IMPROVEMENT OF A RADON DOSIMETRY SYSTEM FOR MINERS BY REPLACING REFERENCE DOSIMETERS WITH RADONPROOF BOXES CONTAINING ACTIVATED CARBON CARTRIDGES

Jörg Dehnert, Andreas Guhr, and Jörg Engelhardt

Abstract—In 1168, the first silver was found in the Saxon Erzgebirge. Mining began shortly thereafter and continues to this day at varying intensities. About 250 miners are permanently engaged in rehabilitation work at old mining sites so that houses and roads are safe and the mine water can drain through galleries. The radon potential in the Erzgebirge is high. Despite radiation protection measures, exposures to more than 6 mSv occurred among 22 miners in 2016 alone. For this reason, the miners are monitored with personal radon dosimeters. The dosimeters consist of diffusion chambers with CR-39 nuclear track detectors. Outside the miners’ working hours, the dosimeters must be stored together with a reference dosimeter. After a 3 mo wearing period, the dosimeters are replaced and the miners’ exposures are determined. For this purpose, the exposures of the reference dosimeters that have occurred outside working hours are subtracted from the exposures of the miners’ dosimeters. In mining practices, this method has caused problems. The conditions of use (storing dosimeters along with a reference dosimeter) were often not met by the miners. To solve the problems, reference dosimeters were replaced by radonproof boxes with activated carbon cartridges inside. The miners stored their dosimeters in the boxes outside working hours. A uniform reference value for the radon activity concentration of 50 Bq m$^{-3}$ was used for all boxes to determine the exposure of miners during working hours. The associated error was small. In future, reference dosimeters and the measurement of a reference value will not be necessary.

Key words: dosimetry; dosimetry, personnel; monitors; radon; radiation protection

INTRODUCTION

In 1186, the first silver was found in the Saxon Erzgebirge. Mining began shortly thereafter and continues to this day at varying intensities. Times of intensive mining are called “Berggeschrey” in the Erzgebirge. The first Berggeschrey was triggered by the silver findings in the 12th century near Freiberg. The second Berggeschrey was based on rich silver ore deposits in 1470 in Schneeberg and shortly afterwards in 1491 near Annaberg-Buchholz. A third Berggeschrey began in 1946 because of the uranium mining of the company SDAG Wismut. Today there are three mines in Saxony where fluor spar, lime, and kaolin are mined. There are many indications that more mines will be added, and the Erzgebirge is at the beginning of a fourth Berggeschrey for lithium, tungsten, tin, and fluor spar.

The historical witnesses to medieval mining and Wismut mining are lovingly remembered in Saxony. Mountain parades and Mettenschichten have become landmarks of the region. Saxony and the Czech Republic have applied for the Montanregion Erzgebirge to be included in the United Nations Educational, Scientific, and Cultural Organization (UNESCO) World Heritage List as a montane cultural landscape.

Long-lasting mining has left countless galleries and shafts in Saxony. Many of them are located near the surface under towns, villages, and roads. Around 250 miners from eight companies are permanently employed in remediation work at old mining sites. They repair mining damage and ensure that houses and roads remain safe in the future and that mine water can drain into the rivers through galleries.

The radon potential in the Erzgebirge is high. Radon activity concentrations of 50,000 Bq m$^{-3}$ to 100,000 Bq m$^{-3}$ are not uncommon at underground construction sites at old mines, and 1 million Bq m$^{-3}$ can also be reached.
shows an example of the course of the radon activity concentration in the gallery Querschlag 68 in Schneeberg (Dehnert 2016a). The reason for the fluctuations in the radon activity concentration in mines is the density-driven flow through the mines caused by the outside temperature. At night, colder and heavier air penetrates from the valleys into open galleries, heats up in the mountain, and is forced out through the shafts on the mountains. During the day, it’s the other way around. The colder and heavier air flows from the tunnel openings into the warmer valleys. This draws in warmer air through the shafts on the mountains, which cools down in the mountain. A detailed description of this is available in Dehnert (2020).

For miners, this means that, in addition to the high radon potential in the mountains, they must also expect constant changes in the radon activity concentration. Therefore, extensive radiation protection measures and careful monitoring of the miners are necessary for the repair work at old mining sites (Dehnert 2016b, 2020).

The radiation protection measures consist of ventilation and the erection of barriers. For ventilation, fresh low-radon air passes through pit ventilators and pipes to the construction site. To ensure that the fresh air does not mix with mine air containing radon and is effectively available to the miners, galleries with barriers made of wood, foil, and expanding foam must be temporarily erected around the underground construction sites. The effort involved is great, because up to 40 smaller and frequently changing construction sites, which operated for a few weeks to several months, are involved each year.

All Saxon miners are monitored. The monitoring consists of operative radiation protection measurements with active radon or radon-decay-product measuring devices and, in most cases, personal radon dosimetry. Measurements of radon or radon decay products are necessary to explore the exposure situations on the construction sites, to determine the radiation protection measures of ventilation and barrier construction, to check the effectiveness of the radiation protection measures later, and to adapt the radiation protection measures to changed conditions. Radon personal dosimetry is required to determine reliable effective annual doses to miners, to check compliance with the Radiation Protection Ordinance limit value of 20 mSv (BfS 2016), to subsequently detect unforeseeable exposure events, and to eliminate them.

Despite the high cost of radiation protection for miners during remediation work in old mines, exposures are comparatively high. In 2016, for example, exposures of more than 6 mSv occurred among 22 miners. Among them was a miner with an effective annual dose of 30.4 mSv. This was caused by an unforeseeable exposure situation during resurfacing work in a shaft and exceeded the limit value of 20 mSv (Fig. 2).

The effective doses to the miners shown here in Saxony’s old mine redevelopment are significantly higher than in other areas of Saxony with radiation-exposed activity. Table 1 shows an overview. According to this, 15,817 people were monitored in Saxony in industry and medicine in 2016. Among them were 10 persons with doses greater than 6 mSv, and there was no exceedance of the limit value of 20 mSv. In the area of natural radioactivity (remediation work in old mines, guided tours of visitor mines, mining, and the remediation of Wismut uranium mining), only 346 people were monitored. Among them were 27 miners and mountain guides with doses greater than 6 mSv, and two limit values were exceeded. The comparison shows the importance of radon personal dosimetry in the monitoring of miners.
In this paper, radon refers to the radionuclide $^{222}\text{Rn}$, and radon activity concentration refers to $^{222}\text{Rn}$ activity concentration, for simplicity.

PERSONAL RADON DOSIMETRY WITH REFERENCE DOSIMETER

Application
Radon personal dosimetry is used to monitor miners in underground mines, guides in visitor mines and caves, staff in radon baths, and employees in waterworks. Personal dose monitoring of radon-exposed workplaces in Saxony is carried out by the State Institute for Personal Dosimetry and Radiation Protection Training, Mecklenburg-Western Pomerania (LPS). Radon dosimeters Altrac Model PD (ALTRAC, Berlin, Germany) are used. These consist of diffusion chambers with CR-39 nuclear track detectors. Employees wear the dosimeters close to their heads in various ways; for example, on the back loop of a miner’s helmet or on the breast pocket of a waterworks worker’s uniform. The dosimeters are worn for 3 mo.

The nuclear track detectors in the radon dosimeters are continuously exposed. In order to determine the exposures during working hours $P_{\text{Person}}$, the dosimeters must be stored outside working hours together with a reference dosimeter. The exposures of the reference dosimeters $P_{\text{Ref}}$, which occurred outside working hours, are subtracted from the exposures of the dosimeters $P$.

$$P_{\text{Person}} = P - \frac{P_{\text{Ref}} (t_{\text{Ref}} - t)}{t_{\text{Ref}}},$$

where $P$ is the dosimeter exposure in MBq h m$^{-3}$, $P_{\text{Ref}}$ is the reference dosimeter exposure in MBq h m$^{-3}$, $t$ is the dosimeter wear time in h, and $t_{\text{Ref}}$ is the reference dosimeter exposure time in h.

The effective dose is calculated from the radon exposure using the official conversion factor from the German Radiation Protection Ordinance (BfS 2016). It is assumed that a radon exposure of 0.32 MBq h m$^{-3}$ corresponds to an effective dose of 1 mSv when the equilibrium factor $F$ between radon and its short-lived decay products is 0.4. If the equilibrium factor $F$ deviates significantly from 0.4, a table with listed exposures for different equilibrium factors is used (BMU 2003).

Table 1. Effective annual doses according to work categories in Saxony 2016.

<table>
<thead>
<tr>
<th>Work categories</th>
<th>Number of supervised persons</th>
<th>Persons with doses &gt; 6 mSv</th>
<th>Persons with doses &gt; 20 mSv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Industry (without natural radiation sources)</td>
<td>2,401</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Medicine</td>
<td>13,416</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>15,817</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Repair work at old mining sites</td>
<td>226</td>
<td>22</td>
<td>1</td>
</tr>
<tr>
<td>Visitor mines</td>
<td>34</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Mining industry</td>
<td>33</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Uranium mining restoration</td>
<td>53</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>346</td>
<td>27</td>
<td>2</td>
</tr>
</tbody>
</table>
The German Radiation Protection Ordinance (BfS 2016) is largely based on International Commission on Radiological Protection (ICRP) 65 using the dose coefficient $F \times 7.8 \text{ mSv (MBq h m}^{-3})^{-1}$ for workplaces (ICRP 1993). But it is important to know that the ICRP suggested new radon dose coefficients, particularly in the recommendations of ICRP 115 (ICRP 2010) and ICRP 126 (ICRP 2014), leading to higher effective doses. The German Commission on Radiological Protection’s (Strahlenschutzkommission [SSK]) discussion and recommendation for the future use of the new coefficients can be found in SSK (2018). In summary, “the SSK recommends keeping the radon dose coefficients in Germany unchanged until the ICRP provides definitive recommendations on the issue and, furthermore, until international regulatory agreement has been reached on the basis of in-depth scientific discussions” (SSK 2018).

Reference sites

Radon activity concentrations at the reference sites must be low. Therefore, the system of radon personal dosimetry with reference dosimeters is subject to regulations for the selection of reference locations. These should ensure uniform boundary conditions and thus guarantee the reliability and quality of the dose determination. Dosimeters and reference dosimeters should be stored outdoors outside working hours, be weatherproof, and be theftproof. The distance between the dosimeters and building walls should be at least 0.2 m, and immediate proximity to doors, windows, and heating and ventilation systems must be avoided.

Enterprises have several and changing construction sites at different distances from the company. Each construction site has its own reference site for storing the dosimeters, and these are often mobile construction-site wagons. These site wagons stand next to mine openings of galleries and shafts or next to stockpiles from which, depending on the outside temperature, strongly radon-containing mine air can come out for hours. Sometimes buildings that are used as reference sites are also located near construction sites. Usually miners keep their dosimeters indoors outside working hours because it is difficult to protect the dosimeters from snow, rain, sunlight, or theft outdoors. Radon activity concentrations inside buildings are known to be much higher than outdoors.

Under the difficult conditions of the remediation of old mines, the applicable regulations for radon personal dosimetry are often not observed by the miners. Radon-containing mine air from shafts, galleries, or stockpiles and the storage of dosimeters inside buildings can lead to comparatively high radon activity concentrations at reference sites, which can cause problems in determining the exposure of miners. Determining the exposures of miners is often difficult. Some dosimeters cannot be evaluated, so alternative doses must be specified by the Radiation Protection Authority.

High radon activity concentrations at reference sites

If high radon activity concentrations occur at reference sites, this leads to high exposures of the dosimeters stored there, e.g., at night or at weekends. During the evaluation of dosimeters after the 3 mo wearing period, reference dosimeter exposures that have taken place outside working hours are subtracted from the exposures of the miners’ dosimeters. If both exposure values are very high and of the same order of magnitude, the differences between the exposures of miners’ dosimeters and reference dosimeters leads to larger errors and to the inability to evaluate the dosimeters. Table 2 provides a course of the radon activity concentration at the reference points at 16 construction sites of the enterprise BsS Bergsicherung Sachsen GmbH carrying out repair work at the old mines in 2013 (bold values mean that the radon activity concentration at the reference point was too high to calculate doses for the miners). At two reference sites, mean radon activity concentrations of 950 Bq m$^{-3}$, 520 Bq m$^{-3}$, and 660 Bq m$^{-3}$ were so high in three quarters that no exposure for the miners could be calculated.

<table>
<thead>
<tr>
<th>Construction site</th>
<th>Quarter I (Bq m$^{-3}$)</th>
<th>Quarter II (Bq m$^{-3}$)</th>
<th>Quarter III (Bq m$^{-3}$)</th>
<th>Quarter IV (Bq m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site wagon 1</td>
<td>80</td>
<td>90</td>
<td>80</td>
<td>950</td>
</tr>
<tr>
<td>Site wagon 2</td>
<td>30</td>
<td>90</td>
<td>40</td>
<td>210</td>
</tr>
<tr>
<td>Site wagon 3</td>
<td>80</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site wagon 4</td>
<td>140</td>
<td>50</td>
<td>110</td>
<td>180</td>
</tr>
<tr>
<td>Site wagon 5</td>
<td>60</td>
<td>70</td>
<td>90</td>
<td></td>
</tr>
<tr>
<td>Site wagon 6</td>
<td>220</td>
<td>520</td>
<td>660</td>
<td>460</td>
</tr>
<tr>
<td>Site wagon 7</td>
<td>80</td>
<td>120</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site wagon 8</td>
<td>60</td>
<td>140</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site wagon 9</td>
<td>50</td>
<td>70</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site wagon 10</td>
<td>80</td>
<td>80</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Site wagon 11</td>
<td>30</td>
<td>240</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site wagon 12</td>
<td>50</td>
<td>160</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site wagon 13</td>
<td>40</td>
<td>170</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site wagon 14</td>
<td></td>
<td></td>
<td>130</td>
<td></td>
</tr>
<tr>
<td>Site wagon 15</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site wagon 16</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
shows the mean radon activity concentrations at 16 reference sites of BsS Bergsicherung Sachsen GmbH for the four quarters of 2013. At two reference sites, mean radon activity concentrations of 950 Bq m$^{-3}$, 520 Bq m$^{-3}$, and 660 Bq m$^{-3}$ were so high in three quarters that no exposure for the miners could be calculated.

**Table 3.** Course of the radon activity concentration at the reference point of the Vereinigt Zwitterfeld zu Zinnwald visitor mine and the calculated averages for each quarter.

<table>
<thead>
<tr>
<th>Period</th>
<th>Reference point</th>
<th>Radon activity concentration, dosimeter (Bq m$^{-3}$)</th>
<th>Calculated quarterly mean value (Bq m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 2011</td>
<td>Locomotive shed</td>
<td>610</td>
<td></td>
</tr>
<tr>
<td>November 2011</td>
<td>Locomotive shed</td>
<td>1,000</td>
<td>660</td>
</tr>
<tr>
<td>December 2011</td>
<td>Locomotive shed</td>
<td>380</td>
<td></td>
</tr>
<tr>
<td>January 2012</td>
<td>Locomotive shed</td>
<td>730</td>
<td></td>
</tr>
<tr>
<td>February 2012</td>
<td>Locomotive shed</td>
<td>610</td>
<td>580</td>
</tr>
<tr>
<td>March 2012</td>
<td>Pithead building</td>
<td>410</td>
<td></td>
</tr>
<tr>
<td>April 2012</td>
<td>Pithead building</td>
<td>830</td>
<td></td>
</tr>
<tr>
<td>May 2012</td>
<td>Pithead building</td>
<td>4,500</td>
<td>1,980</td>
</tr>
<tr>
<td>June 2012</td>
<td>Locomotive shed</td>
<td>620</td>
<td></td>
</tr>
<tr>
<td>July 2012</td>
<td>Locomotive shed</td>
<td>580</td>
<td></td>
</tr>
<tr>
<td>August 2012</td>
<td>Locomotive shed</td>
<td>650</td>
<td>710</td>
</tr>
<tr>
<td>September 2012</td>
<td>Locomotive shed</td>
<td>910</td>
<td></td>
</tr>
<tr>
<td>October 2012</td>
<td>Locomotive shed</td>
<td>820</td>
<td></td>
</tr>
<tr>
<td>November 2012</td>
<td>Locomotive shed</td>
<td>600</td>
<td>840</td>
</tr>
<tr>
<td>December 2012</td>
<td>Locomotive shed</td>
<td>1,100</td>
<td></td>
</tr>
</tbody>
</table>

shows the mean radon activity concentrations at 16 reference sites of BsS Bergsicherung Sachsen GmbH for the four quarters of 2013. At two reference sites, mean radon activity concentrations of 950 Bq m$^{-3}$, 520 Bq m$^{-3}$, and 660 Bq m$^{-3}$ were so high in three quarters that no exposure for the miners could be calculated.

**Variable radon activity concentrations at reference sites**

Radon activity concentrations can change within the 3 mo wearing time of the dosimeters. If the miners’ working times are unevenly distributed during the dosimeter-wearing period due to vacation or illness, this leads to an additional error in the exposure determination according to eqn (1). Usually no monthly measurements of radon activity concentrations or exposures are carried out at reference sites of enterprises. Table 3 therefore shows exemplary monthly measurements at a reference site in the Vereinigt Zwitterfeld zu Zinnwald visitor mine for the years 2011 and 2012. The average monthly radon activity concentrations vary between 380 Bq m$^{-3}$ and 4,500 Bq m$^{-3}$. The calculated quarterly mean values of the radon activity concentrations are between 580 Bq m$^{-3}$ and 1,980 Bq m$^{-3}$. The values at the visitor mine are intended to illustrate the error potential for determining the exposures of miners at construction sites if the working time in the quarter is unequally distributed.

**Change of construction sites**

The dosimeters are worn for 3 mo. Companies operate several small construction sites at the same time, at which only a few miners are employed. Usually the miners are deployed to different construction sites within the wearing time of the dosimeters. There is a reference dosimeter at every construction site. Because miners work at more than one site, exposures must be determined taking into account the time weighting of two or more reference dosimeters. This leads to additional errors related to time weighting in dose determination. Fig. 3 shows once again, for example, measured average monthly radon activity concentrations from the Vereinigt Zwitterfeld zu Zinnwald visitor mine and the calculated quarterly mean values of the radon activity concentration for two quarters. The measured values at the visitor mine should show the error potential in the event that a miner does remediation work at old mining sites at construction site A for 1 mo and at construction site B for the following 2 mo. The monthly measured radon activity concentration at the reference point at the visitor mine is 610 Bq m$^{-3}$, 1,000 Bq m$^{-3}$, and 380 Bq m$^{-3}$ for one quarter used to simulate the situation for construction site A for 1 mo and at construction site B for the following 2 mo. The monthly measured radon activity concentration at the reference point at the visitor mine is 610 Bq m$^{-3}$, 1,000 Bq m$^{-3}$, and 380 Bq m$^{-3}$ for one quarter used to simulate the situation for construction site A, and 730 Bq m$^{-3}$, 610 Bq m$^{-3}$, and 410 Bq m$^{-3}$ for another quarter used to simulate the situation at construction site B. The exposure determination includes the calculated quarterly mean values 660 Bq m$^{-3}$ at construction site A for the first month and 580 Bq m$^{-3}$ at construction site B for the following 2 mo. For the first month, the radon activity concentration at the reference point is 50 Bq m$^{-3}$ too high.
for the miner; for the second month, it is 30 Bq m$^{-3}$ too low; and for the third month, it is 170 Bq m$^{-3}$ too high. Overall, the radon activity concentration calculated by time weighting is 60 Bq m$^{-3}$ too high for the miner’s reference site, so that the exposure calculated for the miner is too low.

**Radon personal dosimetry for foremen, engineers, and other supervisory personnel**

Foremen often do not have a reference location for storing their dosimeters. In the remediation of old mines, they look after several construction sites far apart. Each construction site has its own reference site for the miners working there. The foremen commute between home, company, and their construction sites. Some working days begin or end on a construction site, without the foremen being able to pass by their offices and take or deposit their dosimeters there. Therefore, the establishment of additional reference locations for foremen in the companies cannot solve the problem. When determining exposures for foremen without reference dosimeters, exposures outside working hours must be estimated, resulting in errors.

**MATERIALS AND METHODS**

**Radon dosimeter Altrac Model PD**

Radon personal dosimetry uses diffusion chambers based on nuclear track detectors. The dosimeters consist of lower parts with integrated detector holders and domed upper parts. The square detectors type CR-39 (polydiethylene glycol bis(allyl carbonate)) (Radosys Kft, Budapest, Hungary) have dimensions of 10 mm × 10 mm × 1 mm and are fixed in the middle of the lower parts (Fig. 4). The housings consist of a special plastic combination with a steel fiber content. The diffusion time of radon through the polymer matrix of the plastic into the interior of the dosimeters is approximately 9 min. This ensures that the radon isotopes $^{219}$Rn with a half-life of 3.96 s and $^{220}$Rn with a half-life of 55.6 s cannot contribute to the measurement. When alpha particles impact the polymer matrix of the detectors, channels of damaged material are created. To determine the exposure of the dosimeters, the detectors are etched in a 6.25 N sodium hydroxide solution at 90°C for a period of 4.5 h. The etching process expands the channels created by alpha particles in the polymer matrix of the detectors by about 3 orders of magnitude. They are then visible as particle traces under a light microscope. The determination of the alpha-induced track density on the detector surface is carried out with the computer-aided, automatic image-evaluation system Radometer Microscope V 10 (Radosys Kft). By scanning the detector step by step, 51 mm$^2$ on the surface of the detector are analyzed. The track density is determined as the number of tracks per unit area (cm$^{-2}$).

Assuming a linear relationship between radon exposure and track density on the surface of the nuclear track detector, the proportionality factor $K_{Rn}$ describes the sensitivity of the radon diffusion chambers to radon as:

$$ K_{Rn} = (N - N_0)/P_{Rn}, $$

with $N$ as the mean, alpha-induced track density in tracks per cm$^2$; $N_0$ as the mean background track density in tracks per cm$^2$; and $P_{Rn}$ as the radon exposure:

$$ P_{Rn} = \int C_{Rn}(t) \, dt $$

in Bq h m$^{-3}$. The mean radon activity concentration $C_{Rn}$ is calculated by dividing the radon exposure by the exposure time:

$$ C_{Rn} = P_{Rn}/t. $$

Each manufacturing batch of CR-39 detectors is calibrated by the manufacturer Radosys Kft in the accredited calibration service laboratory of the Federal Office for Radiation Protection (Bundesamt für Strahlenschutz [BfS]). In parallel, ALTRAC additionally calibrates the detectors supplied by Radosys Kft in the BfS. The exposures in the radon chamber of the BfS vary from 150 to 3,500 kBq h m$^{-3}$. The BfS offers four official calibrations throughout the year, which are used by both Radosys Kft and ALTRAC. In addition, there is an intercomparison in spring and a blind test in fall, which also represent calibrations.

Detection limits are determined in accordance with the International Organization for Standardization (ISO) standard ISO 11665-4 (2012). The decision threshold for the dosimeter Altrac Model PD is 13 kBq h m$^{-3}$, and the detection limit is 32 kBq h m$^{-3}$. The mean zero effect of the detectors is 24 tracks cm$^{-2}$. The mean calibration factor is given as $1.36 \times 10^{-2}$ tracks mm$^{-2}$ per exposure to 1 kBq h m$^{-3}$.

From 2003 to 2012, the BfS organized 10 intercomparisons with up to 40 testing and calibration laboratories per year from several continents. Nearly 6,000 dosimeters were...
exposed at 35 different exposure levels. Fig. 5 shows the
distribution of the results of the intercomparisons. The so-
called trumpet curve was derived on the basis of an empiri-
cal formula. The trumpet curve indicates the uncertainty
range of the measurement method. It is assumed that 90%
of all measurement results of a measuring point lie within
this range (Beck et al. 2014).

Based on these practical results, ALTRAC derives the
relative measurement uncertainty of the Altrac Model PD
radon dosimeters from the upper and lower curves in Fig. 5.
Table 4 summarizes the relative measurement uncertainties
of the dosimeter for different exposure areas. According to
this, the detection limit of the PD dosimeter is at an expo-
sure of 32 kBq h m$^{-3}$. For example, if the dosimeter is ex-
posed in the range of 100 to below 200 kBq h m$^{-3}$, the
relative measurement uncertainty according to the trumpet
curve is $\leq 30\%$.

**Radonproof boxes with activated carbon cartridges**

In order to solve the problems of radon personal dos-
ometry with reference dosimeters for miners, it was
considered whether reference dosimeters and reference
locations could be dispensed with. Instead, the dosime-
ters could be protected from exposure outside miners’
working hours by storing them in radonproof boxes with ac-
tivated carbon cartridges. The activated carbon binds radon,
which enters the boxes when the dosimeters are removed
and inserted. Radon activity concentrations in such boxes are
expected to be permanently low during the 3 mo period during
which the dosimeters are worn, even if radon-containing mine

<table>
<thead>
<tr>
<th>Radon exposures (kBq h m$^{-3}$)</th>
<th>Relative measurement uncertainties (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;32 to &lt;50</td>
<td>50</td>
</tr>
<tr>
<td>50 to &lt;100</td>
<td>35</td>
</tr>
<tr>
<td>100 to &lt;200</td>
<td>30</td>
</tr>
<tr>
<td>200 to &lt;500</td>
<td>25</td>
</tr>
<tr>
<td>500 to &lt;1,000</td>
<td>20</td>
</tr>
<tr>
<td>1,000 to &lt;15,000</td>
<td>15</td>
</tr>
</tbody>
</table>

Air is extracted from mine openings or stockpiles at night or if
the radonproof boxes are stored in buildings with high radon
activity concentrations. A uniform, low reference value for
radon activity concentrations in all boxes could be used for
the determination of exposure. Measurement of reference
values would no longer be necessary. The dosimeters in
radonproof boxes would no longer be bound to a reference
site and could be carried and stored by the miners at will.

Boxes from the manufacturer LOCK & LOCK GmbH
(Frankfurt, Germany) were used, which they characterized
as airtight and watertight. The boxes are made of polypro-
pylene. The box HPL 810 with a capacity of 360 mL has
proved to be the most suitable in size from the manufac-
turer’s range of goods.

Inside each box there is an activated carbon cartridge
sealed with filter paper (Whatman Grade 1; GE Healthcare,
Chicago, Illinois, US). The cartridge is a commercially
available centrifuge tube which, according to tests, was
considered the most suitable for the measurement task in

![Fig. 5](image-url)
comparison with smaller cartridges and lower amounts of activated carbon for the 3 mo measurement period. In addition, the size of the cartridge is optimal for storage in the box HPL 810. These cylindrical plastic cartridges with a volume of 50 mL are completely filled with activated Hydraffin CC 8/C2 activated carbon (Donau Carbon, Frankfurt, Germany; Fig. 6). To activate the carbon, it is heated in the drying chamber for 8 h at 180°C to expel the absorbed water vapor present in the pore space. The activated carbon cartridges are then filled with the activated carbon and sealed airtight until they are used in polyethylene with low density/polyamide (PE-LD/PA) packaging bags. The activated carbon cartridges in the radonproof boxes are replaced together with the dosimeters on a quarterly basis.

With the aim of preserving the capacity of the activated carbon during the storage period over 3 mo, each box is provided with a label: “Keep box closed during the day.” The user is also instructed by written directions for use. Under the prediction that the entry and removal of the dosimeter needs 1 min d−1, the box is only open for 90 min in a quarter. Moreover, Hydraffin CC is a special type of activated carbon made of coconut husks, which absorbs less water vapor compared to other varieties of charcoal. Results of tests with activated charcoal stored for 6 mo in the radonproof box and daily use of the dosimeter showed that this activated charcoal still had the ability to bind radon gas.

Experiments

The radon tightness of the boxes with activated carbon cartridges was tested at three different radon activity concentrations. In addition to the activated carbon cartridges, active radon measuring devices were inserted into the boxes, and the courses of the radon activity concentrations inside and outside the boxes were measured. The first two experiments took place in two cellars of buildings and lasted 4 wk each. Two CANARY digital radon monitors (Corentium AS, Oslo, Norway) were used to record the radon activity concentrations in the boxes and in the cellars. The third attempt took place as a worst-case scenario in the mining gallery Querschlag 68 in Schneeberg. There, permanently high radon activity concentrations between 40,000 and 80,000 Bq m−3 occur. A radon monitor DOSEman (Sarad GmbH, Dresden, Germany) was inserted into a radonproof box with activated carbon cartridge. The radon activity concentration in the Querschlag 68 gallery was measured with an AlphaGUARD PQ 2000PRO (Saphymo GmbH, Frankfurt, Germany). The measuring intervals were 30 min for the DOSEman and 10 min for the AlphaGUARD. The experiment lasted 5 d.

For the effectiveness of radon personal dosimetry without reference dosimeters and with radonproof boxes with activated carbon cartridges, a large-scale field test was carried out over 18 mo with up to 80 miners in the Erzgebirge. The aim of the experiment was to check whether radon activity concentrations in the boxes are permanently low during the 3 mo wearing period of the dosimeters and whether the dosimeters are sufficiently protected against radon outside the miners’ working hours. Three enterprises (Bergsicherung Freital GmbH, TS Bau GmbH, and Bergsicherung Schneeberg GmbH & Co. KG) took part in the field test. The miners at these operations received personal, radonproof boxes with activated carbon cartridges. The miners stored their dosimeters (Altrac Model PD) in the boxes outside working hours. An additional dosimeter (Altrac Model PD) was inserted in each box to measure the radon activity concentrations in all boxes. After 3 mo, the miners’ dosimeters and the dosimeters in the radonproof boxes were replaced.

RESULTS

Radon tightness of the boxes

Three tests were carried out to determine whether the boxes were sufficiently radon tight to protect the miners’ dosimeters from exposure to radon outside working hours. Table 5 shows the mean radon activity concentrations inside and outside the boxes during the experiments. Radon retention of the boxes was 91% and 92%, respectively. This makes the boxes sufficiently radon tight. The miners’ dosimeters can be stored in the boxes outside working hours.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Experimental time (d)</th>
<th>Radon activity concentration inside of the box (Bq m⁻³)</th>
<th>Radon activity concentration outside of the box (Bq m⁻³)</th>
<th>Radon retention (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28</td>
<td>12</td>
<td>135</td>
<td>91</td>
</tr>
<tr>
<td>2</td>
<td>28</td>
<td>66</td>
<td>871</td>
<td>92</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>2,600</td>
<td>47,900</td>
<td>95</td>
</tr>
</tbody>
</table>
In addition, Fig. 7 shows the course of the radon activity concentration during the worst-case test in the mine gallery Querschlag 68 in Schneeberg. The radon activity concentration there was 58,000 Bq m$^{-3}$ at the beginning of the experiment and fell to about 46,000 Bq m$^{-3}$ during the measurements. The radon activity concentration in the box remained constant at 2,600 Bq m$^{-3}$. Such high radon activity concentrations do not occur at reference sites for personal radon dosimetry. Nevertheless, even under such extreme conditions, the boxes have a radon retention of 95%.

**Radon personal dosimetry without reference dosimeter**

In a field test in the Erzgebirge, it was determined whether radon personal dosimetry without a reference dosimeter is possible if the miners’ dosimeters are stored outside working hours in radonproof boxes with activated carbon cartridges.

The field test began with 42 miners from two companies. Radon activity concentrations measured with separate dosimeters in all boxes were expected to be low. However, this was not the case after two quarters of evaluation. Instead, an approximately equal distribution of the radon activity concentrations in the boxes occurred in one quarter between 20 and 320 Bq m$^{-3}$ and in the other quarter between 20 and 200 Bq m$^{-3}$. An analysis of the situation revealed that many miners had left their boxes open during working hours, and the additional dosimeters in the boxes were probably exposed during these times.

![Fig. 7. Course of the radon activity concentration inside and outside of the radonproof box in the gallery Querschlag 68 in Schneeberg.](image1)

![Fig. 8. Distribution of the radon activity concentration in 316 radonproof boxes containing activated carbon cartridges for 80 miners from three companies in 2016 (Dehnert et al. 2017).](image2)
The test was therefore extended for another four quarters and extended to a total of 80 miners from three enterprises. The miners were asked to keep the boxes permanently closed. In addition, all boxes were labeled: “Keep box closed during the day!” The boxes were now opened by the miners only to remove or put in the dosimeters. Fig. 8 shows the result of the test. The distribution of the radon activity concentration is shown for 316 boxes from 80 miners over four quarters. As expected, the radon activity concentrations in most boxes were very low. Radon activity concentrations in 273 boxes (86%) were at most 50 Bq m\(^{-3}\). In another 35 boxes, the radon activity concentrations were not higher than 100 Bq m\(^{-3}\). In only 8 boxes, larger concentrations of radon activity were measured, probably again due to boxes accidentally left open during working hours. The field test has shown that radonproof boxes with activated carbon cartridges can protect miners’ dosimeters from exposure to radon outside working hours. In the future, reference locations and reference dosimeters will not be necessary.

**DISCUSSION**

During the field test, radon activity concentrations of not more than 50 Bq m\(^{-3}\) were measured in 86% of the radonproof boxes with activated carbon cartridges. It was obviously possible to establish a uniform reference value of 50 Bq m\(^{-3}\) for the exposure determination of miners for all boxes and to dispense with the measurement of radon activity concentrations in the boxes with additional dosimeters.

Table 6 shows systematic errors of the effective doses of miners per quarter assuming a reference value of 50 Bq m\(^{-3}\) for the radon activity concentration in the radonproof boxes with activated carbon cartridges for annual working times of 100 to 2,000 h and true radon activity concentrations inside of the boxes of 10 to 500 Bq m\(^{-3}\). If the true radon activity concentrations in the boxes are above the reference value of 50 Bq m\(^{-3}\), exposure levels that are too low are subtracted in the exposure determinations according to eqn (1), and the calculated exposures for the miners are greater than the actual exposures. The systematic errors of the effective doses are between 0.1 and 0.3 mSv per quarter at radon activity concentrations up to 100 Bq m\(^{-3}\). The systematic errors in exposure determination are conservative and therefore justifiable. Radon activity concentrations in the boxes above 100 Bq m\(^{-3}\) are usually due to accidental incorrect operation of the system due to nonclosure of the boxes during miners’ working hours. A radon activity concentration of 500 Bq m\(^{-3}\) leads to a conservative error of 3 mSv in the quarter. If such errors are not detected, this is not detrimental to miners because the errors are conservative. If the errors are detected, alternative doses can be determined by the responsible authorities after a successful root cause analysis. This case has occurred once in 2 y since the introduction of radon personal dosimetry without a reference site in January 2017 by the LPS. The effective dose for a miner was 7.4 mSv in a quarter. The Saxon Radiation Protection Authority has determined an alternative dose of 1.1 mSv for this erroneous measurement.

If the true radon activity concentrations in the boxes are below the reference value of 50 Bq m\(^{-3}\), exposure levels that are too high are subtracted in the exposure determinations, and the calculated exposures for the miners are smaller than the actual exposures. Exposures are underestimated. The systematic error of the effective doses is also between 0.1 and 0.3 mSv per quarter. This additional systematic error of a maximum of 0.3 mSv per quarter must be related to the measurement uncertainty of the radon dosimeters (Altrac Model PD) for the determination of radon exposure, the elimination of the nonquantifiable weighting errors of radon personal dosimetry with reference dosimeters, and the legal limit value of the German Radiation Protection Ordinance of 20 mSv y\(^{-1}\) (BfS 2016). In practice this means that if an effective dose of 2 mSv per quarter is measured for a miner, the dosimeter was exposed to 0.64 MBq h m\(^{-3}\). The relative

<table>
<thead>
<tr>
<th>Annual working time (h)</th>
<th>10(^{a})</th>
<th>20(^{a})</th>
<th>30(^{a})</th>
<th>40(^{a})</th>
<th>50</th>
<th>60(^{b})</th>
<th>70(^{b})</th>
<th>80(^{b})</th>
<th>90(^{b})</th>
<th>100(^{b})</th>
<th>200(^{b})</th>
<th>500(^{b})</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>−0.3</td>
<td>−0.2</td>
<td>−0.1</td>
<td>−0.1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>1.0</td>
<td>3.0</td>
</tr>
<tr>
<td>500</td>
<td>−0.3</td>
<td>−0.2</td>
<td>−0.1</td>
<td>−0.1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>1.0</td>
<td>2.9</td>
</tr>
<tr>
<td>1,000</td>
<td>−0.2</td>
<td>−0.2</td>
<td>−0.1</td>
<td>−0.1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.9</td>
<td>2.7</td>
</tr>
<tr>
<td>1,500</td>
<td>−0.2</td>
<td>−0.2</td>
<td>−0.1</td>
<td>−0.1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.8</td>
<td>2.5</td>
</tr>
<tr>
<td>2,000</td>
<td>−0.2</td>
<td>−0.2</td>
<td>−0.1</td>
<td>−0.1</td>
<td>0.0</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.8</td>
<td>2.4</td>
</tr>
</tbody>
</table>

\(^{a}\)True effective doses are greater.

\(^{b}\)True effective doses are smaller, conservative.
measurement uncertainty of the dosimeter according to Table 4 is \( \leq 20\% \) or 0.4 mSv. The measurement result would be 2.0 mSv \( \pm 0.4 \) mSv plus the systematic error of at most 0.3 mSv. At the same time, the problems and weighting errors of the previous radon personal dosimetry with reference dosimeters are eliminated. These can be greater than 0.3 mSv per quarter and can lead to the nonevaluation of dosimeters.

A uniform reference value of 50 Bq m\(^{-3}\) for the radon activity concentration in the boxes was used for two reasons to determine the exposure of miners during working hours. First, a radon activity concentration of 50 Bq m\(^{-3}\) measured during about 3 mo corresponds to an exposure of 110 kBq h m\(^{-3}\). The uncertainty of the measurement at this level is \( \pm 30 \) kBq h m\(^{-3}\) (\( k = 1 \)) according to Table 4 or \( \pm 60 \) kBq h m\(^{-3}\) for \( k = 2 \). Due to this, the error of measured radon activity concentration of 50 Bq m\(^{-3}\) at a reference site is on the same order as the uniform reference value of 50 Bq m\(^{-3}\) for the radon activity concentration in the boxes.

Second, at a reference value of 50 Bq m\(^{-3}\) the errors for smaller or larger true radon activity concentrations are approximately equal. The practicability of the method could thus be carefully examined. If the method proves itself in practice, it must be discussed whether the reference value for the radon activity concentration in the boxes should be reduced. The smaller the reference value in the boxes, the more conservative is the method. If the reference value for the radon activity concentration in the boxes is equated with the outdoor radon activity concentration of 10 Bq m\(^{-3}\), the method is strictly conservative. Then, there is no underestimation of effective doses. The discussion about this is ongoing.

CONCLUSION

A field test with up to 80 miners showed that radonproof boxes with activated carbon cartridges can protect miners’ dosimeters from unwanted radon exposure outside working hours. Radon activity concentrations of not more than 50 Bq m\(^{-3}\) were measured in 86% of the radonproof boxes. Therefore, a uniform reference value for the radon activity concentration of 50 Bq m\(^{-3}\) was used for all boxes to determine the exposure of miners. If the radon activity concentrations in the boxes are lower or higher than the reference value, additional systematic errors occur. These errors are minor. The miners’ effective doses can be underestimated by a maximum of 0.3 mSv per quarter. At the same time, the nonquantifiable weighting errors of radon personal dosimetry with reference dosimeters, which can be much higher, are eliminated. These include the nonevaluability of dosimeters due to high radon activity concentrations at reference sites, errors in variable radon activity concentrations at reference sites with unequally distributed working times in the quarter, weighting errors when changing construction sites in the quarter, and weighting errors in personal radon dosimetry for foremen with several construction sites.

Reference dosimeters, the measurement of reference values, and the storage of dosimeters at reference locations can be dispensed with in the future if instead the dosimeters are stored outside miners’ working hours in radonproof boxes with activated carbon cartridges.

Since January 2017, the LPS has been offering radon personal dosimetry with reference dosimeters and radon personal dosimetry without reference sites with radonproof boxes and activated carbon cartridges. Customers can freely choose between both methods. On the reference date 31 December 2018, 2 y after the introduction of radon personal dosimetry without a reference site, 220 miners were monitored by personal dosimetry in Saxony. Three companies with 89 miners used radon personal dosimetry with reference dosimeters. Seven companies with 131 miners used the new radon personal dosimetry without reference sites with radonproof boxes and activated carbon cartridges. This means that 60% of the miners have switched to the new method. Additionally, two visitor mines in the Erzgebirge with seven guides are using the method. No new problems have been identified by the users within those 2 y.

Radon personal dosimetry without a reference site could be easily integrated into the operational organization of enterprises. User acceptance of radon personal dosimetry has increased. It may be deduced from this that reference-free radon personal dosimetry has proven itself in practice. The Saxon Radiation Protection Authority recommends the use of radon personal dosimetry without reference site with radonproof boxes and activated carbon cartridges by miners and by guides in visitor mines.

The method of radon personal dosimetry without reference site was developed for remediation work by miners in old mines. The method can be used universally for all cases of personal dosimetric monitoring with regard to radon and offers advantages, especially in short-term applications and at reference locations that are difficult to implement.

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