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Quality assurance in radon SSNTD measurements – PHE experience

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Abstract. More than 40 years ago, Public Health England (PHE and its predecessor organizations) established a radon laboratory to deliver services for radon measurements in homes and workplaces in the UK [1]. A key factor in developing these services was to set up stringent quality control and assurance protocols to enable the delivery of reliable and accurate results. There are nearly 40 checkpoints in the process, most exceeding 94% pass rate, starting from a quality check of poly-allyl diglycol carbonate (PADC) polymer and ending with a result modified by seasonal and occupancy correction factors. This work aims to show how to obtain the reliable results of radon measurements.

Keywords: Radon • Passive detectors • Quality assurance

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Introduction

Solid-state nuclear track detectors (SSNTD), particularly PADC, have a long history of application in measurements of radon. Although it is relatively easy to set up and run measurement facilities, obtaining precise and accurate results is not trivial, but quite a challenging task. This study shows that by applying appropriate quality controls, much better quality results are obtained. Moreover, further improvements can be achieved by additional, special control procedures and data manipulation algorithms, like the calibration of every PADC sheet, correction factors to include aging/fading effects, exposure linearity correction, or the introduction of the threshold point between track count and track area-based calculations [2, 3].

Stages of detector processing

Figure 1 shows the summary of processes and accompanied quality assurance (QA) checks and controls that lead to the delivery of the final results from radon measurements using PADC SSNTD. The major steps include the production of the PADC detection elements and assembling them into the detector housing; calibration and blind test; administration (detector issue and return); etching; and finally results reporting. All processes are described below in detail.

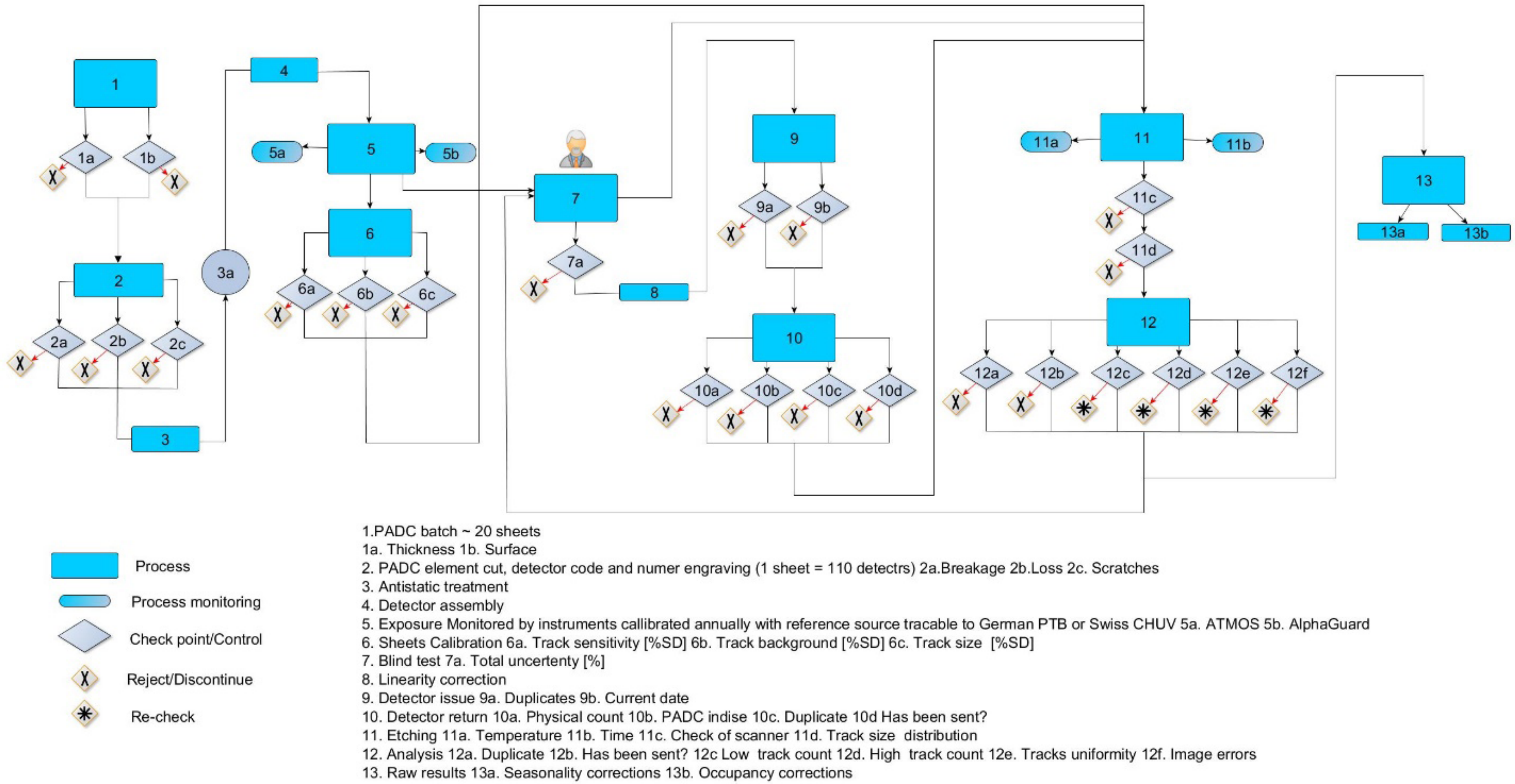

Fig. 1. Stages of detector processing at PHE laboratory; from PADC sheets receipt to results reporting.

Sheet quality checks and detector assembly

The PADC sheets are provided by the MiNet company. On arrival, each batch of 20 sheets undergoes quality checks including thickness and surface checks, and inspection for other undesirable features such as large scratches. Individual PADC detection elements are cut from sheets that have passed the aforementioned QA and are engraved with a unique detector number and a dot code. There are 110 elements cut from each sheet with the following destinations: 12 calibration elements (six exposed and six background), one blind test element, and six spare ones (used in cases of damaged calibration elements or recalibration). Next, all detectors are treated with an antistatic solution to remove a potential surface charge [1]. In the final stage, detectors are assembled into a PHE-designed housing and a barcode sticker, generated from detector element dot code, is attached at the bottom of the housing.

Calibration

Calibration is a procedure applied to each new PADC sheet to determine its sensitivity to radon. Of the 12 calibration elements, six per sheet are exposed to a known radon concentration and the other six are stored in a radon free environment for use in a background assessment.

Calibration elements are exposed to an average radon activity of ~4000 Bq·m^{-3} in PHE's 43 m^3 radon chamber. The approximate integrated concentration that each detector is exposed to is around 400 kBq·h·m^{-3}. This corresponds to a standard 90 days' household measurement at a radon concentration of 200 Bq·m^{-3}, which is the UK Action Level (when remedial action of the dwelling is recommended). The source activity is continuously monitored by an ATMOS 12 DPX system (pulse ionization chamber technology) manufactured by Gammadata Instrument AB, Sweden. In addition, an AlphaGuard EF511, from Genitron Instruments GmbH, Germany is used as a secondary, backup system. Both instruments are calibrated annually with a primary source traceable to either PTB, Germany or CHUV, Switzerland.

Sheet sensitivity is expressed as either track sensitivity T_S,

$$T_S = \frac{\text{tracks}}{\text{cm}^2 \cdot \text{kBq} \cdot \text{h} \cdot \text{m}^{-3}} \tag{1}$$

or area sensitivity A_S,

$$A_S = \frac{\text{pixels}}{\text{cm}^2 \cdot \text{kBq} \cdot \text{h} \cdot \text{m}^{-3}} \tag{2}$$

Two methods of calibration, and later results calculation, are used because at low radon concentrations features, like small scratches or false tracks, may have a significant contribution to the area covered by measurement tracks. In contrast, at high radon concentrations, tracks start to overlap and their distinct separation becomes impossible. For this reason, the track count method and track area measurement are used for low and high radon concentrations, respectively.

A sheet is accepted for use if all calibration, background, and track size consistency values of control elements, expressed as standard deviation from the mean, differ by less than 10%.

In some cases, a second calibration may be necessary. For example, PHE produces detectors sealed in waterproof pouches [4] to protect detectors from water ingress and other result-affecting contaminants such as dust, airborne particles, and so on. However, to account for reduced sensitivity, due to a lower radon diffusion rate into the housing, they must be recalibrated.

Blind test

The final check of detectors before sending them out to customers is carried out during the "blind test". One element from each sheet of the currently passed batch is selected, and a person not involved in the detector production exposes blind test elements and returns them for standard analysis. After analysis, the results are compared with a reference dose to assess the accuracy of the measurements. Only batches that pass the blind test with an uncertainty of less than 15% are used further. The total uncertainty of a blind test is expressed as:

$$\text{total uncertainty} = 100 \times \sqrt{\left[\left(\frac{\text{measured exposure}}{\text{measured exposure}}\right) - 1\right]^2 + \left(\frac{\text{standard deviation}_{\text{exposed blind tests}}}{\text{measured exposure}}\right)^2} \tag{3}$$

Detector issue and return administration

Before the detectors are sent out and on their return, several checks are performed including the existence of a duplicate number in the system and if the current date has been recorded correctly. In addition, on return, detectors are also checked for the presence of a PADC element inside the detector housing, if it was ever sent, if the return date is after the issue date and if exposure period has not exceeded 18 months. If the detector passes all the above checks or when anomalies can be resolved, it goes to the next stage of processing.

Etching

After the calibration or measurement exposure, the created latent alpha tracks in the PADC are revealed by chemical etching with NaOH (5 M) at 75°C for 18 h. Since track size depends on the temperature of the etchant solution and etching time [5], these parameters are strictly controlled during the process. Temperature is controlled by bath thermostat and additionally checked at the start and the end of the etching process with a calibrated, external thermometer, whereas the time is measured with a laboratory, calibrated timer. Consistency in the track size during each and all subsequent etchings is crucial as it is linked to the final results calculation. Even small changes in track size may lead to the incorrect recognition of genuine tracks or, at higher exposure, to the wrong estimation of the area covered by tracks.

Consistency of the track size for each etch is checked by exposing four PADC elements to a known activity of alpha particle source, that is, americium-241. Since alpha particles from ^{241}Am have a similar energy to that generated from ^{222}Rn they produce similarly shaped tracks in PADC. Only two of the four etch control elements are exposed at the time of sheet production. The other two are exposed just before the beginning of the etch. The size of the etched track is measured as the nominal maximum area (NMA), which is the half-peak height value of the modal average maximum area. The NMA value is then used to compare to the last four consistent etches and the process receives a pass mark if the mean difference between them is <10%. This QA check also serves as an aging test for PADC sheets as it can detect tracks and polymer deterioration over time.

Scanning

A Nikon LS5000 (4000 dpi) slide scanner is used to acquire images of detectors prior to track analysis. The PADC elements are mounted into standard 35 mm film slide mounts and stacked into an automatic feeder. Each scan session is accompanied by 15 control elements: 10 are exposed to a known radon concentration and the other five are transit (background). The mean and standard deviation of track densities are calculated for each scan and compared with net track densities of all previous results for this control set. The pass criterion is applied if the total uncertainty of this check falls below 10%. This test can provide a valuable indication of scanner malfunction including, but not limited to: loss of focus, light source problems, and lens contamination.

Analysis

The images are analysed and tracks calculated using the in-house image analysis software. The software was supplied by Synopsis Ltd, UK to a specification provided by NRPB (PHE predecessor). Full details of the first version of the software have been described by Steele *et al*. [6]. The current version of the software has been written in Visual Basic 6. It runs under Windows 7 with the following sequence: detector code recognition, track identification, splitting apart of touching tracks, number of tracks and area covered by track counting, and analysis of track distribution homogeneity between 35 subareas. Algorithms for the detection and counting of genuine nuclear tracks are hybrid methods that include shape (circularity factor), size (track diameter) determination and a context-based image greyscale threshold limit. The shape and size discrimination approach ensures that features like dust or scratches are not falsely counted as tracks, whereas the greyscale threshold limits reduce the number of background elements with false tracks. In the final stage, the image analysis software generates a text file that is exported to a Microsoft Access database for data processing. If the detector passes the administrative checks described earlier and sheet sensitivity and background data exist, the integrated radon exposure is calculated. The overall statistics of major quality checks pass rate since the year 2012 are shown in Table 1.

Table 1. Statistics of quality assurance tests of PHE radon passive detectors since 2012

Track sensitivity	2.66 ± 0.12 tracks·cm^{-2}·kBq^{-1}·m^3·h^{-1}
Track background	12.81 ± 8.22 kBq^{-1}·m^3·h^{-1}
Area sensitivity	84.30 ± 7.02 pixels·cm^{-2}·kBq^{-1}·m^3·h^{-1}
Area background	2253 ± 1920 pixels·cm^{-2}·kBq^{-1}·m^3·h^{-1}
Sheet acceptance	94.3% (n = 756)
Blind tests	Bias –0.58%, STD 4.2%
Etch process rate	98.5% (n = 274)
Scan pass rate	98.9% (n = 3246)
Results reported	51 077

Further quality improvements

Aging/fading adjustments

The aforementioned quality checks apply to an ideal situation where no further adjustments are required. However, in reality, we also have to consider the aging of the sensor plastic and non-linear track count response to the exposure. Aging is a process, mostly related to the oxidative degradation of PADC polymer since the production of sheets until being exposed that results in the loss of sensitivity of the track recording property. Similarly, fading is a process of sensitivity loss of detectors exposed to alpha particles and then left unetched for long periods of time. This process has a smaller significance as most laboratories process detectors fairly quickly

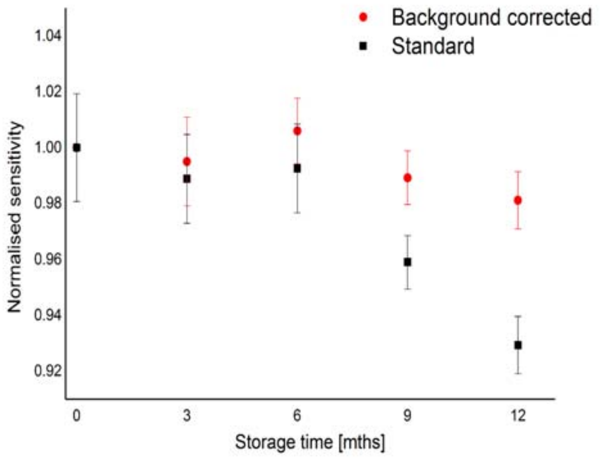

Fig. 2. Sensitivity loss as a function of time under storage in the ambient air.

after their return from exposure. For our PADC, three months fading leads to sensitivity difference of 0.3% and one year fading to 7% when compared to initial, nonfaded results. Figure 2 shows the results of storing radon detectors under ambient conditions for one year.

Statistically, there is no difference in sensitivity for up to six months. However, the loss of sensitivity of around 8% over a period of one year is evident. After corrections for the aged background are applied, this number can drop down to 2% of the initial sensitivity. Hence, adjustments for background and sensitivity loss for long-term detector storage can eliminate aging effects and provide realistic, unbiased results.

Threshold point and linearity

As mentioned earlier, we use two methods to calculate calibration and subsequently exposure results, namely track count-based and area covered by tracks methods.

Figure 3 shows the results of the calculated detector exposure compared to the known exposure values obtained from the calibrated ATMOS12 monitoring system.

For the track count-based method the results accuracy is fairly good, with a linear response up to exposure of 2000 $kBq \cdot h \cdot m^{-3}$. On the other hand, calculations based on the area covered by tracks show that at lower values, results are highly inaccurate and imprecise. At the higher end of the investigated range, results are still inaccurate, but with a relatively low, but acceptable level of precision. Based on a direct comparison of both measurement methods, it is apparent that at low exposures (below 2000 $kBq \cdot h \cdot m^{-3}$), the track count measurement provides much better results, but at higher exposure, results can only be delivered by means of area measurement. As mentioned earlier, at higher exposures, the overlap of tracks is so prominent that single track counting becomes impossible and the area measurement method is the only viable option to provide results. Hence, a threshold point operates to switch between these two methods. In addition, to ensure the detectors' linear response over the full exposure measurement capability, the linearity correction is also introduced. It is achieved by exposing elements from each sheet of a tested batch to a series of known exposures and then extracting polynomial fit coefficients that are used later during the results calculation stage.

Final results corrections – seasonality and occupancy factors

It is well known that indoor radon concentrations follow diurnal, monthly, and seasonal variations [7–9] as well as significant short-term fluctuations. In Figure 4, the variation in a typical house in the UK is shown, and the mean indoor radon concentration reaches a maximum in January and a minimum in July [10].

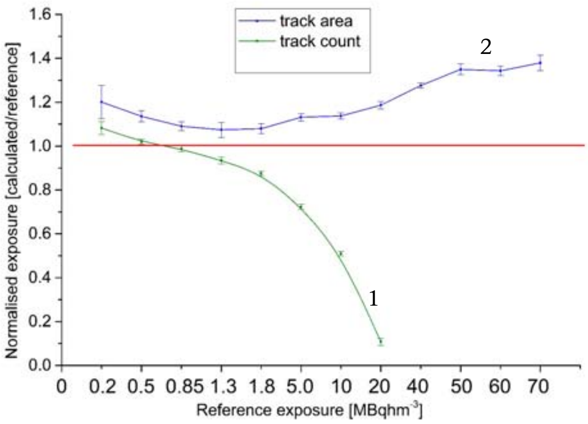

Fig. 3. Calculated exposures based on track count (1) and area covered (2) by tracks methods in relation to reference exposures from ATMOS12 monitoring system.

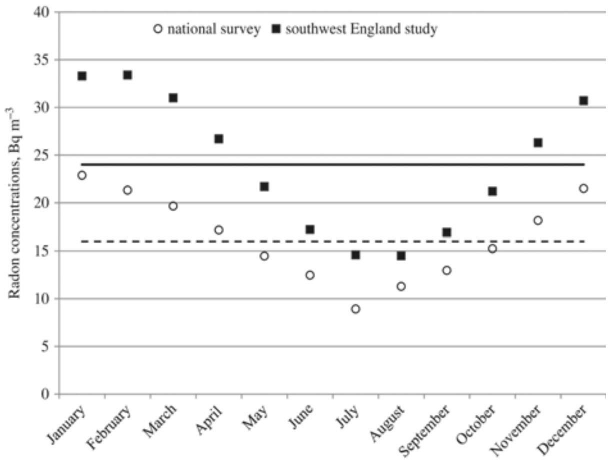

Fig. 4. Mean radon concentrations in homes in the UK from two national surveys. The annual average radon concentrations are given with solid and dashed lines for the South West England study and a national survey, respectively. Taken from [10].

Hence, to account for such variation, 12-month measurements would be ideal. Also, under the UK legal requirements [11], a radon reference level is defined as an "annual average concentration" value. However, it is usually not practical to carry out such long measurements and most radon services offer 3-month measurements instead. This requires recalculation to an annual average value that is achieved by the introduction of seasonal correction multiplying factors. PHE applies seasonal correction factors for all household measurements and indoor workplace measurements.

Householders are sent a pack of two radon passive detectors, one to be placed in the bedroom and the other in the living room, to represent the rooms where most time is spent. The annual average radon concentration for a house is calculated using the results of these two rooms weighted by their occupancy factors (the proportion of indoor time spent in the room). The weighted average occupancy factors for the living area and bedroom are found to be 0.42 and 0.58, respectively [12]. In the case of workplace measurements, the number of supplied detectors depends on the size of the area under investigation. Results are reported individually for each detector, without aggregation of results for an entire site or building.

Intercomparisons

The final, ultimate check of applied QA for radon passive detectors can be assessed by participation in intercomparison exercises. The idea of an intercomparison is that each participant submits measurement devices, which are exposed by the organizer to a series of exposures that are not disclosed to the participants. Participants report results back to the organizer who ranks them against reference exposures. The intercomparison is an excellent tool to provide valuable information to identify and rectify any problem or error in the measurement system and to evaluate the performance of the entire measurement system. PHE participates both in its own [13] and other international intercomparisons, for example, German BfS [14], receiving top scores.

Conclusions

The quality of radon measurements can be greatly improved by the introduction of quality controls during the detector production/assembly stage as well as in the final stage of data processing. PHE's 40 years' experience shows that every quality check, however small, contributes to the quality of the final result. Moreover, an early error or defect identification can prevent further failures and provides continuity of the precision and accuracy of reported results.

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