

Calibration of diffusion barrier charcoal detectors and application to radon sampling in dwellings

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Some calibration conditions of diffusion barrier charcoal canister (DBCC) detectors for measuring radon concentration in air were studied. A series of functional expressions and graphs were developed to describe relationship between radon concentration in air and the activity adsorbed in DBCC, when placed in small chambers. A semi-empirical expression for the DBCC calibration was obtained, based on the detector integration time and the adsorption coefficient of radon on activated charcoal. Both, the integration time for 10 % of DBCC of the same batch, and the adsorption coefficient of radon for the activated charcoal used in these detectors, were experimentally determined. Using these values as the calibration parameters, a semi-empirical calibration function was used for the interpretation of the radon activities in the detectors used for sampling more than 200 dwellings in the major cities of the state of Chihuahua, Mexico.

Keywords: Radon; activated charcoal detectors; diffusion barrier; calibration.

Se estudiaron las condiciones de calibración de los detectores de radón en el aire en forma de contenedores de carbón activado con barrera de difusión (DBCC). Se obtuvieron expresiones funcionales y gráficos para la relación entre concentración de radón en el aire y la actividad adsorbida en el DBCC para el caso de su colocación en cámaras pequeñas. Se obtuvo una expresión semiempírica para la calibración de los DBCC, basada en los tiempos de integración y en el coeficiente de adsorción del radón por el carbón activado de los detectores. Se determinaron experimentalmente los tiempos de integración del 10 % de los DBCC de una misma partida, y el coeficiente de adsorción del carbón activado de los detectores utilizados. Con esos valores como parámetros, se aplicó la función de calibración semiempírica para la interpretación de las actividades resultantes del muestreo de más de 200 domicilios en varias ciudades del estado de Chihuahua, México.

Descriptores: Radón; detectores de carbón activado; barrera de difusión; calibración.

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1. Introduction

At the state of Chihuahua, as well as in other states of Northern Mexico, the lung cancer mortality rate (about 12 deaths per 100000 population) is twice the national figure for the period 1995-2000 [1], however, tobacco habits are approximately the same in Chihuahua as in the other states of the federation. This high mortality rate, by itself, justifies a detailed study of radon concentration in indoor air in homes, to assess the risk associated with inhalation of radon. One of the most usual methods for determining radon concentrations in indoor air is to measure radon adsorbed on activated charcoal. Therefore, in the Environmental Radiological Surveillance Laboratory of the Advanced Materials Research Cen-

ter at Chihuahua, it was decided to employ diffusion barrier charcoal canisters (DBCC) for short term sampling of radon in dwellings.

The procedures for using DBCC are well described in Refs 2 to 6. Some criteria about the assessment of the error inherent in this methodology and its associated detection limits are discussed in Ref. 7. Recently, this procedure was classified as passive and integrating, and compiled together with many other methods in the review of George [8].

Mathematical modeling of the canister response has been done in several papers, without diffusion barrier [9,10], and with it [11]. This paper deals with the analytical solutions of diffusion, adsorption and desorption equations, as well as with experimental determination of parameters, govern-

ing the behavior of DBCC in different conditions. A semi-empirical expression is proposed for calibration of DBCC to be used for sampling of radon indoors.

2. Radon adsorption by DBCC in constant flux chambers

Activated carbon collectors come in different sizes and configurations. Depending on the methodology used and on the collector type, the measurement lengths cover intervals from several hours to one week. The collectors can be open faced or with a diffusion barrier. The barrier slows the diffusion of radon in the carbon bed, but it also minimizes the undesirable entry and adsorption of water vapor and Rn-220 and Rn-119 isotopes of Rn. It is known that water vapor competes with radon for adsorption sites on the carbon bed, and the other isotopes can not be reliably measured this way.

The radon activity adsorbed by a DBCC in a constant flux chamber (a calibration chamber or any room in a house) may be described by the following expressions [3]. Using a compact explanation, the rate at which radon passes through the diffusion barrier is given by diffusion theory as

$$\frac{dQ}{dt} = JA = D \frac{dC}{dx} A = \frac{DA}{L} (C_0 - C_i), \tag{1}$$

where Q_i is the activity of radon passing through the diffusion barrier and adsorbed by the DBCC, J is the diffusion current, D is the diffusion constant, dC/dx is the concentration gradient, C_0 is the constant concentration of radon in the environmental air, D is the diffusion constant, A and L are the cross-section and the thickness of the diffusion barrier, and C_i is the radon concentration within the container.

Introducing the radioactive decay, if λ_{Rn} is the decay constant of radon, then

$$\frac{dQ_i}{dt} = \frac{DA}{L} (C_0 - C_i) - \lambda_{Rn} Q_i \tag{2}$$

Inside the charcoal canister, if radon crosses the diffusion barrier, $C_i \ll C_0$, and the concentration is related to the total adsorbed activity Q_i by

$$Q_i = kmC_i = V_{eq} C_i. \tag{3}$$

Here V_{eq} is equivalent to a volume of air available to the activated charcoal, k is the adsorption coefficient of radon by activated charcoal and m is the mass of activated carbon in the canister. Coefficient k is given by the relation (Bq of $^{222}\text{Rn}/\text{g}$ of carbon)/(Bq of $^{222}\text{Rn}/\text{litre}$ of air) = liter of air/g of carbon. It should be emphasized that Q_i is the quantity, measurable by means of a gamma spectrometer and subjected to calibration. By inserting (3) into (2), the following equation is obtained:

$$\frac{dC_i}{dt} = -\left(\frac{DA}{LV_{eq}} + \lambda_{Rn}\right)C_i + \frac{DA}{LV_{eq}}C_0. \tag{4}$$

This equation may be worked out using

$$\tau = \left(\frac{DA}{LV_{eq}} + \lambda_{Rn}\right)^{-1}; \quad \text{if } P = \frac{DA}{L}$$

$$\text{and } \lambda_a = 1/\tau, \lambda_a = \frac{P}{V_{eq}} + \lambda_{Rn} \tag{5}$$

where for initial conditions $C_i = 0$ for $T = 0$, the solution

$$C_i = C_0(1 - \lambda_{Rn}\tau)(1 - \exp(-T/\tau)) \tag{6}$$

is obtained, and if for $T = 0$, then $C_i = C_{i0}$ and $C_0 = 0$, the solution is

$$C_i = C_{i0} \exp(-T/\tau). \tag{7}$$

In (5) τ is the mean life of radon in the DBCC, or integration time of the DBCC, made up by characteristic of the diffusion in the device and of the radon decay. Then λ_a is the adsorption-desorption constant of the DBCC in a constant flow chamber. P is used as a constant to make calculations easier.

Equation (6) describes the temporary behavior of the amount of radon adsorbed in the DBCC, being T the time during which the DBCC is exposed to air in the chamber. On the other hand, Eq. (7) describes how radon, being accumulated up to an initial concentration C_{i0} , is desorbed from the DBCC, if this is exposed to an atmosphere practically without radon during a time T . The expression (7) allows to determine experimentally the magnitude of the integration time constant τ or its reciprocal λ_a . When the radon concentration to which the DBCC is exposed is not constant, it can be considered that C_0 is the time average concentration of radon in air during the exposure time of the DBCC to the atmosphere. That's the meaning of the "integrating" characteristic of DBCC.

3. Radon adsorption by a DBCC in a closed chamber

The process of adsorption and desorption of radon for a DBCC in a closed chamber is described in Ref. 12 for the case, when an initial concentration C_0 is injected into a small chamber. Quoting these authors, a small closed chamber has a few hundred dm^3 volume. For describing the phenomena of radon adsorption by a DBCC in a closed chamber, the main difference regarding the behavior of radon in a canister within a constant flux chamber is the "constancy" of total radon activity in the closed chamber, when the radioactive decay of radon is ignored. The relationship between the radon adsorbed in the DBCC and the radon concentration in the air in the chamber is given in Ref. 12 by

$$Q_i(t) = V(C_0 \exp(-\lambda_{Rn}t) - C(t)), \tag{8}$$

and the corresponding equation to be solved is

$$\frac{dC(t)}{dt} = C(t) \left[-\lambda_{Rn} - P \frac{V+km}{Vkm} \right] + \frac{C_0 P}{km} \exp(-\lambda_{Rn}t). \tag{9}$$

The expression obtained in Ref. 12 for $C(t)$ -radon concentration in the air of the chamber as a function of the exposure time of the DBCC-, is

$$C(t) = C_0 \left[\frac{km}{V+km} \exp(-at) + \frac{V}{V+km} \exp(-\lambda_{Rn}t) \right], \quad (10)$$

$$a = P \left(\frac{1}{V} + \frac{1}{km} \right) + \lambda_{Rn}. \quad (11)$$

In Ref. 12 it is suggested the use of solution (10) for computing the average concentration of radon in the closed chamber when an initial concentration C_0 is injected. Also it is suggested to perform the calibration of the DBCC by measuring its activity after the exposure to radon inside the chamber. This procedure is proved experimentally in Ref. 12, using a dynamical or "active" radon monitor together with the DBCC.

An alternative to the approach in Ref. 12 is to perform the calibration theoretically. To do this, the magnitude that is determined experimentally, Q_i , should be related to the radon concentration in the air. This calculation should be done from the same Eq. (9), obtained in Ref. 12. The resulting expression is:

$$Q_i(t) = \frac{C_0}{\frac{1}{V} + \frac{1}{km}} [\exp(-\lambda_{Rn}t) - \exp(-at)]. \quad (12)$$

It should be emphasized that, in a closed chamber, magnitudes V and km are different: V is the volume of the chamber in which the radon concentration in the air is tested, and $km = V_{eq}$ is the equivalent volume of air, from which the activated charcoal of a DBCC has adsorbed the radon gas.

4. DBCC calibration

EPA's calibration procedure for DBCC devices in a flow chamber at controlled radon concentration C_0 , is described in Ref. 5. In a few words, it consists on the following: A representative number of devices of the same DBCC batch are introduced into the chamber. Daily, part of them should be removed from the chamber, for performing measurements of their activity levels. The activity of adsorbed radon $Q_i = A_{ads}$ is measured in secular equilibrium with its daughters, by means of NaI(Tl) scintillation detectors inside a suitable lead shield, which counts the gamma rays emitted by the radon decay products on the charcoal. The net area of the spectrum in the region with the most intense lines (contiguous energies of 295, 351 and 609 keV) of the radon daughters is determined. The correspondence between the environmental radon concentration C_0 and the radon activity adsorbed A_{ads} into the DBCC during an exposure time T , is determined by applying the calibration factor CF :

$$CF = \frac{A_{ads}}{C_0 T DC}, \quad (13)$$

where DC is the decay correction for the adsorbed radon [5]:

$$DC = \exp[-\lambda_{Rn} (\text{delay of activity measurement} + T/2)]. \quad (14)$$

The detection efficiency is determined by means of a certified source of ^{226}Ra of activity A_{cert} (in secular equilibrium with ^{222}Rn) uniformly distributed in a container, with geometry and under conditions identical to those of the other DBCC devices, subjected to calibration or measurement. For this task is also tested a blank DBCC from the same batch, which has never been exposed to the atmosphere since its manufacture. The detection efficiency is determined on a daily basis, in each calibration procedure or radon measurement during the sampling. For this purpose, counting rates v_s and v_b , - corresponding to the above mentioned energetic interval- are determined for the certified source and the blank DBCC, respectively. The efficiency may be written as:

$$\varepsilon = \frac{v_s - v_b}{A_{cert}}. \quad (15)$$

The expression (13) is transformed into

$$CF = \frac{v_{exp} - v_b}{C_0 T \varepsilon DC}, \quad (16)$$

where v_{exp} is the counting rate of the DBCC subjected to calibration, and the remaining magnitudes are previously defined. CF units are liters/minute. The procedure in Ref. 5 establishes the fitting of a straight line of calibration of CF versus T for the values obtained.

5. Experiments

The DBCC devices used in this work are manufactured by F & J Specialty Products (catalogue number R40VCD), and consist of a cylindrical metallic container of approximately 10 cm of diameter and 4 cm height (with lid). The canister contains 70 ± 1 g of Calgon Corporation type PCB 6×16 mesh granular activated carbon. The activated charcoal is held firmly in place within the container by a screen that prevent loss of any particles. The screen consists of a metallic mesh, that provides an openness from 30 to 50%, fixed in its place by a metallic ring. Underneath the metallic mesh there is a diffusion barrier formed by a borosilicate glass fiber filter paper and a polyethylene layer, perforated with 20 holes symmetrically distributed.

After sampling, the container is closed hermetically with a sealing tape and a protective cover. Figure 1 shows a schematic of the used DBCC and a characteristic spectrum obtained.

A batch of 90 DBCC were subjected to calibration. The ^{226}Ra canister source, used for efficiency calibration, is certified by Isotopes Products. The 3" X 3" NaI(Tl) detector and its associated spectrometer are from Canberra Inc.

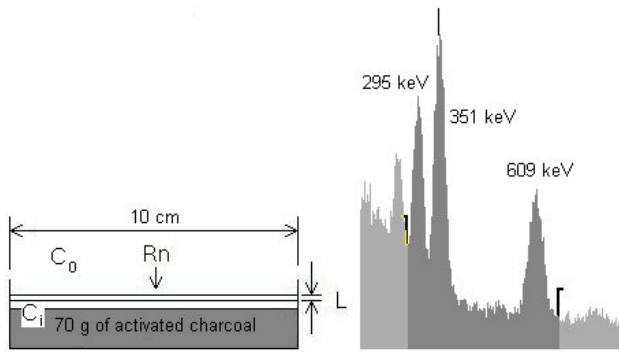


FIGURE 1. Schematic of the DBCC and the spectrum of adsorbed ²²²Rn, from the gamma- rays of its daughters in secular equilibrium.

Since, at this time, there is no controlled flow radon chamber available in Mexico, instead of using the EPA’s procedure for calibration [5], described above, it was decided to determine experimentally the integration time τ of the DBCC devices of the batch and the absorption coefficient k of the activated charcoal they contain, and to use the following expression for the calibration:

$$Q_i(T) = kmC_i = kmC_0(1 - \lambda_{Rn}\tau)(1 - \exp(-T/\tau)), \quad (17)$$

obtained from Eqs. (3) and (6). This approach is theoretically justified, as demonstrated above, and allows the researcher to perform indoor radon samplings with a DBCC, with short-term exposures, and using a calibration specific for the current batch. Furthermore, this procedure is inexpensive and may be applied in the same laboratory that conducts the analysis. The procedures for determining the parameters k and τ are described below.

Ten devices, desorbed for 20 hours in an oven at 110 °C, were chosen at random, and they were consecutively exposed

to radon inside a small chamber hermetically closed, together with abundant uranium mineral extracted from Chihuahua mines. The DBCC devices were exposed during 4 days to radon emanated from the mineral, then they were closed. The initial activity of radon was determined immediately after the secular equilibrium was reached. Later, the devices were opened and were exposed to radon-free air. During 7 consecutive days the remaining activity was determined. The activities were determined by measuring the certified source, the blank, and the corresponding DBCC, by means of the expression

$$A(T) = \frac{v_{exp} - v_b}{\epsilon} \quad (18)$$

and using (15) for the efficiency. For the determination of τ by means of the semi-logarithmic straight lines of desorption, and for calculation of their slopes λ_a , it was necessary to apply a correction for radon disintegration occurring while the containers remain closed, to allow the radon decay products to reach equilibrium, and to measure their activity.

The adsorption coefficient k was determined following the procedure suggested by Zikovsky [13], by means of a technique based on adsorption-desorption of radon by a small amount of activated charcoal. An intense source of radon and a flask of approximately 0.5 liters capacity were used for this purpose. After a moderate adsorption of radon by the activated charcoal, of initial activity A_0 , the sample is placed into a flask of volume V_f , containing air with a negligibly low radon concentration. Then, radon of the activated charcoal will partially desorb to the air, which activity will be A_a . The activity remaining in the charcoal will be A_c at equilibrium, so that $A_a = A_0 - A_c$. The coefficient of adsorption k satisfies the definition

$$k = \frac{(\text{radon adsorbed by activated charcoal} / \text{weight of charcoal sample})}{(\text{radon concentration in air, in equilibrium with radon adsorbed by the charcoal})} \quad (19)$$

(units in liters of air / grams of charcoal).

Then the volume V_f , the mass of the sample m_{ca} , and the activities were experimentally determined to obtain

$$k = \frac{A_c/m_{ca}}{A_a/V_f}. \quad (20)$$

Once the experimental values of k and λ_a , are determined, they should be introduced in (17), to calculate the calibration function $Q_i(T)$ for different exposure times, normalized to C_0 .

The radon concentration in a room is determined by exposing the detector to air, measuring its adsorbed activity, and dividing the result by the corresponding calibration value, $Q_i(T)/C_0$. During the exposure, the device should be placed with the open side up toward the air. Nothing should impede air flow around the device.

For the procedure described above, the minimum detectable activity of radon, and concurrently, the minimum detectable radon concentration, should be determined. The expression, suggested by Hurtgen *et al.*[14], was used to calculate the minimum net counting rate, when there is a net signal from the blank, (based on the statistic u), is

$$L_d = s_{net} = \frac{[u^2 + u\sqrt{(8b + 8 + u^2)}]}{2}, \quad (21)$$

where b is the number of net counts of the signal from the blank, observed at the same time that measurement of the blank and the sample are performed.

6. Results

For the determination of the integration time τ , the initial activity of the DBCC devices reached values between 625 and 1120 Bq of Rn/g of activated charcoal. The statistic of the region of interest in the DBCC was of 10^7 events initially, and finished being 10^5 . The statistical errors were determined by propagation and were negligible. The values of the slopes (λ_a - constant of adsorption-desorption) and of the integration times τ derived from the resulting straight lines of desorption are shown in Table I. The errors in each row represent the standard deviation derived from the measurement statistic. The errors of the average value of the constants are the standard deviations resulting from the dispersion of the individual slopes and integration times.

The adsorption coefficient of activated charcoal k was determined using the following procedure: Activities were measure in the same NaI(Tl) detector, with a vessel of $V_f = 0.546$ liters and a mass of activated charcoal $m_{ca} = 0.2443$ grams. Relative activity measurements were performed every 15 minutes, in 3 sequences of four 30-minute desorption periods. The results were $k = 3.8 \pm 0.7$; 4.2 ± 0.3 and 4.2 ± 2.3 liters/gram, respectively for each sequence. The general average was $k = 4.1 \pm 0.2$ liters /gram, the same as the reported in Ref. 13 for the activated charcoal of Calgon Corporation.

The experimental average results of k and λ_a were replaced in Eq. (17) to obtain the calibration coefficient $Q_i(T)/mC_0$. Figure 2 shows the result of the calculation. The activity adsorbed by a DBCC during an exposure time T , $Q_i(T)$, obtained from the expression (17), is normalized by the constant concentration C_0 and the mass of activated charcoal m . The two curves represent the extreme values of the interval of propagated error of $Q_i(T)$, determined from the experimental standard deviation of k and the standard deviation of the average value of λ_a . The relative random errors of the activity of a DBCC, resulting from the propagation of the nuclear statistics, the calibration error - due to uncertainty of the activity of the certified source-, and of the errors of $Q_i(T)$ are shown in Table II, for different exposure times.

The expression (21) is reduced to

$$L_d = s_{net} = 2.71 + 4.65\sqrt{(b + 1.34)} \tag{22}$$

for the case of a 5% of confidential interval, using $u = 1.645$.

The value obtained from (22) is introduced in the expression (17), in order to know the minimum detectable concentration of radon. The minimum detectable concentration of radon for a 3 days exposure time and a 24-hour delay period before taking measurements, is 20 Bq/m^3 .

In order to compare this calibration to the one suggested by Ref. 5, a chart (Fig. 3) was created, showing the values of CF published in Ref. 5, simple and multiplied by the decay correction DC of Eq. (14). The results of this calibration are shown along with the uncertainty interval and divided by the exposure time, to be analogous with the experimental values

of Ref. 5, and assuming the mass of activated charcoal of the detectors is 70 g.

The values obtained for k and λ_a were also used to illustrate the form of the expressions for the radon concentrations in air and a DBCC in a closed chamber, if an initial concentration C_0 is injected, -given by (14) and (16)-. For this purpose, the value of P was obtained by replacing k and λ_a in the expression (5), to find the value of a using the expression (11). Also it was assumed a charcoal mass $m = 70$ g. Results are shown in Fig. 4.

TABLE I. Adsorption-desorption parameters of the 10 DBCC devices subjected to calibration.

DBCC	$\lambda_a(\text{day}^{-1})$	$\sigma_a(\text{day}^{-1})$	$\tau(\text{days})$	$\sigma_\tau(\text{days})$
1	0.2517	0.0039	3.97	0.06
2	0.8435	0.012	1.19	0.02
3	0.6144	0.0035	1.628	0.009
4	0.6003	0.0027	1.666	0.007
5	0.6177	0.0029	1.619	0.008
6	0.2736	0.0049	1.619	0.07
7	0.3817	0.0065	2.62	0.04
8	0.3061	0.0089	3.27	0.09
9	0.400	0.042	2.5	0.3
10	0.590	0.037	1.7	0.1
average	0.49	0.19	$\Rightarrow 2.0$	1

TABLE II. Relative random errors of the activity of a DBCC, exposed to an unitary radon concentration, and normalized to the mass of the activated charcoal.

T (days)	1	2	3	4	5	6	7	8	9	10
$\frac{\sigma_Q}{Q}$	0.18	0.16	0.14	0.13	0.12	0.11	0.10	0.10	0.10	0.10

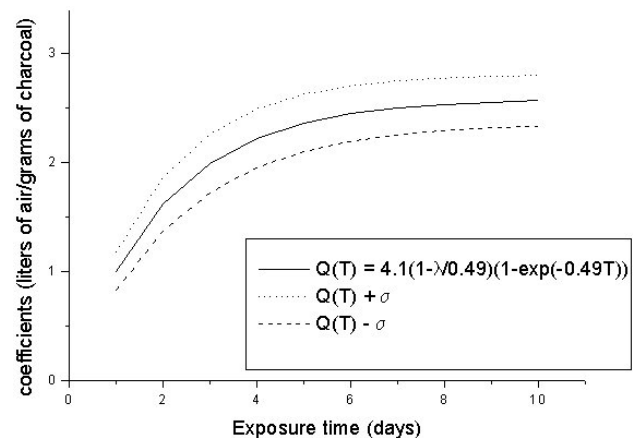


FIGURE 2. Calibration coefficient chart for the activity of a DBCC, as a function of the exposure time. It is assumed that the device is exposed to an unitary constant radon concentration. The coefficients are normalized by the mass of the charcoal in the container. Parameters k and λ_a were obtained experimentally and replaced in Ref. 17. The extreme values of the error interval, propagated from parameters k and λ_a , are also shown.

TABLE III. Average radon concentration in air, determined from measurements by electrets, and obtained with DBCC devices, applying expression (17) for calibration.

Position	Electret's Concentration (Bq/m ³)	Concentration on DBCC # 1 (Bq/m ³)	Concentration on DBCC # 2 (Bq/m ³)
1	229 ± 22	231 ± 39	-
2	137 ± 14	100 ± 17	99 ± 17
3	167 ± 17	155 ± 26	154 ± 26

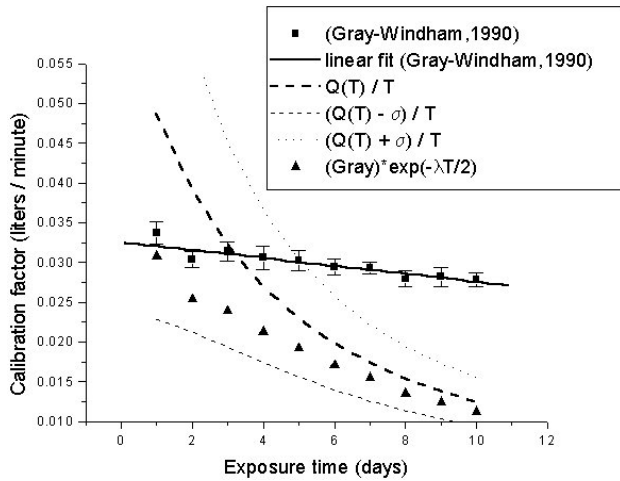


FIGURE 3. Points and fitted straight line of the calibration published in Ref. 5, showing the dispersion of the experimental values (square), and the experimental values multiplied by the decay correction, without the dispersion (triangle). The curves represent the activity of a DBCC -with parameters k and λ_a obtained experimentally-, after been exposed to an unitary constant radon concentration, divided by the exposure time, $Q(T)/TC_0$, and the extreme values of the error interval, propagated from the standard deviations of parameters k and λ_a .

For control purposes, radon concentration in air was measured in a room, where uranium mineral is stored. Five DBCC devices and three electrets [15] were deployed. They were exposed for 4 days, in different positions. The results are shown in Table III.

7. Discussion

In Table I, the values of the integration time of the DBCC set are lower than the mean life of radon, $\tau_{Rn} = 5,52$ days, as expected from (5). The most frequent values are between 1 and 3 days. These facts suggest that DBCC devices should be used for exposure periods of about 3 days, and no greater than 5 days. The calibration procedure recommended in Ref. 5 and the one, provided by manufacturer F&J Specialty Products, range up to 10 days. However, values in Table I suggest, that many detectors are likely to be saturated if radon concentration in chamber has remained constant for more than 5 or 6 days. DBCC batches used in laboratories are of 90 or more containers. It is not practical to calibrate each individual device, but to perform a calibration with a representative part of each batch, as it was done in this work

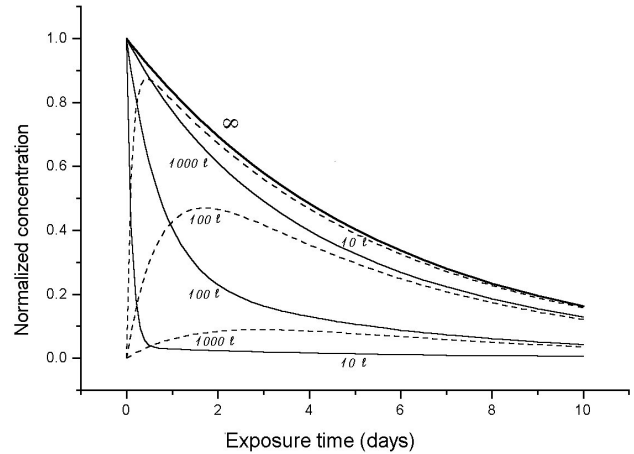


FIGURE 4. Values of the radon concentration in air and for DBCC detector when an initial concentration C_0 is introduced into a closed chamber, with the chamber volume as a parameter. The values are normalized by $C(t)/C_0$ for the air and by $Q(t)/C_0V$ for the charcoal. The DBCC has 70g of activated charcoal; its parameters k , λ_a , P and a are equal to those adsorption-desorption and diffusion parameters, determined experimentally. Solid curves represent the radon concentration in the air, $C(t)$, whereas dotted ones give the radon concentration in the activated charcoal $Q(t)$. For infinite volume of the chamber there is no concentration curve for $Q(t)$. The lower solid curve and the upper dotted one correspond to a volume of 10 liters; the following solid curve (bottom), with the following dotted one (top), correspond to a volume of 100 liters, and so on.

(around 10%). Table I shows a series of very dispersed values for the adsorption-desorption constants. This fact is justified by the natural differences in activated charcoal from containers. This is also noted in Refs. 5 and 6. Measurements with another set of detectors would produce approximately the same average value, because containers were selected randomly.

In Fig. 3, the values for the calibration factor published in Ref. 5 are multiplied by the decay correction in (14). Then, the resulting values are included within the uncertainty interval of the calibration performed for this work, which represents the disparities derived from the mentioned differences among the containers and the production batches.

Figure 4 shows that, when the chamber volume increases, radon concentration in air tends to increase toward the radon concentration of the chamber without DBCC detector (infinite volume). It was described by Ref. 12. This behavior is explained by the product km , that is, by the limited capacity of adsorption of the activated charcoal inside the DBCC.

TABLE IV. Random sampling in Chihuahua and screening results from Parral, Jimenez and Aldama (Chih.)

City	Number of sampled dwellings	Dwellings with $C_0 > 148 \text{ Bq/m}^3$	% of dwellings with $C_0 > 148 \text{ Bq/m}^3$	Average-Min-Max (Bq/m^3)
Chihuahua	128	41	32	137 - <20 - 885
Parral	36	12	33	200 - <20 - 1450
Jimenez	26	8	31	120 - 40 - 380
Aldama	19	9	47	141 - 40 - 390

It is observed from expression (11), in the case of an exposure chamber of very large volume, where a comes closer to the value of λ_a , that the expressions (12) and (17) have similar forms, but nonequal, because the approximation $\exp(-\lambda_{Rn} t) \approx 1$ cannot be done when λ_a is approaching λ_{Rn} . Therefore, it is not possible to assure that the adsorption of radon by a DBCC in closed chamber conditions will behave as in a room.

Values in Table III suggest that the use of DBCC devices for short term sampling periods, with the calibration from expression (17), is similar to the use of electrets. DBCC devices may be useful in research, applying radon screenings and random samplings in dwellings.

8. Applications

In the past 20 years there has been a great concern about the health risk from exposure to radon. This situation has increased the interest in sampling radon in dwellings. Very detailed studies in the United States [16] and United Nations' organizations [17] have proposed different action levels for radon remediation. The action level recommended in the United States is 148 Bq/m^3 , whereas that of the IAEA, in situations of chronic exposition to radon in dwellings, is an annual average Rn-222 concentration in air from 200 to 600 Bq/m^3 .

Indoor radon studies in Mexican houses throughout the country have been performed by several institutions and researchers [18-20], applying almost always long term sampling periods with solid state nuclear track detectors. Generally, average radon concentration in Mexican dwellings has been reported below 148 Bq/m^3 .

The calibration made in this work was applied in the procedures utilized to evaluate the radon concentration in the cities of Chihuahua, Jimenez, Hidalgo del Parral and Aldama, in the state of Chihuahua, in short term sampling periods.

In each experiment, the devices were exposed to indoor radon in different areas far from doors, selecting bedrooms (preferably), and avoiding bathrooms or kitchens. The expo-

sure time was approximately three days. The detection efficiency and the blank counting rate were determined daily.

First, a screening was conducted in one hundred addresses at the city of Chihuahua, using DBCC type detectors and electrets. Subsequently, it was performed a random sampling in Chihuahua city, taking a sample from 128 randomly selected addresses. In this sampling activated charcoal detectors were used and every ten addresses, a duplicate and a solid state track detector were added for quality control. In the cities of Parral, Jimenez and Aldama it was made a single screening. The results are shown in Table IV.

9. Conclusions

It is not recommended to simulate the testing of radon concentration in air with a DBCC in rooms by introducing the container into a closed chamber, with an injected initial activity. A room is better simulated by a constant flow chamber: The subsoil serves as a constant emanation source, and doors and windows of the room allow radon to escape. This allows to maintain an approximately constant radon flow in the chamber. For laboratories that do not have a controlled constant flow chamber, it is recommended to perform the determination of constants k and λ_a , using the procedure described here, and to use the expression (17) for DBCC devices' calibration. The application of the DBCC detectors for the screening and sampling of cities at the state of Chihuahua has given reliable results for assessment of radon concentration in the air in dwellings.

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