Journal of Radioanalytical and Nuclear Chemistry (2023) 332:2945–2951
https://doi.org/10.1007/s10967-023-08997-z

Radon indoor concentration time-variation model

M. Orabi[1]

Received: 31 October 2022 / Accepted: 10 June 2023 / Published online: 21 July 2023

Abstract

The time variation of radon indoor concentration is studied using a semi empirical model. The mass balance formula for radon indoors is applied to put a descriptive equation that considers every source of the radon. The resultant equation is solved analytically with imposing a number of approximate forms that are justified by their empirical background. The model's parameters are fitted to some experimental radon indoor concentration data to estimate a set of descriptive figures for radon entry to indoors from the wall s and ground of a room. The current study focuses on applying the model on a short period of time. The model is successful and provides a good description for the data, with further prediction of the possibility of having an unrecognized source of radon.

Keywords Radiation · Radon · Concentration · Indoors · Time variation · Modelling

Introduction

Radon Is well recognized as a major source for the cancer of lungs [1–6]. Being a gas, the radon atoms could escape from any surface out to the air where they decay to their progeny that may attach to dust particles to create radioactivedust, which we inhale. Early researches on radon were mainly concerned about mines of uranium, but it was realized later that radon levels have to be monitored at all work places and residences, because radon is emitted from everything surrounding us; from ground, walls, water, etc. With these investigations carried on over the years, many articles have been written that report radon concentrations at various places of work, homes and schools, at different cities from different countries. It is, however, worthy of mention that the risk of radon promoting a lung cancer is not only related to its concentration inside the place of concern, but it is also related to how many hours the person stays in that place, and whether they are smokers. Some surveys indicate that smokers could be ten times more susceptible to lung cancer than non – smokers [7–13]. Therefore, in addition to having reports about the concentrations of the indoor radon, it is necessary to have deliberate studies on its behavior. This comes only by carrying both theoretical and experimental researches on all the relevant elements, e.g. the concentration of radon in the constructing walls of the buildings and in the soil underneath. Other important influencing factors are also the levels of radon in the surrounding outside air, the radon diffusive and advective characteristics, different contributors to the radon indoors, and temporal changes. These studies can help in finding and developing methods to minimize the exposure of the individuals to radon.

In this paper, one of the important factors that will be studied is the time variation of the radon indoor concentration. In previous researches, measurements on indoor radon usually focused on long – term temporal variations [14–17], while calculations usually assumed a steady state condition [18–20]. In this research, however, a theoretical investigation is performed on the radon indoor concentration short – term temporal variations; at top, for one or two days, on an hourly basis. This is important for places that have very high radon concentrations, in particular when the residents remain for long time periods indoors, especially in winter with poor ventilation, or for workers at unventilated mines for example. Another remarkable side of the model is that, unlike most of the previous theoretical studies, where only some sources are considered, this model considers all known sources of indoor radon [18–21]. It additionally provides a prediction of possible existence of unknown sources. Furthermore, as different from previous

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✉ M. Orabi
momen_ahmad_orabi@cu.edu.eg

[1] Physics Department, Faculty of Science, Cairo University, Giza 12613, Egypt

schemes, this model gives the radon indoor concentration in an analytical form, not by numerical calculations [18–21]. Moreover, the model, with its semi empirical feature, is expected to give better description to the experimental measurements.

Sources and concentrations of radon

Soil Is the most important radon source. Annual estimation of the radon flow from the ground worldwide is nearly 90×10^{18}Bq [22]. Almost 50% of the radon indoors is from the soil (supposing the room is in the ground floor) [23]. Beside soil, there are other different sources of the indoor radon. These are outlined in Fig. 1. Considerable radon levels can be detected in water streams [24]. The higher layers of these waters constantly release radon to the surrounding atmosphere by volatilization [25]. This indicates that the water lower layers have more concentrations of radon than the higher ones. Similarly, because of radon release to the outside air by advection and diffusion, bottom parts of the soil have higher concentrations of radon than the top parts [25]. From this argument, it is clear that radon concentration can differ widely from one place to another. For instance, in outside air it covers a range of $1\mathrm{Bq.m}^{-3} - 100\mathrm{Bq.m}^{-3}$ [26]. In poorly ventilated residences, it covers a range of $20\mathrm{Bq.m}^{-3} - 2000\mathrm{Bq.m}^{-3}$, with a close range for mines with good ventilation [26]. Mines without good ventilation can have a much larger range [26]. Furthermore, radon concentration can broadly vary with differentseasons and atmospheric conditions [16, 17].

Timerate of variation of the radon indoor concentration

To have an appropriate evaluation of the inhaled dose of the radon indoors, it is sometimes necessary to observe the exposures closely, which in turn means having convenient methods to estimate the changes of the concentrations of the radon indoors in short terms. Due to several factors, the radon concentration is a function of time and position, and therefore to estimate the indoor exposure, an integration must be performed over the dimensions of the room and over the time interval of interest. However, this study concerns about the temporal variation, and so, for simplicity, the radon concentration at a given time is assumed to be the same at all positions in the room, i.e. position independent, and hence the integration over the dimensions will just yield the room's volume. Thus, the exposure to an individual in a time interval $\Delta t = t_2 - t_1$ is taken as $V\int_{t_1}^{t_2} C_i(t)dt$, where $V(\mathrm{m}^3)$ is the room's volume and $C_i(t)\left(\frac{\mathrm{Bq}}{\mathrm{m}^3}\right)$ is the radon indoor concentration at a given time t(h). To have a theoretical evaluation of $C_i(t)$, we begin by the radon mass balance form that describes the different sources of indoor radon and its sinks

$$\text{Radon in a room} = \text{radon sources} + \text{radon sinks}, \tag{1}$$

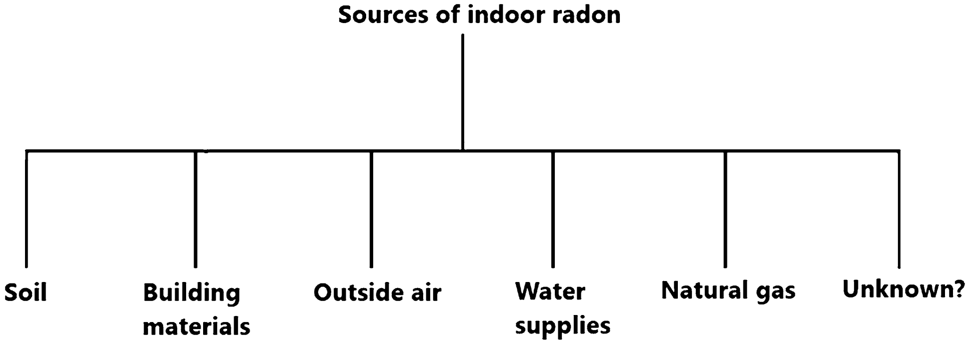
or

$$\frac{dC_i(t)}{dt} = \left.\frac{dC_i(t)}{dt}\right]_{\mathrm{bm}} + \left.\frac{dC_i(t)}{dt}\right]_{\mathrm{S}} + \left.\frac{dC_i(t)}{dt}\right]_{\mathrm{O}} + \left.\frac{dC_i(t)}{dt}\right]_{u} + \left.\frac{dC_i(t)}{dt}\right]_{\mathrm{D}} \tag{2}$$

where $\left.\frac{dC_i(t)}{dt}\right]_{\mathrm{bm}}$ is from building materials, $\left.\frac{dC_i(t)}{dt}\right]_{\mathrm{S}}$ is from soil, $\left.\frac{dC_i(t)}{dt}\right]_{\mathrm{O}}$ is due to exchange with the outside air, $\left.\frac{dC_i(t)}{dt}\right]_{u}$ is from sources that might be unknown, and $\left.\frac{dC_i(t)}{dt}\right]_{\mathrm{D}}$ is due to radon disintegration.

Radon release from walls adds up to the concentration of radon inside the room. In a very short time interval, the rate of that addition can be put in the form $\frac{S_{\mathrm{bm}}}{V}D_{\mathrm{bm}}\left(C_{\mathrm{bm}} - C_i\right)$, where $S_{\mathrm{bm}}(\mathrm{m}^2)$ is the room's internal area with building materials, $D_{\mathrm{bm}}\left(\frac{\mathrm{m}}{\mathrm{h}}\right)$ is the diffusive transfer coefficient through the walls, and $C_{\mathrm{bm}}\left(\frac{\mathrm{Bq}}{\mathrm{m}^3}\right)$ is the concentration of radon in the walls including both the emanated radon atoms and the non-emanated ones. On the other hand, in a very short time interval, the addition rate to the concentration of radon inside the room, by radon release from the soil, can be put in the form $\frac{S_f}{V}.\varphi_s$, where $S_{\mathrm{f}}(\mathrm{m}^2)$ is the floor's area, and $\varphi_s\left(\frac{\mathrm{Bq}}{\mathrm{m}^2\mathrm{h}}\right)$ is the soil radon flux

Fig. 1 Outline of the indoor sources



to the inside of the room. This flux, taking place by advection and diffusion, is given by $\varphi_s = C_s \Delta P_{si} A + D_s (C_s - C_i)$, where $C_s \left(\frac{\mathrm{Bq}}{\mathrm{m}^3}\right)$ is the soil radon concentration, ΔP_{si}(Pa) is the difference in pressure between the inner of the room and the soil, $A\left(\frac{\mathrm{m}}{\mathrm{h.Pa}}\right)$ and $D_s\left(\frac{\mathrm{m}}{\mathrm{h}}\right)$ are the advective and diffusive transfer coefficients through the soil, respectively. Thus [18–21]

$$\left.\frac{dC_i(t)}{dt}\right]_{\mathrm{bm}} = \frac{S_{\mathrm{bm}}}{V} D_{\mathrm{bm}} (C_{\mathrm{bm}} - C_i), \tag{3}$$

$$\left.\frac{dC_i(t)}{dt}\right]_{\mathrm{S}} = \frac{S_f}{V} \left(C_s \Delta P_{si} A + D_s (C_s - C_i)\right), \tag{4}$$

and hence Eq. (2) becomes

$$\begin{aligned}\frac{dC_i(t)}{dt} = {} & \frac{S_{\mathrm{bm}}}{V} D_{\mathrm{bm}} (C_{\mathrm{bm}} - C_i) + \frac{S_f}{V} \\ & \left(C_s \Delta P_{si} A + D_s (C_s - C_i)\right) - \lambda_{\mathrm{v}} (C_i - C_o) + \left.\frac{dC_i(t)}{dt}\right]_u \\ & - \lambda C_i(t),\end{aligned} \tag{5}$$

where

$$\left.\frac{dC_i(t)}{dt}\right]_{\mathrm{O}} = -\lambda_{\mathrm{v}} (C_i - C_o), \tag{6}$$

$$\left.\frac{dC_i(t)}{dt}\right]_{\mathrm{D}} = -\lambda C_i(t), \tag{7}$$

where $\lambda_{\mathrm{v}}(\mathrm{h}^{-1})$ is the ventilation rate, $C_o\left(\frac{\mathrm{Bq}}{\mathrm{m}^3}\right)$ is the concentration of radon in the surrounding outdoor, and $\lambda(\mathrm{h}^{-1})$ is the constant of radon decay. In Eq. (6), the exchange with the outside air is assumed to be due to ventilation only, without taking into account the negligible contribution from the leakage processes.

Solution of the mass balance equation

The mass balance equation in its form as given by Eq. (5) has a number of unspecified functions. This makes it hard to attain its solution. To make it less complicated, and put it in a more convenient form, we approximate the involved functions by making use of some of the data from relevant measurements [14–17, 27–29]. We may develop the formulas

$$C_{\mathrm{bm}} = a_{\mathrm{bm}} C_i, \tag{8}$$

$$C_s = a_s C_i, \tag{9}$$

$$C_o = a_o C_i, \tag{10}$$

where a_{bm} is a parameter that can relate the concentration of radon inside the building material to that of the indoor air, a_s is a parameter that can relate the concentration of radon in the soil to that of the indoor air, and a_o is a parameter that can relate the concentration of radon in the outdoor air to that of the indoor air. All these parameters are dimensionless and they are to be evaluated from the experimental observations.

For not long durations, the term $\left.\frac{dC_i(t)}{dt}\right]_u$ can be assumed to be almost constant

$$\left.\frac{dC_i(t)}{dt}\right]_u \cong \mathrm{U}\,. \tag{11}$$

Substituting Eqs. (8–11) in Eq. (5)

$$\begin{aligned}\frac{dC_i}{dt} = {} & \frac{S_{\mathrm{bm}}}{V} D_{\mathrm{bm}} (a_{\mathrm{bm}} - 1) C_i + \frac{S_f}{V} \\ & \left(a_s \Delta P_{si} A + D_s (a_s - 1)\right) C_i - \lambda_{\mathrm{v}} (1 - a_o) C_i + \mathrm{U} - \lambda C_i,\end{aligned} \tag{12}$$

or

$$\frac{dC_i}{dt} = \left(\mathrm{b}_{\mathrm{bm}} + \mathrm{b}_s - \mathrm{b}_{\mathrm{o}} - \lambda\right) C_i + \mathrm{U}, \tag{13}$$

where

$$\mathrm{b}_{\mathrm{bm}} = \frac{S_{\mathrm{bm}}}{V} D_{\mathrm{bm}} (a_{\mathrm{bm}} - 1), \tag{14}$$

$$\mathrm{b}_s = \frac{S_f}{V} \left(a_s \Delta P_{si} A + D_s (a_s - 1)\right), \tag{15}$$

$$\mathrm{b}_{\mathrm{o}} = \lambda_{\mathrm{v}} (1 - a_o). \tag{16}$$

Putting

$$q = \mathrm{b}_{\mathrm{bm}} + \mathrm{b}_s - \mathrm{b}_{\mathrm{o}} - \lambda, \tag{17}$$

Equation (13) becomes

$$\frac{dC_i}{dt} = q C_i + \mathrm{U}, \tag{18}$$

which has the solution

$$C_i(t) = -\frac{\mathrm{U}}{q} + w e^{qt}. \tag{19}$$

If $C_i(t)$ has an initial value $C_i(0)$ at $t = 0$, then

$$w = C_i(0) + \frac{\mathrm{U}}{q}, \tag{20}$$

and therefore

$$C_i(t) = \frac{\mathrm{U}}{q}\left(e^{qt} - 1\right) + C_i(0)e^{qt}. \tag{21}$$

Applying the model and discussing the results

We start by estimating the parameters a_{bm}, a_s and a_o of Eqs. (8–10). They are dimensionless, with the evaluations

$$a_{\mathrm{bm}} = 229, \tag{22}$$

$$a_s = 100, \tag{23}$$

$$a_o = 0.7 \tag{24}$$

Eqs. (22) and (8) develop from using the formula [27]

$$C_i^{\mathrm{bm}} = \frac{E_s.S_{\mathrm{bm}}}{\lambda_{\mathrm{v}}.V}, \tag{25}$$

together with Fig. 2. C_i^{bm} is the radon indoor concentration occurring by radon release from the constructing material that has an observed areal release rate E_s $(\frac{\mathrm{Bq}}{\mathrm{m^2h}})$. The plot of Fig. 2 is a relation between E_s and concentration of radon in a material [28]. 34 samples were analyzed, where E_s and concentration of radon were measured by applying the sealed can technique [28]. A linear correlation between E_s and concentration of radon was developed, with correlation coefficient 0.95. The straight-line used to describe the data is

$$E_s = 0.433C_{\mathrm{bm}}. \tag{26}$$

In accordance with ref [23], constructing materials shares by ~ 20% of the radon indoor concentr, i.e. $C_i^{\mathrm{bm}} \approx 0.2C_i$. Therefore, using Eqs. (25) and (26)

$$C_i^{\mathrm{bm}} \approx 0.2C_i = \frac{0.433 \times 10^{-3}C_{\mathrm{bm}}S_{\mathrm{bm}}}{\lambda_{\mathrm{v}}V}, \tag{27}$$

or

$$C_{\mathrm{bm}} = \frac{0.2\lambda_{\mathrm{v}}V}{0.433 \times 10^{-3}S_{\mathrm{bm}}}C_i, \tag{28}$$

which gives Eqs. (8) and (22), where

$$a_{\mathrm{bm}} = \frac{0.2\lambda_{\mathrm{v}}V}{0.433 \times 10^{-3}S_{\mathrm{bm}}}. \tag{29}$$

Eqs. (23) and (9) develop from Fig. 3 that relates the concentration of radon indoors to that in soil, for ground-floor rooms [29]. The radon concentration indoor measurements were made by the alpha scintillation cells ASC and the portable AlphaGuard radon monitor. The concentrations of radon in soil were made by the EDA – ASC and the portable RDA – 200 detector [29]. 53 samples were analyzed. From Fig. 3, one can see that most of the data are gathered at small concentrations of the indoor radon. Therefore, in our model, the dots are described by the following straight-line relation

$$C_i = 0.01C_s, \tag{30}$$

or

$$C_s = 100C_i, \tag{31}$$

which means that a_s has the value 100. Eqs. (24) and (10) develop from taking the average of concentrations of radon outdoors recorded at various seasons in relation to that of

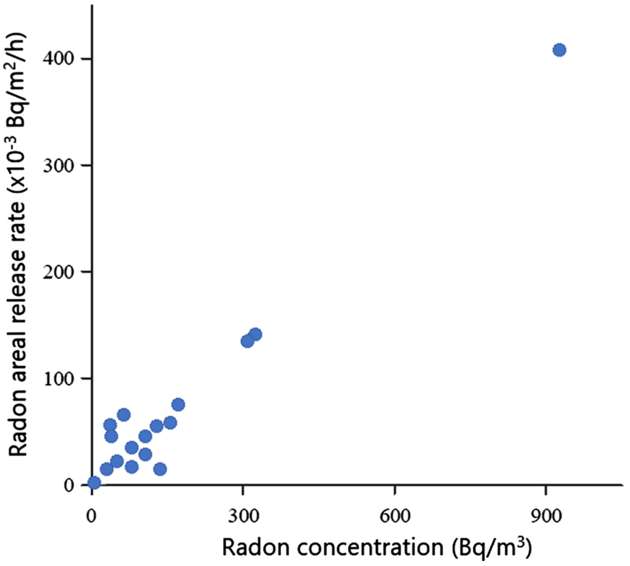


Fig. 2 Radon areal release rate from a material in relation to its radon concentration, according to the measurements in ref [28]

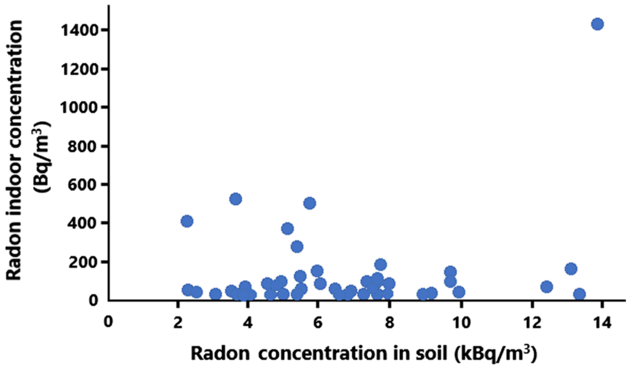


Fig. 3 Relating the concentration of radon indoors to that in soil, for ground-floor rooms, according to the measurements in ref [29]

indoors [15–17]. Better evaluation of a_o could be obtained by taking into account only the season relevant to the radon indoors in study.

Beside a_{bm}, a_s and a_o, there are some parameters that describe the studied room. Because the values of these parameters are not provided with the data of the measured indoor concentrations [30], they are given typical numbers. The length, width and height of the room are taken as 5m, 4mand2.8m, respectively. The volume of the room is therefore $56\mathrm{m}^3$, with $\frac{S_{\mathrm{bm}}}{V} \approx 1.6\mathrm{m}^{-1}$. The rate of ventilation and the soil-indoor difference in pressure are assumed to be $\lambda_{\mathrm{v}} = 0.8\mathrm{h}^{-1}$ and $\Delta P_{si} = 4\mathrm{Pa}$.

All the needed parameters to calculate $C_i(t)$ are now set. Only left, to be evaluated from fitting Eq. (21) to the measured concentrations, are the diffusive transfer coefficient through the walls D_{bm}, the share from unknown-sources U, the advective and diffusive transfer coefficients through the soil, A and D_{s}, respectively.

Figure 4 shows a set of experimental data [30] for the variation of the indoor radon concentration over a couple of days. The measurements were performed by the PQ2000PRO AlphaGuard. 33 samples were analyzed. To fit Eq. (21) to the measurements of ref [30], the D_{bm}, A, D_{s}, and U parameters are found to be

$$D_{\mathrm{bm}} \approx 2.06 \times 10^{-6} \frac{\mathrm{m}}{\mathrm{h}}, \tag{32}$$

$$A \approx 1.04 \times 10^{-3} \frac{\mathrm{m}}{\mathrm{h.Pa}}, \tag{33}$$

$$D_{\mathrm{s}} \approx 0.91 \times 10^{-4} \frac{\mathrm{m}}{\mathrm{h}}, \tag{34}$$

$$\mathrm{U} \approx 30.61 \frac{\mathrm{Bq}}{\mathrm{m}^3.\mathrm{h}}. \tag{35}$$

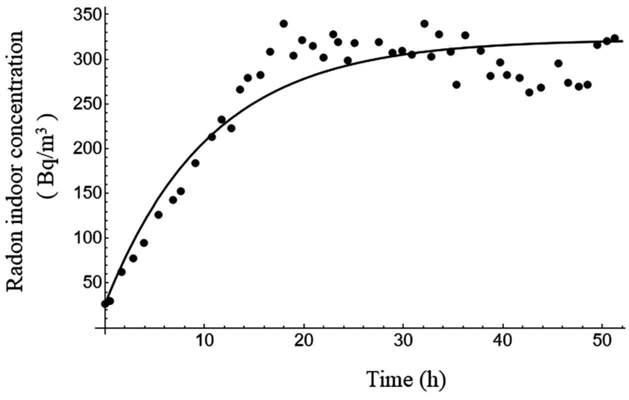


Fig. 4 Results of the model for estimating the radon indoor concentration as compared to the data of ref [30]

These are significant parameters for describing the indoor radon-entry. The good fit demonstrated in Fig. 4 implies the model's efficacy in giving a description of the temporal change of radon indoor concentration. However, the time span during which the model is applicable is not clearly known. Trying to fit Eq. (21) to less data, or more, than those in Fig. 4, causes a slight change in the resulting parameters. Therefore, in order to have a better argument, several sets of data should be involved to test the range of applicability of the adopted approximations that constrain the time validity of the model (Eqs. 10 and 11). For the time being, however, this cannot be carried on as the available radon indoor concentration data are usually from long term observations (not on an hourly basis).

It is important to remark two points; first, the values of the parameters in Eqs. (22–24) are not exactly unique, but can have some ranges. However, it has been tested that, within these ranges, the results of Eqs. (32–35) and Fig. 4 are not so sensitive, given the uncertainties in the experimental data. Second, the results of Fig. 4 and Eqs. (32–35) are not just about a transition from an initial radon concentration to a steady state final one, but it is about how the transition takes place.

The semi empirical side of the presented model gives it the advantage of being able to be refined and updated when further data are provided. This allows the improvement of the underlying approximations and assumptions, and hence the model results. Moreover, it is important to know the exact conditions and descriptions of the room under study, in order to have outcomes that are more precise. Additionally, as suggested by ref [31], the model can be polished further by putting in the scheme the radon areal release rate E_s as observed from the constructed walls in the room instead of using the one measured from a sample of the constructing material.

Conclusion

Time variation of the radon indoor concentration has been studied by the application of the mass balance equation on the radon indoors. Each source and sink of radon was considered. The resultant equation was solved after simplifying its form by involving some approximate relations that were developed from empirical observations. An analytical formula was reached that well described the data of radon indoor concentration. As a result, some significant parameters that describe the entrance of radon into buildings were predicted. It is one of the merits of this model that it can predict radon diffusion coefficients without going through their dependence on the structural specifications of the soil and the building material, like porosity, water saturation fraction, etc. The scheme is designed for describing not long time-span, which is mostly around two days. The model has the important advantage that it can easily be upgraded any time, once new empirical data are available.

In spite of the encouraging results, the model's outcomes still require a comparison to be made to some measurements. In a prospective future work, the model applicability will be tried to be extended by applying it successively on consecutive short periods to describe a long period overall. Meanwhile, if suitable measurements are to be available, a comparison will be made against the results expected by the model.

Funding Open access funding provided by The Science, Technology & Innovation Funding Authority (STDF) in cooperation with The Egyptian Knowledge Bank (EKB).

Declarations

Conflict of interest The author declares that there is no conflict of interest.

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