Development of a Model for Radon Concentration in Indoor Air

Bjørn Petter Jelle [a,b]*

[a] Department of Materials and Structures,
SINTEF Building and Infrastructure, NO-7465 Trondheim, Norway.

[b] Department of Civil and Transport Engineering,
Norwegian University of Science and Technology, NO-7491 Trondheim, Norway.

* Corresponding author: bjorn.petter.jelle@sintef.no (e-mail), 47-73-593377 (phone), 47-73-593380 (fax)

Abstract

A model is developed for calculation of the radon concentration in indoor air. The model takes into account various important parameters, e.g. radon concentration in ground, radon diffusion resistance of radon barrier, air permeance of ground, air pressure difference between outdoor ground and indoor at ground level, ventilation of the building ground and number of air changes per hour due to ventilation. Characteristic case studies are depicted in selected 2D and 3D graphical plots for easy visualization and interpretation. The radon transport into buildings might be dominated by diffusion, pressure driven flow or a mixture of both depending on the actual values of the various parameters. The results of our work indicate that with realistic or typical values of the parameters, most of the transport of radon from the building ground to the indoor air is due to air leakage driven by pressure differences through the construction. By incorporation of various and realistic values in the radon model, valuable information about the miscellaneous parameters influencing the indoor radon level is gained. Hence, the presented radon model may be utilized as a simple yet versatile and powerful tool for examining which preventive or remedial measures should be carried out to achieve an indoor radon level below the reference level as set by the authorities.

Keywords: *Radon, Radon Concentration, Radon Resistance, Radon Diffusion, Airtightness, Air Leakage, Modelling, Indoor Air.*

Introduction

Soil and bedrock on earth contains uranium in varying amounts – from less than 1 ppm in sandstone and limestone to several thousand ppms in alum shales found in Norway and Sweden (NORDIC 2000), to even higher levels in uranium rich ores which are mined for uranium (UNSCEAR 2000). Radon (^{222}Rn) is the decay product of radium (^{226}Ra), and both elements are members of the uranium series (^{238}U). The noble gas radon can be released to soil pores, migrate to the ground surface and accumulate in buildings. Radon and its short-lived progenies (^{218}Po, ^{214}Pb, ^{214}Bi and ^{214}Po) can be deposited in the lung and respiratory tract in general and thereby give rise to high doses from alpha particle radiation ($^{4}He^{2+}$ cores) emitted by ^{222}Rn, ^{218}Po and ^{214}Po.

The three Nordic countries Norway, Sweden and Finland have some of the highest indoor concentrations of radon in the world, which can partly be explained by rather large occurrences of uranium-rich soils and rocks such as alum-shale and uranium rich granites (Sundal et al. 2004a, 2004b) and highly permeable unconsolidated sediments such as moraines and eskers (Sundal et al. 2007). Annual mean radon concentrations up to 56 000 Bq/m^3 have been reported in dwellings located on permeable glacial sediments in Norway (Sundal et al. 2008), which is more than 600 times higher than the mean level of 88 Bq/m^3 in Norwegian dwellings (Strand et al. 2001). It has been estimated from the results of extensive large-scale surveys of indoor radon in Norway that 9 % of the present housing stock (approximately 175 000 dwellings), has an annual average radon concentration exceeding the Norwegian action level of 200 Bq/m^3 (Strand et al. 2001) as recommended by the Norwegian Radiation Protection Authority (NRPA). Note that this is a legal action level and not a strict limit between a safe and unsafe radon concentration. Furthermore, it has been estimated that nearly 30 000 Norwegians live in dwellings where the average radon concentration is higher than 1000 Bq/m^3 (Jensen et al. 2004).

The soil or the building ground under the building site is the most important source of indoor radon in Norwegian dwellings, while building materials and household water from drilled wells are rarely the main cause of indoor radon concentrations exceeding the action level of 200 Bq/m^3 given by the Norwegian authorities (TEK 10 – Byggteknisk forskrift 2010, Rahman and Tracy 2009). It should be noted that there is an on-going discussion in Norway if the action level should be reduced further for new dwellings. The concentration of radon in soil varies from less than a few thousand to more than a million Bq/m^3 in radium rich soil (NORDIC 2000). The concentration of radon in indoor air depends on the permeability of the ground as well as the airtightness of the foundation structure. Note that even very small and sometimes invisible cracks in the foundation floor and walls below the ground level may give rise to significant infiltration of radon to the indoor environment. The importance of safety measures like radon barriers to be carried out to the necessary extent and with the required precision is emphasized, e.g. ensuring satisfactory airtightness in the radon barrier towards the building ground.

Large radon concentrations in the indoor air are also found in several other countries than the Nordic ones, thus there exist an international interest of reducing these radon concentrations to a level as low as possible. Refer to e.g. the review by Rahman and Tracy (2009) for radon control systems in various countries. It should also be noted that radon levels that are regarded as low levels today might not be considered as low levels tomorrow. Hence, to be able to calculate the radon concentration based on the influencing parameters and thereby gaining knowledge about which countermeasures should be effectuated, will be an important tool in this respect. In the available literature several attempts to model and predict the radon concentration in indoor air may be found. Seasonal variations of the indoor radon concentration with prediction through model calculations have been conducted by Arvela (1995). Mathematical modelling and calculation of indoor radon levels have also been performed by Capra et al. (1994) and Man and Yeung (1999). These calculations also include the contribution from building materials. Further modelling and detailed discussions around the various radon transport mechanisms have been carried out by Nero and Nazaroff (1984) and Nazaroff (1992). Several other indoor radon models and predictions may be found in the literature, e.g. Al-Ahmady (1996), Andersen (1992, 1999), Fisk et al. (1992), Font (1997), Font et al. (1999ab), Font and Baixeras (2003), Gadgil (1992), Gunby et al. (1993), Li et al. (1995), Sherman (1992), Wang and Ward (2000) and With and Jong (2011). Several of the models treat selected parts of the many potential radon sources to the radon level in the indoor air environment, where some of the models may be very detailed and involve relatively complex equations covering specific parts of the total radon picture.

This work presents and elaborates the work by Jelle et al. (2011) for the development of a simplified but yet comprehensive, versatile, powerful and easy-to-use model for calculating the radon concentration in indoor air. Various factors influencing the radon concentration in indoor air are treated. Calculation examples with realistic and typical values of the parameters are collected in an overview table and furthermore depicted in selected two and three dimensional graphical plots in order to enhance the understanding and visualization of the factors influencing the radon concentration. Thus, the presented radon model may be applied as a valuable tool in the process of selecting the most efficient and cost-effective measure to achieve a radon level that is well below the action level set by the authorities.

Measures Against Radon

Systems for radon control by prevention for new buildings and by mitigation for existing buildings are based on a combination of the following three different principles:

- Sealing of surfaces which separate the indoor occupied space from the soil or the application of radon barriers or membranes with sufficient high radon diffusion resistance and airtightness under the ground floor of the building.
- Active (fan powered) or passive (no fan) soil depressurization which give a combined effect of ventilation of the building ground and balancing the pressure difference between the indoor air and the surrounding soil.
- Ventilation (balanced) of both occupied rooms (indoor air) and unoccupied spaces such as vented crawl spaces.

The most cost-effective solution for most buildings will usually be a combination of the three principles above. The costs compared to the effectiveness are usually much lower for preventive measures in new constructions, than in existing houses. For more details on the design, performance and effectiveness of the different measures it is referred the WHO Handbook on indoor radon (WHO 2009) and US EPA (2009). Our study focuses on the airtightness of radon barriers or so-called radon membranes. An airtight construction is a premise for other preventive measures to function, e.g. sub-slab depressurization systems. Analyses of different measures show that active sub-slab depressurization systems usually are the most effective preventive measure as a stand-alone solution (WHO 2009), assuming an airtight construction.

Radon Barrier Implementation

Although the safety measures above have been employed for some time, to the author's experience many errors are still being conducted, including careless or too sloppy work with the radon protection measures. It is observed that too often the safety measures are being skipped, while at other times the safety measures are not being carried out to the necessary extent or with the required detailed accuracy.

It is important to ensure satisfactory airtightness in the radon barrier towards the building ground, e.g. by avoiding perforations and ensuring sufficient airtightness in joints and feed-throughs. It should be noted that it may be difficult or rather impossible in practice to ensure that a radon barrier is sufficient airtight just by visual inspection at the building site.

It is crucial to avoid *any* air leakages through the radon barrier. One might suspect that quite many persons actually participating in the placement of the radon barriers may seem to think that some minor perforations or not sufficiently airtight joints or feed-throughs in the radon barriers are not that important. Such thinking might be caused by a misunderstood area consideration, i.e. thinking that these small holes represent only a minor fraction of the total area and should therefore not contribute substantially to the radon indoor air concentration. This is completely wrong as even a very small air leakage into the building from the ground might lead to a very high radon concentration in the indoor air, which will be demonstrated in the following calculations, graphical presentations and discussions. Ageing effects may also play an important role, as e.g. the sealing around feed-through pipes or other joints might degrade during its service life.

Radon Model Development

Simplified the indoor air radon concentration may be seen as a summation of the following contributions:

Radon in indoor air from =
Ventilation and air leakage from outdoor air
+ Diffusion from outdoor air
+ Exhalation from building materials
+ Diffusion from ground
+ Air leakage from ground

which is expressed analytically in the following Equation 1. Normally the radon concentration in outdoor air is close to zero, i.e. the radon diffusion gradient is normally from indoor air to outdoor air (above ground), in addition to the radon diffusion gradient from the ground to indoor air.

The various variables or parameters determining the radon concentration in indoor air for a building are depicted in Figure 1. The radon concentration in indoor air at steady-state may be expressed as in the following model (Jelle et al. 2011):

$$C_a = C_e + P_w(C_e - C_a)\frac{A_w}{V}\cdot\frac{1}{n} + \nu(C_m - C_a)\frac{S}{V}\cdot\frac{1}{n} + P(C_g - C_a)\frac{A}{V}\cdot\frac{1}{n} + q\Delta p(C_g - C_a)\frac{A}{V}\cdot\frac{1}{n} \quad (1)$$

where C_a = radon concentration in indoor air (Bq/m^3), C_e = radon concentration in outdoor air (Bq/m^3), C_m = radon concentration in building materials (Bq/m^3), C_g = radon concentration in ground (Bq/m^3), $P_w = 1 / R_w$ = radon diffusion transmittance between indoor and outdoor air, i.e. through walls and roof (m/s), $P = 1 / R$ = radon diffusion transmittance of radon barrier or whole ground construction (m/s), $R = 1 / P$ = radon diffusion resistance of radon barrier or whole ground construction (s/m), ν = radon building material exhalation (emission) coefficient (m/s), q = air permeance of ground (m^3/(m^{2}hPa)), Δp = air pressure difference between outdoor ground and indoor at ground level (Pa), A_w = building (room) area towards outdoor air (m^2), S = indoor surface area of radon containing building materials (m^2), A = building (room) area towards ground (m^2), V = building (room) volume (m^3), and n = number of air changes per hour due to ventilation, infiltration and exfiltration, through walls and roof as the floor is included in q (air changes/h).

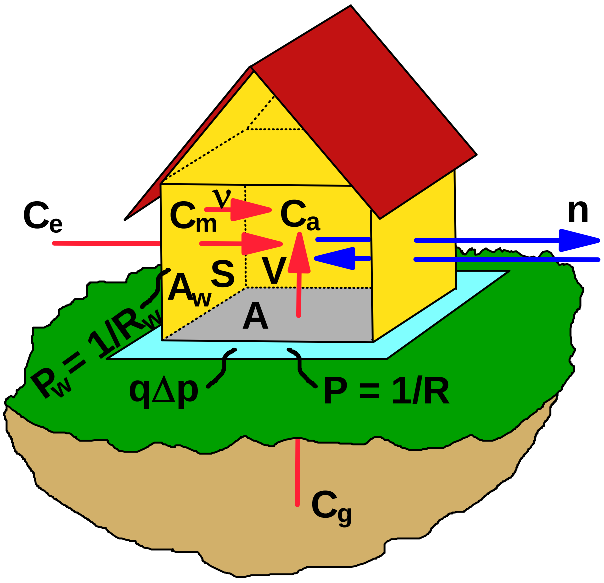

Figure 1. Depicting the various variables determining the radon concentration in indoor air for a building (see Equation 1).

With radon resistance it is meant radon diffusion resistance in this context. Note that P and R may include the total radon diffusion transmittance and resistance, respectively. That is, in addition to the radon resistance (or transmittance) of the radon barrier, the resistance in the various building materials (e.g. concrete floor) under the building is also included. The same is valid for q as it may include the average air permeance of the building ground structure with all its perforations and air leakages in addition to the permeances of the various materials, i.e. not only of the radon barrier. The term qΔpA represents the air leakage (m^3/h).

Ventilation of the building ground, i.e. the ground under the building site, is not explicitly included in the model, but might be viewed in Equation 1 as a reduction of an effective radon concentration in ground, and thus be applied in the calculations. An overall number of air changes per hour (n) includes air leakages between indoor and outdoor air through the walls and roof. Wind increases the air infiltration and exfiltration and the total ventilation and thereby reduces the radon concentration in indoor air, but is not studied further within this work. The product νC_m with unit Bq/(m^2h) may be referred to as a radon building surface material emission or exhalation rate. The above model in Equation 1 gives the steady-state situation where the disintegration of radon is not included (note that ^{222}Rn has a half-life of 3.8 days). Nevertheless, as long as the radon ground source C_g is regarded as constant, i.e. an inexhaustible or continuously replenished radon reservoir in ground and thus time-independent, the presented radon model will also give the near correct answer even for some of the more extreme cases. Note that in some of the more extreme cases where the radon model will not give the correct answer due to the disintegration of radon, we are really not talking about normal buildings any more, e.g. ”artificial or imaginary ultratight boxes”. Above ground, real buildings are neither airtight nor radon-tight as you have at least some ventilation (n is not zero) and windows and doors are opened now and then. Furthermore, in this work realistic input values are given and applied, i.e. for real buildings, so these ”artificial or imaginary ultratight boxes” where the radon disintegration and time-dependency may play a role is really not within the scope of this work.

The radon concentration in outdoor air might often be assumed to be approximately equal to zero ($C_e \approx 0$). In most cases such an assumption is also valid for the radon concentration in building materials ($C_m \approx 0$). When $C_m = 0$ it follows from Equation 1 that the building materials will absorb radon from the indoor air. Assuming this absorption (or emission when $C_m \neq 0$) part to be negligible, one may set $\nu \approx 0$. Furthermore, one may also assume that the radon concentration in the building ground is much higher than the radon concentration in the indoor air ($C_g >> C_a$). These assumptions or simplifications give the approximate expression:

$$C_a \approx \frac{1}{1 + P_w \frac{A_w}{nV}} \left[(P + q\Delta p) \frac{A}{nV} \right] C_g \tag{2}$$

Calculating and solving C_a from Equation 1 without the above simplifications yields the following expression for the radon concentration in indoor air:

$$C_a = \frac{1}{1 + P_w \frac{A_w}{nV} + \nu \frac{S}{nV} + (P + q\Delta p) \frac{A}{nV}} \cdot \left[(1 + P_w \frac{A_w}{nV}) C_e + \nu \frac{S}{nV} C_m + (P + q\Delta p) \frac{A}{nV} C_g \right] \tag{3}$$

where

$$P = 1 / R \tag{4}$$

and (simplified)

$$\Delta p = \frac{M p_{1atm} g h}{R_{gas}} \left[\frac{1}{T_e} - \frac{1}{T_a} \right] \tag{5}$$

where $R = 1 / P$ = radon resistance of radon barrier (s/m), Δp = air pressure difference between outdoor ground and indoor at ground level (Pa), M = air molar mass = 28.97 g/mol, p_{1atm} = air pressure at 1 atm = 101 325 Pa, g = gravitational acceleration on Earth ≈ 9.81 m/s^2, h = indoor/outdoor air pressure equilibrium height (m), R_{gas} = gas constant ≈ 8.31451 J/(Kmol), T_a = indoor air temperature (K), and T_e = outdoor air temperature (K).

The expression in Equation 5 for the driving force for the air leakage from the ground into the building, i.e. the air pressure difference between outdoor ground and indoor at ground level (Δp), is found from the chimney/stack effect expressed in:

$$\Delta p = p_g - p_a \approx p_e - p_a = p_0 - p_a = p_0 - (p_0 - \rho_e g h + \rho_a g h) = (\rho_e - \rho_a) g h \tag{6}$$

where

$$\rho_a = \frac{M p_a}{R_{gas} T_a} \quad \text{and} \quad \rho_e = \frac{M p_e}{R_{gas} T_e} \tag{7}$$

denote the indoor (ρ_a) and outdoor (ρ_e) air mass density, with p_a and p_e as the the indoor and outdoor air pressure and T_a and T_e as the indoor and outdoor air temperature, respectively. The air pressure at outdoor ground level is denoted p_0, while the air pressure in outdoor ground just beneath the radon barrier is denoted p_g. In Equation 6 it is assumed that the driving force for air leakages into the building from the underneath ground, the air pressure difference $\Delta p = p_g - p_a$, may be approximated with $\Delta p \approx p_e - p_a = p_0 - p_a$, i.e. the air pressure difference between the outside air pressure at ground level p_e ($= p_0 \approx p_g$) and the indoor air pressure at ground level p_a. That is, it is assumed that the driving force or pressure difference Δp is approximately independent of the radon barrier depth in ground (h_g), the ground air mass density (ρ_g) and ground temperature (T_g), the latter one varying according to location under the building, or at least that the contributions from these parameters are small compared to the others. Furthermore, introducing the approximation:

$$p_a \approx p_e \approx p_{1atm} \tag{8}$$

and inserting in Equation 7 and Equation 6 yield Equation 5 above as the result for the air pressure difference $\Delta p = p_g - p_a$. If one does not utilize the approximation in Equation 8 it leads to an infinite series for Δp, where one might develop and calculate with as many terms as desirable, which is not found necessary within this context. Observe that Δp is a positive value when $T_a > T_e$, i.e. when the indoor air temperature is higher than the outdoor air temperature. That is, the highest values of Δp occurs typically in winter time or in cold climates.

At normal indoor and outdoor temperatures (<< 273.15ºC), and noting and utilizing that $T = (\theta + 273.15^{\circ}C)$ K/ºC, Equation 5 may be approximated to the easy to remember rule of thumb:

$$\Delta p \approx 0.046(\theta_a - \theta_e)h \approx 0.05(\theta_a - \theta_e)h \tag{9}$$

where 0.05 is given in the unit PaºC/m, and θ_a and θ_e are the indoor and outdoor air temperature in ºC, respectively. See e.g. the work by Schmied (1985) for studies of radon concentration in indoor air related to the stack or chimney effect (Equations 5-9), and the studies by Nazaroff (1992) and Tanaka and Lee (1988) for further information concerning the stack effect.

Graphical Visualization

Two and three dimensional graphical plots based on Equation 3 depicting the radon concentration in indoor air (C_a) as a function of other variables (e.g. C_g and R) and with selected variables constant (e.g. C_g, R, n, q, Δp and V/A) are shown in Figures 2-10, also depicting the action level of 200 Bq/m^3 in indoor air. The assumptions or approximations $C_e \approx 0$ and $C_m \approx 0$ are applied in Equation 3 for the graphical plots. To be able to easily visualize the shape of all the 2D cross-section graphs in the 3D plots in Figures 6, 9 and 10, C_g, Δp and q have not been drawn all the way down to zero, respectively. Note that Figure 1 depicts schematically a building in general, and although it is not seen in the drawing, a basement might also be included.

Today's recommended minimum ventilation in Norwegian dwellings is 0.5 air changes/h, but as this is not fulfilled in many buildings a somewhat more conservative estimate of

0.25 air changes/h is applied in the calculations and in the plots in Figures 2-10. Mechanical ventilation (when used) gives and ensures a much larger control of the air exchange rate than natural ventilation. Energy efficiency aspects do also play an important role in this respect. The radon concentration in indoor air is also strongly dependent upon any air leakages through the radon barrier (or the floor), which here is represented by the $q\Delta p$ term. It may therefore be crucial to ensure sufficient high airtightness in the radon barrier with its joints and feed-throughs, and also to avoid any perforations. By the author's experience many faults and even careless work are being conducted within this area.

A radon concentration in ground below 10 000 Bq/m^3 is considered as low, between 10 000 to 50 000 Bq/m^3 as normal, while above 50 000 Bq/m^3 is considered as high. Nevertheless, considerably higher radon concentrations in ground have been measured, e.g. 2 MBq/m^3.

By calculating various cases with different parameters in Equation 3, it becomes evident that to ensure a very high airtightness of the radon barrier (or floor) will normally be mandatory in order to reach a sufficient low indoor air radon concentration (depending on radon concentration in ground, air exchange rate and other parameters). That is, even a radon barrier with a very high radon resistance may be jeopardized by only a few small air leakages. This also indicates that it might be necessary to weld the various radon barrier joints and feed-throughs in order to obtain a sufficient airtightness of the radon barrier (as adhesive or glued solutions often are not good enough). However, it may be difficult or rather impossible in practice to ensure that a radon barrier is sufficient airtight just by visual inspection at the building site. Ageing effects may also play a crucial role, as e.g. the sealing around feed-through pipes and other joints might degrade during its service life.

The above model given in Equation 1 and the subsequent equations represents a simplified model. That is, all variables have not been included in the model, like for example more complex geometrical considerations and ventilation of the building ground. Nevertheless, ventilation of the building ground might be viewed in the model as a reduction of an effective radon concentration in ground, and thus be applied in the calculations. Additionally, a building ground ventilation may influence the air pressure difference Δp.

Forthcoming investigations may include further development and refining of the present model, also including laboratory and field measurements for direct comparison with the model. The model may be developed further to include the airtightness and air leakage distribution of the building envelope, which in turn affect the air pressure distribution, the indoor/outdoor air pressure equilibrium height h and the number of air changes per hour (ventilation, infiltration and exfiltration), and thus influence the radon concentration in indoor air. The radon resistance and airtightness of other (e.g. traditional building) materials and solutions than the conventional radon barriers will also be investigated.

In Figures 2-6 the following parameter values have been chosen: $C_e = 0$, $C_m = 0$, $\nu = 0$, $n = 0.25\ h^{-1}$, $V/A = 2.4$ m, $q = 10 \cdot 10^{-4}\ m^3/(m^2hPa)$, $h = 2.7$ m, $T_a = 20$ºC and $T_e = 5$ºC, except in Figure 3 where q is set to zero in order to see the radon diffusion part more clearly, and except in Figure 5 where the variation of C_a as a function of n is demonstrated. In addition, $\Delta p \approx 1.7$ Pa, is calculated from Equation 5, where $h = 2.7$ m has been applied with basis in a two-story building and the indoor/outdoor air pressure equilibrium height being somewhat above the floor between the ground and top floor, and with e.g. a closed basement room ($V/A = 2.4$ m). Naturally, the value of h will be varying throughout the day and year, e.g. opening one or several windows will change h.

The value of $q = 10 \cdot 10^{-4}$ $m^3/(m^2hPa)$ is chosen with basis in a q value of $5 \cdot 10^{-4}$ $m^3/(m^2hPa)$ which represents today's maximum air permeance value for radon barriers measured in the laboratory in order to achieve a SINTEF Technical Approval. Note that this value might be subject to change. A typical measured laboratory value is $q = 3 \cdot 10^{-4}$ $m^3/(m^2hPa)$. However, the actual measurement method does not include the radon barrier joint towards the wall perimeter, which in practice might cause large air leakages, and therefore the higher value of $q = 10 \cdot 10^{-4}$ $m^3/(m^2hPa)$ is applied in the calculations.

The given indoor and outdoor air temperatures are chosen as representative values, but they are of course varying substantially throughout the year. A larger air temperature difference between indoor and outdoor causes a larger Δp (Equations 5-9) and hence a larger radon indoor air concentration C_a (Equations 2-3, mathematically estimated in Equation 3 since normally $(P + q\Delta p)A/(nV) << 1$).

As an easy reference and overview, Table 1 gives the radon concentration in indoor air C_a with its variable(s) and typical values for parameters which are kept constant in selected graphical plots depicted in Figures 2-10. For other chosen parameter values and graphical plots it is referred to the work carried out by Jelle et al. (2011).

Table 1. Overview of graphical plots of C_a vs. variable(s) in Figures 2-10 and parameter values kept constant. A bar (-) denotes that the parameter is a variable in that specific figure.

Fig.no.	2	3	4	5	6	7	8	9	10
# dim.	2	2	2	2	3	2	2	3	3
$C_a(x)$ or $C_a(x,y)$	R	R	C_g	n	R,C_g	q	Δp	q,Δp	R,q
C_e (Bq/m^3)	0	0	0	0	0	0	0	0	0
C_m (Bq/m^3)	0	0	0	0	0	0	0	0	0
C_g (kBq/m^3)	50	50	-	50	-	50	50	50	50
R_w (10^7 s/m)	3	3	3	3	3	3	3	3	3
R (10^8 s/m)	-	-	2.6	2.6	-	2.6	2.6	2.6	-
v (m/s)	0	0	0	0	0	0	0	0	0
q (10^{-4} $m^3/(m^2hPa)$)	10	0	10	10	10	-	10	-	-
Δp (Pa)	1.7	1.7	1.7	1.7	1.7	1.7	-	-	1.7
A_w (m^2)	196	196	196	196	196	196	196	196	196
S (m^2)	296	296	296	296	296	296	296	296	296
V/A (m)	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
n (h^{-1})	0.25	0.25	0.25	-	0.25	0.25	0.25	0.25	0.25
h (m)	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
T_a (°C)	20	20	20	20	20	20	20	20	20
T_e (°C)	5	5	5	5	5	5	5	5	5

The above ground radon diffusion gradient term from indoor to outdoor air, i.e. $P_w(C_e - C_a)A_w/(nV)$, may in most cases be neglected for normal buildings, as long as the walls and roof in the building envelope exhibit a certain radon diffusion resistance. In our calculations we have used a conservative (large with respect to normal building walls and roofs) value of $R_w = 3 \cdot 10^7$ s/m, which actually corresponds to a measured value of another radon barrier given by Jelle et al. (2011), and hence a rather low radon diffusion transmittance of $P_w = 1/R_w = 3.33 \cdot 10^{-8}$ m/s from the indoor air to the outdoor air (above ground) when C_e is zero or lower than C_a. The applied P_w value may be up to ten or hundred times larger than $3.33 \cdot 10^{-8}$ m/s without affecting the calculations and the depicted graphical plots substantially.

With conservative in this respect, it is meant that applying a large R_w value for the normal gradient C_a being larger than C_e, and hence a radon diffusion from indoor to outdoor air, the calculations will normally show a larger indoor radon concentration than the real one. These considerations are of course not valid in the opposite case when C_e is larger than C_a, but which will rarely or almost never take place. Note that for normal n values, i.e. n not too small or close to zero (which n never is in normal buildings), the C_e level is considered to be linked directly to n for the steady-state situation, i.e. n is continously replenishing the air inside the building with the outside air with a radon concentration of C_e, which normally amounts to much more than any diffusion. Applying realistic or typical values and combinations of the various parameters in the radon model (e.g. from Table 1) shows that the radon diffusion above ground from the indoor to the outdoor air may be negligible in most practical and normal cases.

The radon concentration in indoor air C_a vs. the radon resistance in the radon barrier R, where the other parameters are kept constant (e.g. C_g = 50 000 Bq/m^3), is depicted in Figure 2. For low radon resistances the radon indoor air concentration decreases rapidly (radon diffusion dominant), while at larger radon resistances the radon indoor air concentration decreases less and less rapidly and approaches a limit value given by the air leakage (air leakage dominant). Figure 3 shows the radon concentration in indoor air C_a versus the radon resistance in the radon barrier R, where the other parameters are kept constant as in Figure 2, but with the air permeance q set to zero so only the radon diffusion part is depicted. It is seen that for low radon resistances, even if the air permeance is zero, the radon concentration in indoor air may increase very much. By comparing Figure 2 and Figure 3 it is seen that at higher radon (diffusion) resistances there is only a small contribution from the radon diffusion to the radon concentration in indoor air, as most of the radon transport is carried out by air leakage for the specific values employed in these calculations.

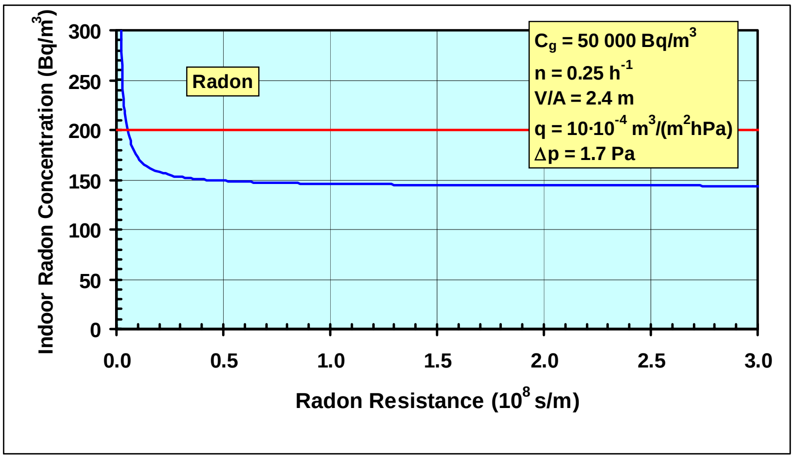

Figure 2. Radon concentration in indoor air vs. radon diffusion resistance in radon barrier.

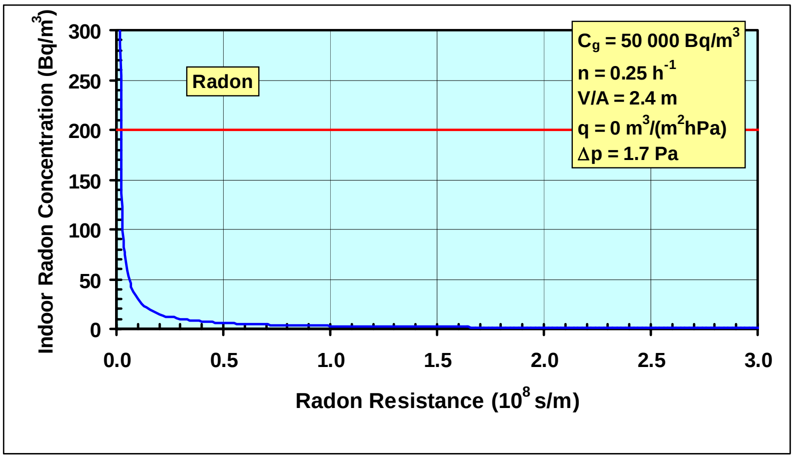

Figure 3. Radon concentration in indoor air vs. radon diffusion resistance in radon barrier at zero air permeance of ground (i.e. only diffusion part of the radon transport depicted).

If the radon resistance is zero or very low, and the ground radon concentration relatively high, the radon concentration in indoor air might reach very high or extremely high values even if the airtightness is satisfactory. This clearly demonstrates that it is important to ensure sufficient radon diffusion resistance in the ground (e.g. by employing radon barriers). Ventilation of the building ground might change this picture. That is, as the ventilation of the building ground is decreasing the effective radon concentration in ground, less radon resistance of the radon barrier (or in the building structure facing the ground) is required.

However, further investigations have to clarify to what extent radon barriers may be omitted if the ventilation of the ground is highly effective (applied as the only safety measure against radon). In these investigations, the radon resistance of various building materials, e.g. concrete floor (Daoud and Renken 1999, 2000), has to be found. It should be noted that the radon barriers may in some cases be the preventive measure that prevents radon from leaking through even very small and sometimes invisible cracks in the foundation floor and walls below the ground level. Daoud and Renken (1999, 2000) investigate radon diffusion through fractured concrete samples.

Nevertheless, it is also clear from the above that with a sufficient high radon resistance in the radon barrier or the building structure facing the ground, the radon transport by air leakage becomes dominant for the specific values employed in these calculations, where the air leakage may occur through accidental perforations, different feed-throughs where sufficient airtightness has not been achieved, radon barrier joints barrier to barrier and barrier to foundation walls, etc.

Figure 4 depicts the radon concentration in indoor air C_a versus the radon concentration in the ground C_g, where the other parameters are kept constant (e.g. $R = 2.6 \cdot 10^8$ s/m). It is seen that C_a increases linearly with increasing C_g. C_a as a function of the air exchange rate n is shown in Figure 5, which demonstrates that it is important to maintain a large number of air exchanges per hour, or at least above some minimum value, in order to keep the radon concentration in indoor air low. C_a as a function of both R and C_g is shown in the 3D plot in Figure 6.

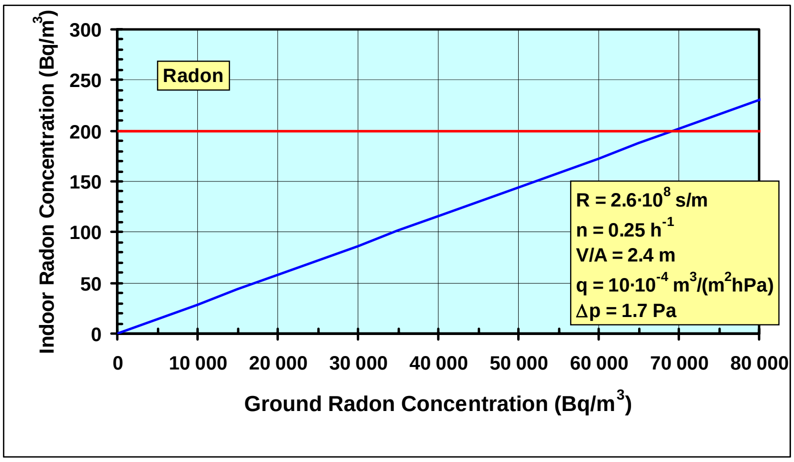

Figure 4. Radon concentration in indoor air vs. radon concentration in ground.

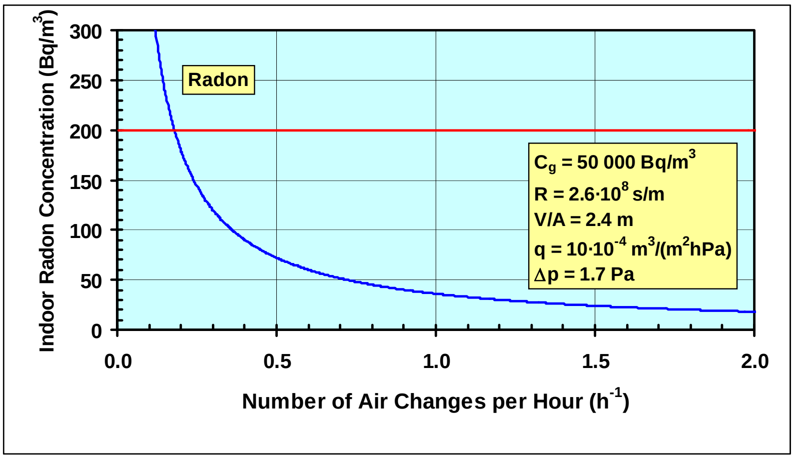

Figure 5. Radon concentration in indoor air vs. number of air changes per hour.

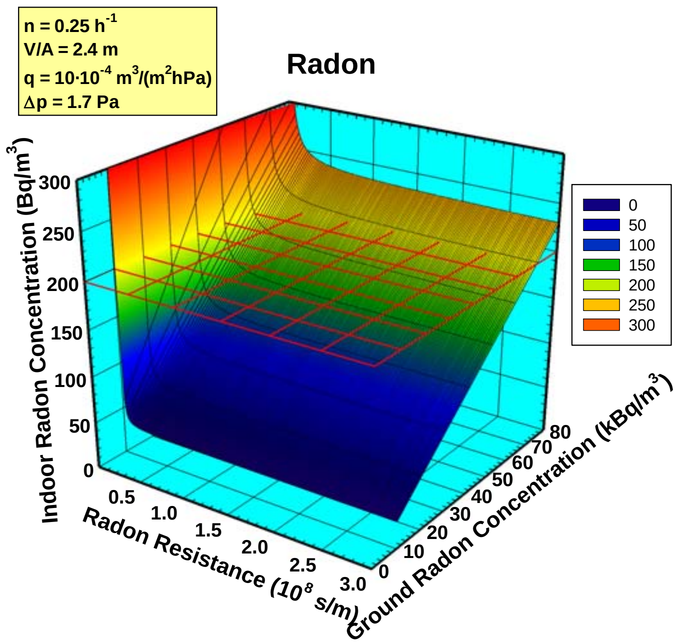

Figure 6. Radon concentration in indoor air vs. radon diffusion resistance in radon barrier and radon concentration in ground.

In Figures 7-9 the following values have been chosen: $C_e = 0$, $C_m = 0$, $\nu = 0$, $C_g = 50\,000$ Bq/m^3, $R = 2.6 \cdot 10^8$ s/m, $n = 0.25$ h^{-1} and $V/A = 2.4$ m. The radon resistance value of $R = 2.6 \cdot 10^8$ s/m is an actual measured resistance of a radon barrier, which may be considered as a typical value within a large variation range for these products (e.g. bitumen and polyolefine products). Figure 7 depicts within this model that the radon concentration in indoor air C_a increases linearly with increasing air permeance q, whereas Figure 8 shows that C_a increases linearly with increasing pressure difference Δp (Equations 2-3, mathematically estimated in Equation 3 since normally $(P + q\Delta p)A/(nV) << 1$). The radon concentration in indoor air C_a as a function of both the air permeance q and the pressure difference Δp is depicted in the 3D plot in Figure 9.

The number of air changes per hour n including air infiltration, exfiltration and ventilation from the walls and the roof is influenced by the air permeance q and air pressure difference Δp, and will affect the shape of the C_a vs. q and C_a vs. Δp curves, which is not included in the calculations here.

The 3D graphical plot in Figure 10 presents a comparison between the significance of radon resistance in radon barrier and air leakage in connection with radon barrier, i.e. visualizing if or when the radon transport into the building is radon diffusion dominant or air leakage dominant. That is, by keeping the radon (diffusion) resistance at a large value or in principle at a constant value and increasing the air permeance, or keeping the air permeance at a low value or in principle at a constant value and decreasing the radon resistance, it is visualized if the radon diffusion or air leakage is dominant.

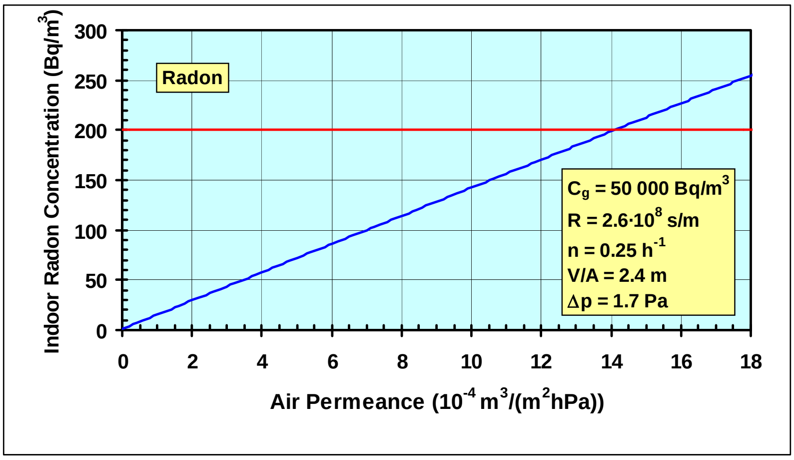

Figure 7. Radon concentration in indoor air vs. air permeance of ground. Note that n including air infiltration, exfiltration and ventilation from walls and roof is influenced by q and Δp, and will affect the shape of the C_a vs. q curve (not depicted here).

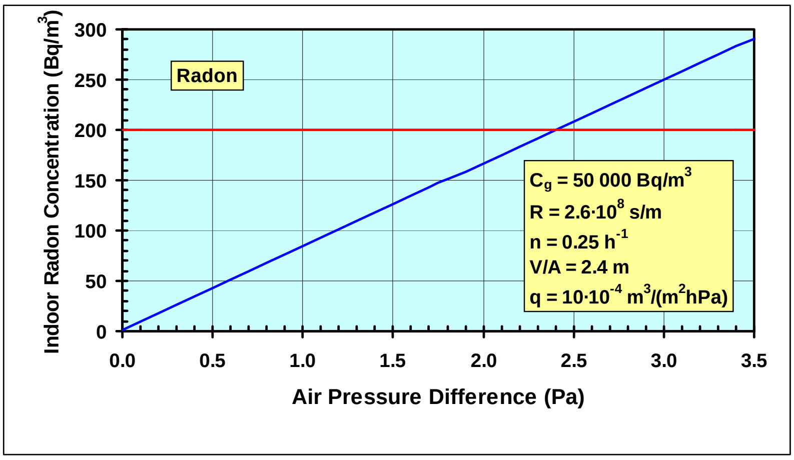

Figure 8. Radon concentration in indoor air vs. air pressure difference between outdoor ground and indoor at ground level. Note that n including air infiltration, exfiltration and ventilation from walls and roof is influenced by Δp and q, and will affect the shape of the C_a vs. Δp curve (not depicted here).

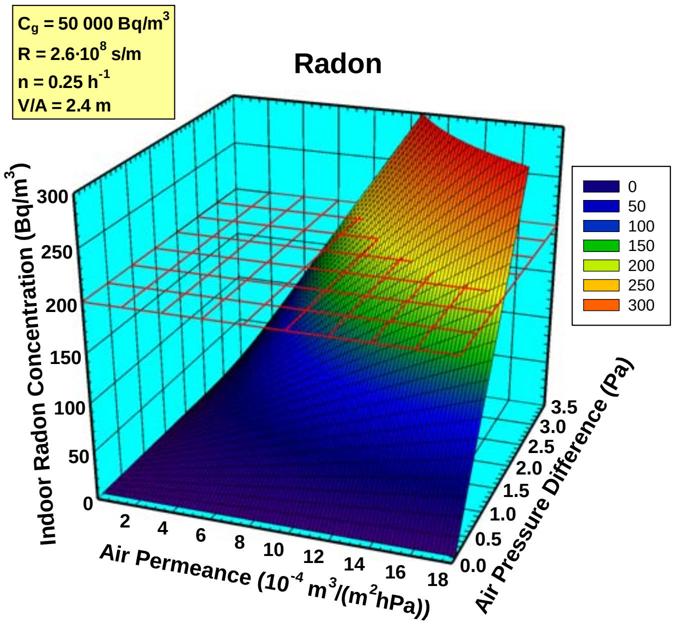

Figure 9. Radon concentration in indoor air vs. air permeance of ground and air pressure difference between outdoor ground and indoor at ground level. Note that n including air infiltration, exfiltration and ventilation from walls and roof is influenced by q and Δp, and will affect the shape of the C_a vs. q and C_a vs. Δp curves (not depicted here).

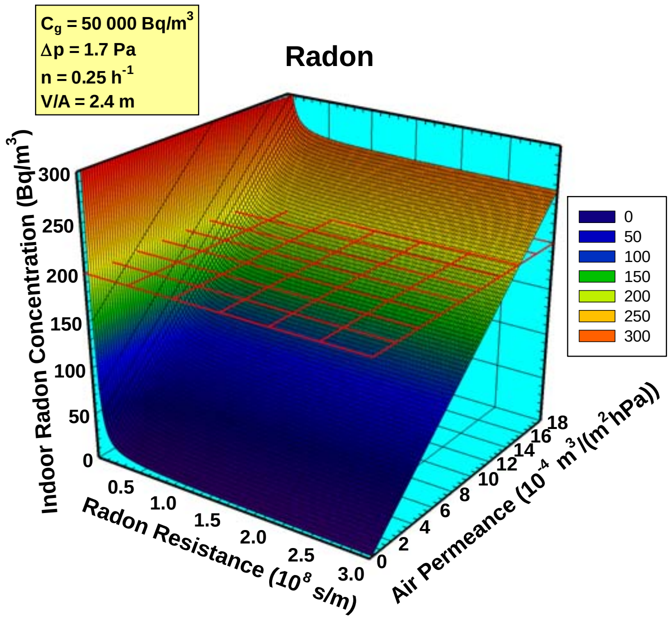

Figure 10. Radon concentration in indoor air vs. radon resistance in radon barrier and air permeance of ground.

Incorporating various and realistic values in a spreadsheet version of the presented indoor air radon concentration model gives valuable information about the influence of the different parameters on the radon level inside buildings. That is, the given model may be utilized as a powerful tool for studying what measures or actions should be carried out in order to obtain satisfactory low radon levels.

Depending on the actual values of the various parameters, the radon transport into buildings might be either dominated by radon diffusion, air leakage or both. The results presented in this work indicate that with realistic or typical values of the parameters, most of the radon supply to the indoor air is caused by air leakage from ground.

Conclusions

Satisfactory airtightness of the radon barrier, or in general rather the building structures, facing the building ground has to be ensured, e.g. by avoiding perforations and securing sufficient airtightness in joints and different feed-throughs, in order to keep the radon concentration in indoor air as low as possible. The radon barriers should be combined with stable and continuous mechanical ventilation of the indoor air, thus ensuring that the air exchange rate is sufficient and that the ventilation system balances/reduces the pressure differences between indoor air and the surroundings.

Based on various parameters a simple yet versatile and powerful model for calculating the radon concentration in indoor air has been developed. Characteristic calculation examples are depicted in selected two and three dimensional graphical plots for easy visualization and interpretation. Incorporation of different and realistic values in a spreadsheet version of the indoor radon model gives valuable information about the influence of various parameters on the radon level.

Hence, the presented model may be applied as a tool in the process of selecting the most efficient and cost-effective measure to achieve a radon level that is well below the action level set by the authorities. The radon transport into buildings might be dominated by diffusion, pressure driven flow or a mixture of both depending on the actual values of the various parameters. The results of our work indicate that with realistic parameter values, most of the transport of radon from the building ground to the indoor air is due to air leakage driven by pressure differences through the construction.

Acknowledgements

This work has been supported by the Research Council of Norway, AF Gruppen, Glava, Hunton Fiber as, Icopal, Isola, Jackon, maxit, Moelven ByggModul, Rambøll, Skanska, Statsbygg and Takprodusentenes forskningsgruppe through the SINTEF/NTNU research project ”*Robust Envelope Construction Details for Buildings of the 21st Century*” (ROBUST).

References

K. K. Al-Ahmady, ”Characterization of wind-induced pressure differentials as driving forces affect indoor radon entry and removal”, *International Radon Symposium IIP*, 3.1-3.10, 1996.

C. E. Andersen, ”Entry of soil gas and radon into houses”, Risø National Laboratory, Risø-R-623(EN), Roskilde, Denmark, April 1992.

C. E. Andersen, ”Numerical modelling of radon-222 entry into houses: An outline of techniques and results”, *Radon in the Living Environment*, Athens, Greece, 19-23 April, 1999.

H. Arvela, ”Seasonal variation in radon concentration of 3000 dwellings with model comparisons”, *Radiation Protection Dosimetry*, **59**, 33-42, 1995.

D. Capra, C. Silibello and G. Queirazza, ”Influence of ventilation rate on indoor radon concentration in a test chamber”, *Radiation Protection Dosimetry*, **56**, 15-18, 1994.

W. Z. Daoud and K. J. Renken, ”Laboratory measurements of the radon gas diffusion coefficient for a fractured concrete sample and radon gas barrier systems”, *Proceedings of International Radon Symposium*, American Association of Radon Scientists and Technologists (AARST), Las Vegas, Nevada, USA, 1999.

W. Z. Daoud and K. J. Renken, ”Further investigation on radon gas diffusion through fractured concrete samples coated with a sealant”, *Proceedings of International Radon Symposium*, American Association of Radon Scientists and Technologists (AARST), Milwaukee, Wisconsin, USA, 2000.

W. J. Fisk, M. P. Modera, R. G. Sextro, K. Garbesi, H. A. Wollenberg, T. N. Narasomhan, T. Nuzum and Y. W. Tsang, ”Radon entry into basements: Approach, experimental structures, and instrumentation of the small structures research project”, Lawrence Berkeley Laboratory, LBL-31864, February 1992.

L. Font Guiteras, ”Radon generation, entry and accumulation indoors”, *Ph.D. Thesis*, Universitat Autònoma de Barcelona, Spain, 1997.

L. Font, C. Baixeras, C. Domingo and F. Fernandez, ”Experimental and theoretical study of radon levels and entry mechanisms in a Mediterranean climate house”, *Radiation Measurements*, **31**, 277-282, 1999.

L. Font, C. Baixeras, G. Jönsson, W. Enge and R. Ghose, ”Application of a radon model to explain indoor radon levels in a Swedish house”, *Radiation Measurements*, **31**, 359-362, 1999.

L. Font and C. Baixeras, ”The RAGENA dynamic model of radon generation, entry and accumulation indoors”, *Science of the Total Environment*, **307**, 55-69, 2003.

A. J. Gadgil, ”Models of radon entry”, *Radiation Protection Dosimetry*, **45**, 373-379, 1992.

J. A. Gunby, S. C. Darby, J. C. H. Miles, B. M. R. Green and D. R. Cox, ”Factors affecting indoor radon concentrations in the United Kingdom”, *Health Physics*, **64**, 2-12, 1993.

B. P. Jelle, K. Noreng, T. H. Erichsen and T. Strand, ”Implementation of radon barriers, model development and calculation of radon concentration in indoor air”, *Journal of Building Physics*, **34**, 195-222, 2011.

C. L. Jensen, T. Strand, G. B. Ramberg, L. Ruden and K. Ånestad, ”The Norwegian radon mapping and remediation program”, *11th International Congress of the International Radiation Protection Association*, Madrid, Spain, www.irpa11.com, 2004.

NORDIC, ”Naturally occurring radioactivity in the Nordic countries – Recommendations”, *The Radiation Protection Authorities of Denmark, Finland, Iceland, Norway and Sweden*, Stockholm, ISBN 91-89230-00-0, 2000.

W. G. Li, Q-Y. Yao and W-T. Chen, ”Indoor radon prediction for residential houses”, *Proceedings of Third International Symposium on Uncertainty Modeling and Analysis, ISUMA-NAFIPS '95*, 188-191, 1995.

C. K. Man and H. S. Yeung, ”Modelling and measuring the indoor radon concentrations in high-rise buildings in Hong Kong”, *Applied Radiation and Isotopes*, **50**, 1131-1135, 1999.

W. W. Nazaroff, ”Radon transport from soil to air”, *Reviews of Geophysics*, **30**, 137-160, 1992.

A. V. Nero and W. W. Nazaroff, ”Characterising the source of radon indoors”, *Radiation Protection Dosimetry*, **7**, 23-39, 1984.

N. M. Rahman and B. L. Tracy, ”Radon control systems in existing and new construction: A review”, *Radiation Protection Dosimetry*, **135**, 243-255, 2009.

H. Schmied, ”Combined stack effect in houses and eskers explaining transients in radon source”, *Science of the Total Environment*, **45**, 195-201, 1985.

M. Sherman, ”Simplified modeling for infiltration and radon entry”, *Proceedings of ASHRAE-DOE-BTECC Conference on Building Thermal Envelopes*, Clearwater Beach, Florida, USA, 1992.

A. V. Sundal, H. Henriksen, S. E. Lauritzen, O. Soldal, T. Strand and V. Valen, ”Geological and geochemical factors affecting radon concentrations in dwellings located on permeable glacial sediments – A case study from Kinsarvik, Norway”, *Environmental Geology*, **45**, 843-858, 2004(a).

A. V. Sundal, H. Henriksen, O. Soldal and T. Strand, ”The influence of geological factors on indoor radon concentrations in Norway”, *Science of the Total Environment*, **328**, 41-53, 2004(b).

A. V. Sundal, C. L. Jensen, K. Ånestad and T. Strand, ”Anomalously high radon concentrations in dwellings located on permeable glacial sediments”, *Journal of Radiological Protection*, **27**, 1-12, 2007.

A. V. Sundal, V. Valen, O. Soldal and T. Strand, ”The influence of meteorological parameters on soil radon levels in permeable glacial sediments”, *Science of the Total Environment*, **389**, 418-428, 2008.

T. Strand. K. Ånestad, L. Ruden, G. B. Ramberg, C. L. Jensen, A. H. Wiig and G. Thommesen, ”Indoor radon survey in 114 municipalities”, StrålevernRapport 2001:6, Østerås, *Norwegian Radiation Protection Authority*, 2001.

H. Tanaka and Y. Lee, ”Stack effect and building internal pressure”, *Journal of Wind Engineering and Industrial Aerodynamics*, **29**, 293-302, 1988.

TEK 10 - Byggteknisk forskrift, ”FOR 2010-03-26 nr 489: Forskrift om tekniske krav til byggverk (Byggteknisk forskrift)” (”FOR 2010-03-26 no 489: Regulations for technical requirements for constructions (Technical building regulations)”), §13-5 Radon, Kommunal- og regionaldepartementet (KRD), Norway, 2010.

US EPA, www.epa.gov/radon, 2009.

F. Wang and I. C. Ward, ”The development of a radon entry model for a house with a cellar”, *Building and Envronment*, *35*, 615-631, 2000.

G. de With and P. de Jong, ”Simulation of thoron and thoron progeny concentrations in the indoor environment”, *Journal of Building Physics*, doi: 10.1177/1744259111398634, 2011.

World Health Organization, ”Handbook on indoor radon”, *WHO*, Geneva, Switzerland, 2009.