IAEA-TECDOC-1564

Intercomparison of Personal Dose Equivalent Measurements by Active Personal Dosimeters

Final Report of a joint IAEA-EURADOS Project

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International Atomic Energy Agency

November 2007

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FOREWORD

Active personal dosimeters (APD) are widely used in many countries, i.e. in the medical field and as operational dosimeters in nuclear power plants. Their use as legal dosimeters is already established in a few countries, and will increase in the near future. In the majority of countries, APDs have not undergone accreditation programmes or intercomparisons.

In 2001, an EURADOS (European Radiation Dosimetry Group) Working Group on harmonization of individual monitoring was formed, funded by the European Commission, in the fifth framework programme, and by the participating institutes. The work addressed four issues; inter alia also an inventory of new developments in individual monitoring with an emphasis on the possibilities and performance of active (electronic) dosimeters for both photon/beta and neutron dosimetry. Within the work on this issue, a catalogue of the most extensively used active personal dosimeters (APDs) suitable for individual monitoring was made.

On the basis of the knowledge gained in this activity, the organization of an international intercomparison, which would address APDs, was considered of great value to the dosimetric community.

The IAEA in cooperation with EURADOS organized such an intercomparison in which most of the testing criteria as described in two internationally accepted standards (IEC61526 and IEC61283) were used. Additionally, simulated workplace fields were used for testing the APD reactions to pulsed X ray fields and mixed gamma/X ray fields. This is the first time that results of comparisons of such types are published, which is of great importance for APD end users in medical diagnostic and surgery X ray applications.

Nine suppliers from six countries in Europe and the USA participated in the intercomparison with 13 different models. One of the models was a special design for extremity dose measurements.

Irradiations and readout was done by two accredited calibration laboratories in Belgium and France and the French standard laboratory. The final results, as assessed by the irradiation laboratories and discussed with the APD suppliers, were:

- The general dosimetric performance of the tested APD is comparable with the performance of standard passive dosimetric systems;
- The accuracy at reference photon radiation, the reproducibility and the repeatability of measurements are even better than for most passive dosimeters;
- Only three devices have given satisfactory results both for 60 kV (RQR4) and for 120 kV (RQR9) pulsed radiation.

Not all the devices have been designed for any radiation field and the end-user should at least take into account information about the dose equivalent rate and energy ranges before using the dosimeters.

The performance results confirm that the IEC standard requirements are adequate but that they can be insufficient for some applications such as with pulsed radiation fields.

The IAEA officer responsible for this publication was J. Zeger of the Division of Radiation, Transport and Waste Safety.

EDITORIAL NOTE

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CONTENTS

1. BACKGROUND

In line with its statutory function on providing for the application of safety standards, the IAEA has been assisting its Member States in their provision of appropriate occupational radiation monitoring for protection purposes. The IAEA has been organizing international and regional intercomparisons in the field of external and internal dosimetry since the early 1980's [1 - 3].

The objectives of this intercomparison are:

(1) To facilitate the estimation of similarities or dissimilarities in the measurements of radiation protection quantities performed,

(2) To foster exchanges of information and experience relating to the measurement of radiation protection quantities and to methods for estimating derived quantities,

(3) To provide access to resources, which might otherwise not be available to some Member States, for the calibration of radiation protection monitoring devices,

(4) To provide the opportunity to the Member States to report in those quantities in the frame of the international legal conventions in the field of nuclear safety.

In this respect, the intercomparison of active personal dosimeter for individual monitoring of external exposure from photon and beta radiation was organized as a joint venture project with the European Radiation Dosimetry Group (EURADOS) to assess the technical capabilities of all types of electronic personal dosimeters and other new developments available on the market. This report presents the results of the joint intercomparison and gives some recommendations for the proper use of the tested devices.

2. EURADOS ACTIVITIES IN PERSONAL DOSIMETRY AND INTERCOMPARISONS

EURADOS was created to be a scientific network of European laboratories involved in research in radiation dosimetry. The objective is to advance the scientific understanding and the technical development of the dosimetry of ionising radiation by stimulating collaboration between European facilities.

In 1997 EURADOS started a working group called "Harmonization and Dosimetric Quality Assurance in Individual Monitoring for External Radiation" with the objective of promoting the quality of individual monitoring in the European Union (EU) and of facilitating harmonized procedures [4]. Three tasks were carried out:

- an inventory of procedures for routine individual dose assessment of external radiation,
- a catalogue of dosimeters and dosimetric services able to estimate external radiation doses as personal dose equivalent,
- the organization of a performance test of dosimetric services in the EU Member States and Switzerland for the routine assessment of individual doses for photon, beta and neutron radiation. In total 69 sets of dosimeters participated in the study.

The tests were designed to reproduce realistic irradiation conditions and to verify the ability of the most commonly used dosimeters of each country to determine and to report the personal dose equivalent. The results of the comparison show that many dosimetric services for photons (particularly) and beta particles can meet, or should be able to meet proposed requirements for dosimetric accuracy, but some relaxation may be required for neutron dosimetric services. Detailed discussion of the findings and conclusions were published in Radiation Protection Dosimetry journal [5].

In particular, it was concluded that there remained challenges and that there were new developments which recommended to further pursue harmonisation. Thus, in 2001, a second EURADOS working group on "Harmonisation of Individual Monitoring" was formed, funded by the European Commission, in the fifth framework program, and by the participating institutes.

The working group consisted of experts from almost all EU Member States, several candidate Member States and other European countries. The work addressed four issues:

(1) An overview of the national and international standards and other documents of relevance that are of importance for the quality, in the broadest sense, of individual monitoring and therefore could be or should be part of the requirements for approval of technical services.

(2) An inventory of methods and services for assessing the dose due to external radiation and of direct and indirect methods for assessing the dose due to internal contamination. An important aspect that was addressed is the extension to which these different methods are harmonised such that the numerical dose values can be added to result into the total effective dose of the worker.

(3) An inventory of new developments in individual monitoring with an emphasis on the possibilities and performance of electronic dosimeters for both photon/beta and neutron dosimetry.

(4) An inventory of problems of non-dosimetric origin in individual monitoring that impair the quality of the dose assessment as for example the additional uncertainty in

the annual dose caused by non-return of dosimeters or technical problems like failure of film developing or evaluating equipment etc.

The results of the investigations were published in Radiation Protection Dosimetry journal [6] and presented during the Individual Monitoring Workshop, IM2005, in Vienna.

Within the third issue, a catalogue of the most extensively used active personal dosimeters (APD) suitable for individual monitoring was made [7]. APD are defined in the context of this report as all devices with personal dose equivalent direct reading capability. The catalogue contained information on the legal status of APD in the various countries, the relevant standards, the dosimetric characteristics of the devices and on type tests performed by both manufacturers and independent organizations.

Following this analysis it was concluded that APD are widely used in many countries, mainly, as operational dosimeters in nuclear power plants. Advantages as compared with passive dosimeters are:

- instant or direct reading and audible alarms, which facilitate optimization of practices,
- data transfer to and from a computer network, which can provide easy and on line exchange of information as well as a centralised dose record management,
- lower detection limit,
- dose memory options to asses dose for specific workplaces or tasks.

The recent improvements in the performance and reliability of such detectors, together with their interesting technical features in comparison with passive systems, have brought about general concerns about the possibility of accepting them as legal primary dosimeters.

However, only few countries, such as the United Kingdom or Switzerland, have already established formal approval or accreditation procedures to use an APD as a primary legal dosimeter. In the majority of countries, APD have not undergone accreditation programs or intercomparisons.

Based on the above mentioned observations, the organization of an international intercomparison, which would address active personal dosimeters, was considered of great value to the dosimetric community. The common interest of IAEA and EURADOS in the project led to the organization of this intercomparison. The intercomparison is the first organized on international basis and could stimulate constructors to improve their instruments and give end-users suggestions for calibration procedures and for applicability in the different fields of interest.

3. INTERNATIONAL STANDARDS OF RELEVANCE

A large number of standards are available for radiation protection and individual monitoring purposes, a thorough review of them can be found in reference [8]. However, for the purpose of this intercomparison, IEC 61526 [9] is of major importance, together with ISO 4037-1 [10], ISO 4037-2 [11], ISO 4037-3 [12], ISO 6980-1 [13], ISO 6980-2 [14], and ISO 6980-3 [15] for the radiation field characteristics and the calibration procedures.

A summary of the main considerations and requirements stated in IEC 61526 will be presented in this paragraph. In accordance with ICRP [16] and IAEA [17] recommendations, the IEC standard establishes as operation quantities for individual monitoring the personal dose equivalent H_p(d).

H_p(d) was first defined in ICRU 39 [18] as the personal dose equivalent in soft tissue below a specified point on the body at an appropriate depth *d.* In ICRU Report 47 [19], the definition of the quantity was extended for the purpose of calibration, to include the dose equivalent at the depth *d* in a phantom made of ICRU tissue and having the same size and shape as the phantom used in the calibration of the dosimeters.

For dosimeters worn on the human torso, ISO has defined the water slab phantom (30 cm x 30 cm x 15 cm) with walls made of PMMA and filled with water as the calibration phantom in simplified conditions.

Thus the quantity $H_{p,slab}(d,\alpha)$ was defined as the dose equivalent at the depth d below the point where the dosimeter is to be calibrated on a slab phantom (30 cm x 30 cm x 15 cm) made of ICRU 4 elements soft tissue; $H_{p,slab}(d,\alpha)$ surrogate $H_p(d)$. For weakly penetrating radiation, a depth of 0.07 mm for the skin is employed and for strongly penetrating radiation, a depth of 10 mm is employed. α represent the angle of incidence of the radiation from the source; 0° is the normal at the front surface of the slab phantom. Here after, in order to simplify the notation, $H_p(d)$ is used instead of $H_{p,slab}(d)$.

IEC 61526:2005 Radiation protection instrumentation — Measurement of personal dose equivalents H_p(10) *and* H_p(0.07) for X, gamma, neutron and beta radiations — Direct reading personal dose equivalent meters and monitors and personal warning devices

This international Standard applies to non-passive direct reading personal dose equivalent meters and monitors used for measuring the personal dose equivalents H_p(10) and H_p(0.07) for X, gamma, neutron and beta radiations and to personal warning devices used to give an indication of the personal dose equivalent rate. It provides requirements on the general and mechanical characteristics, dosimetric, electrical, electromagnetic and environmental performance of the dosimeters.

It is the second edition of the international standard IEC 61526 [20], which was first published in 1998, and replaces the former standards IEC 61283 [21], IEC 61323 [22] and IEC 61525 [23] in one standard. Moreover, it includes technical changes such as the determination of the uncertainty of the measured dose value and the consideration of the relevant ISO standards on reference radiations and calibration.

Depending on the application of the dosimeter the standard defines 6 combinations of quantities and radiation type:

(1) $H_p(10)$ and $H_p(0.07)$ from X and gamma radiations;

(2) $H_p(10)$ and $H_p(0.07)$ from X, gamma and beta radiations;

(3) $H_p(10)$ from X and gamma radiations;

(4) $H_p(10)$ from neutron radiations;

(5) $H_p(10)$ from X, gamma and neutron radiations;

(6) $H_p(0.07)$ from X, gamma and beta radiations.

The devices tested in the intercomparison belong to one of the "categories" 1, 2, 3 or 6. Neutron radiation measurement (categories 4 and 5) was not considered due to the existence of very few available APD for neutron dosimetry [6].

4. ORGANIZATION OF THE INTERCOMPARISON

4.1. Scope of the intercomparison

Pursuant to General Conference resolution GC(43)/RES/13(1999), the IAEA is organizing international intercomparisons for monitoring purposes with the goal of helping Member States to comply with dose limitation requirements and of harmonizing the use of internationally agreed quantities and recommended assessment methods.

In reaction to the beginning trend in some Member States to accept active personal devices as legal dosimeters, the IAEA wanted to get more knowledge about the technical capabilities of these devices.

The overall objective was to verify performance of the different APD types available in the market. This was to be achieved with the following specific objectives of the intercomparison:

(1) To assess the capabilities of the APD to measure the quantity Hp(d) in photon and beta radiation fields.
(2) To help the Member States achieving a sufficiently accurate knowledge about the possibilities of modern active dosimeters.
(3) To provide guidelines for improvements to APD suppliers, if necessary.

4.2. Organization of the intercomparison

To get this basic knowledge about active personal devices, the IAEA organized an intercomparison incorporating devices from different suppliers.

This intercomparison was organized in cooperation with EURADOS, the European Dosimetry Group, who had already, within it's Working Group 2, compiled a catalogue of commercially available APD. The organization of the intercomparison started with preliminary planning during the annual meeting of EURADOS in 2004. The technical details of the applied irradiation test were discussed during the year and finalized during the next annual meeting of EURADOS in 2005.

Based on available information the commercially active suppliers have been contacted (Annex, Table A-1). Not all of the contacted suppliers answered to the proposition of the intercomparison and some declined to use the opportunity for various reasons. Finally a group of suppliers evolved, who participated with different models of APD.

The scope of the intercomparison was aimed at electronic dosimeters capable to measure the quantity $H_p(d)$ in photon and beta fields. Several technical characteristics have been tested, excluding the alarm function.

The objectives mentioned above could be reached by an intercomparison, which was performed by irradiating dosimeters in single energy photon and X ray fields (ISO N and S series qualities, and different irradiation angles), in mixed quality fields, simulating real work places, and in pulsed X ray fields.

The irradiation programme was shared between three laboratories: SCK-CEN (Belgium), IRSN (France) and LNE/LNHB at CEA/LIST (France).

The schedule to perform the intercomparison was agreed by the organizers, but had to be adjusted, due to delays in dosimeter provision by the suppliers and some additional tests in the range of beta irradiation (Annex, Table A-2).

After initial problems, which brought about a delay of almost six months, the project ran smoothly. The dosimeters were delivered from irradiation lab to irradiation lab very quickly and could be returned to the suppliers in August 2005.

All irradiation were performed on the ISO slab phantom and with parallel or nearly parallel beams. The intercomparison included two categories of tests: IEC 61526 performance tests and simulated work-place fields. Table A-3 in the Annex contains the parameters to be verified, the irradiation conditions used and the three different laboratories, which performed the irradiations for this intercomparison.

4.3. IEC 61526 performance tests

The following characteristics have been checked:

(1) Reproducibility of response between 3 different units of every tested dosimeter.

(2) Repeatability of the response (5 readings for each irradiation condition in one unit of each tested dosimeter).

(3) Photon energy response (ISO 4037-1 qualities): S-Cs, S-Co, N-30, N-80, N-120.

(4) Beta energy response (ISO 6980 qualities): ^{90}Sr-^{90}Y, ^{85}Kr, ^{147}Pm

(5) Angular response for S-Cs: 0º, 45º and 60º

(6) Angular response for beta radiation: ^{90}Sr-^{90}Y (0º, ± 30º, ± 60º), ^{85}Kr (0º, ± 30º)

(7) Influence of dose equivalent rate (relative response at 1.00 Sv/h and 1.00 mSv/h).

Note: The beta energy and angular response was only checked for devices sensitive to beta radiation.

4.4. Work-place simulation performance tests

To investigate the APD response in simulated work-place fields the following additional irradiation fields were used:

(1) Pulsed fields defined in IEC 61267 [24], pulse width of 1600 ms; 16 mAs; 60 kV (RQR4) and 120 kV (RQR9)

(2) Mixed photon field: S-Cs and N-80 for normal incidence.

5. IRRADIATION LABORATORIES

5.1. Nuclear Calibration Laboratory at the Belgian Nuclear Research Center (SCK-CEN)

5.1.1. General

The Belgian Nuclear Research Centre (SCK-CEN) is a foundation of public utility employing about 600 people, of which one third has an academic degree. The statutory mission gives the priority to research on problems of societal concern:

- Safety of nuclear installations.
- Radiation protection.
- Safe treatment and disposal of radioactive waste.
- Fight against uncontrolled proliferation of fissile materials.

The available know-how and infrastructure are also used for services to industry and for training.

The Nuclear Calibration Laboratory is part of the radiation protection division and operates several radioactive sources for the calibration of a wide range of nuclear equipment. The available sources are also used when very precise dose/dose rate irradiations are needed for research purposes. For the calibration of neutron monitors and devices sensitive to gamma-, X or beta rays, the laboratory uses:

- Three ^{252}Cf sources.
- Six ^{60}Co and five ^{137}Cs sources.
- A 250 kV X ray equipment.
- An EPD irradiator (Siemens) containing ^{241}Am and ^{36}Cl.
- A Buchler beta standard with ^{90}Sr/^{90}Y and ^{204}Tl sources.

5.1.2. Irradiation facilities and equipment

For the intercomparison the following installations and sources were used:

- ^{137}Cs and ^{60}Co in the horizontal beam (Figure 5.1),
- ^{60}Co in the vertical beam (Figure 5.2),
- a combined field of the ^{137}Cs of the panoramic beam (Figure 5.3) and the N-80 quality of the X ray machine (Figure 5.4).

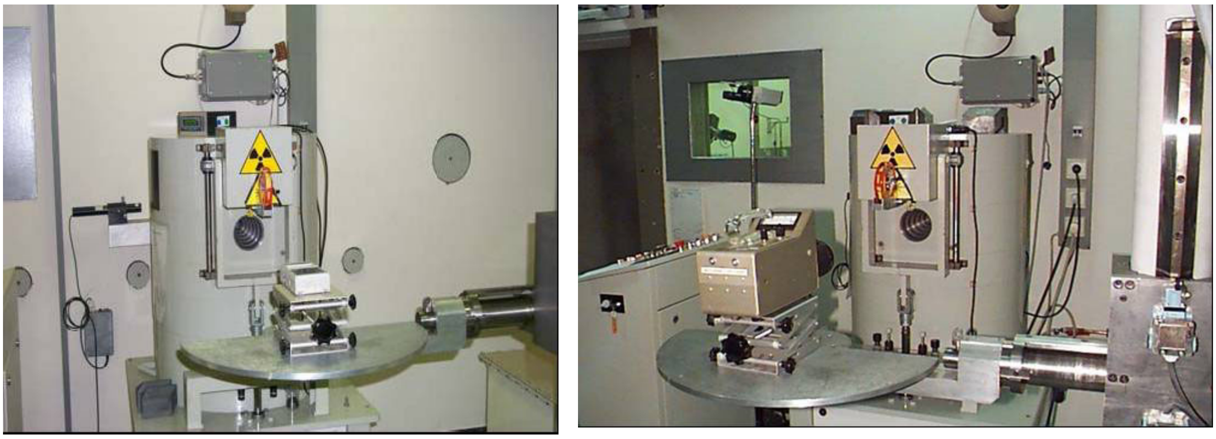


Figure 5.1 ^{137}*Cs horizontal beam.*

Figure 5.2 ^{60}*Co vertical beam.*

Figure 5.3 Panoramic beam.

Figure 5.4 XR tube.

5.1.3. Traceability and quality assurance

All sources are traceable to primary standards. For gamma- and X ray sources the traceability is assured by means of a primary calibrated ionization chamber. Photon beam calibration is performed in accordance with ISO 4037-1, 4037-2 and 4037-3

The quality assurance (QA) system that is operated at the Nuclear Calibration Laboratory forms part of the overall system used at SCK-CEN. This entails secured access to files, procedures and instructions in which the different steps of a calibration are systematically and unambiguously described. The calibration equipment is periodically checked and calibrated. The traceability to primary standards and the accuracy analysis are described in a validation report. In this way, the QA system guarantees complete traceability and sustainable quality. The Belgian Nuclear Research Center was the first Belgian institute for nuclear research and development to obtain the ISO17025 accreditation through the Beltest and BKO (Belgian Calibration Organization) organizations.

An accreditation of the Belgian Calibration Organization is available for the gamma irradiations performed with the horizontal, vertical and panoramic beam, and for irradiations with neutrons and the Siemens irradiator for the calibration of the Siemens EPD's.

- quantities: K_{air}, $H^*(10)$, $H_p(10)$ and $H_p(0.07)$,
- energy range: ^{137}Cs and ^{60}Co,
- dose equivalent rate range: $H_p(10)$: from 3 μSv.h^{-1} to 3 Sv.h^{-1} for ^{60}Co, from 8 μSv.h^{-1} to 2 Sv.h^{-1} for ^{137}Cs.

5.1.4. Uncertainties

The relative uncertainties associated to the reference quantities $H_p(10)$ for the sources used in the intercomparisons are ±4.6% for ^{137}Cs beams; ±4.6% for ^{60}Co horizontal beams; ±4.7% for ^{60}Co vertical beams; ±6.1% for ^{137}Cs and N-80 mixed field (k=2).

5.2. Laboratory of ionizing radiation dosimetry at the Institute for Radiological Protection and Nuclear Safety (IRSN)

5.2.1. General

The Institute for Radiological Protection and Nuclear Safety (IRSN) field of expertise covers all the risks related to ionizing radiation used within industry or medicine, or even natural radiation. More precisely, the IRSN is carrying out missions relating to analysis and research in the following fields:

- Safety of nuclear installations, including those relating to defence.
- Safety of the transport of radioactive and fissile materials.
- Protection of man and environment against ionizing radiation.
- Protection and control of nuclear materials and products likely to be used in the manufacture of weapons.
- Protection of installations and transport against acts of malevolence (theft or misappropriation of nuclear materials, or even sabotage).

Research activities, most often carried out within the framework of international programmes, enable the IRSN to maintain and to develop its expertise.

The laboratory of ionizing radiation dosimetry is located in Fontenay-aux-Roses and is composed of eleven people.

The activities of this laboratory consist in:

- performing studies, research and expertise in the field of the assessment of the dose received by individuals for usual practices and in case of accidents (external exposure): development of tools (instruments, software) and methods;
- operating facilities producing beta, gamma and X ray reference beams, COFRAC-accredited activity:
  - for the needs of research and studies carried out in the laboratory,
  - for the calibration or the qualification of radiation protection instruments.

5.2.2. Irradiation facilities and equipment

For the intercomparison, some beam qualities indicated in ISO standard 4037-1 were applied (N-80, N-120, N-30, S-Co and S-Cs).

Three types of installations were used:

- X ray generator ISOVOLT HS 320 kV (SEIFERT) for N-80 and N-120 beam qualities (Figure 5.5),
- X ray generator 100 kV (PHILIPS) for N-30 beam quality (Figure 5.6),
- Gamma irradiator containing two sources (Figure 5.7): ^{137}Cs (1 TBq in May 2005) and ^{60}Co (0.35 TBq in May 2005).

Figure 5.5 X ray generator ISOVOLT HS 320 kV (SEIFERT) used for N-80 and N-120 beam qualities.

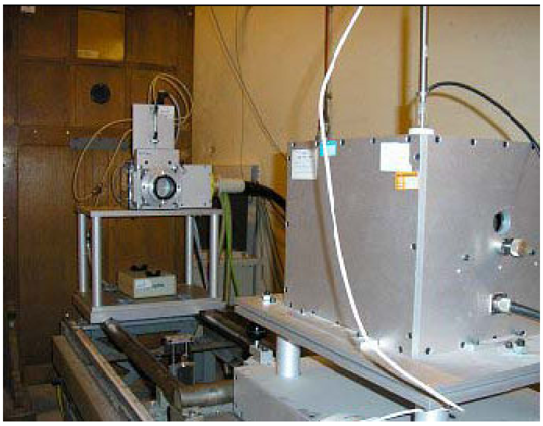


Figure 5.6 X ray generator 100 kV (PHILIPS) used for N-30 beam quality.

Figure 5.7 Irradiator containing two photon sources (^{137}Cs and ^{60}Co).

5.2.3. Traceability and quality assurance

The ionization chambers used for the calibration of the X ray and gamma (^{137}Cs and ^{60}Co) beams are linked to the French primary reference laboratory every 3 years.

The last calibration was made in May 2003 for the cavity chamber ”Victoreen” n°415 C n°46 and the free air chamber SDOS98.

The metrology laboratory is accredited by the French accreditation committee (COFRAC) according to the ISO standard 17025 (accreditation COFRAC – calibration section number 2-1612).

This accreditation is given in the field of ionizing radiation for:

- quantities: X, K_{air}, $H^*(10)$, $H'(0.07)$, $H_p(10)$ and $H_p(0.07)$,
- energy range: between 8 keV to 300 keV for X rays and for ^{137}Cs and ^{60}Co,
- dose equivalent rate range: from 50 µSv.h^{-1} to 8 Sv.h^{-1} for X rays, from 1 µSv.h^{-1} to 25 Sv.h^{-1} for ^{60}Co, from 1 µSv.h^{-1} to 120 mSv.h^{-1} for ^{137}Cs.

5.2.4. Uncertainties

The relative uncertainties associated to the reference quantities $H_p(10)$ and $H_p(0.07)$ are ±4.3% for X ray and ^{137}Cs beams; and ±4.2% for ^{60}Co beams (k=2).

5.3. Laboratoire National Henri Becquerel (LNE-LNHB) at the Commissariat à l'Energie atomique (CEA/LIST)

The Laboratoire National Henri Becquerel (LNHB) is the French National Metrology Laboratory for ionizing radiation since 1969, date of creation of the Bureau National de Métrologie (BNM). According to the reorganization of French metrology in 2005, the BNM was replaced by the Laboratoire National de métrologie et d'Essais (LNE) as National Metrology Institute. In this frame, the LNHB is today one of the four French national laboratories, federated by the LNE to cover the entire domains of metrology (time, length, mass, electricity, and others).

The LNHB is in charge of the metrology of absorbed dose and activity. At present, it operates (i) a Manganese-bath for neutron primary standard of flux; (ii) ^{60}Co and ^{137}Cs collimated beams for radiation protection and radiotherapy; (iii) high-energy RX photons and electrons from a LINAC for external radiotherapy; (iv) ^{192}Ir HDR and PDR for brachytherapy; (v) soft X rays for diagnosis, mammography and industry; and (vi) beta radiation fields for radiation protection purposes of workers and patients.

The mains tasks of the LNHB are (i) to maintain the existing references at the best level; (ii) to create new references meeting the needs of the society for health and industry; and (iii) to transfer the references to the users through Secondary Standard Labs (SSL) or directly when commercial services do not exist. The LNHB is accredited by the French accreditation body (COFRAC) to ISO 17025 and participates in the Mutual Recognition Arrangement (MRA) between National Metrology Institutes.

5.4. Irradiation facilities and equipment

For this comparison, it has been proposed to use two kinds of radiation fields (i) diagnostic pulsed X rays beams and (ii) beta radiation fields. The following tables 5.1 and 5.2 show the characteristics of these radiations fields.

Table 5.1. Soft X ray radiation field characteristics

Radiation quality	High voltage	Mean energy (kerma weighted)	HVL (mm Al)
RQR4	60 kV	31.6 keV	2.0
RQR9	120 kV	48.8 keV	4.5

Radiation quality	Pulse width (ms)	mAs	Averaged conversion coefficient from air kerma to personal dose equivalent	Personal dose equivalent $H_p(10,0°)$ mSv	Personal Dose equivalent rate $\dot{H}_p(10,0^o)$ Sv/h
RQR4	1600	16	1.098	0.75	1.68
RQR9	1600	16	1.485	0.66	1.49

The medical X ray generator is a MPH65 (GEMS). The RQR definition can be found in the standard IEC 61267. The primary reference has been established in terms of air kerma using a free air chamber (MD03) specially designed for energies up to 150 keV (Figure 5.8). The reference value in terms of personal dose equivalent at $H_p(10,0°)$ has been calculated by multiplying the air kerma by the corresponding average conversion coefficient.

The average conversion coefficient from air kerma free in air to personal dose equivalent, has been derived from individual conversion coefficients taken from ICRU 57 [25], combined with X ray fluence spectra calculated using the software Xcomp5 [26] (Figure 5.9).

Figure 5.8 Diagnostic X ray facility, on the right hand side the specially designed free air chamber used for measuring the air kerma.

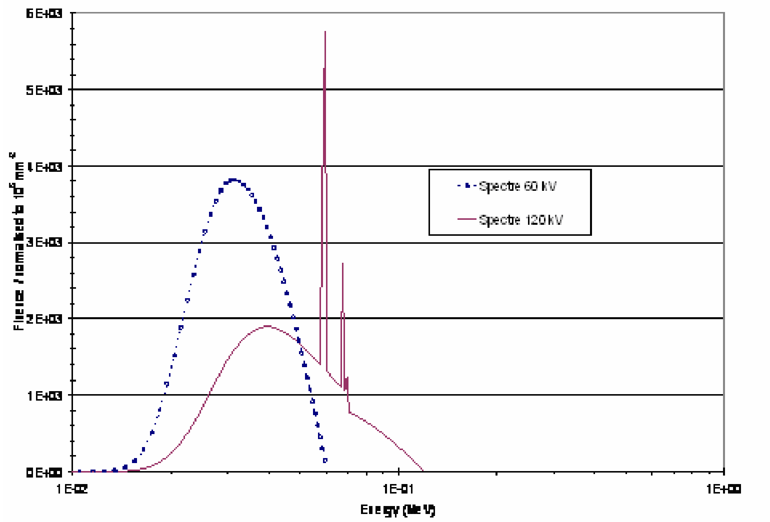


Figure 5.9 Example of fluence spectra for RQR4 and RQR9 radiation qualities.

Table 5.2. Beta radiation field characteristics [13, 14, 15]

Radionuclide	Maximum energy	Irradiation distance	$H_p(0.07,0°)$ target values
^{90}Sr-^{90}Y	2.274 MeV	30 cm	1 mSv
^{85}Kr	0.687 MeV	30 cm	1 mSv
^{147}Pm	0.225 MeV	20 cm	1 mSv

Radionuclide	Calibration distance cm	Source to filter distance cm	Filter material and dimensions
^{147}Pm	20	10	One disc of polyethylene terephthalate, of radius 5 cm and mass per unit area 14 mg cm^{-2}, with hole of radius 0.975 cm at centre
^{85}Kr	30	10	Two concentric discs, 1 disc of polyethylene terephthalate, of 4 cm radius and mass per unit area 7 mg cm^{-2}, plus one disc of polyethylene terephthalate, of 2.75 cm radius and mass per unit area 25 mg cm^{-2}
$^{90}Sr + ^{90}Y$	30	10	Three concentric discs of polyethylene terephthalate, each with mass per unit area of 25 mg cm^{-2} and of radii 2 cm, 3 cm and 5 cm

A BSS2 irradiator is operated with improved distance measurements. Reference radiation source characteristics are specified in ISO 6980-1. The sources used for this comparison were taken from the series 1, this means that beam flattening filters (described in Table 5.2) were used to produce a uniform dose rate over an area of about 15 cm in diameter, e.g. for the calibration of a number of individual dosimeters simultaneously. Despite this possibility, only one dosimeter was irradiated at a time.

French reference values have been measured in terms of $D_t(0.07; \text{source}; 0°)$ according to the standard ISO 6980-2 using an extrapolation chamber. It is assumed than the conversion coefficient $h_{p,D}(0.07; \text{source}; 0°)$ from $D_t(0.07; \text{source}; 0°)$ to $H_p(0.07; \text{source}; 0°)$ is equal to 1 Sv/Gy.

All irradiations were carried out on ISO water slab phantom as defined in ISO standard for whole body dosimeters, the point of reference of the dosimeter being placed at the point of test at which the conventional true value of the quantity to be measured is known.

The ISO water slab phantom is of outer dimensions 30 cm x 30 cm x 15 cm made of PMMA walls (front wall 2,5 mm thick, other walls 10 mm thick) filled with water.

The relative uncertainties associated to the reference quantities $H_p(10)$ and $H_p(0.07)$ are given in Table A-3.

6. SUPPLIERS

Nine suppliers with 13 different models participated in the intercomparison. Table 6.1 shows the list of participants. Table A-4 in the annex gives more details on the nominal basic characteristics of the devices: energy and angle response, dose rate measurement range and weight.

Table 6.1. List of participants

Manufacturer	Type	Quantity Measured
Atomtex	AT2503 AT3509B	$H_p(10)$ $H_p(10)$, $H_p(0.07)$
Eurisys/Canberra	DOSICARD	$H_p(10)$
Graetz Strahlungsmesstechnik	ED150	$H_p(10)$
Polimaster	PM1604A PM1621	$H_p(10)$ $H_p(10)$
Science Applications International Corporation (SAIC)	PD-12i	$H_p(10)$
Synodys Group GP Instruments SA	DMC2000S DMC2000X DMC2000XB	$H_p(10)$ $H_p(10)$ $H_p(10)$, $H_p(0.07)$
Synodys Group Rados Technology OY	RAD-60S	$H_p(10)$
Thermo Electron Corporation	EPD Mk2.3	$H_p(10)$, $H_p(0.07)$
Unfors	NED-30	$H_p(0.07)$

Figures 6.1. and 6.2. show, respectively, a photograph of the 13 participating APD and some examples of irradiation set-up.

Figure 6.1 Photograph of the 13 APD participating in the intercomparison.

Figure 6.2 Examples of irradiation set-up.

7. RESULTS

IEC 61526 requirements have been applied, in general, for the evaluation of the tested APD. The analysis of results also takes into account the general dosimetric requirements established by ICRP [16, 27] and represented by the so-called "trumpet curves" [28]. In particular these general criteria are the only available for the evaluation of the measurements in pulsed radiation and mixed fields.

In each irradiation condition, three units of the same type of dosimeter were tested. Five repeated readings were then performed in each point of test for one of the three available units of each type of dosimeter. To evaluate the performance of the dosimeters the following parameters were calculated:

Response: It is the ratio between the dosimeter reading and the conventional true value for the point of test.

$$\text{Response} = \frac{\frac{1}{3}\sum_{i=1}^{3} L_i}{H_{pt}(d)} \qquad (1)$$

Where: L_i is the first reading of each of the 3 different units of each type of dosimeter.

H_{pt}(d) is the conventional true value for the personal dose equivalent at the point of test.

Reproducibility: It quantifies the reproducibility in response between different units of the same type of dosimeter. It is calculated as:

$$\text{Reproducibility} = \frac{\sqrt{\frac{1}{2}\sum_{j=1}^{3}\left(L_j -_i \frac{1}{3}\sum_{i=1}^{3} L_i\right)^2}}{\frac{1}{3}\sum_{i=1}^{3} L_i} 100 \qquad (2)$$

Where: L_i is the first reading of each of the 3 different units of each type of dosimeter.

Repeatability: It quantifies the repeatability in response of one unit. It is calculated from the 5 readings in each point of test, as follows:

$$\text{Repeatability} = \frac{\sqrt{\frac{1}{4}\sum_{j=1}^{5}\left(L_j - \frac{1}{5}\sum_{k=1}^{5} L_k\right)^2}}{\frac{1}{5}\sum_{k=1}^{5} L_k} 100 \qquad (3)$$

Where: L_k are different readings of a single dosimeter.

Relative response: It is the ratio between the dosimeter response calculated using expression (1) and the dosimeter response for some reference conditions.

The reference energy considered in the tables for the energy response test is S-Cs for $H_p(10)$; N-120 for $H_p(0.07)$ for photon and $^{90}Sr/^{90}Y$ for $H_p(0.07)$ for beta radiation.

The reference angle for the angular response test is a normal incidence.

In the dose equivalent rate influence test data, the response at high energy rate has been referred to the 1 mSv/h response.

The results of each dosimeter are summarized in several tables which indicate the tested influence quantity, the dosimeter response, the reproducibility, the repeatability and the relative response as defined above. A separate table is provided for IEC and non-IEC tests. When available, different tables are presented for $H_p(10)$ and $H_p(0.07)$ and for photon and beta radiation.

The overall results of each dosimeter are represented using the "trumpet curve" representation, where H_{pt} (mSv) stands for the conventionally true value for $H_p(d)$ and the response is calculated as the ratio between the dosimeter reading H_{pm} and the conventionally true value H_{pt}.

For the pulsed radiation tests and the dose equivalent rate influence test only $H_p(10)$ was evaluated. Moreover, for S-Cs and S-Co radiation qualities, a reference value for $H_p(0.07)$ is not available due to the lack of charged particles electronic equilibrium. Exceptionally, for the UNFORS NED extremity dosimeter which only indicates $H_p(0.07)$ but is meant to be used in the energy range (140 keV, 1200 keV), $H_p(0.07)$ is considered to be numerically equal to $H_p(10)$, in agreement with Grosswendt conversion coefficients [29].

Only those tests which were within the dosimeter performance characteristics have been included in the IEC-test tables. In the case of non-IEC test results all measurements are indicated in the tables and figures. However, whenever the device gave a reading outside the recommended range of the dosimeter in terms of energy and dose equivalent rate, the value in the table is shaded and the test is noted with an asterisk in the figure. These readings should be interpreted with caution.

On one hand, for RQR4 pulsed radiation quality, an energy threshold of 50 keV is high enough for prohibiting any reliable measurement because the maximum energy of the photon in this beam is about 60 keV. This is not the case for RQR9 quality because the upper part of the spectrum (up to 120 keV) lies above this threshold. Due to that, the response of a dosimeter having such an energy threshold could be less than one but the radiation should still be measurable.

On the other hand, when the dose equivalent rate of the radiation field is higher than the maximum dose equivalent rate acceptable by the dosimeter, one cannot rely on the results. Sometime the reading is 0, sometime it is "overload", sometime the variation from one reading to another is so large that there is no link with the dose equivalent value, thus in this case the response could not be assessed properly.

8. SUMMARY OF THE PERFORMANCE OF EACH TESTED PERSONAL DOSIMETER

8.1. ATOMTEX AT2503

Table 8.1. IEC tests for photon response – $H_p(10)$

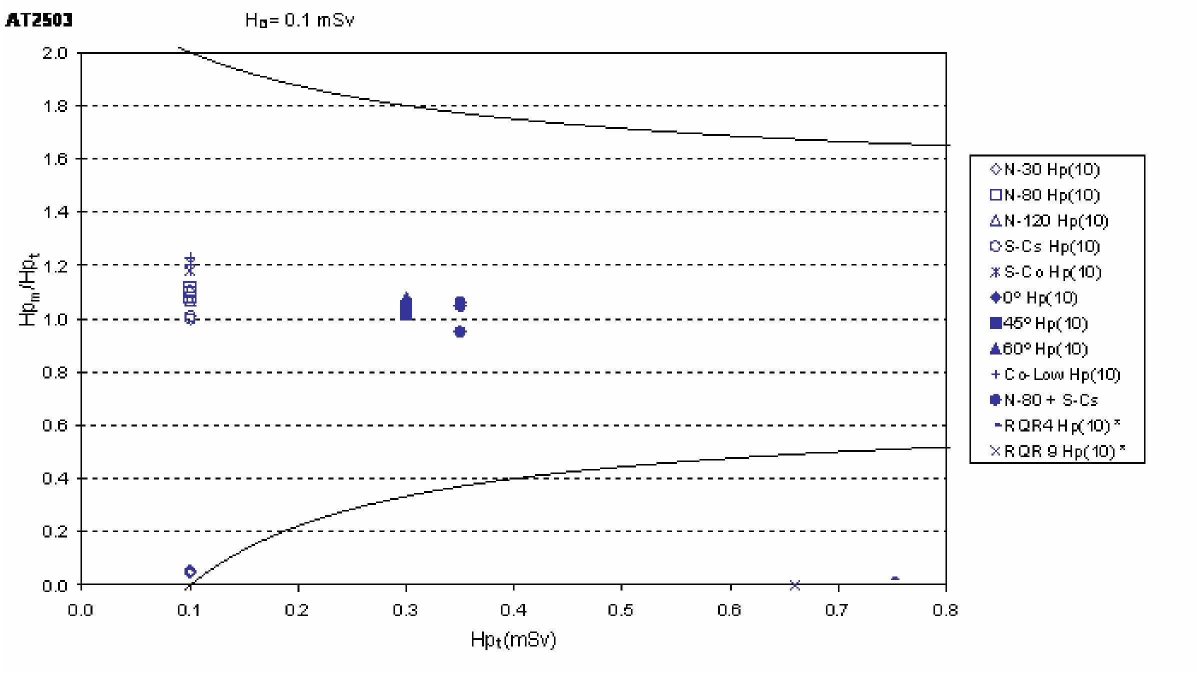
Influence quantity	Response	Reproducibility	Repeatability	Relative response
Quality of radiation (normal incidence)				**(R.R. to S-Cs)**
N-80	1.10	1.8	0.8	1.10
N-120	1.10	2.1	0.4	1.09
S-Cs	1.00	0.6	0.5	1.00
S-Co	1.20	1.4	0.4	1.20
Angle of incidence (degrees). S-Cs				**(R.R. to 0º)**
0	1.06	1.3	0.6	1.00
45	1.02	1.1	0.9	0.97
60	1.07	1.3	0.7	1.01
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	1.22	1.4	0.6	1.00
1 Sv/h (1)	1.12	21	0.7	0.91

(1) The personal dose equivalent rate of this field is higher than the available range for this APD but the observed performance is within the Standard requirement.

Table 8.2. Non-IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	1.02	6	0.27	1.02
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4) (1)	--	--	--	--
120 kV (RQR9) (1)	--	--	--	--

(1) The personal dose equivalent rate of this field is higher than the available range for this APD. The device indicated 0.



(+) The energy threshold of the dosimeter is 48 keV, thus N-30 and RQR4 are outside the device energy measuring range.
(*) The personal dose equivalent rate of this field is higher than the available range for this APD.

Figure 8.1 Trumpet curve for ATOMTEX AT2503 for $H_p(10)$.

ATOMTEX AT2503 is meant to measure $H_p(10)$ for X and gamma radiation, it belongs to IEC third “category”. It fulfils IEC 61526 testing requirements for penetrating radiation (80 keV to 1.5 MeV). It is not sensitive to N-30 radiation quality.

As regards workplace simulation performance test it measures satisfactorily in a mixed photon energy field (N-80 + S-Cs). Concerning the pulsed radiation fields, the maximum dose equivalent rate claimed by the manufacturer (0.5 Sv/h) is not high enough for measuring the dose rates in the pulsed radiation fields used for this comparison.

The dosimeters dose equivalent rate range does not cover the IEC recommended range (see [9]).

The dosimeter response is within the “trumpet” curve limits for penetrating photon radiation.

8.2. ATOMTEX AT3509B

Table 8.3. IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-30	1.02	0.6	0.8	1.04
N-80	0.94	2.5	0.4	0.96
N-120	0.87	2.9	0.13	0.90
S-Cs	0.98	4	0.21	1.00
S-Co	0.85	3	0.7	0.87
Angle of incidence. S-Cs				**(R.R. to 0º)**
0	0.98	4	0.20	1.00
45	0.93	5	0.5	0.95
60	0.96	6	0.4	0.98
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	0.87	4	1.0	1.00
1 Sv/h	0.89	2.6	0.3	1.02

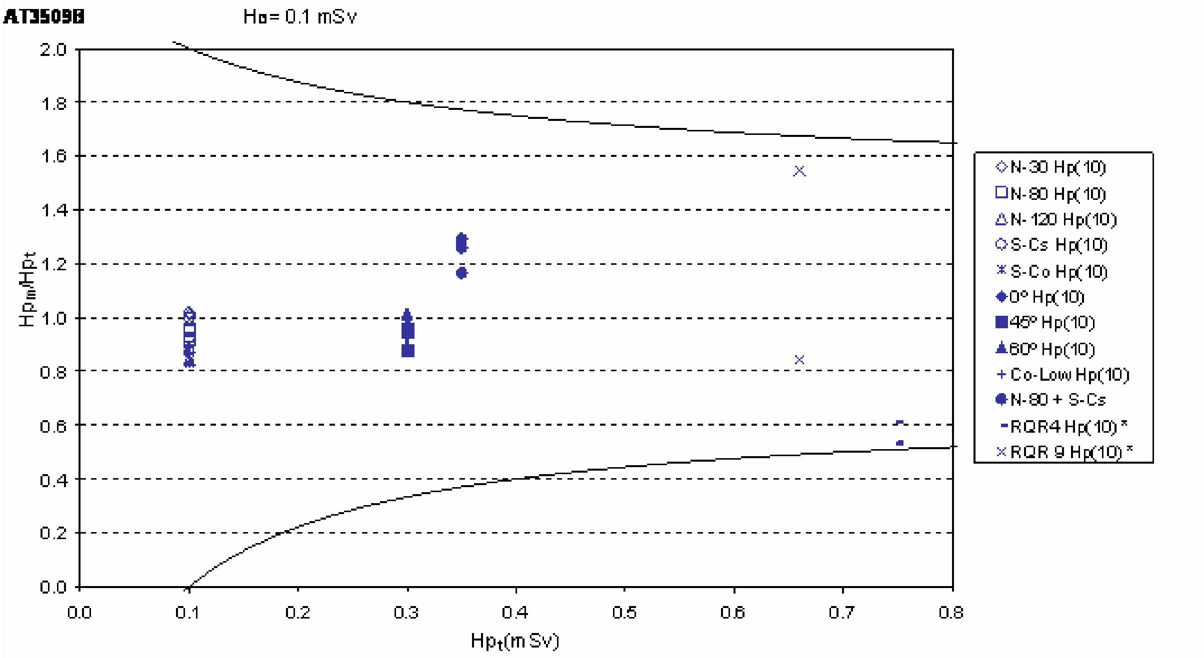
Table 8.4. IEC tests for photon response – $H_p(0.07)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to N-120)**
N-30	0.91	4	0.4	0.78
N-80	1.05	2.6	0.7	0.90
N-120	1.16	1.9	0.5	1.00

Table 8.5. Non-IEC tests for photon response – $H_p(10)$

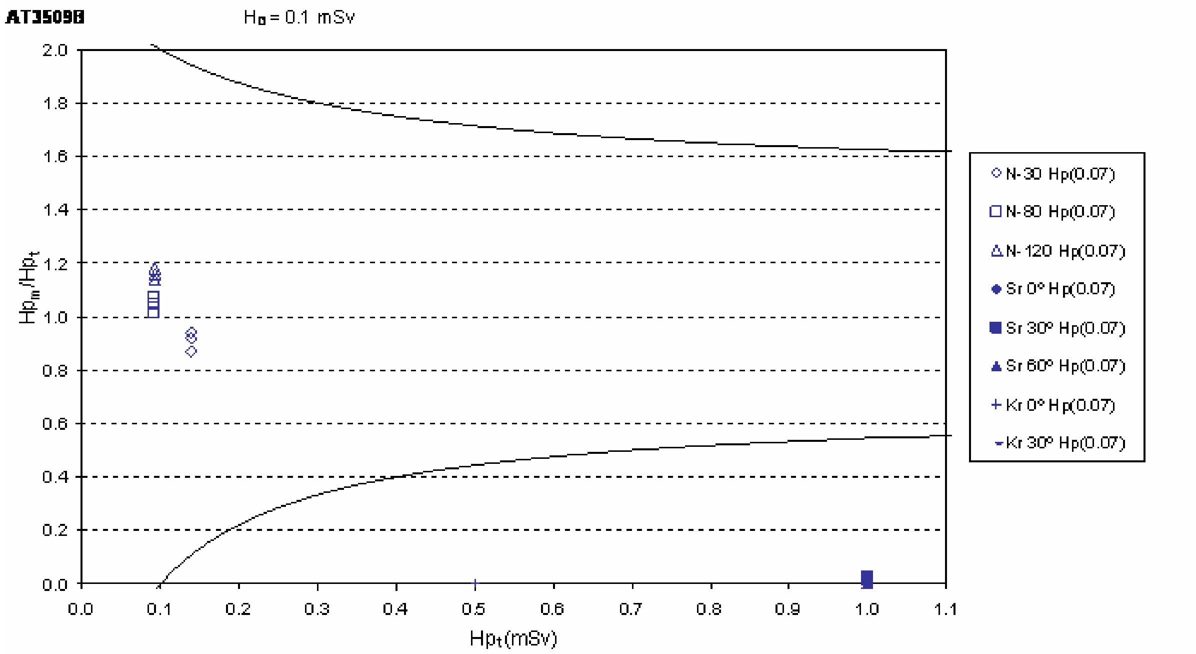
Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	1.24	5	0.5	1.27
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4)(1)	0.7	36	162	---
120 kV (RQR9) (1)	6.5	142	23	---

(1) The personal dose equivalent rate of this field is higher than the available range for this APD. A large variability in the readings was observed.



(*) The personal dose equivalent rate of this field is higher than the available range for this APD. The readings obtained for this quality are to be interpreted with caution. Some of the readings obtained in the pulsed radiation fields are not represented because they are out of the graph scale.

Figure 8.2. Trumpet curve for ATOMTEX AT3509B for $H_p(10)$.



(*) According to manufacturer specifications this APD is not sensitive to beta radiation.

Figure 8.3 Trumpet curve for ATOMTEX AT3509B for $H_p(0.07)$.

ATOMTEX AT3509B is meant to measure $H_p(10)$ and $H_p(0.07)$ for X and gamma radiation, it belongs to IEC first “category”. It fulfils IEC 61526 testing requirements for penetrating and non penetrating radiation (20 keV to 1.5 MeV). As regards workplace simulation performance tests, it measures satisfactorily in a mixed photon energy field (N-80+S-Cs) and is sensitive to 60 kV and 120 kV pulsed radiation. However, the response for RQR9 and RQR4 qualities could not be assessed properly due to the available dose equivalent rate for these qualities which are higher than the dosimeters dose equivalent rate range.

It was verified that the dosimeter is not appropriate for beta radiation measurement.

The dosimeter response is within the “trumpet” curve limits for photon radiation, except for the tested pulsed radiation fields.

8.3. CANBERRA DOSICARD

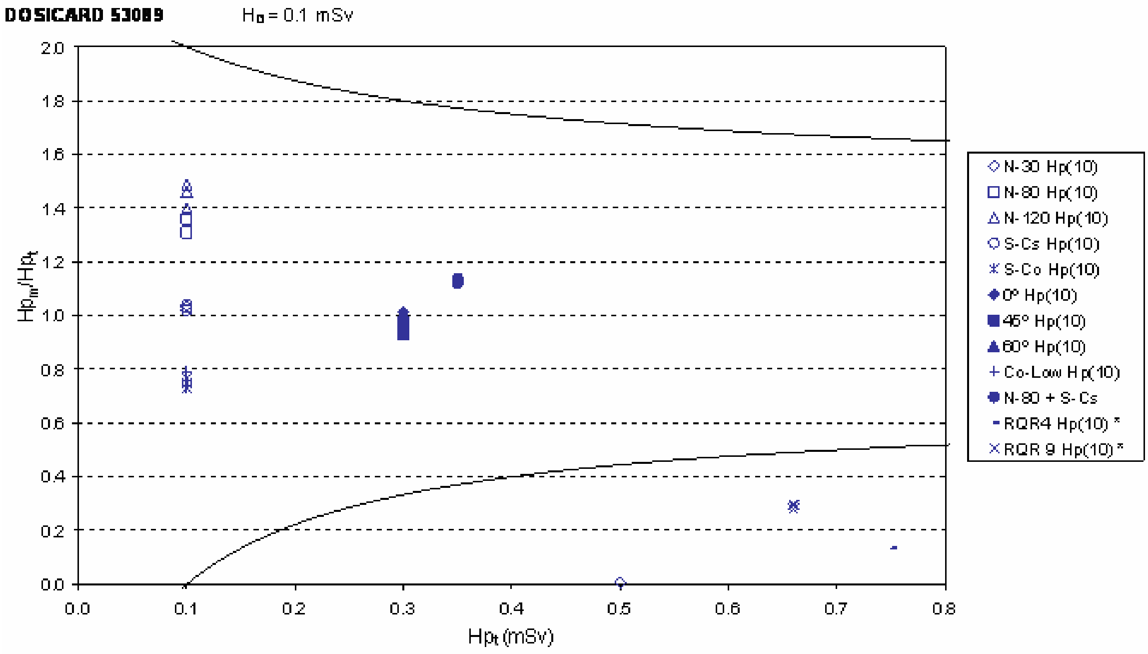
Table 8.6. IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-80	1.33	2.2	1.2	1.29
N-120	1.45	3.2	1.1	1.41
S-Cs	1.03	1.0	1.3	1.00
S-Co	0.75	2.7	1.7	0.73
Angle of incidence, S-Cs				**(R.R. to 0º)**
0	1.00	1.1	0.6	1.00
45	0.96	1.5	0.4	0.96
60	0.95	1.2	0.0	0.95
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	0.76	3	1.3	1.00
1 Sv/h	0.54	1.9	0.0	0.71

Table 8.7. Non-IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	1.13	0.8	0.3	1.10
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4) (1)	0.13	---	0	---
120 kV (RQR9) (1)	0.29	2.7	2.0	0.28

(1) The energy threshold of the dosimeter is 60 keV, thus RQR4 lies outside the device energy measuring range. In addition to that the maximum dose equivalent rate of the radiation field is higher than the available range for this APD.



(*) The energy threshold of the dosimeter is 60 keV, thus N-30, RQR4 and partially RQR9 are outside the device energy measuring range. In addition to that the maximum dose equivalent rate of the pulsed radiation fields is higher than the available range for this APD.

Figure 8.4. Trumpet curve for CANBERRA DOSICARD for $H_p(10)$

CANBERRA DOSICARD is meant to measure $H_p(10)$ for X and gamma radiation, it belongs to IEC third “category”.

According to IEC 61526, the variation of the relative response due to dose equivalent rate dependence shall not exceed ± 20% for all dose rates from 0.5 µSv/h to 1 Sv/h. If this requirement cannot be met up to 1 Sv/h, it shall be met up to at least 100 mSv/h. This dosimeter does not meet the requirement for 1 Sv/h but unfortunately its response at 100 mSv/h has not been verified.

CANBERRA DOSICARD fulfils IEC 61526 testing requirements for penetrating radiation (80 keV to 1.5 MeV). DOSICARD is not sensitive to N-30 radiation quality.

As regards workplace simulation performance tests, it measures satisfactorily in a mixed photon energy field (N-80 + S-Cs), but detects less than 30 % of the reference dose equivalent contribution from 120 kV (RQR9) pulsed radiation field, and less than 20 % of the 60 kV (RQR4) pulsed radiation field. These results are due to both energy threshold and maximum available dose equivalent rate of the dosimeter.

The dosimeter response is within the “trumpet” curve limits for penetrating photon radiation.

8.4. GRAETZ ED150

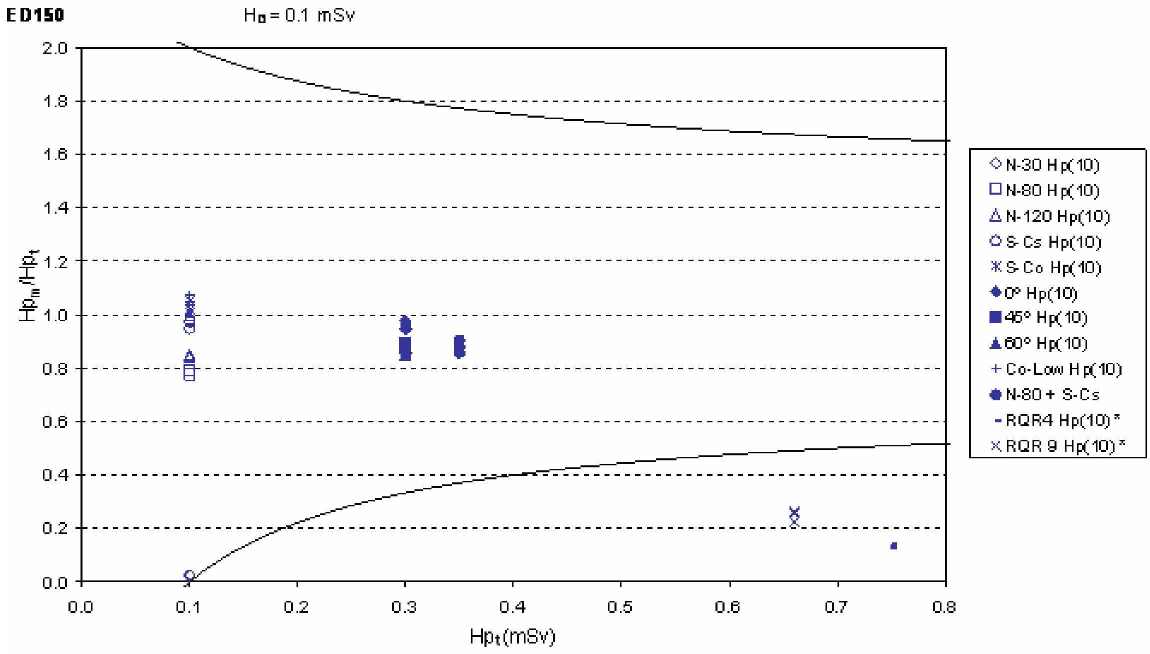
Table 8.8. IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-80	0.79	1.1	0.4	0.81
N-120	0.90	10	1.0	0.93
S-Cs	0.97	1.6	0.3	1.00
S-Co	1.03	2.2	0.4	1.06
Angle of incidence. S-Cs				**(R.R. to 0º)**
0	0.96	1.6	0.5	1.00
45	0.89	0.8	0.21	0.93
60	0.86	1.6	0.28	0.90
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	1.05	1.8	0.6	1.00
1 Sv/h	1.05	1.4	0.15	1.00

Table 8.9. Non-IEC tests for photon response – Hp(10)

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	0.88	2.6	0.0	0.91
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4)(1)	0.13	5	7	0.17
120 kV (RQR9) (1)	0.25	8	18	0.26

(1) The energy threshold of the dosimeter is 50 keV, thus RQR4 lies outside the devices energy measuring range. RQR9 should be partially detected. The maximum dose equivalent rate of the pulsed radiation fields is of the order of the maximum available range for this APD.



(*) The energy threshold of the dosimeter is 50 keV, thus N-30, RQR4 are outside the devices energy measuring range. RQR9 should be partially detected.

Figure 8.5. Trumpet curve for GRAETZ ED150 for $H_p(10)$

GRAETZ ED150 is meant to measure $H_p(10)$ for X and gamma radiation, it belongs to IEC third "category". It fulfils IEC 61526 testing requirements for penetrating radiation (80 keV to 1.5 MeV). It is not sensitive to N-30 and RQR4 radiation qualities.

As regards workplace simulation performance test it measures satisfactorily in a mixed photon energy field (N-80+S-Cs) but detects 25 % of the reference dose equivalent contribution from 120 kV (RQR9) pulsed radiation fields.

The dosimeter response is within the "trumpet" curve limits for penetrating photon radiation.

8.5. MGP DMC2000S

Table 8.10. IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-80	1.09	1.8	0.8	1.09
N-120	0.95	1.1	0.9	0.95
S-Cs	1.00	1.5	1.4	1.00
S-Co	0.83	1.4	0.5	0.82
Angle of incidence. S-Cs				**(R.R. to 0º)**
0	1.00	0.5	0.8	1.00
45	1.04	1.4	0.4	1.05
60	1.07	1.3	0.18	1.08
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	0.85	1.2	0.7	1.00
1 Sv/h	0.89	0.8	0.06	1.05

Table 8.11. Non-IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	1.00	1.0	0.4	0.99
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4) (1)	0.36	2.2	1.0	0.44
120 kV (RQR9) (1)	1.13	2.0	1.0	1.13

(1) The energy threshold of the dosimeter is 50 keV, thus RQR4 and partially RQR9 are outside the device energy measuring range.

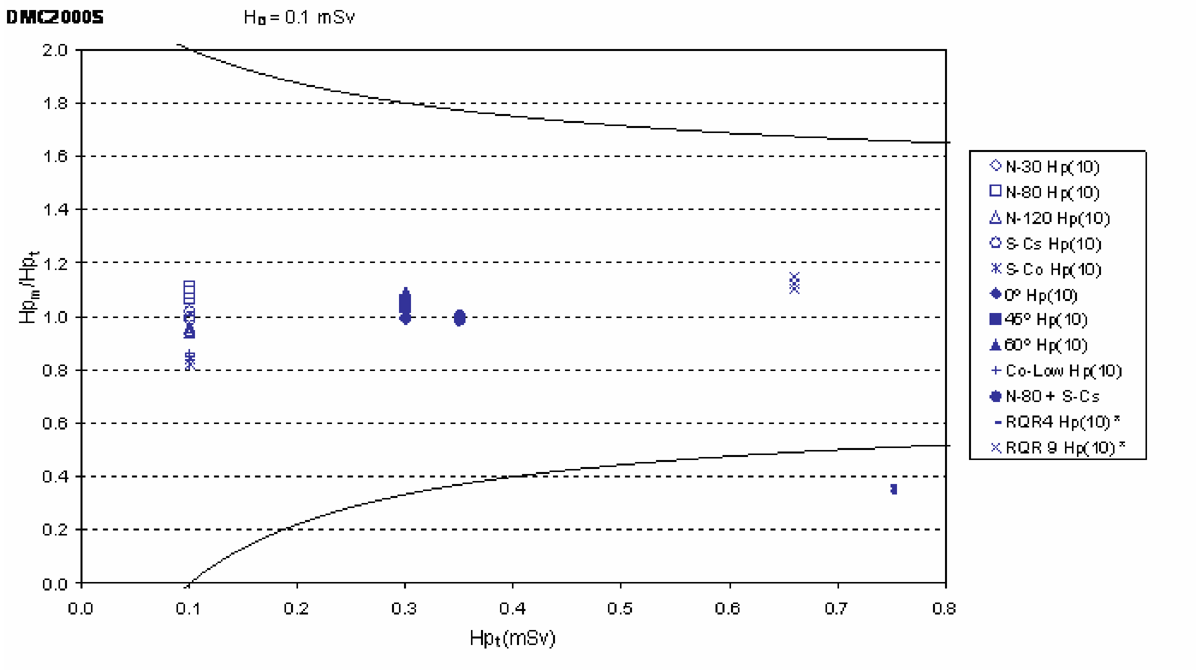


Figure 8.6. Trumpet curve for MGP DMC 2000S for $H_p(10)$.

MGP DMC2000S is meant to measure $H_p(10)$ for X and gamma radiation, it belongs to IEC third "category". It fulfils IEC 61526 testing requirements for penetrating radiation (80 keV to 1.5 MeV). It is not sensitive to N-30 radiation quality. As regards workplace simulation performance tests, it measures satisfactorily in a mixed photon energy field (N-80+S-Cs) and in a 120 kV (RQR9) pulsed radiation field despite the energy threshold of the dosimeter (50 keV). The 60 kV (RQR4) pulsed radiation field is not correctly quantified because of the energy threshold of the dosimeter (50 keV).

The dosimeter response is within the "trumpet" curve limits for penetrating photon radiation.

8.6. MGP DMC2000X

Table 8.12. IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-30	0.77	10	1.7	0.79
N-80	1.05	1.4	0.4	1.09
N-120	0.92	1.9	1.0	0.95
S-Cs	0.97	1.0	0.9	1.00
S-Co	0.84	1.4	1.3	0.87
Angle of incidence. S-Cs				**(R.R. to 0º)**
0	0.96	0.5	0.7	1.00
45	0.96	0.9	0.9	1.00
60	0.99	1.2	0.3	1.03
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	0.86	2.4	1.8	1.00
1 Sv/h	0.91	0.8	0.06	1.06

Table 8.13. Non-IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	0.97	2.1	0.6	1.00
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4)	0.85	6	6	0.88
120 kV (RQR9)	1.20	2.6	1.9	1.24

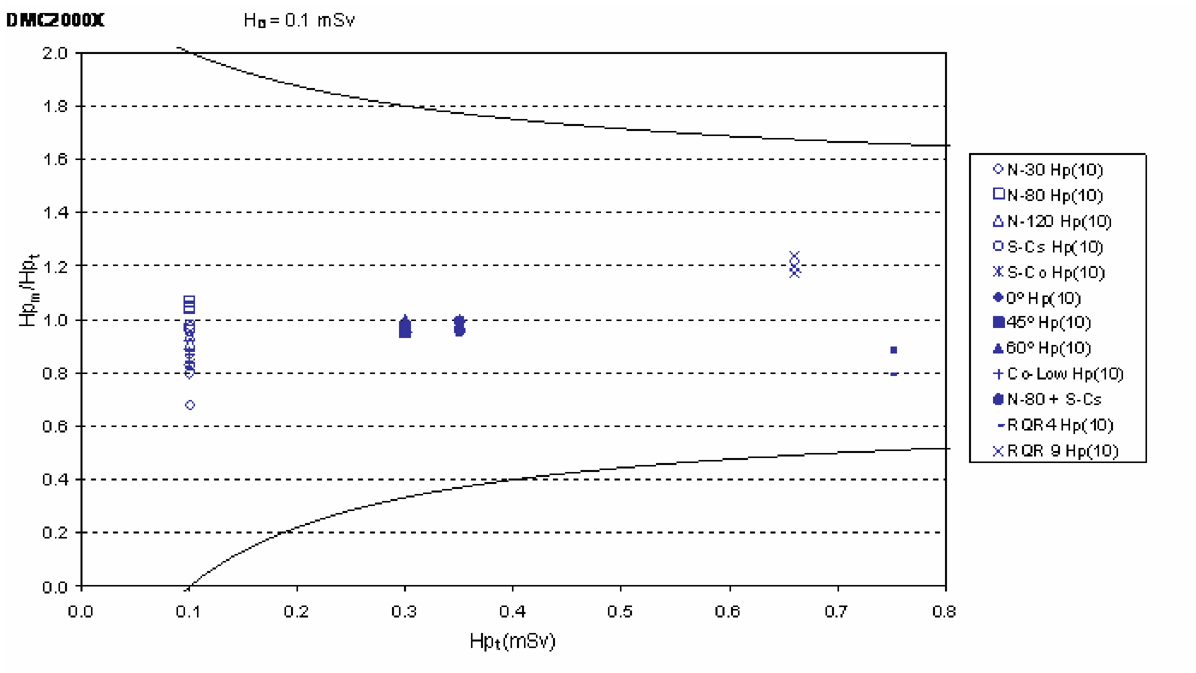


Figure 8.7. Trumpet curve for MGP DMC 2000X for $H_p(10)$.

MGP DMC2000X is meant to measure $H_p(10)$ for X and gamma radiation, it belongs to IEC third "category". It fulfils IEC 61526 testing requirements for penetrating and non penetrating radiation (20 keV to 1.5 MeV).

As regards workplace simulation performance tests, it measures satisfactorily in a mixed photon energy field (N-80+S-Cs) and in a 60 kV (RQR4) and 120 kV (RQR9) pulsed radiation field.

The dosimeter response is within the "trumpet" curve limits for photon radiation.

8.7. MGP DMC2000XB

Table 8.14. IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-30	0.94	3	1.1	0.96
N-80	1.04	8	1.2	1.07
N-120	0.89	7	1.4	0.91
S-Cs	0.97	2.6	0.6	1.00
S-Co	0.86	2.3	1.6	0.88
Angle of incidence. S-Cs				**(R.R. to 0º)**
0	0.98	1.6	0.7	1.00
45	0.98	1.5	0.4	1.01
60	1.00	1.3	0.3	1.03
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	0.89	2.8	1.1	1.00
1 Sv/h	0.94	5	0.2	1.05

Table 8.15. IEC tests for photon response – $H_p(0.07)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to N-120)**
N-30	0.66	7	2.5	0.65
N-80	1.09	7	1.0	1.08
N-120	1.01	5	2.5	1.00

Table 8.16. Non-IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	0.95	5	0.6	0.98
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4)	1.14	3	2.8	1.18
120 kV (RQR9)	1.28	0.4	1.2	1.32

Table 8.17. IEC tests for beta response – $H_p(0.07)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to ^{90}Sr)**
^{147}Pm	0.79	8	1.0	0.78
^{85}Kr	0.93	9	0.5	0.92
^{90}Sr	1.01	7	1.3	1.00
Angle of incidence. ^{90}Sr				**(R.R. to 0°)**
60	0.52	16	1.3	0.51
30	1.01	9	1.1	1.00
0	1.01	7	1.3	1.00
-30	1.01	9	1.6	1.00
-60	0.50	14	2.4	0.49
Angle of incidence. ^{85}Kr				**(R.R. to 0°)**
30	0.84	8	1.9	0.90
0	0.93	9	0.5	1.00
-30	0.86	8	1.5	0.92

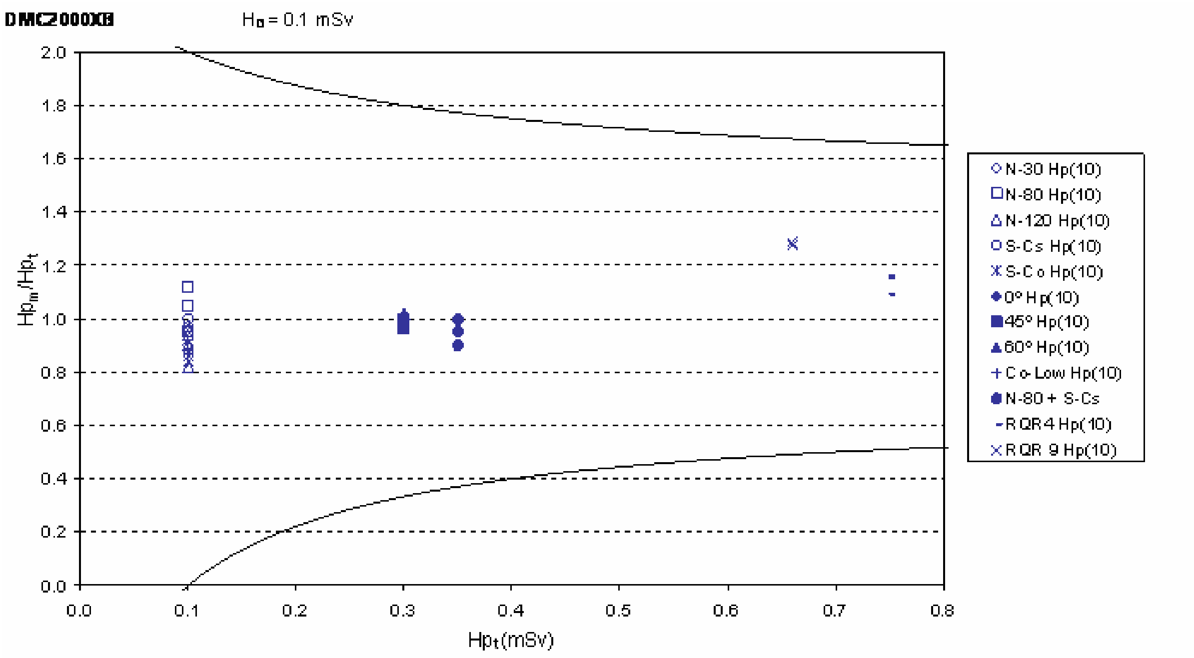


Figure 8.8. Trumpet curve for MGP DMC 2000XB for $H_p(10)$.

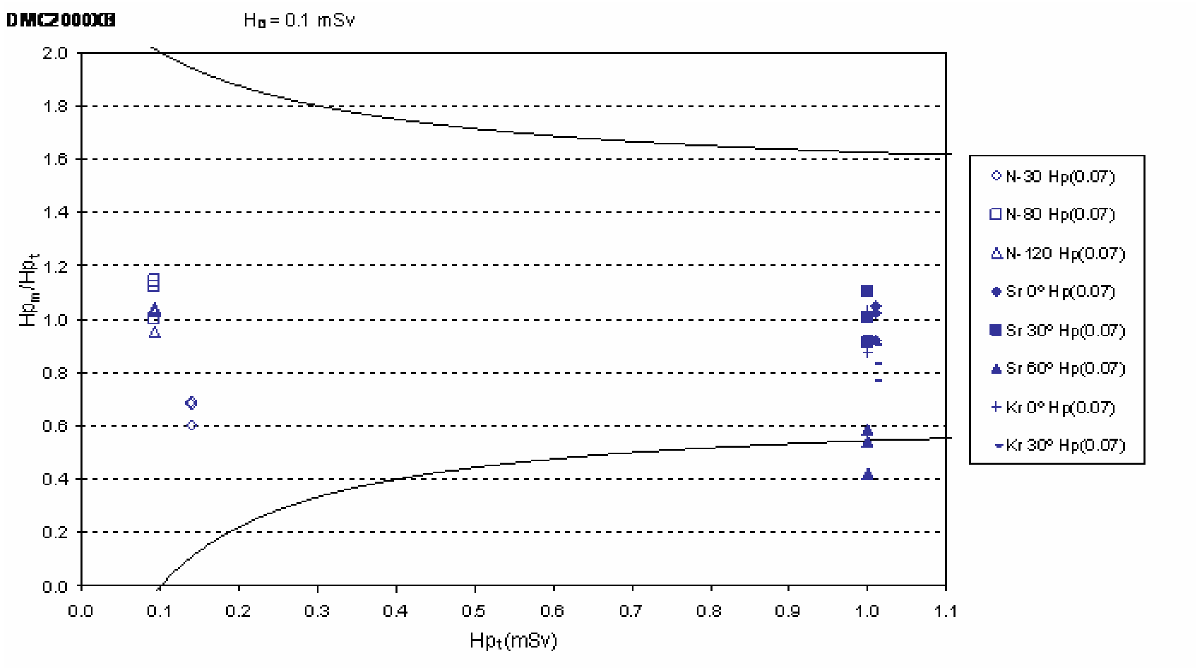


Figure 8.9. Trumpet curve for MGP DMC 2000XB for $H_p(0.07)$.

MGP DMC2000XB is meant to measure $H_p(10)$ and $H_p(0.07)$ for X, gamma and beta radiation, it belongs to IEC second "category". It fulfils most of the IEC 61526 testing requirements for penetrating and non penetrating photon radiation (20 keV to 1.5 MeV) and for beta radiation. The angular response for beta radiation at 60º incidence for $^{90}Sr/^{90}Y$ exceeds the IEC limit of -29%. However the dosimeter has a good response for normal incidence of ^{147}Pm beta particles, which is not a requisite in the Standard. The response of the dosimeter for $H_p(0.07)$ for N-30 is 0.66 but the Standard does not specify a variation limit for $H_p(0.07)$ below 30 keV.

As regards workplace simulation performance test, the dosimeter measures satisfactorily in a mixed photon energy field (N-80+S-Cs) and in a 60 kV (RQR4) and 120 kV (RQR9) pulsed radiation field.

The dosimeter response is within the "trumpet" curve limits for photon and beta radiation except for ^{90}Sr-^{90}Y irradiation at an incident angle of 60º.

8.8. POLIMASTER PM1604A

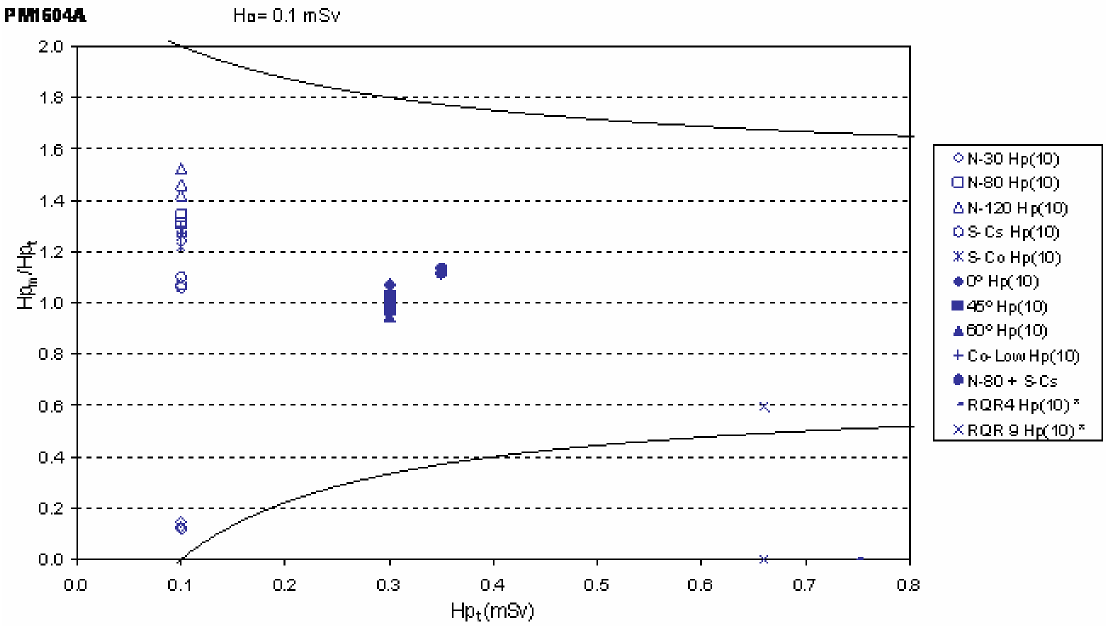
Table 8.18. IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-80	1.33	1.3	0.4	1.24
N-120	1.47	3.4	0.8	1.36
S-Cs	1.08	1.9	0.5	1.00
S-Co	1.25	2.4	2.1	1.16
Angle of incidence. S-Cs				**(R.R. to 0º)**
0	1.05	2.6	0.8	1.00
45	1.00	2.8	4	0.95
60	0.97	2.9	1.0	0.92
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	1.28	1.6	1.6	1.00
1 Sv/h	1.21	1.3	0.8	0.95

Table 8.19. Non-IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	1.13	1.0	0.7	1.05
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4) (1)	--	--	(91)	--
120 kV (RQR9) (1)	--	--	(92)	--

(1) The personal dose equivalent rate of this field is within the available range for this APD (5 Sv/h), however, readings ranged from 0 to 392 µSv for a given dose of about 700 µSv, thus it cannot be interpreted.



(+) The energy threshold of the dosimeter is 48 keV, thus N-30 and RQR4 are outside the device energy measuring range.

(*) Readings ranged from 0 to 392 for a given dose of about 700 µSv, results cannot be interpreted.

Figure 8.10 Trumpet curve for POLIMASTER PM1604A for $H_p(10)$.

POLIMASTER PM1604A is meant to measure $H_p(10)$ for X and gamma radiation, it belongs to IEC third "category". It fulfils IEC 61526 testing requirements for penetrating radiation (80 keV to 1.5 MeV). It is not sensitive to N-30 radiation quality.

As regards workplace simulation performance tests, it measures satisfactorily in a mixed photon energy field (N-80+S-Cs). Concerning the measurements in pulsed radiation fields, the results could not be properly evaluated for RQR4 beam because of the energy threshold (48 keV) of this dosimeter. In the case of RQR9 beam, readings ranged from 0 to 392 for a given dose of about 700 µSv, this wide spread could not be explained because of the dose equivalent rate of the field since the dosimeter measuring dose equivalent rate indicated by the manufacturer is 5 Sv/h. Only 1 detector was tested, thus the column "reproducibility" is left empty, but a wide range of readings was observed in the repeated measurements.

The dosimeter response is within the "trumpet" curve limits for penetrating photon radiation except in the case of pulsed radiation.

8.9. POLIMASTER PM162

Table 8.20. IEC tests for photon response – $H_p(10)$

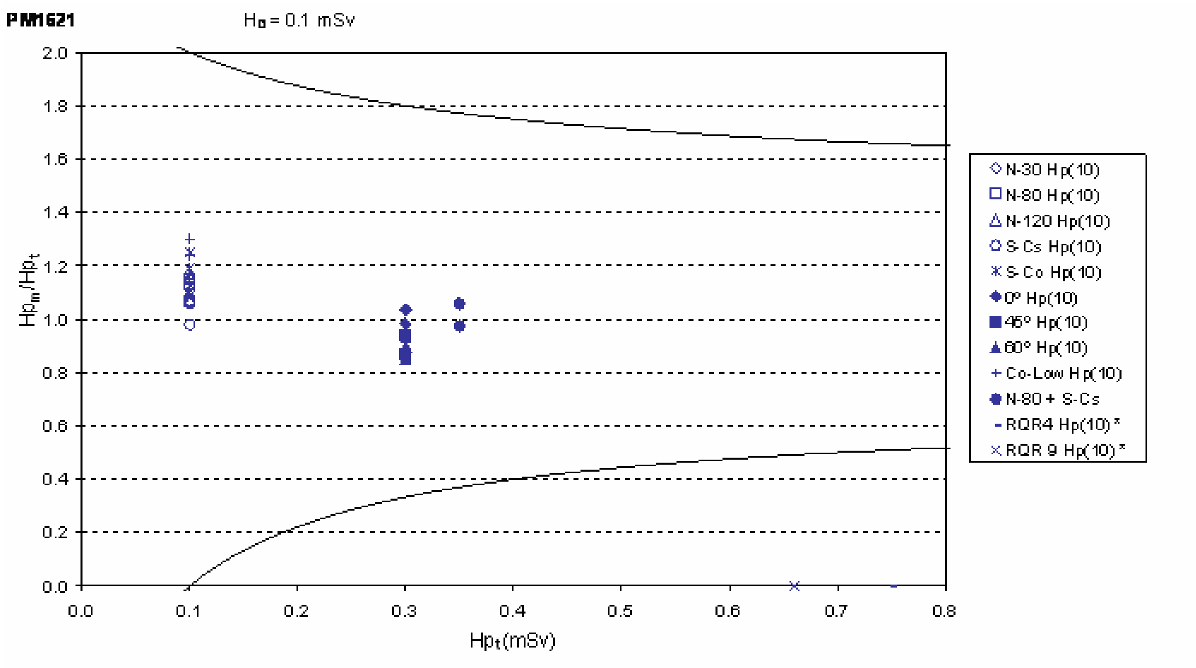
Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-30	1.11	4	0.4	1.07
N-80	1.12	4	2.1	1.08
N-120	1.11	4	0.6	1.07
S-Cs	1.04	5	0.5	1.00
S-Co	1.18	6	0.7	1.14
Angle of incidence, S-Cs				**(R.R. to 0º)**
0	1.00	3	1.6	1.00
45	0.91	5	1.6	0.91
60	0.87	3	0.7	0.87
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	1.23	6	0.5	1.00
1 Sv/h(1)	1.45	63	1.9	1.18

(1) The personal dose equivalent rate of this field is higher than the available range for this APD but the observed performance is within the Standard requirement.

Table 8.21. Non-IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	1.03	5	0.16	0.99
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4) (1)	--	--	(91)	--
120 kV (RQR9) (1)	--	--	(86)	--

(1) The personal dose equivalent rate of this field is higher than the available range for this APD. Readings cannot be interpreted.



(*) The personal dose equivalent rate of this field is higher than the available range for this APD. Readings ranged from 0 to 100 for a given dose of about 700 µSv, thus it cannot be interpreted.

Figure 8.11. Trumpet curve for POLIMASTER PM1621 for $H_p(10)$.

POLIMASTER PM1621 is meant to measure $H_p(10)$ for X and gamma radiation, it belongs to IEC third "category". It fulfils IEC 61526 testing requirements for penetrating and non penetrating radiation (20 keV to 1.5 MeV).

As regards workplace simulation performance tests, it measures satisfactorily in a mixed photon energy field (N-80+S-Cs). The maximum dose equivalent rate claimed by the manufacturer is 100 mSv/h. This dose rate is too low compared to the dose rates in the pulsed radiation fields used for this comparison. The dosimeter dose equivalent rate range does not cover the IEC recommended range (see [9])

The dosimeter response is within the "trumpet" curve limits for photon radiation, except for the tested pulsed radiation fields.

8.10. RADOS RAD-60S

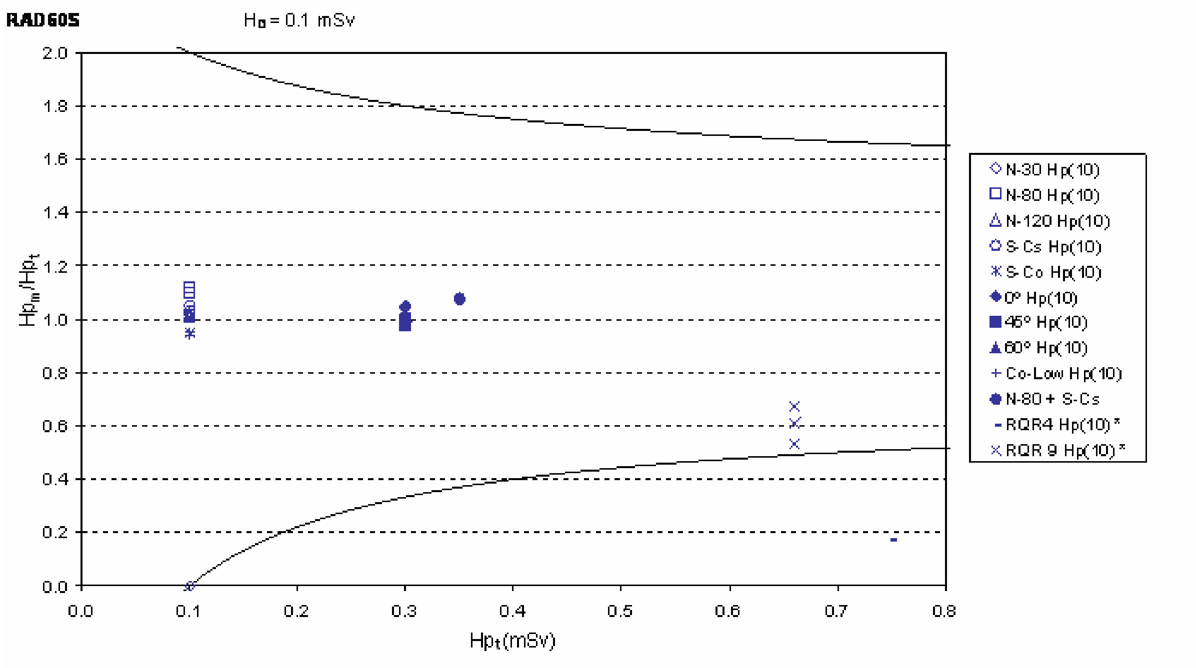
Table 8.22. IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-80	1.11	1.0	0.0	1.08
N-120	1.01	0.6	0.9	0.98
S-Cs	1.03	1.5	1.4	1.00
S-Co	0.95	0.0	1.2	0.92
Angle of incidence. S-Cs				**(R.R. to 0º)**
0	1.05	0.3	0.27	1.00
45	0.99	1.0	0.5	0.94
60	1.00	0.5	0.5	0.96
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	0.95	0.6	1.6	1.00
1 Sv/h	0.99	0.5	0.19	1.05

Table 8.23. Non-IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	1.08	0.15	0.5	1.04
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4) [(1)]	0.17	---	(45)	---
120 kV (RQR9) [(1)]	0.61	11	14	0.59

[(1)] The energy threshold of the dosimeter is 55 keV, thus RQR4 is outside the device energy measuring range and RQR9 is partially outside.



(*) The energy threshold of the dosimeter is 55 keV, thus N-30, RQR4 are outside the device energy measuring range, RQR9 is partially outside.

Figure 8.12. Trumpet curve for RADOS RAD60S for $H_p(10)$.

RADOS RAD60S is meant to measure $H_p(10)$ for X and gamma radiation, it belongs to IEC third "category". It fulfils IEC 61526 testing requirements for penetrating radiation (80 keV to 1.5 MeV). It is not sensitive to N-30 radiation quality.

As regards workplace simulation performance tests, it measures satisfactorily in a mixed photon energy field (N-80+S-Cs) but detects only about 50 % of the reference dose equivalent contribution from 120 kV (RQR9) pulsed radiation fields. The 60 kV (RQR4) pulsed radiation field is hardly detected because of the energy threshold of the dosimeter (55 keV).

The dosimeters minimum dose equivalent rate range, 5 µSv/h, is higher than the IEC recommended value (see [9]).

The dosimeter response is within the "trumpet" curve limits for penetrating photon radiation.

8.11. SAIC PD2i

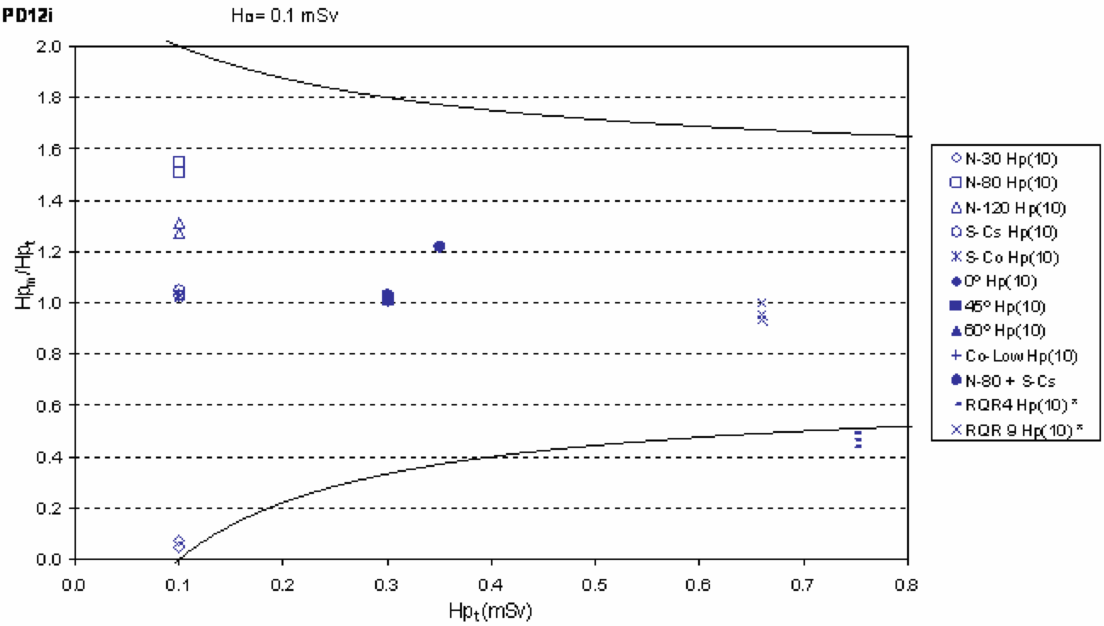
Table 8.24. IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-80	1.53	1.9	1.5	1.47
N-120	1.29	2.2	0.5	1.24
S-Cs	1.04	1.4	1.6	1.00
S-Co	1.03	0.7	0.5	0.99
Angle of incidence. S-Cs				**(R.R. to 0º)**
0	1.01	0.23	0.5	1.00
45	1.02	0.7	0.6	1.01
60	1.03	0.7	0.5	1.02
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	1.03	--	1.0	1.00
1 Sv/h	0.96	--	2.5	0.93

Table 8.25. Non-IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	1.22	--	2.4	1.17
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4)(1)	0.47	6	2.7	0.45
120 kV (RQR9)(1)	0.96	4	3	0.92

(1) The energy threshold of the dosimeter is 55 keV, thus RQR4 is outside the device energy measuring range, and RQR9 is partially outside.



(*) The energy threshold of the dosimeter is 55 keV, thus N-30 and RQR4 are outside the device energy measuring range and RQR9 is partially outside.

Figure 8.13. Trumpet curve for SAIC PD2i for $H_p(10)$.

For dose rate and mixed fields tests only 1 detector was tested, therefore the column "reproducibility" in the results table is blank. One of the three devices received did not work properly and could not be used in some of the tests.

The dosimeter SAIC is meant to measure $H_p(10)$ for X and gamma radiation, it belongs to IEC third "category". It fulfils IEC 61526 testing requirements for penetrating radiation (80 keV to 1.5 MeV). It is not sensitive to N-30 radiation quality because of the energy threshold of the dosimeter (55 keV).

As regards workplace simulation performance tests, it measures satisfactorily in a mixed photon energy field (N-80+S-Cs) and in a 120 kV (RQR9) pulsed radiation field, despite the energy threshold. The 60 kV (RQR4) pulsed radiation field could not be correctly quantified because of the energy threshold of the dosimeter (55 keV).

The dosimeter response is within the "trumpet" curve limits for penetrating photon radiation.

8.12. THERMO ELECTRON EPD Mk2.3

Table 8.26. IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to S-Cs)**
N-30	1.19	2.2	0.9	1.16
N-80	1.02	2.6	0.5	0.99
N-120	0.91	5	1.1	0.89
S-Cs	1.03	0.6	1.5	1.00
S-Co	0.86	1.2	0.6	0.84
Angle of incidence, S-Cs				**(R.R. to 0º)**
0	1.00	1.3	0.6	1.00
45	0.96	1.4	0.9	0.96
60	0.96	1.6	0.5	0.96
Dose rate, S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h	0.88	1.3	0.6	1.00
1 Sv/h	0.83	1.4	0.14	0.95

Table 8.27. IEC tests for photon response – $H_p(0.07)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to N-120)**
N-30	1.09	1.7	0.7	1.24
N-80	1.10	23	1.5	1.24
N-120	0.88	14	6	1.00

Table 8.28. Non-IEC tests for photon response – $H_p(10)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to S-Cs)**
N-80 + S-Cs	0.99	0.8	0.16	0.97
Pulsed radiation field				**(R.R. to S-Cs)**
60 kV (RQR4)	0.82	1.2	0.9	0.79
120 kV (RQR9)	1.00	0.7	0.5	0.97

Table 8.29. IEC tests for beta response – $H_p(0.07)$

Influence quantity	**Response**	**Reproducibility**	**Repeatability**	**Relative response**
Radiation energy (normal incidence)				**(R.R. to ^{90}Sr)**
^{85}Kr	0.96	2.1	1.8	0.92
^{90}Sr	1.05	2.7	0.9	1.00
Angle of incidence. ^{90}Sr				**(R.R. to 0°)**
60.00	0.81	5	2.0	0.78
30.00	1.05	4	1.9	1.00
0.00	1.05	2.7	0.9	1.00
-30.00	1.23	2.1	1.7	1.18
-60.00	0.79	5	2.2	0.76
Angle of incidence. ^{85}Kr				**(R.R. to 0°)**
30.00	0.82	5	1.5	0.85
0.00	0.96	2.1	1.8	1.00
-30.00	0.81	4	2.2	0.84

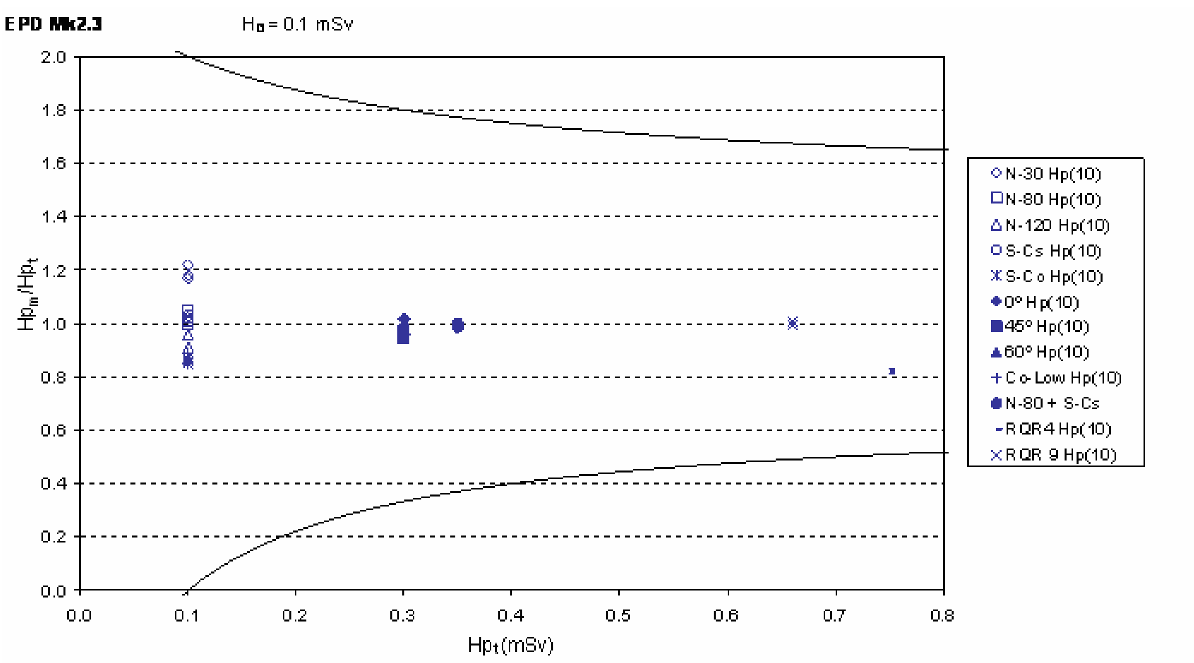


Figure 8.14. Trumpet curve for THERMO ELECTRON for $H_p(10)$.

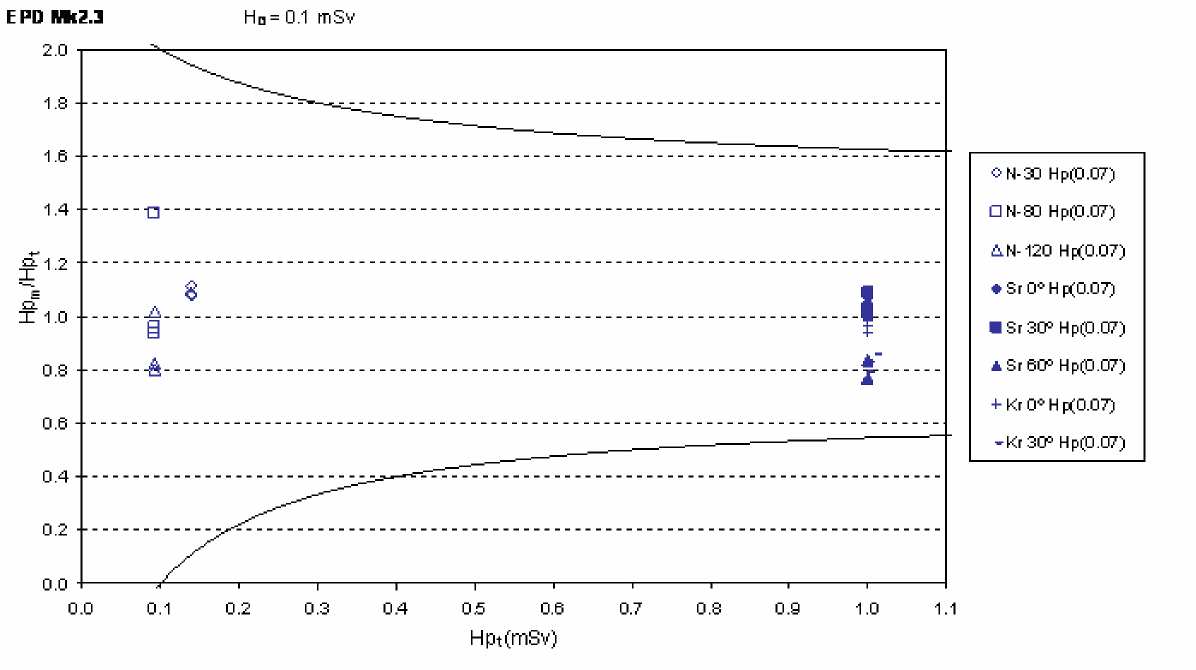


Figure 8.15 Trumpet curve for THERMO ELECTRON EPD Mk2.3 for $H_p(0.07)$.

THERMO ELECTRON EPD MK2.3 is meant to measure $H_p(10)$ and $H_p(0.07)$ for X, gamma and beta radiation, it belongs to IEC second "category". It fulfils the IEC 61526 testing requirements for penetrating and non penetrating photon radiation (20 keV to 1.5 MeV) and for beta radiation. The dosimeter does not detect ^{147}Pm beta particles, but this is not a standard requirement.

As regards workplace simulation performance tests, the dosimeter measures satisfactorily in a mixed photon energy field (N-80+S-Cs) and in a 60 kV (RQR4) and 120 kV (RQR9) pulsed radiation field.

The dosimeter response is within the "trumpet" curve limits for photon and beta radiation.

8.13. UNFORS NED

Table 8.30. IEC tests for photon response – $H_p(0.07)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Radiation energy (normal incidence)				**(R.R. to N-120)**
N-30 [(1)]	3.6	1.4	0.2	1.38
N-80 [(1)]	4.6	0.23	0.3	1.75
N-120 [(1)]	2.6	0.24	0.1	1.00
S-Cs [(2)]	0.92	3	0.5	0.35
S-Co [(2)]	0.85	1.4	0.29	0.32
Angle of incidence. S-Cs				**(R.R. to 0º)**
0 [(3)]	--	1.4	0.24	1.00
45 [(3)]	--	1.5	0.4	0.94
60[(3)]	--	1.1	0.11	0.98
Dose rate. S-Co				**(R.R. to 1 mSv/h)**
1 mSv/h [(3)]	--	4	0.8	1.00
1 Sv/h [(3)]	--	1.1	0.11	1.02

(1) UNFORS NED energy range goes from 140 to 1200 keV, thus this quality is outside the device measuring range.

(2) A reference conventional true value is not available. However as a first approximate to calculate the APD response for these energies, $H_p(0.07)$ is considered equal to $H_p(10)$.

(3) A reference conventional true value is not available, this column is left blank. In this test the relative response is the most interesting quantity.

Table 8.31. Non-IEC tests for photon response – $H_p(0.07)$

Influence quantity	Response	Reproducibility	Repeatability	Relative response
Mixed energy radiation				**(R.R. to N-120)**
N-80 + S-Cs[(1)]	0.88	0.8	0.10	0.34
Pulsed radiation field				**(R.R. to N-120)**
60 kV (RQR4) [(2)]	5.2	0.5	0.10	2.00
120 kV (RQR9) [(2)]	4.8	0.5	0.05	1.84

(1) A reference conventional true value is not available. However as a first approximate to calculate the APD response for these energies, $H_p(0.07)$ is considered equal to $H_p(10)$.

(2) UNFORS NED energy range goes from 140 to 1200 keV, thus this quality is outside the device measuring range.

UNFORS NED is an electronic extremity dosimeter meant to measure $H_p(0.07)$ for gamma radiation (140 keV to 1250 keV). However this quantity is not well defined for energies higher than 300 keV. Therefore, there is not yet a specific standard for such devices. In this report UNFORS NED has been evaluated considering IEC 61526 requirements for the sixth "category" of dosimeters.

The device has been designed for a very specific energy range and therefore does not fulfil most of the IEC 61526 requirements. There is an important overestimation of the received dose equivalent for X ray qualities, mixed photon energy fields (N-80+S-Cs) and 60 kV (RQR4) and 120 kV (RQR9) pulsed radiation fields. There is another version of this device which is calibrated for X ray radiation fields but it was not tested in the intercomparison.

The angular response for S-Cs is correct and the influence of dose equivalent rate is also within limits. Due to the limited range of use of this dosimeter the trumpet curves are not included in the report.

9. COMPARISON OF THE CHARACTERISTICS AND PERFORMANCE OF THE 13 TESTED PERSONAL DOSIMETERS

9.1. $H_p(10)$ response for ISO photon qualities

The response of the tested dosimeters to the ISO photon qualities is shown in Figures 9.1 to 9.5. UNFORS NED does not provide a measurement of $H_p(10)$ and thus it is not included in the graphs. All the devices fulfil satisfactorily the IEC requirement for photon energy response for penetrating radiation. Only 5/13 devices measure within IEC limits N-30 quality, this behaviour is consistent with the manufacturers declared performance. The response to ^{137}Cs, which is the reference calibration energy, is within 10 % for all the dosimeters.

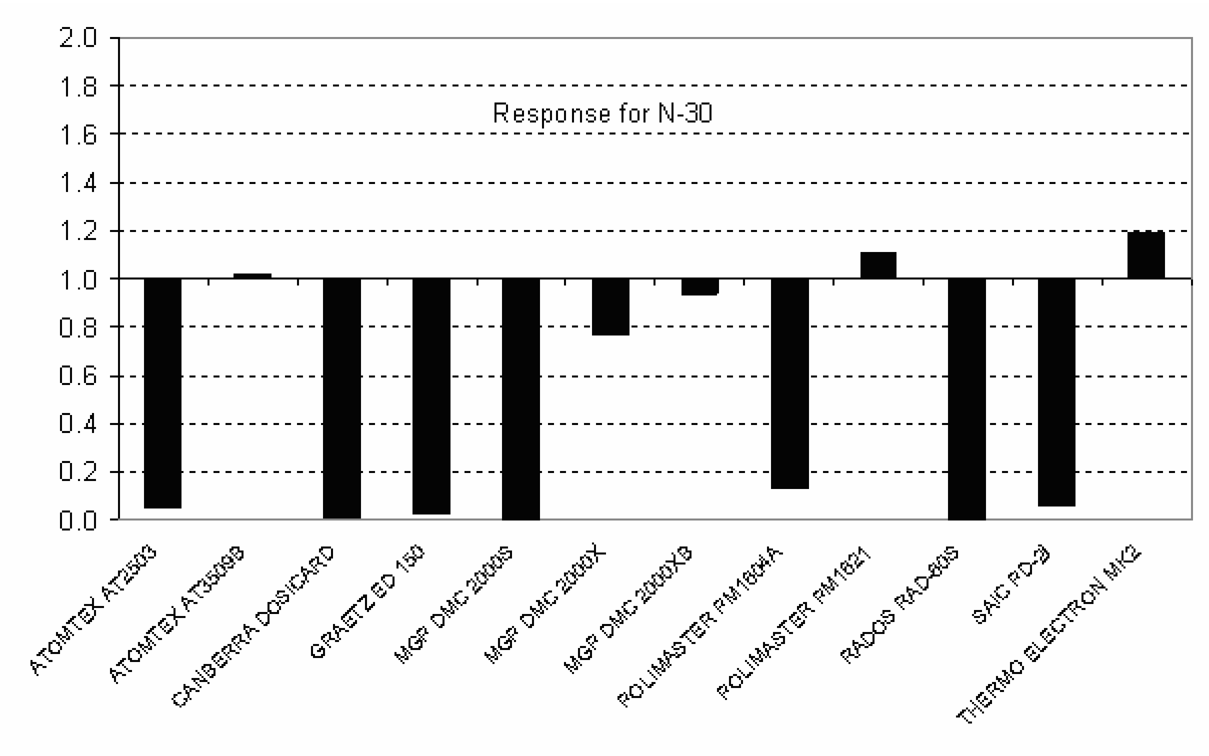


Figure 9.1. $H_p(10)$ dosimeter response to N-30.

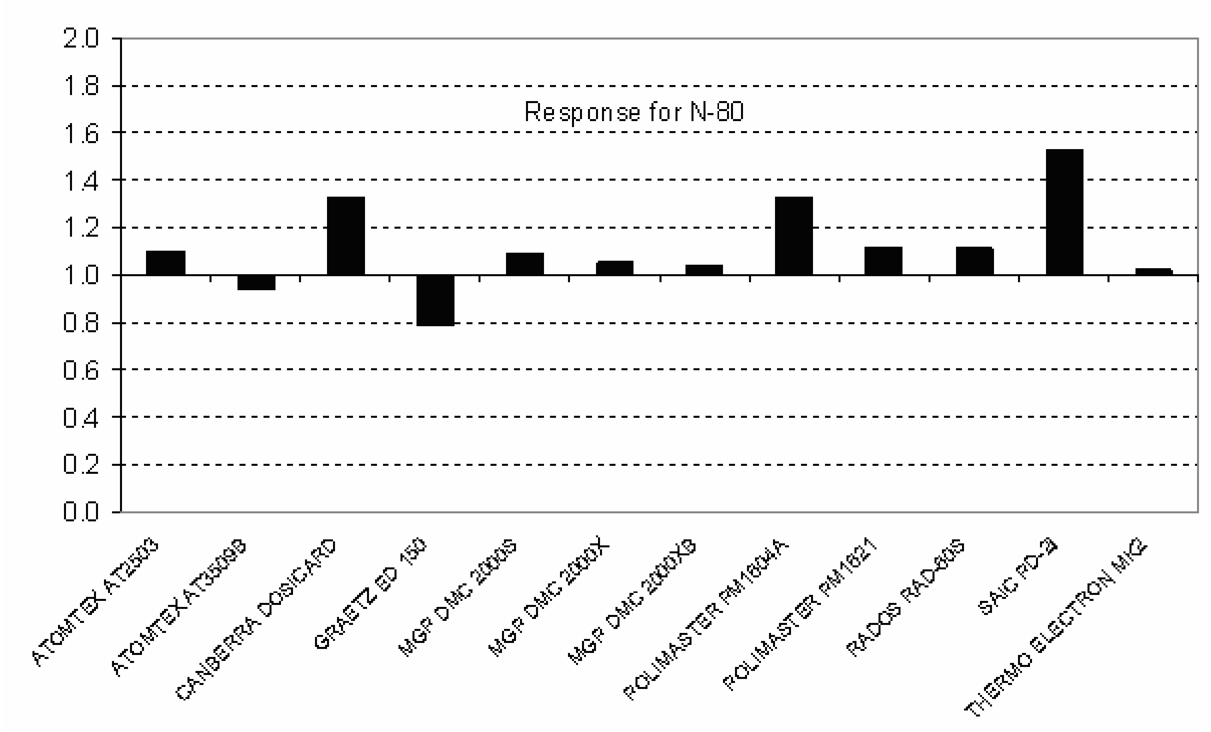


Figure 9.2. $H_p(10)$ dosimeter response to N-80.

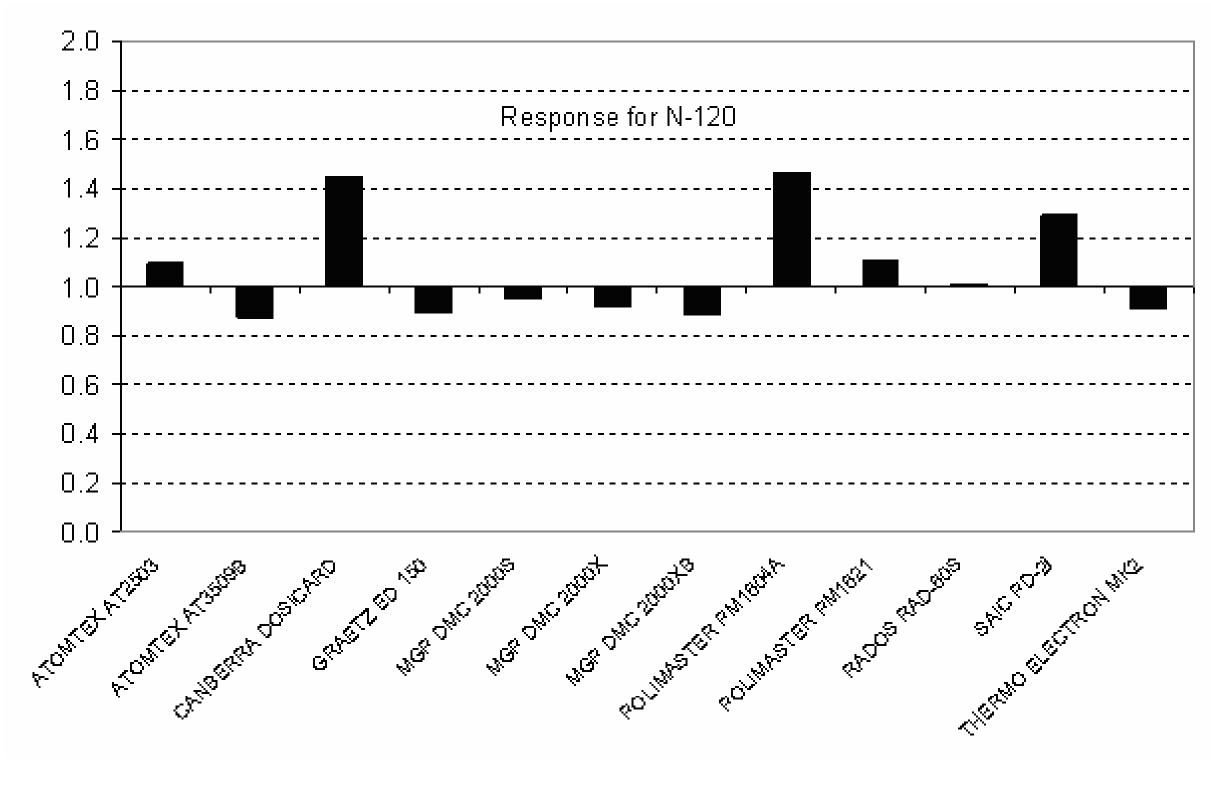


Figure 9.3. $H_p(10)$ dosimeter response to N-120.

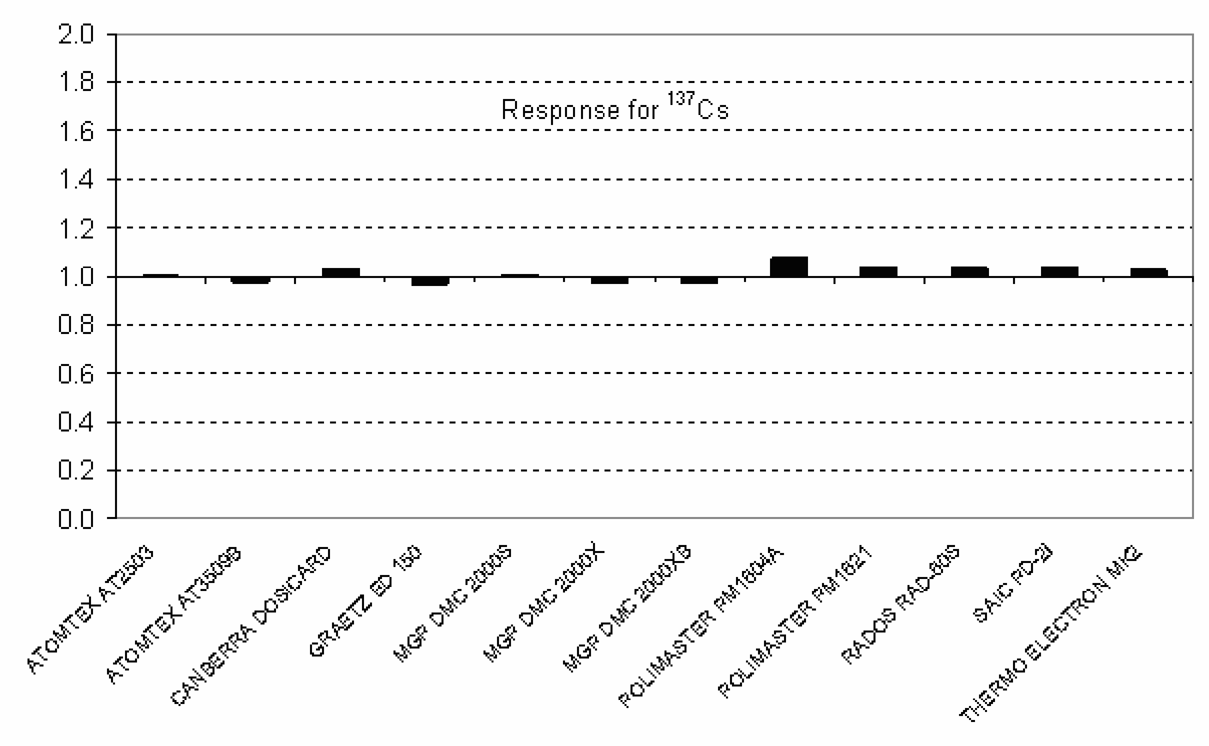


Figure 9.4. $H_p(10)$ dosimeter response to ^{137}Cs.

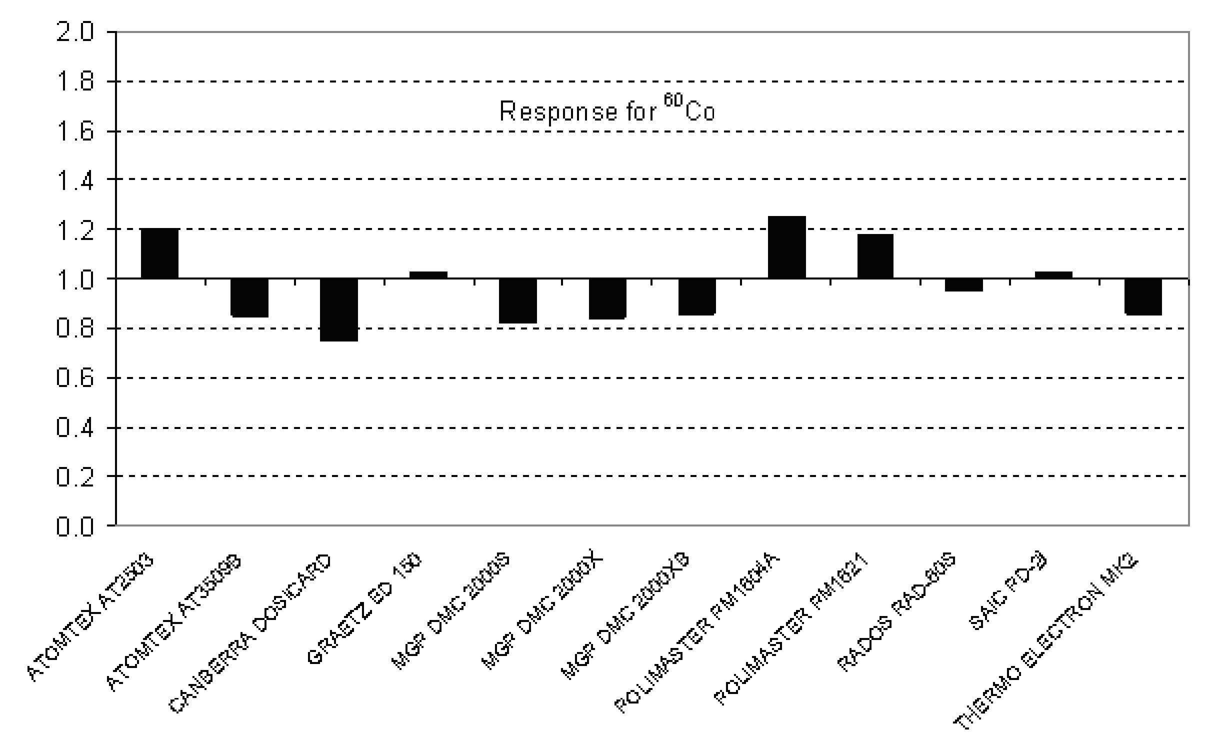


Figure 9.5. $H_p(10)$ dosimeter response to ^{60}Co.

9.2. $H_p(0.07)$ response to photon and beta ISO radiation qualities

Only four dosimeters measure $H_p(0.07)$ and of those only two are sensitive to beta radiation. Figures 9.6 and 9.7 summarize the response to this quantity. UNFORS NED results are not presented in the graph since its response is outside the graphic scale (see comment 1 to table 8.30). The other three dosimeters, ATOMTEX AT3509B, MGP DMC2000XB and THERMO ELECTRON MK2, present an energy response within IEC limits (see comment in paragraph 8.7 for MGP DMC2000XB response to N-30).

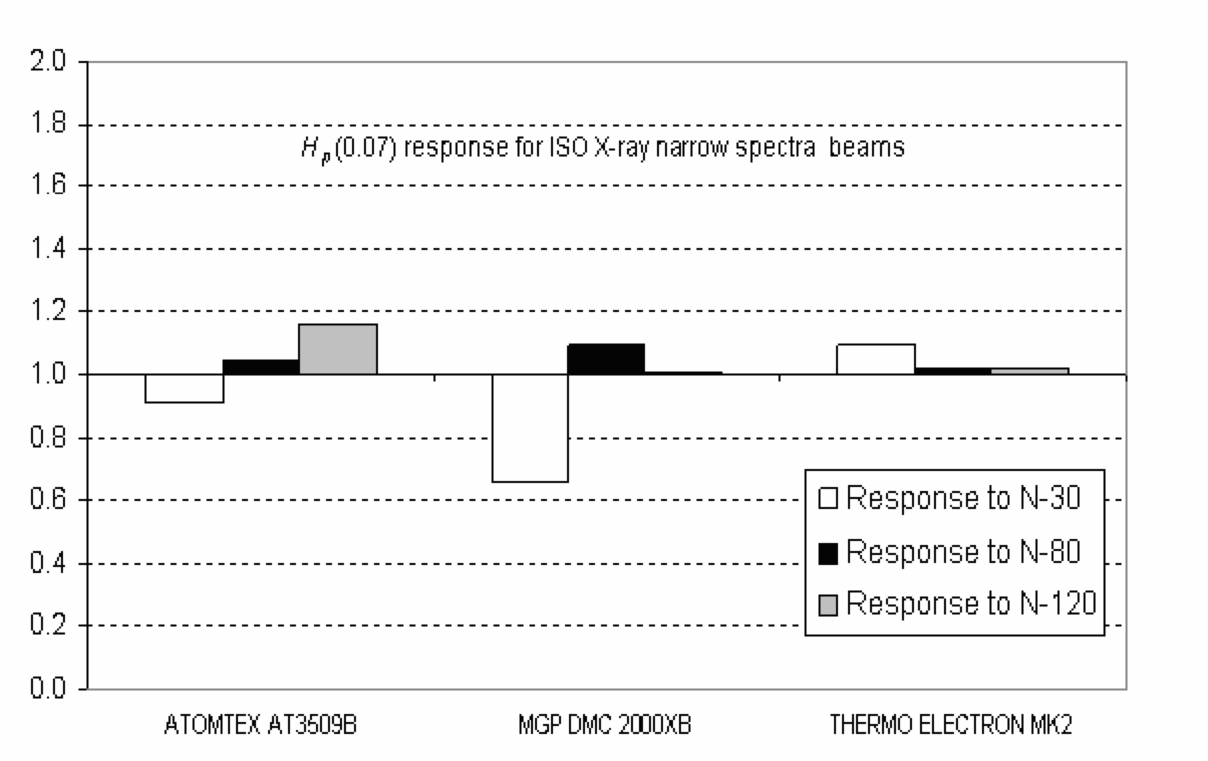


Figure 9.6. $H_p(0.07)$ dosimeter response to ISO X ray narrow spectra beams.

MGP DMC2000XB and THERMO ELECTRON MK2 fulfil IEC requirements for beta radiation since the detection of ^{147}Pm is not a requirement in the Standard.

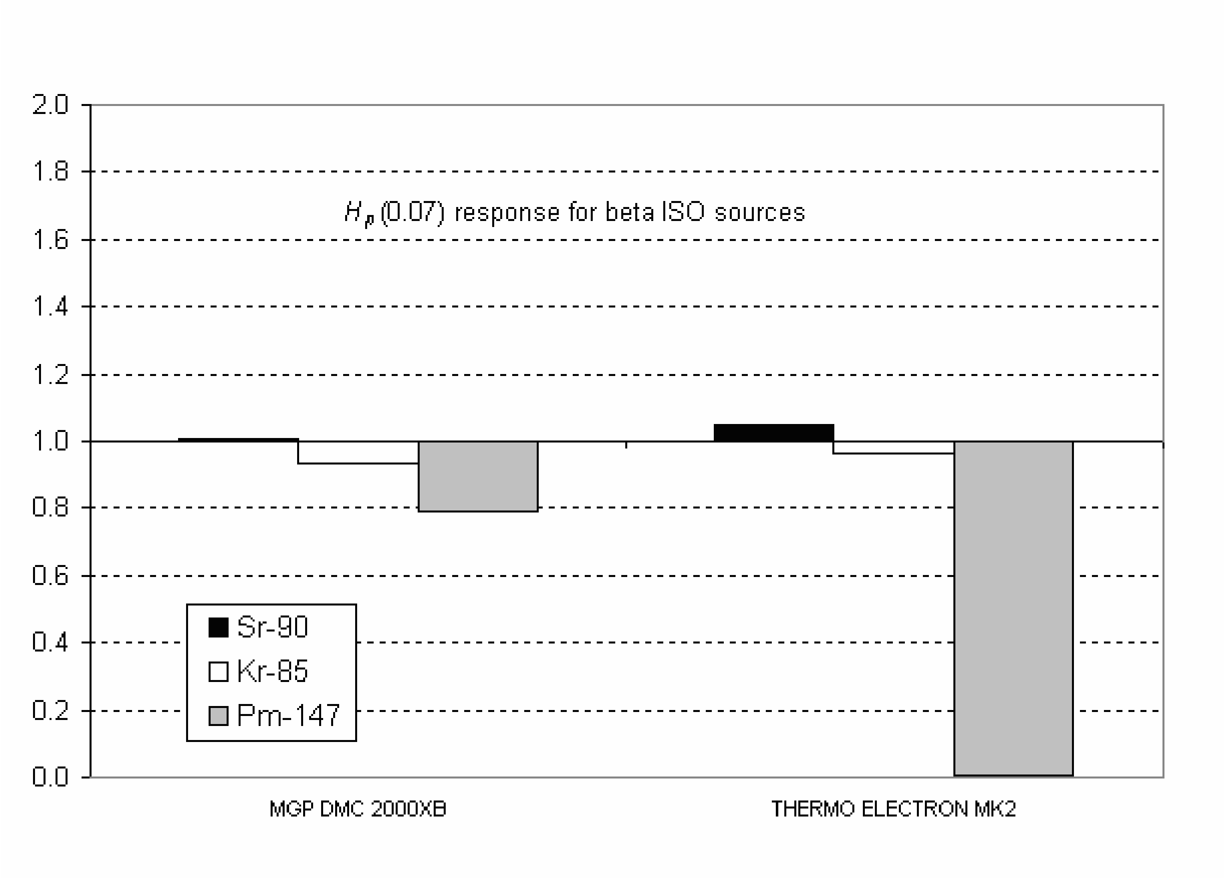


Figure 9.7 $H_p(0.07)$ dosimeter response to beta ISO sources.

9.3. Angular response

The angular response to photon radiation was tested at an angle of 45º and 60º the relative angular response at those angles for the 13 tested dosimeters is shown in Figure 9.8. It can be observed that all the devices present a satisfactory angular response to ^{137}Cs.

For MGP DMC2000XB and THERMO ELECTRON MK2, that measure beta radiation the angular response was also tested at ± 60º and ± 30º for $^{90}Sr/^{90}Y$ and ± 30º for ^{85}Kr. The results are summarized in Figure 9.9. The IEC requirements are fulfilled except for MGP DMC2000XB at 60º for $^{90}Sr/^{90}Y$.

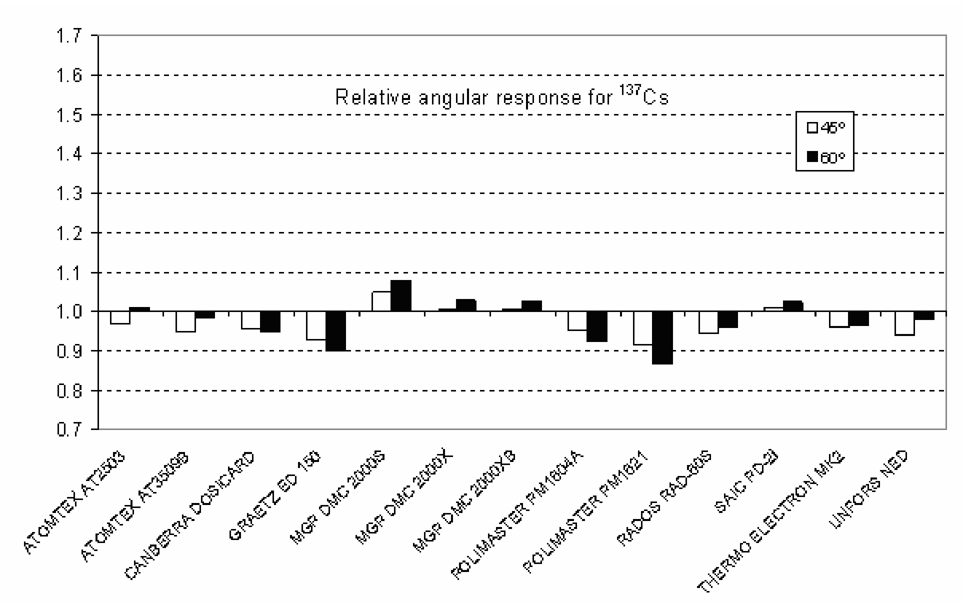


Figure 9.8. $H_p(10)$ relative angular response to ^{137}Cs sources.

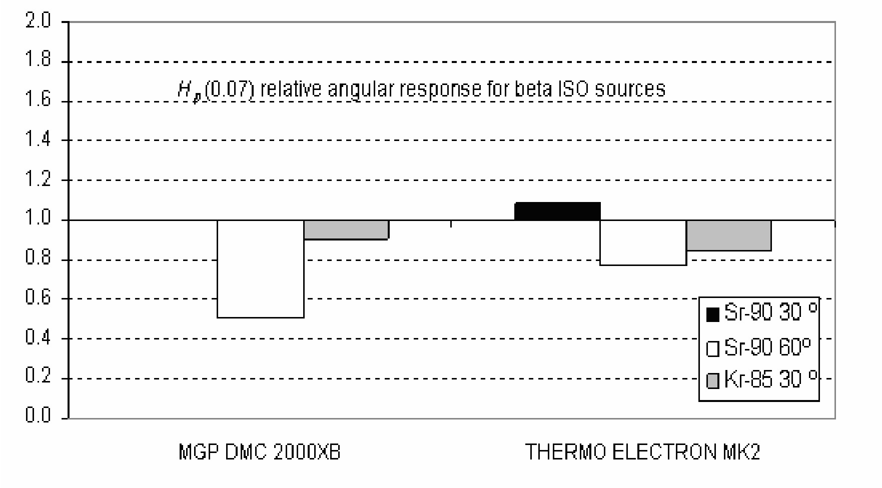


Figure 9.9. $H_p(0.07)$ relative angular response to beta ISO sources.

9.4. Statistical fluctuation of dose measurement

Figure 9.10 indicates the repeatability of the 13 tested dosimeters for a personal dose equivalent, $H_p(10)$, of 100 µSv for ^{137}Cs. It is shown that all the dosimeters present a statistical fluctuation far below the IEC 61526 limit of 5 %.

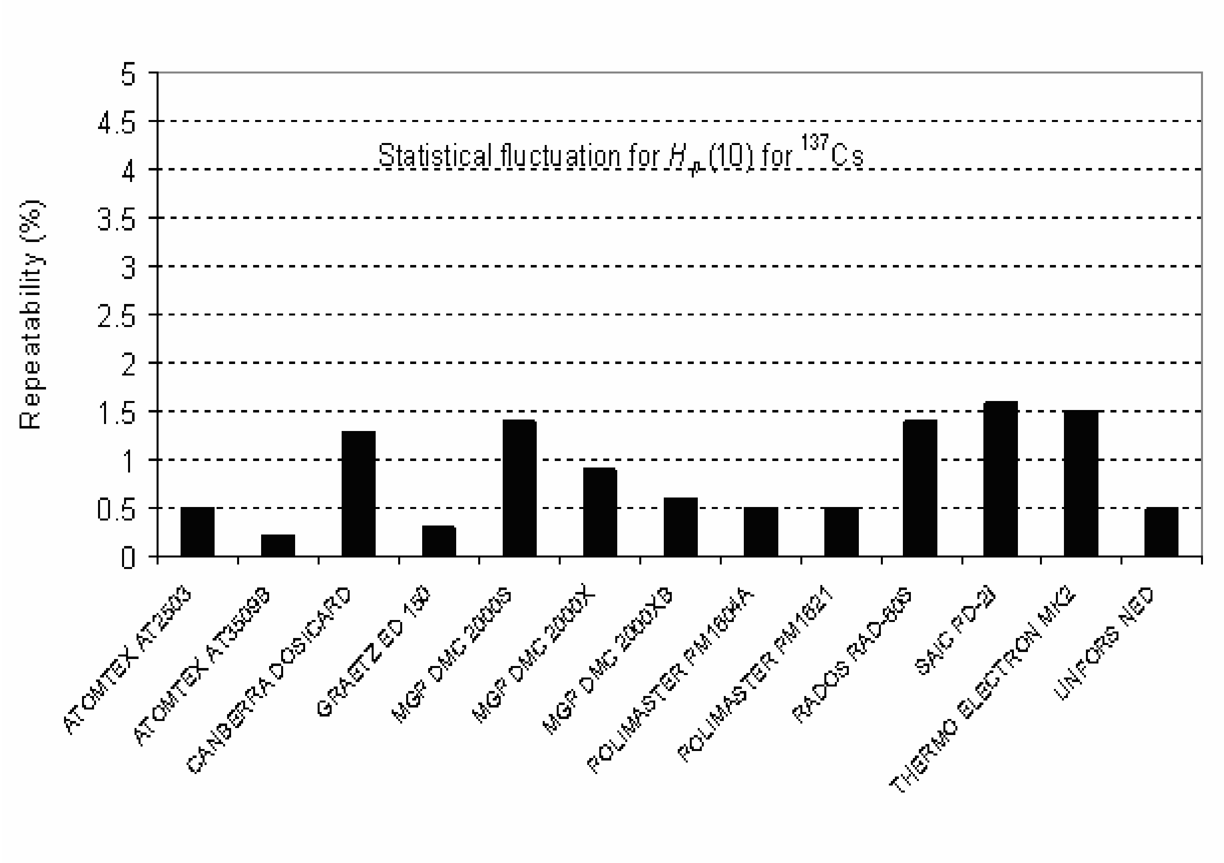


Figure 9.10. Dosimeter statistical fluctuation for $H_p(10)$ for ^{137}Cs.

Figure 9.11 shows the repeatability of the four tested dosimeters that measure the personal dose equivalent, $H_p(0.07)$, for N-120; together with the repeatability for $^{90}Sr/^{90}Y$ for MGP DMC2000XB and THERMO ELECTRON MK2. According to IEC 61526, the limit of variation of the statistical fluctuation of $H_p(0.07)$ for X and beta radiation for a dose of 100 µSv is 8.4% and for 1 mSv is 5%. All the dosimeters fulfil the standard requirement.

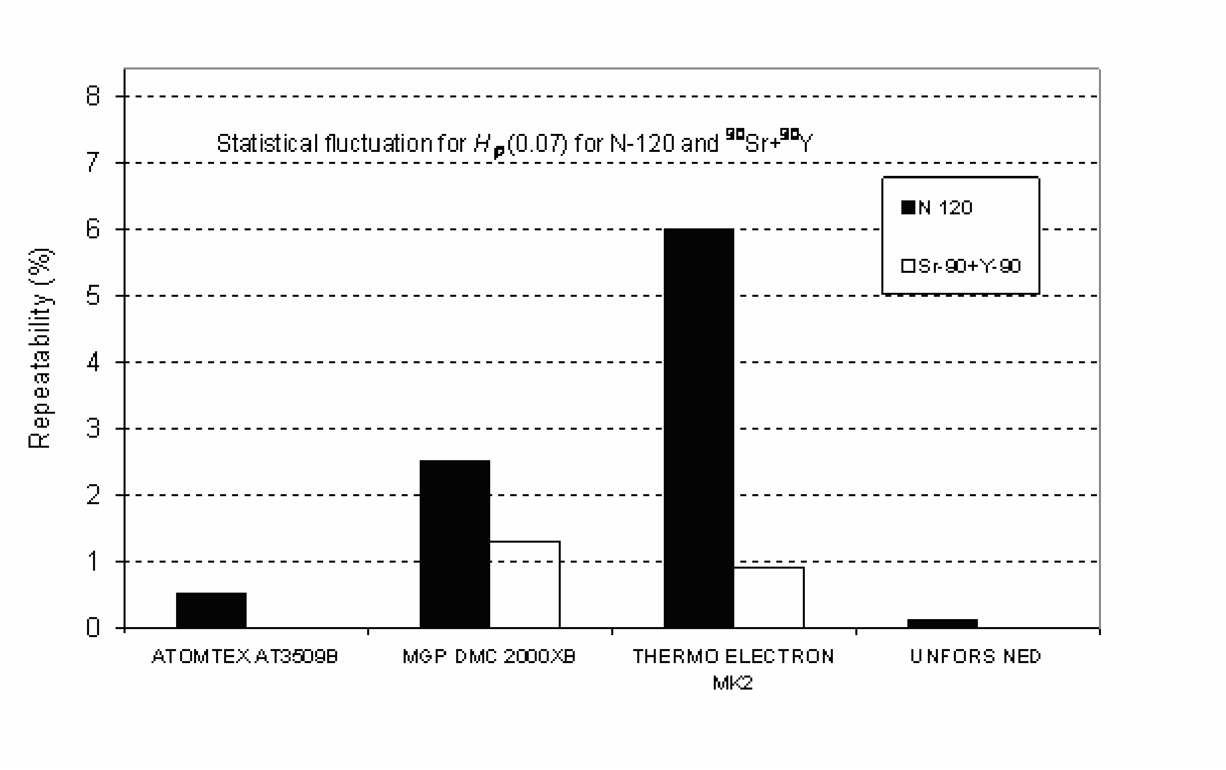


Figure 9.11. Dosimeter statistical fluctuation for $H_p(0.07)$ for N-120 and $^{90}Sr+^{90}Y$.

9.5. Influence of dose equivalent rate

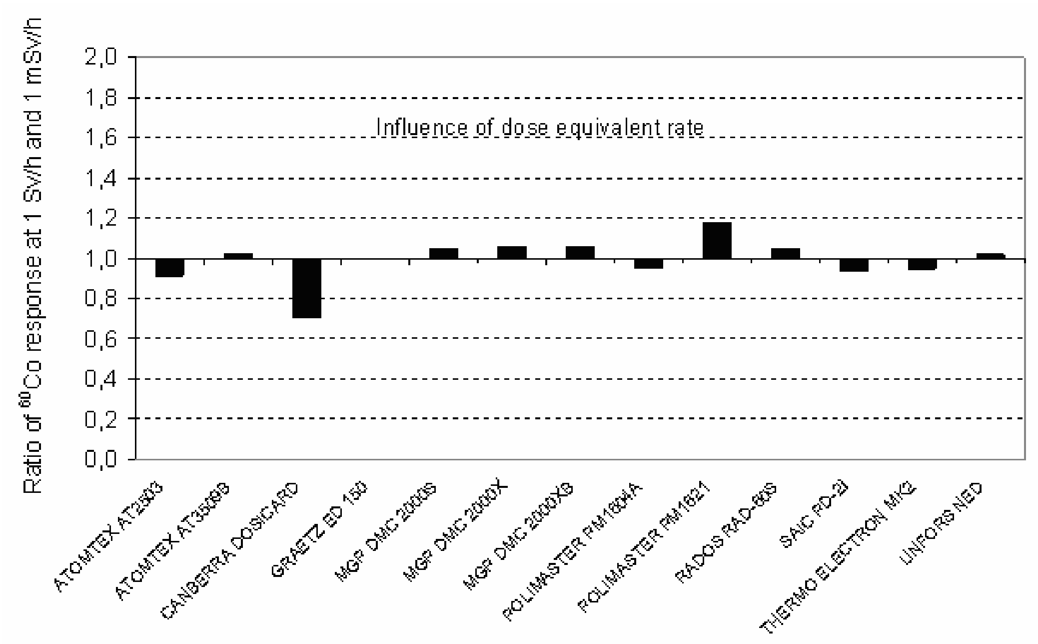


Figure 9.12. Variation of the response due to dose equivalent rate dependence of dose measurements.

According to IEC 61526, the variation of the relative response due to dose equivalent rate dependence shall not exceed ± 20% for all dose equivalent rates from 0.5 µSv/h to 1 Sv/h. If this requirement cannot be met up to 1 Sv/h, it shall be met up to at least 100 mSv/h. The IEC requirement for this quantity is fulfilled by all the dosimeters except for CANBERRA DOSICARD. This dosimeter does not meet the requirement for 1 Sv/h and unfortunately its response at 100 mSv/h has not been verified.

9.6. Mixed-field response in terms of $H_p(10)$

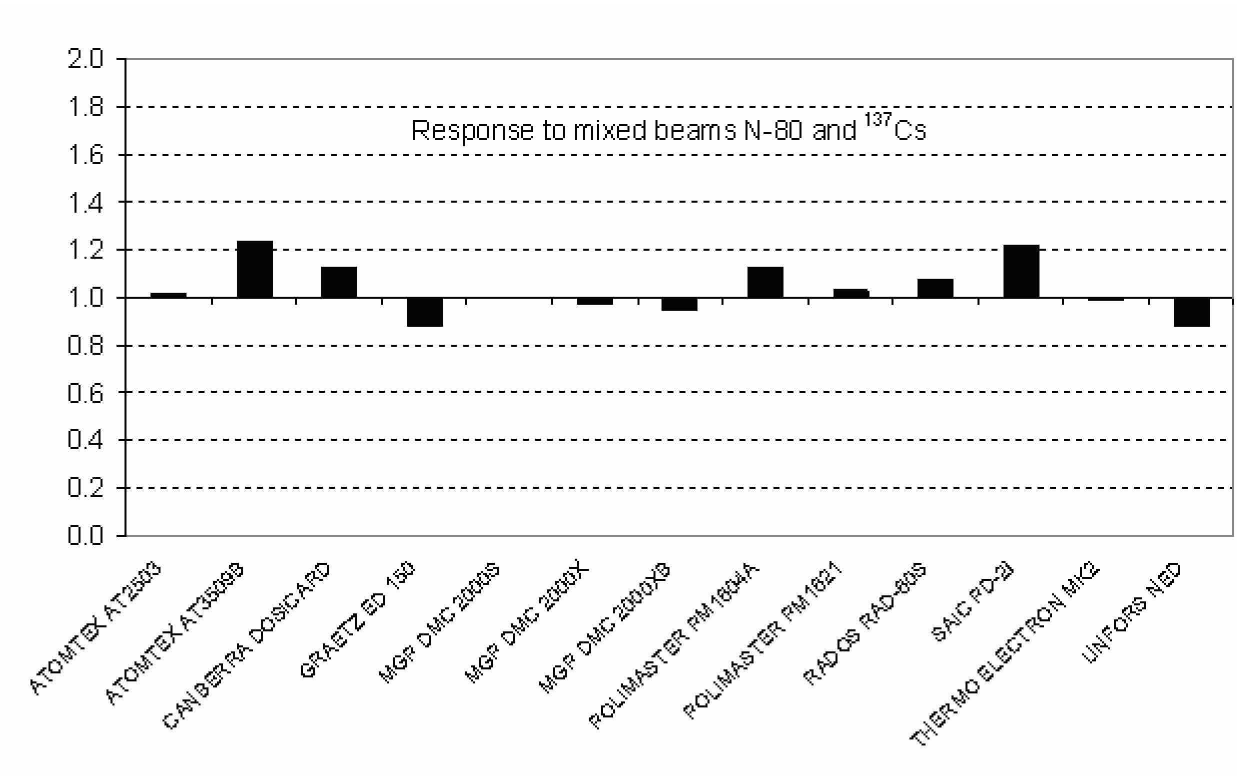


Figure 9.13 : Dosimeter response to mixed photon beams (N-80+^{137}Cs).

The response of the dosimeters in mixed radiation fields is not detailed in the IEC standard. However, all the devices have a satisfactory result for the tested mixed photon fields.

9.7. Pulsed radiation response

The IEC standard explicitly avoids giving requirements for dosimeter response to pulsed radiation fields. However, the 120 kV (RQR9) radiation field has been satisfactorily measured by 6/13 devices. Figure 9.14 shows the response of these six dosimeters to this quality.

The responses of ATOMTEX AT2503, ATOMTEX AT3509B, CANBERRA DOSICARD and POLIMASTER PM1621 are not given in the figure because the dose equivalent rate of the beam quality was outside the dosimeter measuring range, thus the performance could not be evaluated. Only $H_p(10)$ reference values were available and therefore UNFORS NED is also not included in Figure 9.14. GRAETZ ED150 only detected 25% of the given dose equivalent for this quality and POLIMASTER PM1604 readings were not consistent. The results of those two dosimeters are also not shown in the graph and they are considered to be not appropriated for measurements in pulsed radiation fields.

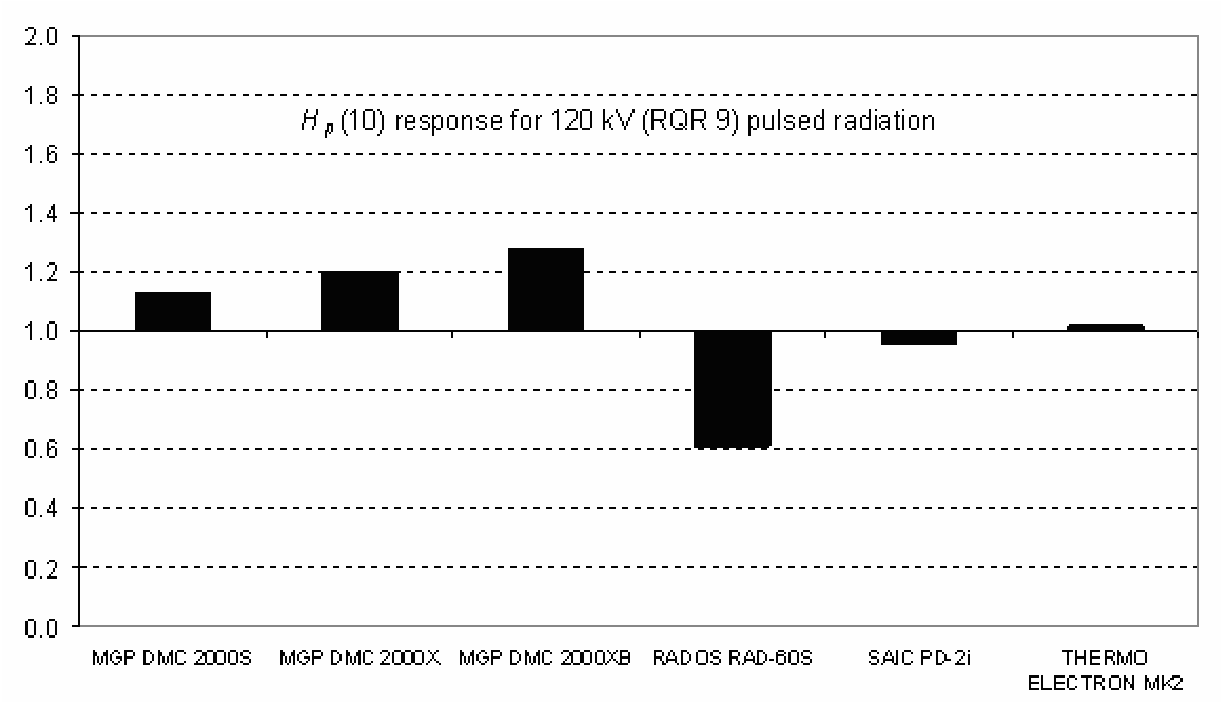


Figure 9.14. Dosimeter response to 120 kV (RQR9) pulsed radiation.

The 60 kV (RQR4) radiation field has been satisfactorily measured by 3/5 devices which are sensitive to low energy photons. The results are shown in Figure 9.15. The responses of ATOMTEX AT3509B and POLIMASTER 1621 could not be assessed because the RQR4 dose equivalent rate was outside their measuring dose equivalent rate range.

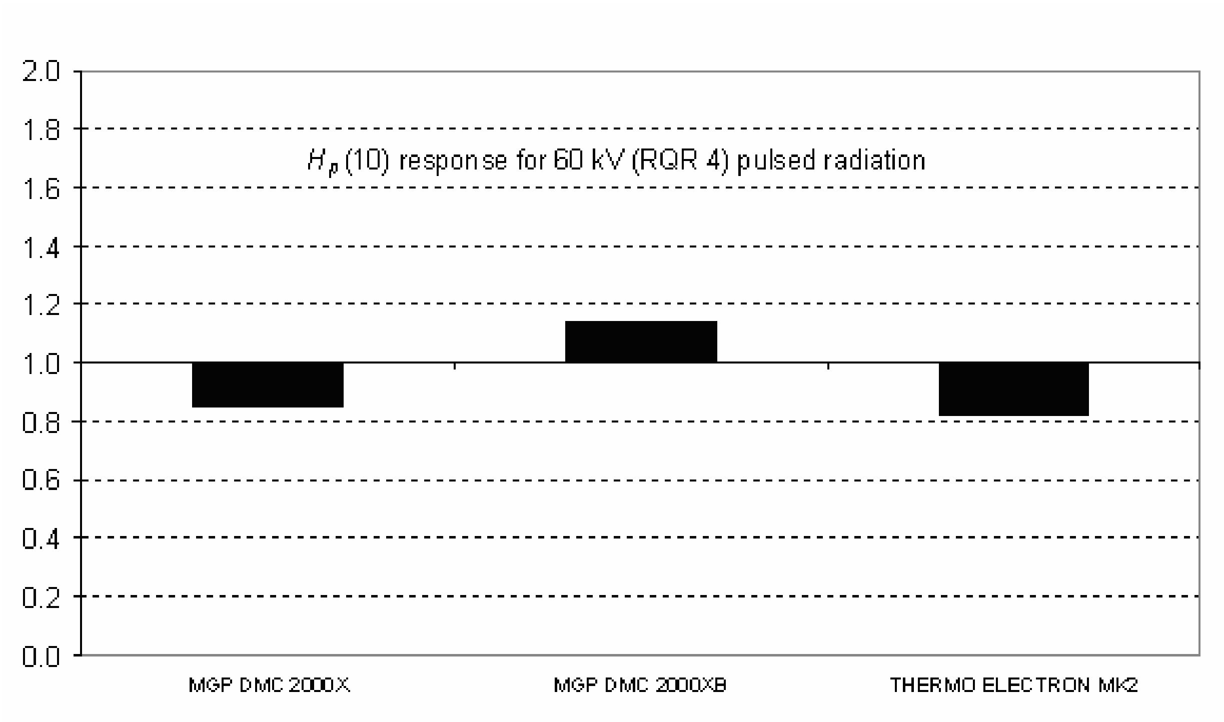


Figure 9.15 Dosimeter response to 60 kV (RQR4) pulsed radiation.

10. SUMMARY AND CONCLUSIONS

10.1. Dosimeter categories

Table 10.1 summarizes the result of the 13 tested APDs. The dosimeters are classified in "categories" in this text, depending on the combinations of quantities and radiation specified in IEC 61526:

(1) $H_p(10)$ and $H_p(0.07)$ from X and gamma radiations;
(2) $H_p(10)$ and $H_p(0.07)$ from X, gamma and beta radiations;
(3) $H_p(10)$ from X and gamma radiations;
(4) $H_p(0.07)$ from X, gamma and beta radiations.

It can be seen that most dosimeters (9/13) belong to category 3, which means that they measure $H_p(10)$ from X and gamma radiations. In general they measure penetrating radiation but two of them can also be used for low energy photon. All the dosimeters in this "category" fulfil the applicable IEC testing requirements. As regards the influence of dose equivalent rate in dosimeter response, CANBERRA DOSICARD could not be fully evaluated (see comment in paragraph 8.3).

ATOMTEX AT3509B belongs to "category 1", it measures $H_p(10)$ and $H_p(0,07)$ from X and gamma radiations. It fulfils applicable IEC testing requirements.

MGP DMC2000XB and THERMO EPD MK2 belong to "category 2", they are the most complete dosimeters, they can measure $H_p(10)$ and $H_p(0.07)$ from X, gamma and beta radiations. They comply with all the IEC requirements except that MGP DMC2000XB exceeds the IEC limit for the angular response for beta radiation (60° for ^{90}Sr-^{90}Y source). Both dosimeters present satisfactory response to mixed photon fields and pulsed radiation. Moreover MGP DMC2000XB can also measure ^{147}Pm.

As it has been mentioned in the text UNFORS NED cannot be identified with any specific "category" considered in the IEC standard, since it measures $H_p(0.07)$ for penetrating photon radiation, whereas the 6th category included in the standard for the measurement of this quantity comprises a wider type of radiation measurements (Table A-2). From the results of this dosimeter one can state that this dosimeter has been designed for a very specific type of application, nuclear medicine, and that in this field the dosimeter could give satisfactory measurements. However, in low energy photon fields the dose is highly overestimated.

10.2. Type of tests

Apart from IEC 61526 Standard tests, the intercomparison has included a test performance of the dosimeters in pulsed radiation fields RQR9 and RQR4, defined in IEC 61267. This is the first time that results of such type of comparison are published, which is of great importance for APD end users in medical diagnostic and surgery X ray applications. The tested reference fields are similar, both, in energy and dose equivalent rate, to realistic medical diagnostic fields. It is also necessary to point out that the dosimeters were positioned in the beams.

This irradiation condition can be met in some cases but the most usual conditions are the scattered radiation fields where the dose equivalent rate is lower. Studies are in progress within EURADOS Working Groups to propose such fields in the future.

10.3. Summarized results

Only three devices, MGP DMC2000XB, MGP DMC2000X and THERMO EPD Mk2, have given satisfactory results both for 60 kV (RQR4) and 120 kV (RQR9) pulsed radiation. SAIC PD-12i, RADOS RAD60S and MGP DMC200S present good results for 120 kV (RQR9) pulsed radiation, which shows that those dosimeters can be used in pulsed radiation fields within their energy range of measurement.

Unfortunately, the response to pulsed radiation could not be assessed, because of the limited dose equivalent rate range, for ATOMTEX AT2503, AT3509B and POLIMASTER PM1621. This is of major concern especially for dosimeter ATOMTEX AT3509B and POLIMASTER PM1621 because they are meant to be used for low energy X rays. It was shown that POLIMASTER PM1604 is not appropriate to be used in RQR9 pulsed radiation fields.

The intercomparison results show that the general dosimetric performance of the tested APDs is comparable to the performance of standard passive dosimetric systems [2, 4], (except for beta and low photon energy radiation and pulsed radiation fields). The accuracy at reference photon radiation, the reproducibility and repeatability of measurements are even better than for most passive dosimeters. However, the study highlights that not all the devices have been designed for any radiation field and that the end-user should take into account at least information about the dose equivalent rate and energy ranges before using the dosimeter. It is also shown that two different APD can measure simultaneously $H_p(10)$ and $H_p(0,07)$ for low and high penetrating radiation with satisfactory results.

The performance results confirm that the IEC standard requirements are adequate but that they can be insufficient for some applications such as pulsed radiation fields. In addition it is shown that extremity active personal dosimeters are still not as developed as whole body dosimeters and that the standards in this field are not sufficiently developed yet.

Table 10.1. Summary of APD performance

IEC "Category"		**1**	**2**		**3**								**6 ***
Characteristic under test or influence quantity		AT3509B	DMC 2000XB	EPD MK	DMC 2000X	PM1621	ED150	SAIC PD2i	PM1604A	AT2503	RAD 60S	DMC 2000S	DOSICARD	NED-30
IEC 61526 requirements														
Relative intrinsic error Photon radiation (^{137}Cs)		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Photon energy response	33 keV-1.5 MeV	Yes	Yes	Yes	Yes	Yes	NA	NA	NA	NA	NA	NA	NA	No(1)
	60 keV-1.5 MeV	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Angle of incidence (^{137}Cs) (0 to ± 60 º)		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Influence of dose rate		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	NE(2)	Yes
Statistical fluctuation for $H_p(10)$		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Statistical fluctuation for $H_p(0,07)$		Yes	Yes	Yes	NA	NA	NA	NA	NA	NA	NA	NA	NA	Yes
Relative intrinsic error Beta radiation ($^{90}Sr/^{90}Y$)		NA	Yes	Yes	NA	NA	NA	NA	NA	NA	NA	NA	NA	No(1)
Beta energy response	E_{max}>0.78 MeV	NA	Yes	Yes	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Angle of incidence $^{90}Sr/^{90}Y$ (0 to ± 60 º) ^{85}Kr (0 to ± 30 º)		NA	No(3)	Yes	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Other Tests														
Relative intrinsic error Beta radiation (^{147}Pm)		NA	Yes	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Mixed photon fields N-80+ ^{137}Cs		Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
60 kV pulsed radiation		NE	Yes	Yes	Yes	NE	NA	NA	NA	NA	NA	NA	NA	NA
120 kV pulsed radiation		NE	Yes	Yes	Yes	NE	No(4)	Yes	No(4)	NE	Yes	Yes	NE	NA

Note:

NA stands for not applicable because the measuring energy range does not include this quality or radiation quantity.

NE stands for not evaluated because the experimental dose rate range exceeded the dosimeter dose rate measuring range.

(1) NED as indicated in paragraph 10.13 is designed for a very specific application and does not fulfil the IEC requirements for category 6.

(2) The dosimeter does not fulfil the IEC requirement up to 1 Sv/h, but the intercomparison has not tested the performance at 100 mSv/h (see paragraph 10.3).

(3) The IEC requirement is exceeded for an angle of incidence of 60º for $^{90}Sr/^{90}Y$.

(4) Although the dosimeter should partially detect this radiation field, readings only detect 25 % of the given dose in the case of GRAETZ ED150 and are inconsistent, ranging from 0 to 392 for a given dose of 700 µSv/h for PM1604A.

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ANNEX
ORGANIZATION OF THE INTERCOMPARISON

Table A-1. Contacted APD suppliers

Manufacturer	Address	Participation
AEA Technology Isotrack	AEA Technology QSA GmBH Amersham Buchler Site Gieselweg 1, Braunschweig, D-38110 Germany	no answer
Aloka	**ALOKA Ges.m.b.H.** Industriezentrum NÖ-Süd Strasse 2a, Objekt M29, A-2351 Wiener Neudorf, Austria	no answer
Atomtex	5, Gikalo Street Minsk 220071 , Belarus	**YES**
Automess	Daimlerstrasse 27 D -68526 Ladenburg, Germany	**NO**
Berthold Technologies GmbH	Ameisgasse 49–1 A-1140 Vienna, Austria	**NO**
China Nuclear Energy Industry Corporation (CNEIC)	P.O. Box 822, 3A Nan Li Shi Lu, XICheng Dist Beijing 100037, China	no answer
Panasonic Industrial Europe	Panasonic House, Willoughby Road, Bracknell, Berks, RG12 8FP, United Kingdom	**NO**
DOSITEC	Dositec, Inc. 7 Ave D Hopkinton, MA 01748 USA	no answer
Eurisys/Canberra	Canberra Packard Central Europe GmbH Wienersiedlung 6 A-2432 Schwadorf, Austria	**YES**
Fuji Electric	1, Fuji-machi, Hino-city, Tokyo 191-8502, Japan	no answer
Gamma Technical Corporation	PO Box 1 Fehervari Ut 85, H-1509 Budapest Hungary	no answer
Graetz Strahlungsmesstechnik	Graetz Strahlungsmesstechnik GmbH Postf 8100, Westiger Strasse 172, D-58762 Altena, Germany	**YES**

Manufacturer	Address	Participation
Polimaster	MEET Handels GmbH Tamariskengasse 102/13/5, A-1220 Vienna, Austria	**YES**
Science Applications International Corporation (SAIC)	16701 West Bernardo Drive, San Diego, California 92127 United States of America	**YES**
Saphymo	5, rue du Theatre, F-91884 Massy Cedex, France	no answer
Synodys RadPro International GmbH	RadPro International GmbH Burger Strasse 28, D-42929 Wermelskirchen, Germany	**YES**
MGP Instruments SA synOdys Group	BP 1, FR-13113 Lamanom	**YES**
RADOS Technology Oy synOdys Group	Mustionkatu 2, P.O. ox 506, FI-20101 Turku	**YES**
Target Systemelectronic GmbH	Koelner Strasse 99, D-42651 Solingen, Germany	no answer
Thermo Electron Corporation	Viktoriastrasse 5, D-42929 Wermelskirchen 1, Germany	**YES**
Unfors Instruments AB	Uggledalsvagen 27, SE-427 40 Billdal, Sweden	**YES**
Victoreen	Elimpex Medizintechnik Ges.m.b.H., Spechtgasse 32, A-2340 Mödling, Austria	no answer

Table A-2. Time schedule

	Action	*Goal*	*Responsible*	*Deadline*
1	**Preparation**			
1.1	Consultants meeting	Define criteria, project coordinator, set-up protocol & questionnaire	IAEA/EURADOS	January 2004
1.2	Contact possible irradiating laboratories	Select irradiating laboratories	IAEA/EURADOS	March 2004 (at PTB)
1.3	Distribute invitation and questionnaire to suppliers / manufacturers	Inform about intercomparison,	IAEA	May 2004
1.4	Confirm participants and request dosimeters	Selection	IAEA	September 2004
1.5	Formal agreement with Irradiating labs	Contract	Irradiating labs	December 2004
2	**Intercomparison**			
2.1	Send dosimeters to project coordinator (IAEA)		Participants	February 2005
2.2	Send dosimeters to irradiating laboratories.		Project coordinator	March 2005
2.3	Irradiation and read out.		Irradiating labs	April – August 2005
2.4	Return dosimeters via project coordinator to the suppliers		Irradiating labs and Project coordinator	August 2005
2.5	Evaluate intercomparison and report to project coordinator	Preparation of an interim report	Project coordinator	November/ December 2005
2.6	Results discussion meeting	Information to and feedback from suppliers	Project coordinator at EURADOS annual meeting	Jan 2006
2.7	Forward individual results and interim report to participants		Project coordinator	February 2006
2.8	Presentation of results at a workshop with suppliers	Discuss results and needs for further action	IAEA/EURADOS, participants	April 2006
2.9	Preparation of project evaluation		IAEA/EURADOS	June 2006

Table A-3. Irradiation conditions

Laboratory	Parameter to be tested	Radiation quality	Dose to be delivered	Uncertainty(*) (k=2)
IRSN Laboratoire de Dosimétrie des Rayonnements Ionisants DRPH/SDE/LDRI	Energy response Photon	S-Co S-Cs N-30 N-80 N-120	0.1 mSv per quality	4 µSv
Belgian Nuclear Research Centre Radiation Protection	Dose rate response Photon	S-Co	100 mSv (at 1Sv/h) 100 µSv (at 1 mSv/h)	5 mSv 5 µSv
Belgian Nuclear Research Centre Radiation Protection	Angular response Photon	S-Cs (Horizontal rotation)	300 µSv (for each angle: 0^o, 45^o, 60^o)	14 µSv
Belgian Nuclear Research Centre Radiation Protection	Mixed field Photons	N-80 + S-Cs 0^o angle	350 µSv	21 µSv
LNE-LNHB **CEA / DRT - LIST**	Pulsed radiation from a diagnosis X ray generator	RQR4 (60 kV) RQR9 (120 kV)	750 µSv (at 1,68 mSv/h) 660 µSv (at 1,49 mSv/h)	30 µSv (including a 4% uncertainty on the conversion coefficient from K_{air} to $H_p(d)$.
LNE-LNHB **CEA / DRT - LIST**	Response to Beta particle radiations in terms of $H_p(0.07)$	^{90}Sr-^{90}Y: -60^o to $+60^o$ in steps of 30^o ^{85}Kr : -30^o, 0^o, $+30^o$ ^{147}Pm: 0^o	1 mSv (very few irradiations were done at 2 mSv)	18 µSv 19 µSv 24 µSv

Table A-4. Main characteristics of tested APD as provided by the manufacturer

APD type and manufacturer	Energy response E_{min} (keV)	E_{max} (keV)	Deviat. (%)	Angular response Deviat. to Cs-137 (%)	Dose rate range (mSv/h)	Weight incl. battery (g)
ATOMTEX AT2503	50	1500	30%	IEC 61283	$10^{-4} – 5\cdot10^{2}$	70
ATOMTEX AT3509B	15 1500	1500 10000	25 % 50 %	IEC 61526	$10^{-4} – 1\cdot10^{3}$	100 + bat
CANBERRA DOSICARD	60	1250	15%	0°-90°±25% (Co-60)	$10^{-4} – 1\cdot10^{3}$	65
Graetz ED 150	50	2000	Not given	Not given	$10^{-4} – 1.5\cdot10^{3}$	160
MGP DMC 2000S	50	6000	20%	IEC 61283	$10^{-4} – 1\cdot10^{4}$	70
MGP DMC 2000X	20	6000	30%	IEC 61283	$10^{-4} – 1\cdot10^{4}$	70
MGP DMC 2000XB	20	6000	30%	IEC 61283	$10^{-4} – 1\cdot10^{4}$	70
POLIMASTER PM1604A	48 3000	3000 6000	30% 50 %	0°-60°±20%	$10^{-3} – 5\cdot10^{3}$	85
POLIMASTER PM1621	10	20000	15 %	0°-60°±20%	$10^{-4} – 1\cdot10^{2}$	150
RADOS RAD-60	55 3000	3000 6000	25% 35%	IEC 61283	$5\cdot10^{-3} – 3\cdot10^{3}$	80
SAIC PD-2i	55	6000	25%	Not given	$10^{-4} – 5\cdot10^{3}$	90
THERMO ELECTRON Mk2	15	7000	20%	IEC 61526	$10^{-4} – 4\cdot10^{3}$	95
UNFORS NED (sensor)	140	1200	10%	0°-60°:25% (140 keV)	$0.18 – 9\cdot10^{3}$	50

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Consultants meetings

EURADOS General Assembly, Braunschweig, Germany, 8–11 March 2004

EURADOS General Assembly, Krakow, Poland, 19–21 January 2005

EURADOS General Assembly, Oxford, United Kingdom, 24–27 January 2006

Results discussion meeting with suppliers, Vienna, Austria, 11–12 April 2006