Active methods & instruments for personal dosimetry of external radiation: present situation in Europe and future needs
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Abstract Active personal dosimeters (APD) are progressively more and more used in radiation protection. Despite their success APDs are relatively new devices for individual monitoring of workers. Interesting characteristics of APDs compared to passive dosemeters are: instant or direct reading, data transfer to and from computer network, lower dose sensitivity, audible alarms and dose memory options for distant readout. A wide range of APDs for gamma and beta are commercially available, their performances are in general sufficient for radiation protection. Recently also commercial neutron devices appeared on the market. In modern radiation protection APDs are strictly necessary operational tool to satisfy the ALARA principle.

1 INTRODUCTION

In this paper we will give an overview of the legal framework in Europe for the use of APDs. A description of different techniques used for APDs will show the state of the art of the devices. Calibration and testing of the APDs is important, and several national and international standards exist. An overview will be given, as well as an outline of the quantities to be used. Finally, some reflections are made concerning the use of APDs at the workplace by the end user.

1.1 Recommendations and Legal requirements

Electronic and instant reading devices are extensively used in Europe for radiation protection of workers although the 96/29 European Union directive [1], based on the recommendations of ICRP 60 [2], does not specify the type of dosemeters to be used for individual monitoring. Substantial improvements on radiation protection programs and procedures, as required by European directives, were achieved using active devices. The 96/29 European Union directive reinforces basic recommendations previously established, namely: justification of exposure, optimisation of protection and dose limitation, requiring the submission of certain practices involving ionising radiation to a system of reporting and prior authorisation. In the context of optimisation, all exposures shall be kept as low as reasonably achievable and dose constraints should be used for radiological protection purposes. This requires the implementation of control measures and monitoring relating to the
different areas and working conditions including individual monitoring, which should be systematic for exposed category A workers. This monitoring shall be based on individual measurements that are established by an approved dosimetry service. A record containing the results of the individual monitoring shall be made for each exposed category A worker. In the case of an accidental or emergency exposure, the results of individual monitoring shall be submitted without delay. Legal dosimetry for dose record is mostly performed with passive dosemeters except for some pilot countries, such as the United Kingdom and Switzerland, where APDs are accepted if approved by accredited services. In other countries plans to accept some APD for legal dose record are being set up.

APD systems present powerful capabilities for day-to-day and job-to-job processing of data, which will optimise the application of the ALARA principle.

Several European countries considered that APDs are necessary for optimisation of radiation protection of special categories of workers (ex: A) or in special areas (ex controlled area). The recommendations of the European directive, in the field of operational external dosimetry, are widely spread in European countries even when a transcription to the national law is not yet realized. The concept of individual dosimetry for radiation protection of workers is applied wherever possible. In many sectors, though not in all, employers consider APDs as an efficient and reliable way to satisfy ALARA principle and management of doses for optimisation. In several European countries APD use is either considered as a license condition for some workplaces (nuclear power plants: NPP, fuel production and spent fuel reprocessing, some medical practices, industrial radiography…) or mandatory in special cases (in high dose level areas or for potential accidental situations, for itinerant workers). In many places they are used also on a voluntary base.

Recommendations of the European directive are widely applied as regards individual dosimetry at work places. Nevertheless, progress must still be done in the industrial and medical sectors.

1.2 Calibrations and Standards

According to the 96/29 European Union directive, the undertaking are responsible for assessing and implementing arrangements for the radiological protection of exposed workers. Member States shall require the undertaking to consult qualified experts or approved occupational health services on the examination and testing of protective devices and measuring instruments comprising in particular:

- Regular checking of effectiveness of protective devices and techniques,
- Regular calibration of measuring instruments and regular checking that they are serviceable and correctly used.

The directive does not specify requirements on calibration but these are established by member states. In most countries, APDs are calibrated and regularly tested following national directives. ISO Standard 17025 [3] for accredited services is progressively established in Europe. European or IEC standards for APD use are only applied in some countries: progress has still to be done to harmonize the use of international and European standards for calibration and testing procedures. In table 1 the relevant standards for APDs are summarized.
Table 1 standards relevant for APDs

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC</td>
<td>IEC 1525: Radiation protection instrumentation – X, gamma, high energy beta and neutron radiations – Direct reading personal dose equivalent and/or dose equivalent rate monitors. IEC 1525, 1996</td>
</tr>
<tr>
<td>IEC</td>
<td>IEC: Radiation Protection Instrumentation. Measurement of Personal Dose Equivalent $H_p(10)$ and $H_p(0.07)$ for X, Gamma and Beta radiation: Direct Reading Personal Dose Equivalent and/or Dose Equivalent Rate Dosemeters. IEC 61526 (1998)</td>
</tr>
<tr>
<td>IEC</td>
<td>IEC 1323: Radiation Protection Instrumentation – Neutron radiation - Direct reading personal dose equivalent and/or dose equivalent rate monitors IEC-1323 (1995)</td>
</tr>
</tbody>
</table>

2. INSTRUMENTS AND METHODS

2.1 Detectors

Active personal dosemeters, commercially available, for gamma and beta are based mainly on Geiger-Müller, silicon diodes and on direct ion storage (DIS) detectors. For neutrons personal dosimetry only silicon diodes and direct ion storage plus bubble devices [4] are used. Geiger-Müller tube detectors are pulse type ion chambers operated in electron sensitive mode. Ion chambers have been used as reference devices for a long time and are described in many textbooks. [5,6]. The main difficulty to be overcome, in order to use them for personal dosimetry, is to maintain a high constant electric field to collect the ionisation charges before they recombine. Due to their higher mobility electrons have collection time shorter than ions. For that reason, commercially available personal dosemeters based on ion chambers are working on Geiger-Müller electron sensitive mode. Silicon diodes have a much higher sensitivity to radiation than ionisation chambers. The mean energy spent by the charged particles to produce an electron-hole pair in silicon semiconductors is about ten times smaller than in gases. The ionisation process is than ten times more efficient in silicon diodes than in ionisation chambers [7].

The DIS detector (figure 1) is an hybrid between an ion chamber and a MOSFET data storage device [8]. It can be used simultaneously as a passive or as an active dosemeter but it needs an initial reference voltage value. Integrated dose can be obtained by measuring the shift of the voltage from the initial value. Dose rates are obtained by measuring step by step the shift voltage. Silicon diodes and DIS are well-established detectors for gamma-beta dosimetry. Table 2 gives the main characteristics of 22 devices used in Europe [9].
Most devices are calibrated in units of personal dose equivalent, $H_p(10)$ or $H_p(10)$ and $H_p(0.07)$ when they are manufactured for the European market and fulfil some requirements stated in the IEC 61526 and IEC 61283 Standards. However, there still exist big differences between manufacturers as regards the standard and the type of testing procedure followed. This seems to be variable depending on the main users of the dosemeter and the country where it is used. Generally speaking, the overall radiological behaviour of active personal dosemeters compared to the behaviour of passive dosemeters is satisfactory in particularly as regards as accuracy for photon and beta radiation, measurement range and dose linearity. The poor performance at low photon energy described for earlier dosemeters is now overcome by a few APDs.

Most APDs listed in table 2 have specific software for dose recording and can be connected to a centralised dosimetry system. Many new developments related to the transmission and handling of data are being implemented.

![Figure 1](image.png)

**Figure 1** Photon sensitive ion chamber Wall Material: Graphite or Teflon

### Table 2: Main Characteristics of a set of 22 photon APDs (information provided by manufacturers)

<table>
<thead>
<tr>
<th>APD Reference</th>
<th>Energy range (keV)</th>
<th>Angular response % $^{137}$Cs</th>
<th>Weight (g)</th>
<th>Volume (cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AEA Tech. DoseGuard S10</td>
<td>60 3000</td>
<td></td>
<td>80</td>
<td>115.0</td>
</tr>
<tr>
<td>Aloka PDM112</td>
<td>40 1000</td>
<td></td>
<td>50</td>
<td>52.2</td>
</tr>
<tr>
<td>Automess ADOS</td>
<td>70 3000</td>
<td>0º-45º 20%</td>
<td>190</td>
<td>133.9</td>
</tr>
<tr>
<td>Canberra Dosicard</td>
<td>50 2000</td>
<td>0º-90º 25% (Co-60)</td>
<td>65</td>
<td>83.3</td>
</tr>
<tr>
<td>Comet APD (Panasonic Ind. Eur.)</td>
<td>20 1600</td>
<td>0º-60º 20%</td>
<td>109</td>
<td>93.5</td>
</tr>
<tr>
<td>Dositec L36</td>
<td>60 6200</td>
<td>25%</td>
<td>77</td>
<td>57.1</td>
</tr>
<tr>
<td>Fuji Electric NRY 20001</td>
<td>50 6000</td>
<td>0º-60º 20%</td>
<td>100</td>
<td>85.0</td>
</tr>
<tr>
<td>Graetz ED 150</td>
<td>50 2000</td>
<td></td>
<td>160</td>
<td>92.5</td>
</tr>
<tr>
<td>MGP DMC 2000S</td>
<td>50 6000</td>
<td>30%</td>
<td>IEC 61283</td>
<td>70</td>
</tr>
<tr>
<td>MGP DMC 2000X</td>
<td>20 6000</td>
<td>30%</td>
<td>IEC 61283</td>
<td>70</td>
</tr>
<tr>
<td>MGP DMC 2000XB</td>
<td>20 6000</td>
<td>30%</td>
<td>IEC 61526</td>
<td>70</td>
</tr>
<tr>
<td>MGP SOR/R</td>
<td>50 6000</td>
<td></td>
<td>IEC 61283</td>
<td>55</td>
</tr>
<tr>
<td>Mini Instruments 6100</td>
<td>30 1000</td>
<td>20%</td>
<td>125</td>
<td>118.8</td>
</tr>
<tr>
<td>Polimaster PM1203</td>
<td>60 1500</td>
<td>25%</td>
<td>90</td>
<td>126.0</td>
</tr>
<tr>
<td>Rados DIS-1</td>
<td>15 9000</td>
<td>30%</td>
<td>20</td>
<td>16.2</td>
</tr>
<tr>
<td>Rados RAD-51/51T</td>
<td>60 3000</td>
<td>25/35%</td>
<td>IEC 61283</td>
<td>90</td>
</tr>
<tr>
<td>Rados RAD-60/62</td>
<td>60 3000</td>
<td>25%</td>
<td>IEC 61283</td>
<td>80</td>
</tr>
<tr>
<td>Rados RDD-20/RDR-20</td>
<td>50 1500</td>
<td>30%</td>
<td>IEC 61283</td>
<td>24</td>
</tr>
<tr>
<td>Saic PD-2/3I</td>
<td>55 6000</td>
<td>25%</td>
<td>90</td>
<td>58.8</td>
</tr>
<tr>
<td>Saphydose Gamma</td>
<td>50 1300</td>
<td>30%</td>
<td>IEC 61283</td>
<td>165</td>
</tr>
<tr>
<td>Siemens EPD1, EPD2 (Mk1)</td>
<td>20 10000</td>
<td>20%</td>
<td>IEC 61526</td>
<td>170</td>
</tr>
<tr>
<td>Siemens Mk2</td>
<td>15 7000</td>
<td>20%</td>
<td>IEC 61526</td>
<td>95</td>
</tr>
</tbody>
</table>
Recent developments on dosemeters based on industrial diamond were reported in a review on solid state detectors [7]. The advantages of diamond are its equivalence to biological tissues and its resistance to high radiation doses; on the other hand its detection efficiency is low compared to that of silicon. This characteristic makes diamond more suitable for high doses measurements for radiotherapy.

Some developments on CCD-based readout for silicon or caesium iodine detectors [10] and on metallic-oxide-semiconductors (MOS) [11] are devoted to improving low doses measurements (down to the µSv region).

Recently some electronic dosemeter for extremities have also been developed and commercialised. Several papers highlight the advantage of these devices compared to conventional skin and extremity TLDs [12], mainly in the estimate of hand or finger doses during interventional radiology and radio pharmaceutical manipulation. At present these are still rarely used due to practical limitations. The latest developments consist of electronic dosemeters, which are made of a small sensor and a recording unit. The small sensor is positioned in the part of the body where the dose is to be measured, usually the fingertips. The recorder is bigger and it is usually kept in the wrist or in a pocket; unfortunately, at the moment, there does not exist a specific Standard for extremity electronic dosemeters, and there are not many published data related to the calibration and characterisation of such devices.

For neutron a few silicon devices are commercially available since a few years and several prototypes are under development. State of the art of APDs for neutron are given in references [13]; the response functions presented in figure 2 show that only one of the devices, the SAPHYDOSE-n has an almost constant response from thermal to 14 MeV. This device has also interesting spectrometric characteristics (figure 3); it can roughly identify the energy range of the detected neutron [14]. Its main drawback is its high cost due to the sophisticated detection technique based on an epitaxial silicon strip detector covered with several convertors.

DIS detectors can also be used as neutron dosemeters [15]. The prototype detector, described in figure 4, use a double chamber system to separate neutron from photons. The chamber wall is a tissue equivalent material which converts neutrons into alpha particle and protons.

The region between 1 eV to 100 keV is still under investigation for all devices since no mono-energetic reference data exist in this region but broad resonance; an extrapolation method to cover this region has been proposed in reference [16]. Some APDs for neutrons are currently under test in the framework of the EC project EVIDOS [17].
Figure 3a: Simulation of the energy deposits of the neutrons at 144 keV, 250 and 565 keV and of the photons of the $^{60}$Co in a depleted zone of 5 µm

Figure 3b: Comparison of spectra in energy deposited, experimental and numerical
Figure 4 Neutron/photon sensitive ion chamber Wall Material: A-150/PE containing $^6$Li

2.2 Measured quantities

The ICRP60 publication (1991) [2] defines and recommends the use of the effective dose $E$ for radiological protection purposes. However, this quantity cannot be directly measured; and in practice, the operational quantities, ambient dose equivalent ($H^*$) and personal dose equivalent ($Hp$), as defined in the ICRU 51 report (1993) [18] are recommended to estimate the effective dose $E$. These operational quantities are related, through calculated conversion coefficients "$h^*$", to the measurable function fluence $f(z)$ by:

\[
H^* = \int h^* f(z) \, dz \, dy \, dp \\
Hp = \int h^p f(z) \, dz \, dy \, dp
\]

$\frac{\partial}{\partial \theta}$ is the distribution of the fluence with respect to energy (energy $\gamma$ and direction $\theta$); $h^*$ or $h^p$ are the fluence to operational quantity conversion coefficients as defined by the ICRU 57[19]. The ambient dose equivalent $H^*(10)$ (defined in reference [19]) is an isotropic function independent of the angle which, if correctly measured, approximates with accepted accuracy the protection quantity $E$. $Hp (10)$ (which is defined as the dose equivalent at 10 mm in the body at the location where the personal dosimeter is worn) on the other hand, is a directional function, which depends not only on energy but also on the angle of the radiation field. The coefficients $h^p$ are calculated [19] only for angles between 0° and 75°, for these reasons $Hp (10)$ accurately approximates $E$ only in certain field geometries and certain energies. In figure 5a the ration of $Hp/E$ as function of photon energy for AP,ROT and PA field geometry fields present discrepancies at low energy [20]. This problem, as shown in figure 5b, is more important for neutron because in some energy range $Hp$ underestimates $E$ which should be avoided for radiation protection purposes. More calculations and developments have to be done in order to achieve a better approximation of the effective doses. Facilities simulating workplace conditions for calibration and studies are an important tool to improve dosimetry instruments and methods.
Figure 5a Ratio of personal dose equivalent $H_p$ to effective dose equivalent as function of energy for photons at AP, ROT and PA field geometry

Figure 5b Ratio of personal dose equivalent $H_p$ to effective dose equivalent as function of energy for neutrons at AP, ROT and PA field geometry
Figure 6. The IRSN CANEL Facility assembly (a), Neutron fluence energy distribution measured and MCNP calculated (b) and neutron fluence energy distribution in directional intervals from 0° to 50° in the calibration area (c);
As an example, the CANEL facility of IRSN in Cadarache (figure 6a shows the assembly), which produces neutron spectra encountered in the nuclear industry, has been fully characterised in fluence as function of energy (Figure 6b [21]), angular distribution have been calculated [22] and used to study the behaviour of APDs in the framework of EVIDOS [17]. Workplace studies using instrumented anthropomorphic [23] phantoms may also allow to foresee important information since introducing dosemeters at well-defined places, representing human organs, in the phantom will give directly the measurement of the effective dose. The comparison of these effective dose measurements to measurements of operational quantities using conventional instruments will evaluate the deviation of operational quantities from radiation protection quantities in several real workplace situations. APD can be useful in studying geometry considerations in workplaces because of their direct reading and resetting capabilities.

2.3 Calibration and testing

As already mentioned, compliance to standards is not always required for APDs but in several European countries APD approval is delivered by authorized services that apply international standards. For instance in France a legal decree requires for APD:

- To be adapted to the type of radiation and follow the European or, failing this, French standards;
- To be individual and personal, worn on the body trunk;
- To present an instantaneous reading of personal dose equivalent and personal dose equivalent rate over one period of wearing;
- To offer the possibility of adjusting the alarm levels.

European standards are often a transcription of international standards. For photon radiation the standard ISO 4037 [24] and specifications given in paragraph 8 of the IEC-61526 [25] standard apply for calibration. The reference photon radiation qualities are: filtered X-radiation in the energy range 12 keV - 300 keV and radioactive gamma sources $^{137}\text{Cs}$ (662 keV) and $^{60}\text{Co}$ (1.25 MeV) defined in the ISO [24] standard from the International Organization for Standardization. For the purpose of personal dosemeter calibration and testing, the operational quantity $H_p (d)$, is defined as the dose equivalent at a depth $d$ in a phantom made of ICRU tissue [26]. For strongly penetrating radiation the depth $d$ of 10 mm is used to approximate the effective dose; for weakly penetrating 0.07 mm is used for skin doses and 3 mm for the length of the eye. Three phantom types defined by ISO 4037-3 are used for calibration purposes: a slab water phantom, 300 mmx300 mmx150 mm in dimension to approximate the human torso, a pillar water phantom: 73 mm diameter x 300 mm length cylinder for calibration of wrist dosemeters; and a PMMA rod phantom: 19 mm diameter x 300mm length cylinder for calibration of finger dosemeters. Table 3 lists the main radiological tests to be performed on the APDs according to ISO and IEC standards. Together with the listed requirements, IEC 61526 also includes several environmental tests (such as electromagnetic compatibility, temperature, humidity, etc.). These tests are expensive and constructors do not always perform all of them. Although manufacturers are required to comply with standards, sometimes they don’t specify which tests have been performed with their instruments. For this reason, in several countries, comparisons of APDs have been performed to verify their compliance to standards, to offer constructors suggestions to improve their instruments, and to help users in choosing the APD best adapted to their own application.
Table 3: Tests performed and limits given by standards. $H_p(10)$ has been determined using an ISO water slab phantom.

<table>
<thead>
<tr>
<th>Name</th>
<th>Standard</th>
<th>Method</th>
<th>Calibration Quantity</th>
<th>Radiation</th>
<th>Dose equivalent rate</th>
<th>Limits given by standards</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reproducibility of the reading</td>
<td>ISO 4037</td>
<td>3 measurements done periodically, on each EPD, during all the study (1 year)</td>
<td>Hp (10) $^{137}Cs$</td>
<td>7 mSv.h$^{-1}$</td>
<td>±2 %</td>
<td></td>
</tr>
<tr>
<td>Repeatability of the reading</td>
<td>ISO 4037</td>
<td>10 successive measurements on each EPD</td>
<td>Hp (10) $^{137}Cs$</td>
<td>7 mSv.h$^{-1}$</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Dose equivalent rate dependence</td>
<td></td>
<td>Irradiation of each EPD at different dose equivalent rate for different dose equivalents between 0.8 and 800 mSv.</td>
<td>$H(10)$ $^{60}Co$</td>
<td>1, 10, 100 and 1000 mSv.h$^{-1}$</td>
<td>&lt; ±20 %</td>
<td></td>
</tr>
<tr>
<td>Relative intrinsic error</td>
<td></td>
<td>Test of EPD effective range (20, 40 and 80 % of each decade) for dose equivalents and dose equivalent rates</td>
<td>$H(10)$ $^{137}Cs$</td>
<td>&lt; 1 mSv.h$^{-1}$</td>
<td>Dose equivalent &lt; ±20 + x %</td>
<td></td>
</tr>
<tr>
<td>Response as function of radiation energy</td>
<td></td>
<td>5 measurements on each EPD with different filtered X-radiations and gamma sources</td>
<td>Hp (10) X-radiations (12 to 250 keV), $^{137}Cs$ (taken as reference), $^{60}Co$</td>
<td>~10 mSv.h$^{-1}$</td>
<td>&lt; ±30 %</td>
<td></td>
</tr>
<tr>
<td>Response as function of radiation angle of incidence</td>
<td></td>
<td>3 measurements for each angle (0° to ±75°, every 15°) in one horizontal and vertical plane with respect to the front face of the dosemeter</td>
<td>Hp (10) $^{137}Cs$ and filtered X-radiations of 65 keV</td>
<td>~10 mSv.h$^{-1}$</td>
<td>&lt; ±20 % ($^{137}Cs$)</td>
<td></td>
</tr>
<tr>
<td>Retention of reading</td>
<td></td>
<td>Verification of the EPD reading each hour during 8 hours after irradiation</td>
<td>Hp (10) $^{137}Cs$</td>
<td>5 mSv.h$^{-1}$</td>
<td>&lt; ±2 %</td>
<td></td>
</tr>
<tr>
<td>Accuracy of alarm levels</td>
<td></td>
<td>Dose equivalent: Irradiation at the alarm level ±20 % Dose equivalent rate: Irradiation at the alarm level ±15 %</td>
<td>$H(10)$ $^{137}Cs$</td>
<td>Depends on the alarm levels</td>
<td>Lower levels: 10 min irradiation without alarm Upper Levels: Start of the alarm in less than 5 s</td>
<td></td>
</tr>
<tr>
<td>Response time</td>
<td></td>
<td>Time of stabilization of the reading after a factor 10 increase of the dose equivalent</td>
<td>Hp (10) Filtered X-radiations at 118 keV</td>
<td>&gt; 10 µSv.h$^{-1}$</td>
<td>Stabilization time lower than 5 s</td>
<td></td>
</tr>
<tr>
<td>Neutron sensitivity</td>
<td></td>
<td>Irradiation with neutrons</td>
<td>Hp (10) Am-Be with cadmium shield</td>
<td>-</td>
<td>Reading due to neutrons &lt; 5 % $H(10)$ of neutrons</td>
<td></td>
</tr>
<tr>
<td>Indication in overload</td>
<td></td>
<td>Irradiation with dose equivalents and dose equivalent rates 10 times higher than the upper limit of the EPD</td>
<td>$H(10)$ $^{60}Co$</td>
<td>10 times the upper limit of the EPD</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

*Paragraph in standard IEC 61526

Dosemeters should be calibrated and tested on a phantom not only in laboratory conditions but also when their performances are investigated in workplaces. Nevertheless the reading of personal dosemeters on phantoms represent only on average the reading on a human body, which means that two personal dosemeters giving the same response in laboratory conditions may give different responses, in the same workplace, when worn by two workers which have different morphologies. To calibrate and test personal dosemeters, their reading has to be compared to reference values. In laboratory, reference values are well known while in work places they are not always easy to determine since they may vary in space and time. In some workplaces, measurements cannot be reproduced in exactly the same conditions. For all these
reasons, if the accuracy of personal dosemeters can be of the order of 10 to 20% (at 95% confidence level) in laboratory conditions, it can be much larger in workplace conditions (a factor 1.5 or more for neutron or for low dose measurements). In order to improve the accuracies of personal dosemeters, studies can be performed using laboratory simulated workplaces facilities.

**Intercomparisons**

In the past 5 years, several comparisons of APDs have been performed based on IEC standard requirements [27,28,29], [As an example, Figure 7 shows the energy response of some APDs. It can be noticed that the energy response varies very much in the energy range indicated by the constructor and that there might be up to a factor of two between the response of two devices.

![Figure 7: Response as function of radiation energy of the studied APDs](image)

Measurements showed a large variation of performance among the different tested electronic dosemeters. A few devices satisfied most of the IEC 61526 technical requirements and had only little minor non-compliance, whereas some other dosemeters presented important limitations that could imply the loss of dosimetry information or a misreading of the registered dose. The different studies agreed to outline as most critical parameters, the response at low energy photon and beta radiation and the mechanical resistance. Other limitations such as differences in background estimate, dead time corrections at high dose rates or spurious alarm signals were also reported. On the other hand, the behaviour of the tested dosemeters at temperatures from –20°C to 40°C, as well as in the presence of external electromagnetic fields, was in general satisfactory. All referred papers pointed out the need to have a well-defined international standard, such as IEC 61526, and recommended to manufacturers to give technical specifications in accordance to such a standard, in order to allow users to make a proper selection, depending on their needs. An International APD comparison will be organized by AIEA starting in 2004.
2.4 APD use in workplaces

Since several years, the use of active personal dosemeters became common practice in most nuclear installations. Also in smaller companies and hospitals, APDs are starting to find their way. So among the users, there is already a lot of experience on practical aspects of APDs. The use of an APD is likely to be different in a hospital than in a nuclear power plant. Because the radiation environment can be completely different, dosemeters adjusted for these specific fields might have to be used. The knowledge of on the one hand the real characteristics of the dosemeter, and on the other hand the radiological situation in the workplace, is not sufficient to ensure the correct use of the APDs. While passive dosemeters are often supplied by an external service, the APDs are used mostly completely in-house. This enhances the risk of wrong use and misinterpretation of the easily retrievable results from an APD. It is very easy to get a result with electronic dosemeters, but the correct interpretation of the result is more difficult. Some users devote a lot of attention to the APD results, while for others it is just a tool for ALARA that is used occasionally. In most power plants with a strongly evolved radiation protection awareness and over a thousand APDs in use, much more attention is given to the correct use of the APDs, than in a small hospital with only a few occasionally used APDs. The situation will of course also change from country to country, reflecting the different legislations. It might be allowed to use the APD for dose record, there might be the obligation to use it as an alarm dosemeter, or there might be no requirement for APDs at all. Not in all countries the use of APDs is under regulator control.

Most users still use both passive and electronic dosemeters in parallel. With a general tendency to reduce the costs, some users want to use only APDs as dosemeter instead of a double dosimetry system. Still, there is hardly any record on how many failures occur with the APDs, and what other practical difficulties are encountered with the use of APDs.

In the framework of the European project EURADOS, a working group on Harmonization of individual dosimetry will publish by the end of 2004 a report on the status of APDs, which will contain among other information a catalogue of the APDs most frequently used in Europe and an image of the present usage of the APDs.

As an example the adequacy of APDs to the range of energy in several practical applications is reported. Photon energy spectra in some activities have already been reported in references: [30,31,32], and are shown in fig 8.
If one looks at the energy response of the most common APDs, there is usually no problem for photons in the range from 50 keV to a few MeV. This is the range encountered in most end-users from the fuel cycle NPPs, industrial companies and research institutes. Only some problems might arise for the 6 MeV photons in NPPs, or for some specific fields in research institutes (around high-energy accelerators). Some difficulties might also arise with the low and very high-energy photons and betas in hospitals, figure 9, as well as with the measurement of pulsed radiation in medical linear accelerators. The number of APDs used in hospitals is of course still very low.

In activities where both passive and active dosemeters are used, some comparisons of results are performed. In some nuclear power plants this is done in a systematic way, on a monthly base. The differences between both sets of data are generally reported to be between 3 and 8%, but some users report differences up to 20%. As soon as the differences are beyond a certain value (sometimes 10%, sometimes dependent on the dose value), the reason for the differences is investigated.

### 2.5 Users requirements

In the framework of the program EURADOS, supported by the European commission, the working group “harmonisation of individual monitors” sent a questionnaire [9] to APD end users in order to identify what characteristics would be considered ideal for an electronic dosemeter. The best characteristic was considered to be a low price. Next, technical parameters such as energy response, together with mechanical characteristics (robustness, shock resistance...) were selected as second important, closely followed by the environmental characteristics (temperature, humidity resistance...). Much less attention was given to the response to other radiation types like neutrons and betas. Clearly, gammas and X-rays are considered, by all types of users, to be the most important radiation. Many users find it important that a longer battery life could be attained. To the question what the major problems were, mechanical problems were reported to
be the most important. However, better mechanical characteristics were not considered of high priority. This might mean that encountered mechanical problems are not solely attributed to the dosemeters, but partly to wrong and inattentive use. Improvements to the software were considered least important. Spurious alarms were also considered less important. Most end-users assume that the present dosemeters measure the radiation adequately. The wish for an electronic neutron dosemeter is not often expressed. In most workplaces in nuclear industry, neutron doses contribute only a small percentage of the total dose. But in some workplaces, like fuel production, spent fuel manipulation and transport action, neutrons are a very important contribution to the total dose. The project EVIDOS, supported by the European Commission, aims to evaluate the individual neutron dosimetry method in the European nuclear industry, including commercial and prototype APDs for neutrons. Some preliminary results are reported in ref [17]

3 CONCLUSIONS AND FUTURE NEEDS

The analysis of the state of the art in APDs highlights the fact that present technology for photon APDs has reached a level of reliability comparable or even better than passive techniques for most radiological applications. In the case of nuclear power plants, there is now especially great experience in APD use and there are records of APD readings compared with conventional TLD measurements. These data confirm the advantages of APDs over conventional dosimetry, mainly related to alarm features, direct reading and optimisation of practices. Improvements related to low-energy photon response as well as immunity to a wide range of environmental conditions have been reported for the latest developments.

Furthermore, within the framework of the EU 96/29 Directive in Europe, a wide consensus has now been reached regarding the operational quantity of external radiation for individual monitoring dosimetry for radiation protection purposes, which is the personal dose equivalent Hp(d) at depths of 0.07, 3 and 10 mm defined by ICRU. There is also a good agreement on calibration procedures and calibration standards. Nevertheless improvements on effective dose assessment will need developments and studies on angular response function of personal dosemeters. This is of primary importance for neutrons but not negligible for photons. Knowledge of the energy and of the geometry of neutron, and photon fields have to be taken into account to correctly measure fluence and dose equivalent energy distributions. Spectrometry results at workplaces may help users to adapt radiation protection instruments to their working conditions and to choose calibration sources and procedure [33] Spectrometric methods currently applied for nuclear industry measurements may be used also in other domains such as medical applications for better patient treatment planning.

Unfortunately, agreement is not as widespread with respect to APD performance requirements and the type testing standards. In this field, significant differences are observed among countries and manufacturers, as has been shown through independent intercomparisons. Standards for active extremity dosemeters and for photon pulsed radiation fields are not yet available.

In the last decade great efforts have been devoted to the development of APDs for neutron dosimetry. At present there are several prototypes and some commercial APDs, which clearly improve passive dosimetry results. However, further work is still needed in this field to improve energy response of neutron dosemeters and to lower the price of available devices. Greater efforts are also needed to gather and analyse the experience of different types of APD users. There is very little knowledge about failures and workplace performance of APDs. Moreover, preliminary data show large differences among users. This information can be of great importance for improvements in APD design and use and for the development of new standards, in particular as regards the legal use of APDs for dose records.
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