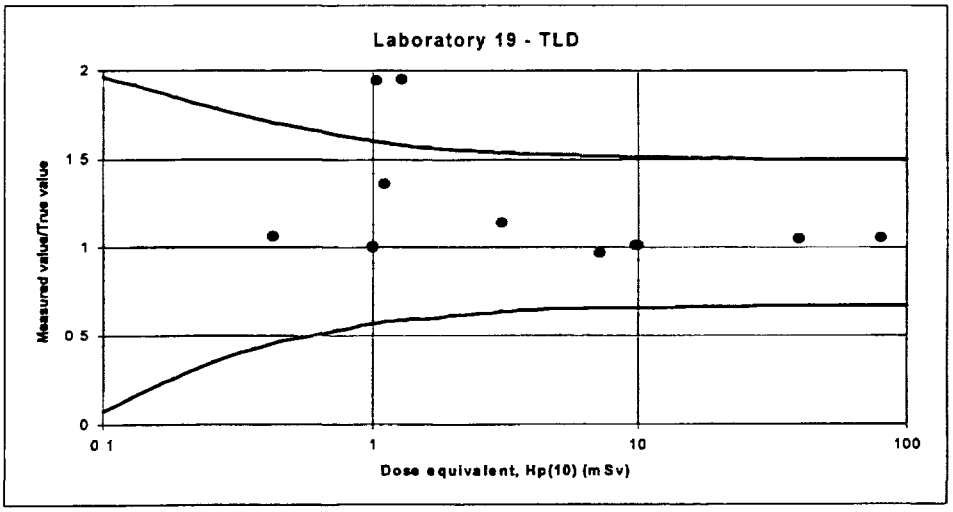


Results for the Individual Dosimetry System 19 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.77	24/7/98	±80	300	9.9		ROT	1.01
2	Ir-192	9.99	28/7/98	0 (50%) ±80 (50%)	280	10.1		AP-ROT	1.01
3	Ir-192	0.996	16/7/98	0	310	1		AP	1.00
4	Ir-192	40	10/7/98	0	310	42		AP	1.05
8	S-Co+W-80	3.07	17/7/98	0 (50%) ±80 (50%)	95	3.5		AP-ROT	1.14
9	S-Co+W-80	80.339	20/7/98	0 (20%) ±80 (80%)	130	85		AP-ROT	1.06
10	S-Co+W-80	0.999	21/7/98	0 (80%) ±80 (20%)	150	1		AP-ROT	1.00
11	W-80	0.425	16/7/98	±80	59	0.45		ROT	1.06
15	R-F	7.21	22/06/98 + 14/07/98	0 (50%) ±80 (50%)	260	7		AP-ROT	0.97
16	R-F+W-300	1.1	22/06/98 +15/07/98	0 (50%) ±80 (50%)	340	1.5		AP-ROT	1.36
17	R-F	1.03	22/06/98	0	1250	2		ROT	1.94
18	R-F (*)	1.28	23/06/98	0	1250	2.5		AP	1.95

(*) Without electronic equilibrium

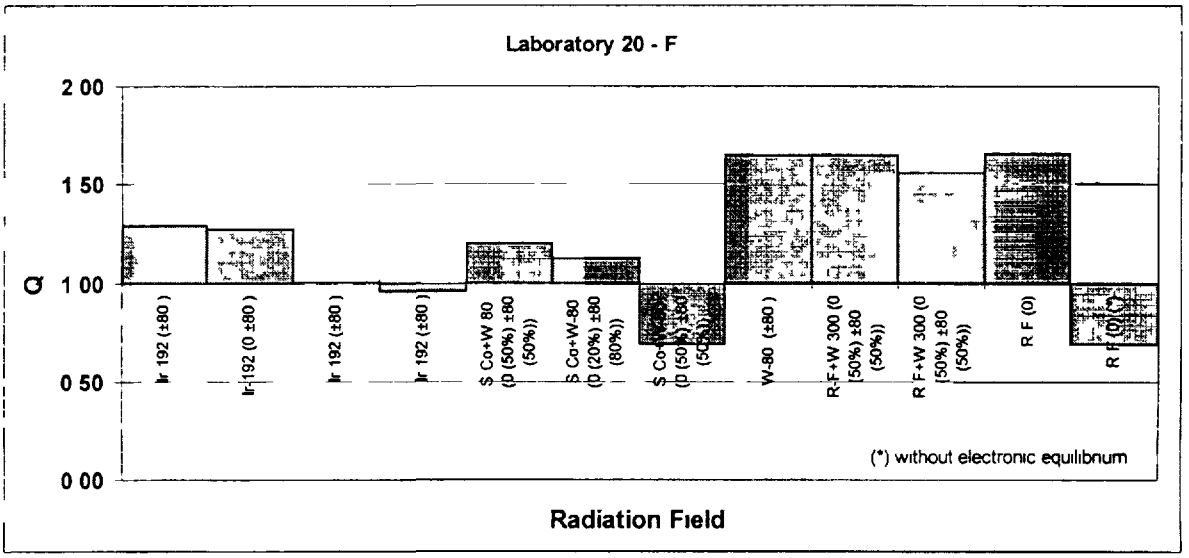


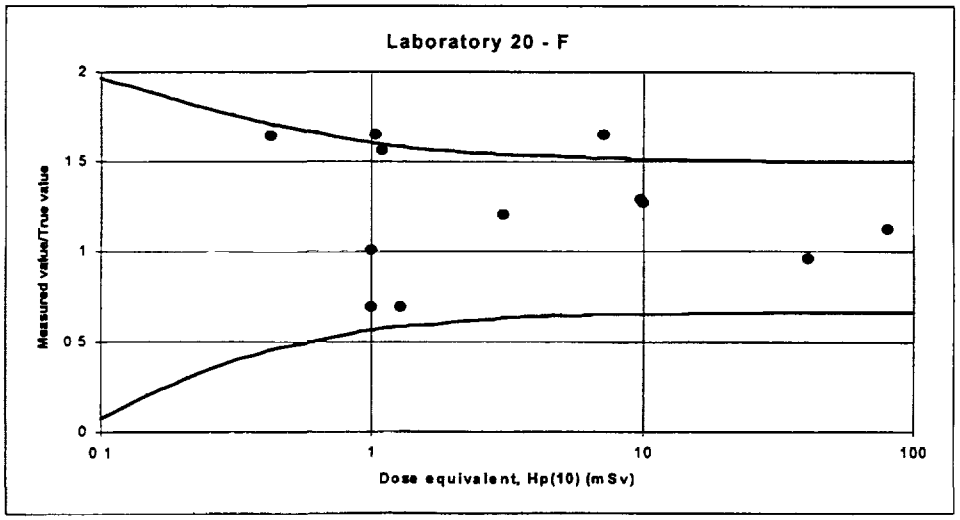


Results for the Individual Dosimetry System 20 - Film

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9 84	23/7/98	±80		12 7			1 29
2	Ir-192	9 99	28/7/98	0 (50%) ±80 (50%)		12 7			1 27
3	Ir-192	0 996	16/7/98	0		1			1 00
4	Ir 192	41	6/7/98	0		39 5			0 96
8	S-Co+W-80	3 071	17/7/98	0 (50%) ±80 (50%)		3 7			1 20
9	S-Co+W-80	80 328	20/7/98	0 (20%) ±80 (80%)		90 4			1 13
10	S-Co+W-80	1 001	21/7/98	0 (80%) ±80 (20%)		0 7			0 70
11	W-80	0 426	16/7/98	±80		0 7			1 64
15	R-F	7 23	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		11 9			1 65
16	R-F+W-300	1 09	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1 7			1 56
17	R-F	1 03	22/06/98	0		1 7			1 65
18	R-F (*)	1 29	23/06/98	0		0 9			0 70

(*) Without electronic equilibrium

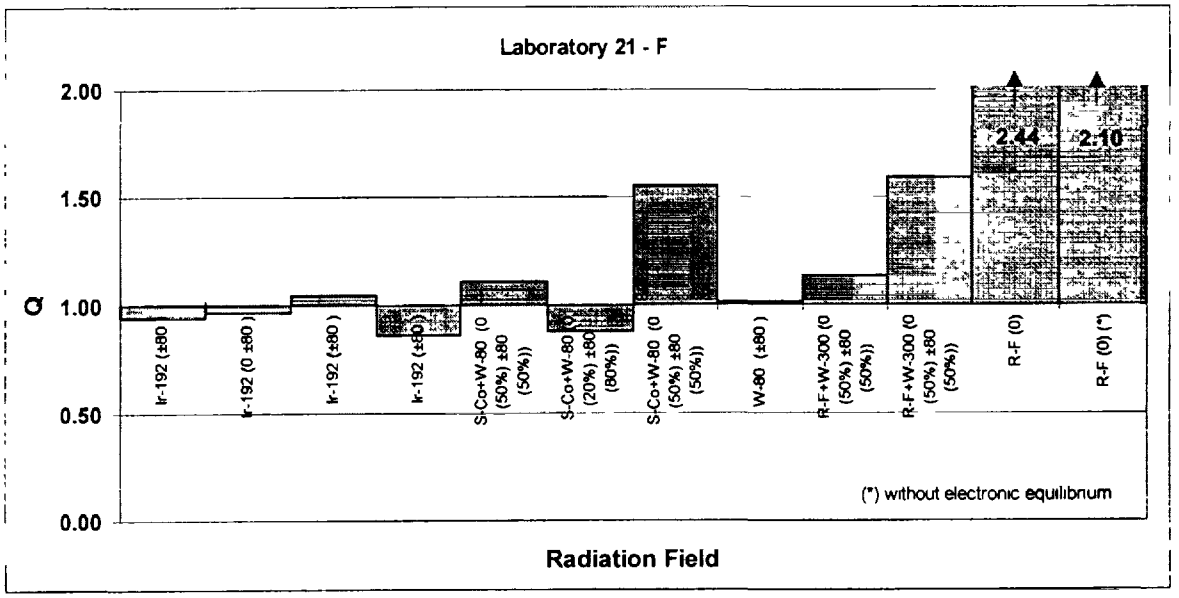


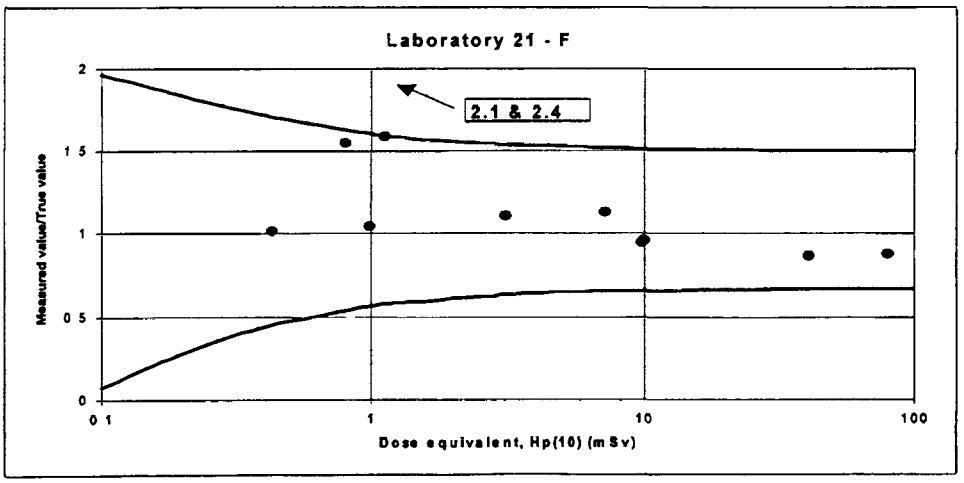


Results for the Individual Dosimetry System 21 - Film

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9 83	1/0/00	±80	450	9.26	+/- 60		0.94
2	Ir-192	9 99	1/0/00	0 (50%) ±80 (50%)	450	9.64	0°		0 96
3	Ir-192	0 99	1/0/00	0	700	1 03	0°		1 04
4	Ir-192	41	1/0/00	0	500	35.33	0°		0 86
8	S-Co+W-80	3 07	17/7/98	0 (50%) ±80 (50%)	100	3.39	+/- 60		1 10
9	S-Co+W-80	80 157	20/7/98	0 (20%) ±80 (80%)	150	70 17	+/- 60		0 88
10	S-Co+W-80	0 799	21/7/98	0 (80%) ±80 (20%)	150	1 24	+/- 60		1.55
11	W-80	0.425	16/7/98	±80	60	0.43	+/- 60		1.01
15	R-F	7 23	22/06/98 + 14/07/98	0 (50%) ±80 (50%)	300	8.18	+/- 60		1.13
16	R-F+W-300	1 12	22/06/98 +15/07/98	0 (50%) ±80 (50%)	800	1.78	30°		1.59
17	R-F	1.05	22/06/98	0	>1000	2 56	0°		2 44
18	R-F (*)	1 31	23/06/98	0	400	2 75	0°		2 10

(*) Without electronic equilibrium

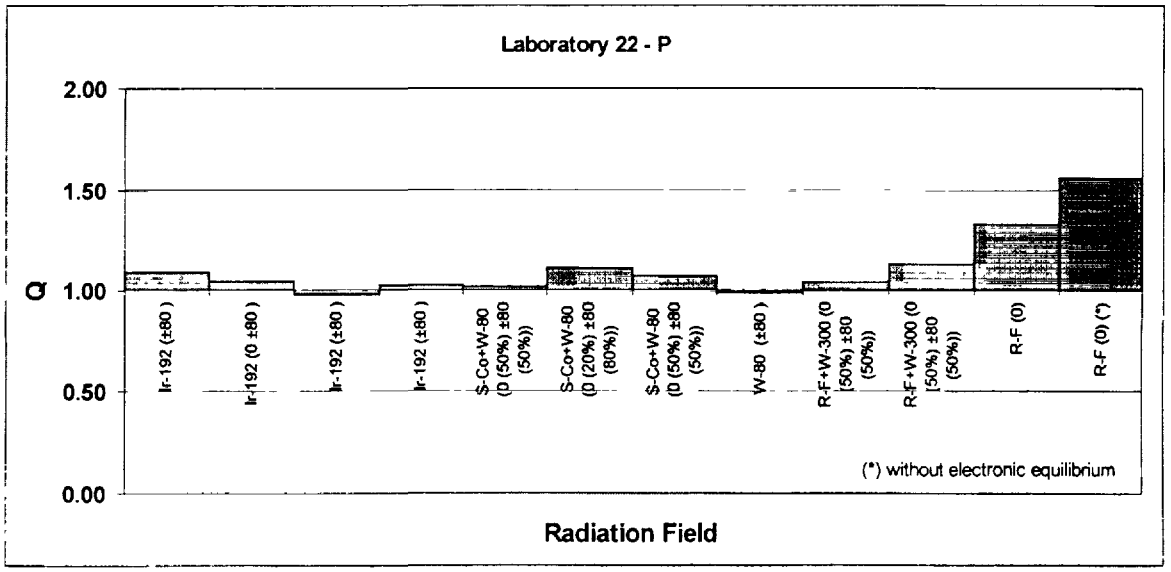


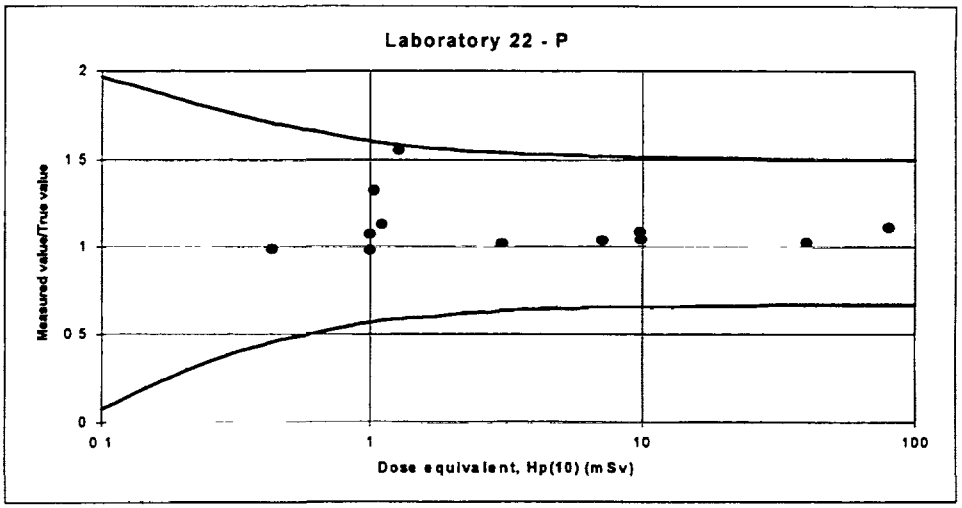


Results for the Individual Dosimetry System 22 - P

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.76	24/7/98	±80	> 150	10.6			1.09
2	Ir-192	9.97	28/7/98	0 (50%) ±80 (50%)	> 150	10.4			1.04
3	Ir-192	0.996	16/7/98	0	> 150	0.98			0.98
4	Ir-192	40.1	13/7/98	0	> 150	41.1			1.02
8	S-Co+W-80	3.071	17/7/98	0 (50%) ±80 (50%)	70 - 150	3.12			1.02
9	S-Co+W-80	80.381	20/7/98	0 (20%) ±80 (80%)	70 - 150	89.1			1.11
10	S-Co+W-80	0.999	21/7/98	0 (80%) ±80 (20%)	70 - 150	1.07			1.07
11	W-80	0.425	16/7/98	±80	70 - 150	0.42			0.99
15	R-F	7.21	22/06/98 + 14/07/98	0 (50%) ±80 (50%)	> 150	7.47			1.04
16	R-F+W-300	1.1	22/06/98 +15/07/98	0 (50%) ±80 (50%)	> 150	1.24			1.13
17	R-F	1.03	22/06/98	0	> 150	1.37			1.33
18	R-F (*)	1.28	23/06/98	0	> 150	1.99			1.55

(*) Without electronic equilibrium

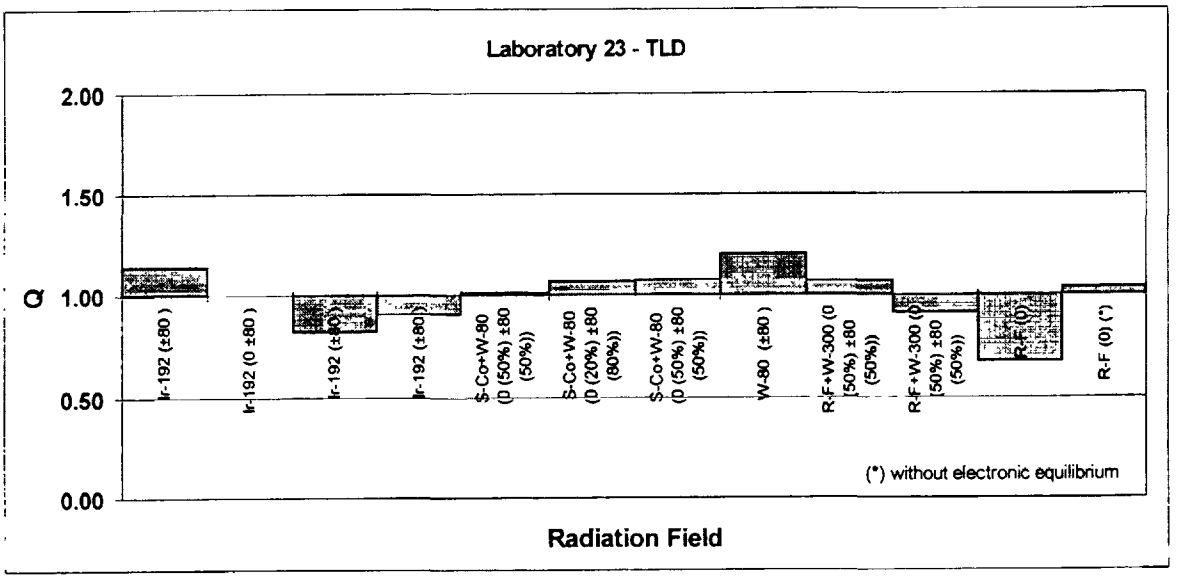


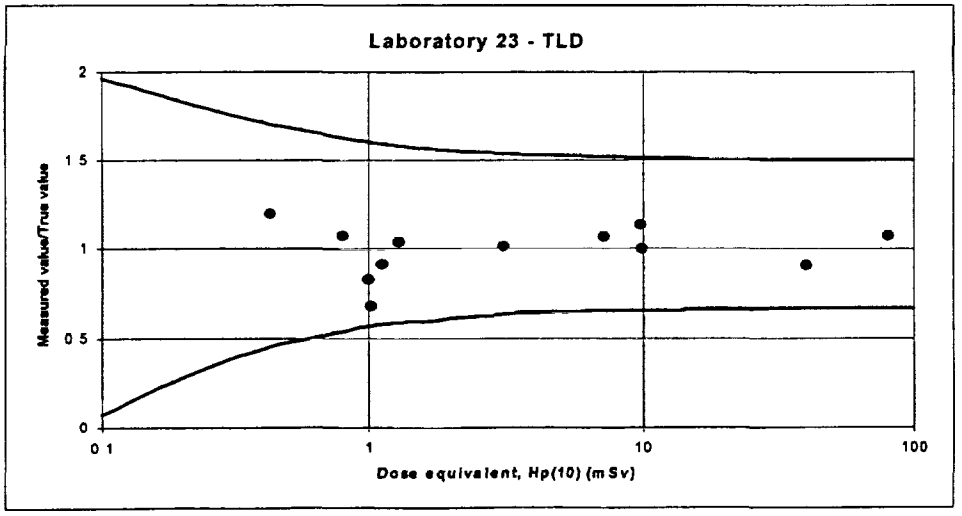


Results for the Individual Dosimetry System 23 - TLD

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	9.76	24/7/98	±80		11.11			1.14
2	Ir-192	9.97	28/7/98	0 (50%) ±80 (50%)		9.96			1.00
3	Ir-192	0.995	16/7/98	0		0.82			0.82
4	Ir-192	40 1	12/7/98	0		36.36			0.91
8	S-Co+W-80	3.071	17/7/98	0 (50%) ±80 (50%)		3.11			1.01
9	S-Co+W-80	80.302	20/7/98	0 (20%) ±80 (80%)		86.05			1.07
10	S-Co+W-80	0.799	21/7/98	0 (80%) ±80 (20%)		0.86			1.08
11	W-80	0.425	16/7/98	±80		0.51			1.20
15	R-F	7.21	22/06/98 + 14/07/98	0 (50%) ±80 (50%)		7.72			1.07
16	R-F+W-300	1.12	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1.02			0.91
17	R-F	1.02	22/06/98	0		0.69			0.68
18	R-F (*)	1.28	23/06/98	0		1.33			1.04

(*) Without electronic equilibrium





Results for the Individual Dosimetry System 24 - PEN

Dos N°	Irradiation data given by the IAEA				Irradiation data given by the participant				Quotient
	Radiation Quality	$H_p(10)$ mSv	Irradiation date	Angle deg	Mean energy keV	$H_p(10)$ mSv	Angle	Remarks	Quotient
1	Ir-192	2	30/07/98	±80		1.93			0.97
2	Ir-192	1.99	30/07/98	0 (50%) ±80 (50%)		1.9			0.95
3	Ir-192	1.99	30/07/98	0		1.833			0.92
4	Ir-192		1/0/00	0		0			
8	S-Co+W-80	2.284	17/7/98 + 22/07/98	0 (50%) ±80 (50%)		2.05			0.90
9	S-Co+W-80	0	1/0/00	0 (20%) ±80 (80%)		0			
10	S-Co+W-80	0.999	21/7/98 + 15/07/98	0 (80%) ±80 (20%)		1.22			1.22
11	W-80	0.425	16/7/98	±80		0.7			1.65
15	R-F	3.05	22/06/98 + 16/07/98	0 (50%) ±80 (50%)		3.04			1.00
16	R-F+W-300	1.11	22/06/98 +15/07/98	0 (50%) ±80 (50%)		1.3			1.17
17	R-F	1.06	23/06/98	0		1.1			1.04
18	R-F (*)	0.75	23/06/98	0		1.2			1.60

(*) Without electronic equilibrium