A new passive integrating detector for measurement of individual radon exposure at working places.

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Abstract. A new instrument was developed to measure radon exposure with the use of passive monitors like nuclear track etch detectors. It is based on a device to be switched on and off to permit accurate measurements of timed exposures. The detector arrangement consists of a small cylindrical chamber, a mobile piston inside, a filter holder, a detector holder. The internal sampling volume is variable. The piston is air-tight to fulfill the pumping function: when pull the piston air is driven inside through the filter, and when push the piston all the radon laden air is driven out. The piston can reduce the volume of air adjacent to the track detector to near zero to avoid track detector exposure during storage and shipment. The new dosimeter distinguishes itself from others by the fact that the exposure monitoring begins when the piston device is opened and stops when it is closed. Different prototypes have been realized and tested. The unique characteristics of new ENEA radon dosimeter allow optimizing calibration procedures. Experimental facilities have been realized which allow starting detector exposure only at stationary conditions to avoid effects of varying radon concentration during exposure of passive integrating detectors. An outstanding application of this new technique concerns monitoring radon exposure at work places. Personal dosimeters can be worn to measure the radiation exposure of a person at different working areas and can be used to document an exposure. Sequential exposures can be monitored to correlate the presence of workers with radon exposure during working shifts. The aim of the paper is to briefly describe the main characteristics of this novel technique and the results of experimental performances of different prototypes.

1. Introduction

The concentration of radon indoors presents great variations, due to geological factors, type of building and climatic parameters. The main aim of the radiation protection is the reduction of the exposure with the prevention by remedial actions to reduce the radon concentration in work places or with the exposure control with personal dosimeters for the working time under these critical conditions. The radon exposure estimation is considerably influenced by the ventilation system and work processes. For this reason the remedial actions are not always possible for the exposure reduction due to the influence of the working conditions and other technical factors. An individual radon exposure monitor is necessary for control and optimization of the working time under high radon concentration.

Long-term measurement has proved to be the most used technique for large-scale surveys worldwide. Various types of chamber design have been proposed to register radon and/or its decay products. Based on the diffusion principle, they consists of a small sized chamber into which radon diffuses through a filter membrane or glass fiber filter. The number of alpha particle tracks recorded is proportional to the time integral of the radon gas concentration external to the dosimeter. The personal radon dosimetry in workplaces with high radon levels is up to now not sufficient resolved. The occupational radon exposure should be expressed with some real dose quantity for each person in the workplace. It is the dose that counts; there is no way to use concentration data in a meaningful way, without additional information about the variation of the concentration with time and the actual time a person is exposed to the varying concentrations.
Personal monitoring based on passive radon detectors is a practical measurement technique to assessing compliance with national radon standards. The application of this technique in above ground workplaces and the estimation of individual cumulative doses of employees worked during week measurement period are still being assessed.

Since 2001 the Radon Laboratory of the Radioprotection Institute of ENEA has been conducting a pilot programme of personal monitoring in workplaces with high radon concentrations. A research project has been developed with the aim of identifying a suitable radon monitoring device. This study demonstrated that the passive radon exposure meter, first developed by the ENEA for personal dosimetry, has shown the most suitable set of characteristics.

2. The EPA indoor measurement protocols: recommendations concerning precision monitoring (duplicate measurements) and timely deployment

Indoor Radon and Radon Decay Product Measurement Device Protocols have been established by U.S. Environmental Protection Agency (EPA) [1]. The purpose of a Quality Assurance Program (QAP) is to identify accuracy and precision of the measurements. The quality assurance program for alpha track measurements involves five parts:

- calibration
- known exposure measurements (or spiked samples).
- duplicate detectors
- control detectors.

Spiked samples consist of detectors that have been exposed to known concentrations in a radon calibration chamber. Control detectors ensure that the measurements are not influenced by exposure from sources outside the environment to be measured. Duplicate detectors provide a check on the quality of the measurement result, and allow the user to make an estimate of the relative precision.

Precision error can be an important component of the overall error, so it is important that all users monitor precision. The precision should be monitored using the results of the duplicate detectors as described in the EPA protocol, rather than a precision quoted by the manufacturer. As with spiked samples introduced into the system as blind measurements, the precision of duplicate measurements should be monitored and recorded in the quality assurance records. Duplicate measurements should be side-by-side measurements made in selected locations. The samples selected for duplication should be distributed systematically throughout the entire population of measurements.

Anyone providing measurement services with AT devices should place duplicate detectors in enough houses to test the precision of the measurement. Anyone selling measurements to homeowners can accomplish this by providing two detectors instead of one to a random selection of purchasers, with instructions to place the detectors side-by-side. The pair of detectors should be treated identically in every respect and not identified as duplicates to the processing laboratory.

Consideration should be given to providing some means to ensure that the duplicate devices are not separated during the measurement period.

In order to minimize high background exposures AT detectors should be sealed, shipped, opened, installed, removed, and resealed. Practical EPA recommendations include:

- the stored detectors should remain tightly sealed
• the detector and the radon-proof container should be inspected to make sure that they are intact and have not been physically damaged in shipment or handling
• the sampling period begins when the protective cover or bag is removed. The edge of the bag must be cut carefully, or the cover removed, so that it can be reused to reseal the detector at the end of the exposure period
• users should deploy AT detectors into houses or workplaces as soon as possible after delivery from the supplier
• if the storage time exceeds more than a few months, the background exposures from a sample of the stored detectors should be assessed to determine if they are different from the background of detectors that are not stored for long periods.

The technique of detector sealing inside radon-proof bags, largely used at present, may have several shortcomings. Plastics sheets and aluminum foil bags are supplied to protect detectors from extra-exposure during shipment; however it was evidenced that, “despite the apparent integrity of their foil package, all detectors should be kept out of high Rn environments both before and after the sampling period.”[2].

Another aspects concerns how the film is handled after exposure. It is particularly important that, especially at low radon levels, detectors are not exposed to any extraneous post-sampling alpha radiation. An experimental study evidenced that “the practice of enclosing the detectors in plastic bags after exposure should be limited as it can lead to further etching of detectors and an overestimation of the intended measurement.”[3].

The use of a radon-free container for the storage and mailing personal dosimeters was proposed. The ANPA-holder [4] is a radon free container based on adsorption characteristics of activated carbon. This technique can be used to set up a container, which can be considered virtually radon-free, because the K coefficient depend on various parameters, in particular by the ambient temperature.

3. The need to turn on/off the radon passive integrating dosimeter at workplaces.

The radon monitors cannot be turned off at the end of the exposure run, e.g., at the end of a calibration test or a working shift. The question of accurate evaluation of the individual exposure at workplaces should be discussed in detail (5). Radon detectors in workplaces should be exposed only during the working hours, thus requiring the storage of the detectors when not exposed. This problem is enhanced by the fact that radon is everywhere and the exposure time of the passive personal monitors is only a small fraction of the total storage time of the detector. By contrast with the measurements in dwellings, this problem is not marginal in workplaces, due to the difficulty to turn off the devices when not worn.

To overcome these difficulties different solutions have been tentatively adopted, e.g. the storage at low level areas. Dosimeters, when not in use, need to be stored in areas where radon levels are known to be low. These operations should be made under the supervision of trained staff to identify the areas where to store the dosimeters when not being worn and to carry out monitoring with control dosimeters (5).

4. Technical characteristics of the prototype of the novel ENEA Radon Piston Dosimeter

The ENEA Radon Piston Dosimeter is an alpha particle detector of the “passive” (i.e. motor less) and open-air usage type. The device comprises the following essential parts:
cylinder housing, a mobile piston, a filter holder and a detector holder. The use of a cylindrical geometry instead of hemispherical or conical detector holder is prevailing for its simple design and it is generally used worldwide. The piston is air-tight to fulfil the pumping function: when pull the piston air is driven through the filter, and when push the piston all the radon laden air is driven out. The detector holder can be fitted in a slot on the piston surface or on the bottom closure, adjacent to the filter holder. The internal sampling volume is variable, defined by the piston and the detector holder surface. The piston when pushed can reduce the air volume adjacent to the track detector to zero. The device has been patented (ENEA-Italian Patent No. TO2002A000868).

The figure 1 shows two different prototypes of the used equipment. The prototypes have been realized with a special design which allows to be fitted on the coupling flanges of radon exposure facilities for calibration purposes. Unlike other devices that limit to the covering function of the detector surface, the new device has two functions: a. covering function of detector surface: the piston effectively turns "on" and "off" the radon monitor with the opening and closing action, b. pump function: the air-tight piston fulfils the sampling function and the complete renewal of the air inside (sampling cycle).

Users can measure radon gas volume activity in all types of buildings including work places, schools and homes. Technical characteristics allow personal and area monitoring. Sequential exposures can be monitored. For discrete radon measures, the piston can be activated during a radon survey, especially in working areas, to correlate the presence of workers with radon exposure. Personal dosimeters, of similar form, can be worn to measure the radiation exposure of a person at different working areas.

The passive integrating radon personal dosimeter developed by the ENEA Radon Laboratory [6] has the unique feature that a special on-off device allows to control the exposure time. An outstanding application of this new technique concerns monitoring radon exposure at work places: with fast sampling and addition of sequential exposures the correlation between timed monitoring and worker exposure can be assessed (personal and area monitoring during working shifts).

Unlike others, this dosimeter can be stored before use without keeping it in sealed bags and can be kept for several months after exposure before being returned for analysis. It does not need to be used in conjunction with transit dosimeters or express delivery with “Rn-proof” foil bag package.

A double chamber version, named twin radon piston dosimeter, has also been designed, which, in a very compact size, allows monitoring radon air concentration sequentially or simultaneously (Fig.2). This device also fulfils the requirements of EPA protocols concerning duplicate measurements (devices set side by side) [1].
5. Calibration procedures

Best practices concerning qualification tests of radon passive dosimeters recommend the application of standard reference atmosphere at stationary conditions. To perform calibration trials a set of passive radon dosimeters is positioned inside the exposure facility. During transfer of radon from the radon generator (generally standard liquid or solid Ra-226 sources) into the enclosed volume of radon chamber exposure of passive dosimeters
starts immediately. Three main factors influence response of passive integrating detectors:

- the radon volume activity during the initial transient before the stationary conditions
- air-membrane-air radon transfer and time lag to obtain radon equilibrium in the detector internal volume
- post-exposures due to the residual radon decay inside the internal volume of radon dosimeters (tail effect).

These effects can be avoided using the radon piston dosimeters. A new calibration procedure has been set up at the ENEA radon laboratory. The procedure is based on the dynamical transfer of radon from standard $^{226}$Ra liquid solution to maintain a constant radon volume concentration during detector exposure. Exposure facilities and standard calibration protocols based on the 1 m$^3$ ENEA radon climatic chamber have been described [7], [8], [9]. Two flanges been fitted on the door with adapters to connect a set of passive monitors (Fig.3). This experimental device allows to activate piston dosimeters on and off from outside to permit accurate timed exposures without opening the facility enclosure. When the internal reference atmosphere reaches stationary standard conditions, the exposure run is started pulling the piston of each device. After appropriate time intervals, at the end of each exposure run piston is positioned at the off status with fast extraction of radon laden air. The pumping effect avoids further detector exposure after completion of calibration test. This technique also allows carrying out sequential exposures of different detectors at the same experimental conditions, during each calibration run, saving time and improving reproducibility. A detailed description of experimental facilities and protocols is given elsewhere [6].

FIG. 3. A frontal view of the Climatic Radon Chamber at C.R. Casaccia

6. Experimental results

The diffusion chamber adopted consists of a cylindrical aluminium container of approximate height 2 cm and diameter 3 cm. and which contains a track detector for the registration of alpha particles. The calibration of these passive personal radon dosimeters was performed at the ENEA Casaccia Center (Rome, Italy); the resulting sensitivity factor is about 1.5 tracks.cm$^{-2}$ per kBq.m$^{-3}$.h for the detectors electrochemically etched and
counted by means of an automated scanning system. Experimental studies were carried out to determine the optimum dimensions of the diffusion chamber. The reproducibility of the dosimeter response has also been tested.

The novel piston dosimeters have been tested for the evaluation of the calibration factor at different experimental conditions. In particular, for the piston dosimeter prototypes volume (SP configuration), tests have been carried out to compare the dosimeter performances inside radon chamber and over external flange of the Climatic Radon Chamber. The values of the calibration factor obtained in the two different measurement conditions are coincident inside the combined uncertainty. Different prototypes of passive dosimeters have been tested in the Radon Chamber of IRP-Casaccia. The tested prototypes include: short piston (SP), long piston (LP) and the standard old ENEA dosimeter (ED).

<table>
<thead>
<tr>
<th>Prototype code</th>
<th>Volume (cc)</th>
<th>Diameter (mm)</th>
<th>Height (mm)</th>
<th>Detector film</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP Short piston</td>
<td>24.7</td>
<td>3.7</td>
<td>2.3</td>
<td>CR-39</td>
</tr>
<tr>
<td>LP Long piston</td>
<td>75</td>
<td>3.7</td>
<td>7.0</td>
<td>CR-39</td>
</tr>
<tr>
<td>ED Standard dosimeter</td>
<td>73.5</td>
<td>6.0</td>
<td>2.6</td>
<td>CR-39</td>
</tr>
</tbody>
</table>

In the Table I geometrical characteristics of tested dosimeters are reported. The detectors have been normalized, using the ENEA circular type laser cutted Cr-39 film. The film has a diameter of 32 mm and a thickness of 0.3 mm. The filtering device uses a glass fiber filter.

![Comparison of calibration factor Ft for ENEA dosimeters](image)

**FIG. 4.** Comparison of calibration factor $F_t$ vs dosimeter volume
A diagram, shown in figure 4, has been realized selecting three prototypes of ENEA dosimeters (SP, LP, ED) characterized by a similar geometry but different volume. The mean integrated response $F_t$ obtained in various tests has been reported as a function of volume. The figure shows a good accordance of the behaviour of the mean values of the calibration factor with increasing volume, in particular for piston dosimeters (SP and LP). Diagram also shows that time integrated response $F_t$ increases as the dosimeter volume increases, as a consequence of growing efficiency.

![Calibration factor on volume (R) vs volume for cylindrical dosimeters](image)

**FIG. 5.** Time integrated response $F_t/volume$ of different ENEA passive radon detector prototypes as function of internal cell volume.

To evaluate the piston prototype performance, the ratio $R$ between calibration factor $F_t$ and volume has been reported as a function of volume for prototypes having cylindrical geometry (Fig. 5). It can be observed that $R$ decreases with increasing the prototype volume. The $R$-values related to LP and ED dosimeter are about the same: they depends only on the volume (respectively 75 and 73.5 cc) and not on the geometrical parameters, i.e. the radius and the height of each device (see Table I).

Different prototypes have been exposed inside a big experimental room to simulate real ambient of workplaces (Fig.6). The figure 7 shows the variation of radon concentration as a function of time inside the experimental room. During a preliminary test radon levels ranged from about 3 to 10 kBq/m$^3$. Detectors were exposed during about 140 hours at an overall exposure of about 1000 kBq/m$^3$. Test results were consistent with the time integrating response of passive short piston dosimeters. Further tests are in progress to compare the response of different types of passive devices.
FIG. 6. Sketch of the experimental room at the Radon Building of C.R. Casaccia

FIG. 7. Variation of radon concentration as a function of time inside the experimental room.

7. Final remarks

The new dosimeter distinguishes itself from other dosimeters by the fact that it works both ON/OFF covering and pumping function: the exposure monitoring begins when the piston device is opened and stops when it is closed. The unique characteristics of the new ENEA radon dosimeter allow optimizing calibration procedures. Experimental facilities have been realized which allow starting detector exposure only at stationary conditions to avoid the effects of varying radon concentration during exposure of passive integrating detectors. To achieve this goal special flanges have been fitted to radon chambers to be able to control the exposure interval of passive detectors by acting the pistons on/off.

Using the above described technique very fast calibration run can be carried out because
long exposure intervals are unnecessary to minimize the initial transient contributions to the overall exposure, due to the build up of radon level inside the radon chamber and to the transfer rate of radon inside the detector volume up to equilibrium. A better accuracy of calibration factor is obtained. Unlike others, this dosimeter can be stored before use without keeping it in sealed bags and can be kept for several months after exposure before being returned for analysis. It does not need to be used in conjunction with transit dosimeters or express delivery with “Rn-proof” foil bag package.

A double chamber version, named twin-chamber radon piston dosimeter, has also been designed which, in a very compact size, allows monitoring radon air concentration sequentially or simultaneously. This device also complies with the requirements of EPA measurement protocols.

An outstanding application of this new technique concerns monitoring radon exposure at work places. Personal dosimeters can be worn to measure the radiation exposure of a person at different working areas and can be used to assess individual exposure. This dosimeter was originally designed to be used for monitoring radon exposures at working places and for any applications which require the addition of sequential exposures during timed monitoring intervals. This technique allows to correlate the presence of workers with radon exposure during working shifts, using both personal and area monitoring. Experimental work is in progress to test prototypes inside the ENEA experimental room simulating different workplace types and operating conditions.

REFERENCES