1

Implementation of Radon Barriers, Model Development and Calculation of Radon Concentration in Indoor Air

Bjørn Petter Jelle [a,b]*, Knut Noreng [a], Tore Henrik Erichsen [a] and Terje Strand [c]

[a] Department of Building 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.

[c] Geoterm AS,
Sleiverudsåsen 26, NO-1354 Bærums Verk, Norway.

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

Abstract

Norway has some of the highest concentrations of radon in indoor air in the world. Based on large-scale surveys by direct measurements of radon in indoor air it has been estimated that nearly 9 % of the housing stock has an annual mean indoor radon concentration which is higher than the current action level of 200 Bq/m^3. Preventive measures that focuses on saving energy and avoiding moisture problems in a cold climate, and by not introducing any specific measures to reduce the infiltration of radon and/or balanced ventilation of the indoor air, can lead to high indoor radon concentrations. It is of vital importance that the ground floor structure is as airtight as possible; both to reduce the infiltration of soil gas radon by using, e.g. airtight and resistant membranes, and as a premise for other preventive measures to function, e.g. sub-slab depressurization systems. Sufficient airtightness may be achieved by using a radon barrier towards the ground, e.g. by avoiding perforations and ensuring sufficient airtightness in joints and feed-throughs. Various factors influencing the radon concentration in indoor air are discussed. Based on these factors a simplified model for calculating the radon concentration in indoor air is presented. Furthermore, the examples are depicted in selected two and three dimensional graphical plots for visualization. By incorporating various and realistic values in a spreadsheet version of the indoor radon concentration model, valuable information about the different parameters influencing the indoor radon level is gained. Hence, the presented model may be utilized as a tool for examining which preventive or remedial measures should be carried out in order to achieve an indoor level of radon below the reference level as set by the authorities. The radon transport into buildings might be dominated by diffusion, pressure driven flow or something in between 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.

1.   Introduction

Radon (^{222}Rn) is the decay product of radium (^{226}Ra), and both elements are members of the uranium series (^{238}U). Soil and bedrock everywhere 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 is a noble gas and 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 give rise to high doses to lung tissue from alpha particle radiation (^{4}He^{2+} cores) emitted by ^{222}Rn, ^{218}Po and ^{214}Po.

Norway, together with Sweden and Finland, has some of the highest indoor concentrations of radon in the world. This can partly be explained by the geology due to 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). In dwellings located on permeable glacial sediments in Norway, annual mean radon concentrations up to 56 000 Bq/m^3 have been reported (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). Based on the results of extensive large-scale surveys of indoor radon in Norway it has been estimated 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). It has further 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).

As the energy requirements continuously are becoming stricter and more demanding, and also safety measures towards moisture problems, today's new buildings are being built more airtight than earlier. In addition, more thermal insulation is being added to existing buildings. By comparing the results of nation-wide surveys in dwellings built before 1980 (Strand et al. 1992) with results of recent surveys in today's housing stock (Strand et al. 2001) it has been concluded that the indoor radon concentration in dwellings is 70-75 % higher today than it was 20-30 years ago (Jensen et al. 2004). Recent analysis of the data has revealed that this difference partly can be explained by differences in sampling and how the measurements are made (Rudjord et al. 2009). However, still there is a significant difference which could be explained by reduced ventilation of the indoor air in addition to other factors such as extensive use of permeable aerated concrete, e.g. light expanded clay aggregate concrete, in the foundation walls which can result in higher infiltration of radon.

The soil or the building ground 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. Note 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 becquerel per cubic metre 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. Even very small and sometimes invisible cracks in the foundation floor and walls below the ground level can give rise to significant infiltration of radon to the indoor environment. Measurements of radon concentrations in soil have been made by several authors (e.g. Ennemoser et al. 1994 and 1995, Sundal et al. 2008) and initiatives have been taken in order to prepare a map of soil gas radon in European countries (Dubois 2005). The influence of geological factors on radon concentrations in indoor air in Norwegian dwellings has been investigated by Sundal et al. (2004a, 2004b) and levels up to 700 000 Bq/m^3 have been measured in radium rich black soil consisting of alum shale fragments.

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). Other indoor radon models and predictions may be found in the literature, e.g. Al-Ahmady (1996), Font et al. (1999), Gunby et al. (1993) and Li et al. (1995).

The objective of this work is to discuss (a) implementation of radon safety measures with special focus on radon barriers, (b) the importance of safety measures like radon barriers to be carried out to the necessary extent and with the required precision, e.g. ensuring satisfactory airtightness in the radon barrier towards the building ground, (c) factors influencing the radon concentration in indoor air, (d) a simplified but yet versatile and powerful model for calculating the radon concentration in indoor air, and finally, (e) calculation examples with realistic or typical values of the parameters depicted in selected two and three dimensional graphical plots in order to enhance the understanding and visualization of the factors influencing the radon concentration.

2.   Preventive and Remedial Measures against Radon

Radon control systems for prevention (new buildings) as well as mitigation (existing buildings) are based on a combination of 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.

In most buildings the most cost-effective solution 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.

3.   Examples of Radon Barrier Implementation

The safety measures above have been employed for some time, but still many errors are being conducted, including careless or too sloppy work with the radon protection measures. 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. In figs.1-2 there are shown two general overview photos from implementation of two different radon barriers. Note that in the period 2005 to 2007 when the building construction activity was high in Norway, the sales turnover of radon barriers decreased (Byggeindustrien no. 1, 2009). This fact gives rise to concern.

Fig.1. Placement of radon barrier under thermal insulation under baseplate of building.

Fig.2. Placement of radon barrier above thermal insulation under baseplate of building.

In figs.3-5 there are depicted several joints and feed-through pipes in the radon barrier, where it is essential to ensure satisfactory airtightness at all locations. Easy implementation and durable solutions are emphasized. When people are walking on the radon barrier as shown in fig.6, special care has to be taken in order to not perforate the radon barrier.

Fig.3. By placement of radon barriers it is essential to ensure satisfactory airtightness in joints and various feed-throughs.

Fig.4. Trying to ensure satisfactory airtightness in a radon barrier at a feed-through pipe applying a sealant. Close-up from fig.3.
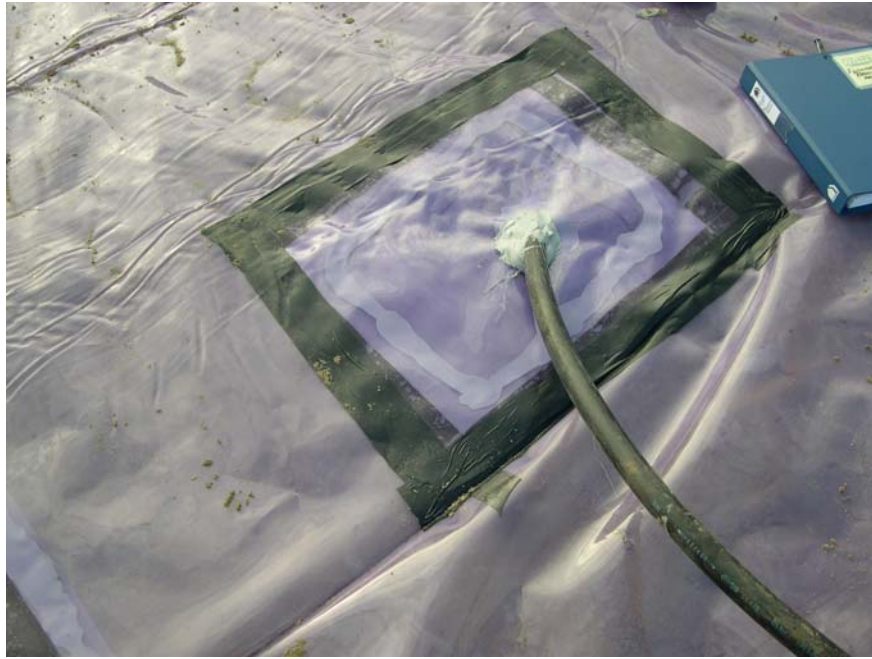
Fig.5. Trying to ensure satisfactory airtightness in a radon barrier at a feed-through pipe applying a sealant. Close-up from fig.3.

Fig.6. Joints have to be satisfactory airtight and care has to be taken when people are walking on the radon barrier before covering, in order to avoid any perforations.

Figure 7 demonstrates that air leakage through or in connection with a radon barrier might be caused by several factors. Reinforcement bars with support represent a risk for perforation of the radon barrier. Satisfactory airtightness around feed-through pipes might be difficult to ensure, especially close to walls or other obstructions. In addition, satisfactory airtightness must also be ensured towards the concrete wall. Figure 8 demonstrates a reinforcement bar which actually has penetrated the radon barrier, which if not properly repaired will result in an undesired air leakage with radon gas into the building. Outer and inner wall corners (fig.9) represent yet another area where proper care has to be taken in order to obtain satisfactory airtightness. Figure 10 depicts various junctions, corners and turn-ups which represent areas where proper care has to be taken in

order to obtain satisfactory airtightness. Care has also to be taken in the cutting of the radon barrier. However, it should be noted that it may be difficult or rather impossible in practise to ensure that a radon barrier is sufficient airtight just by visual inspection at the building site.

Fig.7. Air leakage through or in connection with the radon barrier might be caused be several factors. The photo above depicts a reinforcement bar with support which represent a risk for perforation of the radon barrier. To ensure satisfactory airtightness around feed-through pipes might be difficult, especially close to walls or other obstructions. In addition, satisfactory airtightness must also be ensured towards the concrete wall.

Fig.8. Care has to be taken in order to avoid any perforations in the radon barrier. This example depicts a reinforcement bar which has perforated the radon barrier.

Fig.9. Outer and inner wall corners represent another area where proper care has to be taken in order to obtain satisfactory airtightness.

Fig.10. Various junctions, corners and turn-ups represent areas where proper care has to be taken in order to obtain satisfactory airtightness. Care has to be taken during cutting of the radon barrier.

It has to be emphasized that 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. Completely wrong, even a very small air leakage into the building from the ground might lead to a very high radon concentration in the indoor air. This fact will be demonstrated in the following calculations, graphical presentations and discussions. It also has to be noted that ageing effects may play a crucial role, as e.g. the sealing around feed-through pipes or other joints might degrade during its service life.

4.   Measurement of Radon Concentration in Indoor Air

The radon concentration in indoor air may be measured by application of a trace film box or electronic registration. Measured average radon concentration during the period of use by people decides if radon safety measures, and maybe more than one safety measure, have to be applied. The measurement periods should at least extend to some months in order to include the relatively rather large fluctuations of radon concentration in indoor air which frequently occur. Measurement issues are found in the literature, e.g. by Gammage et al. (1992) and Jönsson (1995, 1997). Often the indoor air radon concentration will be higher during a winter period than a summer period.

For further information, selection of radon safety measures and evaluation of these it is referred to SINTEF Byggforsk Kunnskapssystemer (SINTEF Building and Infrastructure Building Research Design Sheet) 520.706 and 701.706 for protection against radon for new building constructions and safety measures against radon in existing buildings, respectively. It falls outside the scope of this article to treat detailed radon measurement techniques.

5.   Factors Influencing the Indoor Air Radon Concentration

The radon concentration in indoor air in buildings is depending upon several factors. In the following we will look closer at a simplified model which may be utilized for calculation of the indoor air radon concentration. These factors are:

- Radon concentration in outdoor air (Bq/m^3).
- Radon concentration in building materials (Bq/m^3).
- Radon concentration in ground (Bq/m^3).
- Radon building material exhalation (emission) coefficient (m/s).
- Radon diffusion resistance (s/m) or transmittance (m/s) between indoor and outdoor air, i.e. through walls and roof.
- Radon diffusion resistance (s/m) or transmittance (m/s) of radon barrier under the ground floor of the building (might in these terms include the total radon resistance or transmittance under the building in the model).
- Air permeance of ground ($m^3/(m^2hPa)$)
- Air pressure difference between outdoor ground and indoor at ground level (Pa).
- Building (room) area towards outdoor air (m^2).
- Building (room) volume to building (room) indoor surface area of radon containing building materials ratio ($m^3/m^2 = m$).
- Building (room) volume to building (room) area towards ground ratio ($m^3/m^2 = m$).
- Number of air changes per hour due to ventilation, which might also include infiltration and exfiltration (air changes/h).
- Ventilation of the building ground (not explicitly included in the following model, but might be viewed in the model as a reduction of an effective radon concentration in ground, and thus be applied in the calculations).

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 hence expressed analytically in the following eq.1. Note that usually 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.

6. Model Development and Calculation of Radon Concentration in Indoor Air

Based on the factors mentioned above and the drawing given in fig.11, the following simplified model for the radon concentration in indoor air at steady-state may be expressed as:

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

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).
v = Radon building material exhalation (emission) coefficient (m/s).
q = Air permeance of ground ($m^3/(m^2hPa)$).
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).
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).

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 $q\Delta pA$ represents the air leakage (m^3/h). Furthermore, it should be noted that ventilation of the building ground is not explicitly included in the model, but might be viewed in eq.1 as a reduction of an effective radon concentration in ground, and thus be applied in the calculations.
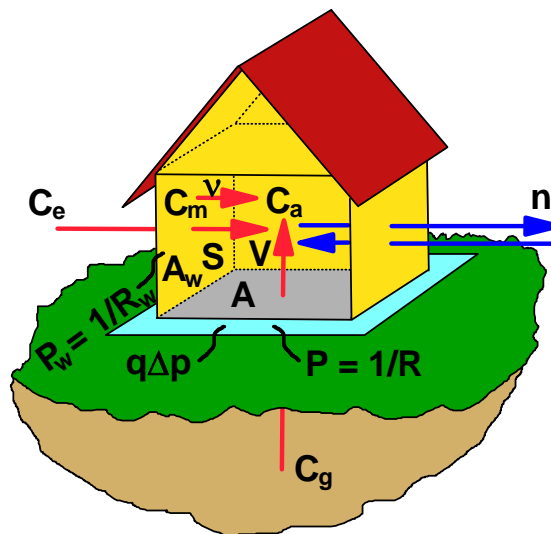

Fig.11. Simplified model for radon penetration and ventilation in a building (see eq.1). The radon concentration in outdoor air (C_e) and radon concentration in building materials (C_m) are normally very low and may therefore often be set as zero in the calculations.

Air leakages between indoor and outdoor air through the walls and roof are included in an overall number of air changes per hour (n). Wind will increase the air infiltration and exfiltration and the total ventilation and thereby reduce the radon concentration in indoor air, but is not studied further within this work. The product νC_m with unit $Bq/(m^2 h)$ may be referred to as a radon building surface material emission or exhalation rate. The above model gives the steady-state situation where the desintegration of radon is not included.

Often one might assume that the radon concentration in the outdoor air is approximately equal to zero ($C_e \approx 0$). Such an assumption is also in most cases valid for the radon concentration in building materials (i.e. $C_m \approx 0$). When $C_m = 0$ it follows from eq.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 $\nu \approx 0$. In addition, one may also assume that the radon concentration in the building ground is much higher than the radon concentration in the indoor air ($C_g \gg C_a$). These assumptions or simplifications give the approximate expression:

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

Calculating *without* the above simplifications and solving eq.1 with respect to C_a yields the following expression for the radon concentration in indoor air:

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

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).
        T_e = Outdoor air temperature (K).

The expression in eq.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 following, i.e. the chimney/stack effect (see fig.12):

$$\Delta p = p_g - p_a \approx p_e - p_a = p_0 - p_a = p_0 - (p_0 - \rho_e gh + \rho_a gh) = (\rho_e - \rho_a)gh \qquad (6)$$

where

$$\rho_a = \frac{Mp_a}{R_{gas}T_a} \quad \text{and} \quad \rho_e = \frac{Mp_e}{R_{gas}T_e} \qquad (7)$$

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. In eq.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. In other words, 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

$$p_a \approx p_e \approx p_{1atm} \qquad (8)$$

and inserting in eq.7 and eq.6 yield eq.5 above as the result for the air pressure difference $\Delta p = p_g - p_a$. Note that not utilizing the approximation in eq.8 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). Note 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, typically the highest values of Δp occurs in winter time or in cold climates.
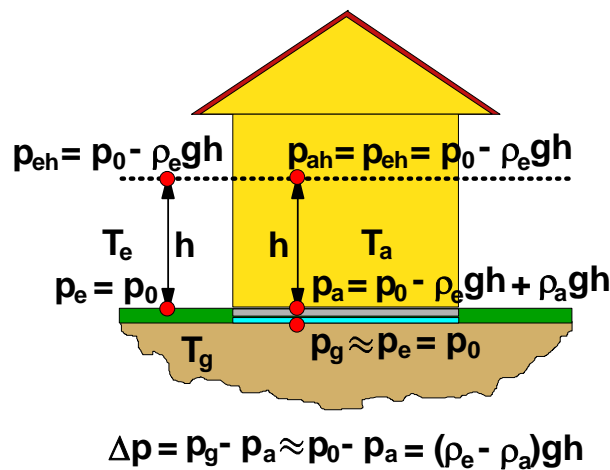

Fig.12. Schematics for calculating the air pressure difference $\Delta p = p_g - p_a$ in order to estimate the air leakage contribution to the indoor radon concentration.

At normal indoor and outdoor temperatures ($\ll 273.15^\circ C$), and noting that $T = (\theta + 273.15^\circ C)\ K/^\circ C$, eq.5 may be approximated to the easy to remember rule of thumb:

$$\Delta p \approx 0.046(\theta_a - \theta_e)h \approx 0.05(\theta_a - \theta_e)h \qquad (9)$$

where 0.05 is given in the unit Pa$^\circ$C/m, and θ_a and θ_e are the indoor and outdoor air temperature in $^\circ$C, respectively.

7.   Graphical Visualization and Discussion of Radon in Indoor Air

In order to visualize the expression in eq.3 one may graphically depict the radon concentration in indoor air (C_a) as a function of some of the other variables (e.g. C_g and R) in two or three dimensional plots with selected variables constant (e.g. C_g, R, n, q, Δp and V/A). Examples of such graphical plots are shown in figs.13-21, where also the safety limit level of 200 Bq/m^3 in indoor air is depicted. The assumptions or approximations $C_e \approx 0$ and $C_m \approx 0$ are applied in eq.3 for the graphical plots. Note that to be able to easily visualize the shape of all the two dimensional cross-section graphs in the three dimensional plots in figs.17, 20 and 21, C_g, Δp and q have not been drawn all the way down to zero, respectively. Figures 11-12 depict schematically a building in general, and although it is not seen in the drawings, a basement might also be included.

Today's recommended minimum ventilation in Norwegian dwellings is 0.5 air changes/h, but this is not fulfilled in many buildings, and thus in the plots in figs.13-21 a somewhat more conservative estimate of 0.25 air changes/h is applied in the calculations. 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 qΔp 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 experience one knows that many faults and even careless work are being conducted within this area.

Radon concentrations in ground below 10 000 Bq/m^3 is considered as low, between 10 000 to 50 000 Bq/m^3 is considered 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. In the graphical plots in figs.13-21 ground radon concentrations between 0 to 200 000 Bq/m^3 have been applied.

By calculating various cases with different parameters in eq.3, it becomes evident that to ensure a very high airtightness of the radon barrier (or floor) is mandatory in order to reach a sufficient low indoor air radon concentration (depending on radon concentration in ground 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 practise to ensure that a radon barrier is sufficient airtight just by visual inspection at the building site. Note that 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 (eq.1 and the following equations) is a simplified model, where not all variables have been taken into account, e.g. more complex geometrical considerations and ventilation of the building ground have not been included. 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. In addition, such a building ground ventilation may influence the air pressure difference Δp. At the moment we are in the process of initiating a research project which will be able to address and investigate these and other radon matters further. The investigations will include further development and refining of the given model, in addition to laboratory and field measurements for direct comparison with the model. The model might be developed further to include the airtightness and air leakage distribution of the building envelope, which 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.

For easy reference and overview, table 1 gives the function (i.e. C_a) with its variable(s) and typical values for parameters which are kept constant in selected graphical plots depicted in figs.13-21.

14

Table 1. An overview of the graphical plots of C_a versus variable(s) in figs.13-21 and typical example values for parameters which are kept constant. A bar (-) denotes that the parameter is a variable in that specific figure.

Fig.	# dim.	$C_a(x,y)$	C_e (Bq/m^3)	C_m (Bq/m^3)	C_g (Bq/m^3)	R_w (s/m)	R (s/m)	v (m/s)	q (m^3/ (m^{2}hPa))	Δp (Pa)	A_w (m^2)	S (m^2)	V/A (m)	n (h^{-1})	h (m)	T_a (ºC)	T_e (ºC)
13	2	R	0	0	100 000	$3 \cdot 10^7$	-	0	$5 \cdot 10^{-4}$	1.7	196	296	2.4	0.25	2.7	20	5
14	2	R	0	0	100 000	$3 \cdot 10^7$	-	0	0	1.7	196	296	2.4	0.25	2.7	20	5
15	2	C_g	0	0	-	$3 \cdot 10^7$	$3 \cdot 10^7$	0	$5 \cdot 10^{-4}$	1.7	196	296	2.4	0.25	2.7	20	5
16	2	n	0	0	100 000	$3 \cdot 10^7$	$3 \cdot 10^7$	0	$5 \cdot 10^{-4}$	1.7	196	296	2.4	-	2.7	20	5
17	3	R , C_g	0	0	-	$3 \cdot 10^7$	-	0	$5 \cdot 10^{-4}$	1.7	196	296	2.4	0.25	2.7	20	5
18	2	q	0	0	100 000	$3 \cdot 10^7$	$3 \cdot 10^7$	0	-	1.7	196	296	2.4	0.25	2.7	20	5
19	2	Δp	0	0	100 000	$3 \cdot 10^7$	$3 \cdot 10^7$	0	$5 \cdot 10^{-4}$	-	196	296	2.4	0.25	2.7	20	5
20	3	q , Δp	0	0	100 000	$3 \cdot 10^7$	$3 \cdot 10^7$	0	-	-	196	296	2.4	0.25	2.7	20	5
21	3	R , q	0	0	100 000	$3 \cdot 10^7$	-	0	-	1.7	196	296	2.4	0.25	2.7	20	5

In the graphical presentations in figs.13-17 the following values have been chosen: $C_e = 0$, $C_m = 0$, $v = 0$, $n = 0.25$ h^{-1}, V/A = 2.4 m, $q = 5 \cdot 10^{-4}$ m^3/(m^{2}hPa), h = 2.7 m, $T_a = 20$ºC and $T_e = 5$ºC, except in fig.14 where q is set to zero in order to see the radon diffusion part more clearly, and except in fig.16 where the variation of C_a as a function of n is depicted. In addition, $\Delta p \approx 1.7$ Pa, is calculated from eq.5. The value of h = 2.7 m is chosen 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 $q = 5 \cdot 10^{-4}$ m^3/(m^{2}hPa) is chosen as this represents today's maximum air permeance value for radon barriers 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^{2}hPa). However, the actual measurement method does not include the radon barrier joint towards the wall perimeter, which in practice might cause large air leakages (e.g. see figs.7, 9 and 10). The given indoor and outdoor air temperatures are chosen as representative values, but they are of course varying very much during the year. A larger air temperature difference between indoor and outdoor causes a larger Δp (eq.6) and hence a larger radon indoor air concentration C_a (eqs.2-3, mathematically in eq.3 since normally $(P + q\Delta p)A/(nV) << 1$).

Furthermore, it should be noted that 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 calculation we have used a conservative (large) value of $R_w = 3 \cdot 10^7$ s/m, i.e. the same as the example radon barrier with $R = 3 \cdot 10^7$ s/m, and hence a 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, which by the way will rarely or almost never take place. Also 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 too 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.

Figure 13 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 (e.g. $C_g = 100\ 000\ Bq/m^3$). 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 14 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 fig.13, but where the air permeance q is 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 fig.13 and fig.14 it is observed 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.

From this it is clear that it is important to ensure sufficient radon diffusion resistance in the ground (e.g. by employing radon barriers). 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. 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, 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. 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.

Figure 15 shows 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. $R = 3 \cdot 10^7$ s/m). It is seen that C_a increases linearly with increasing C_g. The radon concentration in indoor air C_a as a function of the air exchange rate n is shown in fig.16. From this it is clear that to maintain a large number of air exchanges per hour, or at least above some minimum value, is important in order to keep the radon concentration in indoor air low. The radon concentration in indoor air C_a as a function of both the radon resistance in the radon barrier R and the radon concentration in the ground C_g is depicted in the three dimensional plot in fig.17, where the other parameters are kept constant.
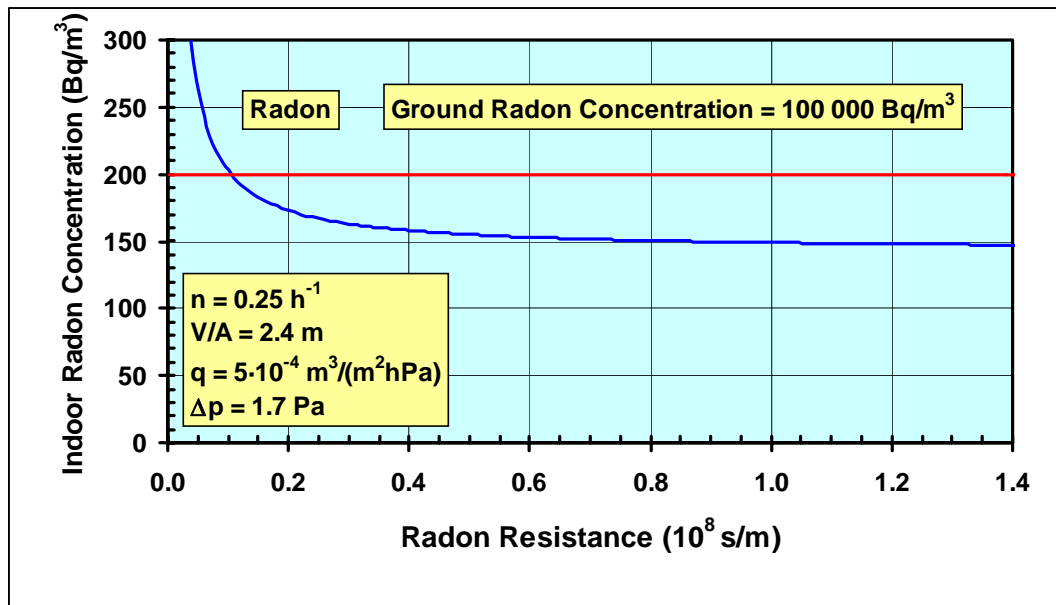
Fig.13. Radon concentration in indoor air versus radon resistance in radon barrier for selected values of radon concentration in ground, number of air changes per hour, building volume/area towards ground ratio, air permeance of ground and air pressure difference between outdoor ground and indoor at ground level.
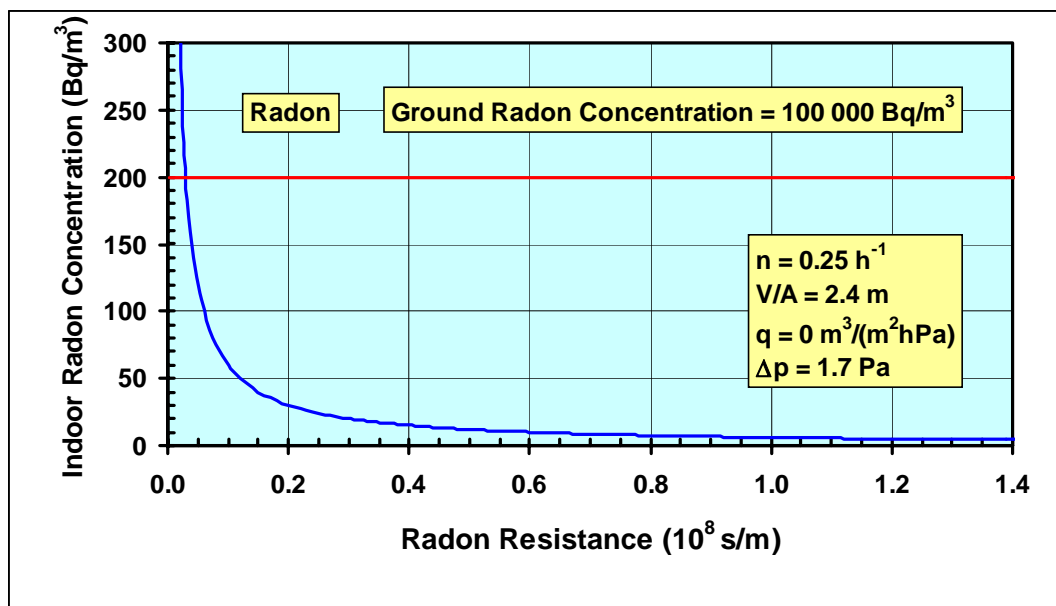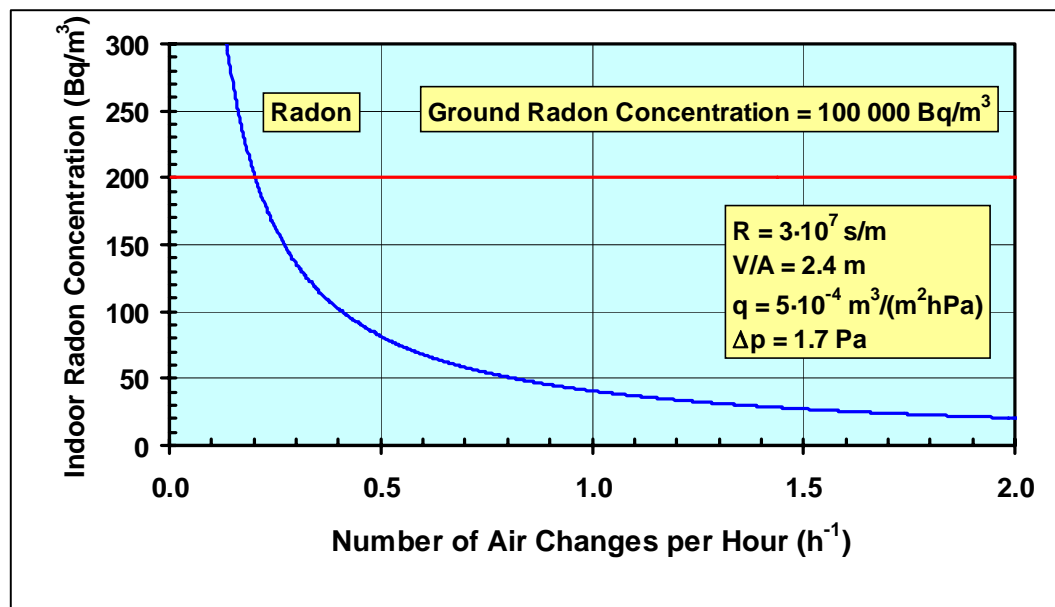

Fig.14. Radon concentration in indoor air versus radon resistance in radon barrier for selected values of radon concentration in ground, number of air changes per hour, building volume/area towards ground ratio, air pressure difference between outdoor ground and indoor at ground level and zero air permeance of ground (i.e. only diffusion part of the radon transport depicted).
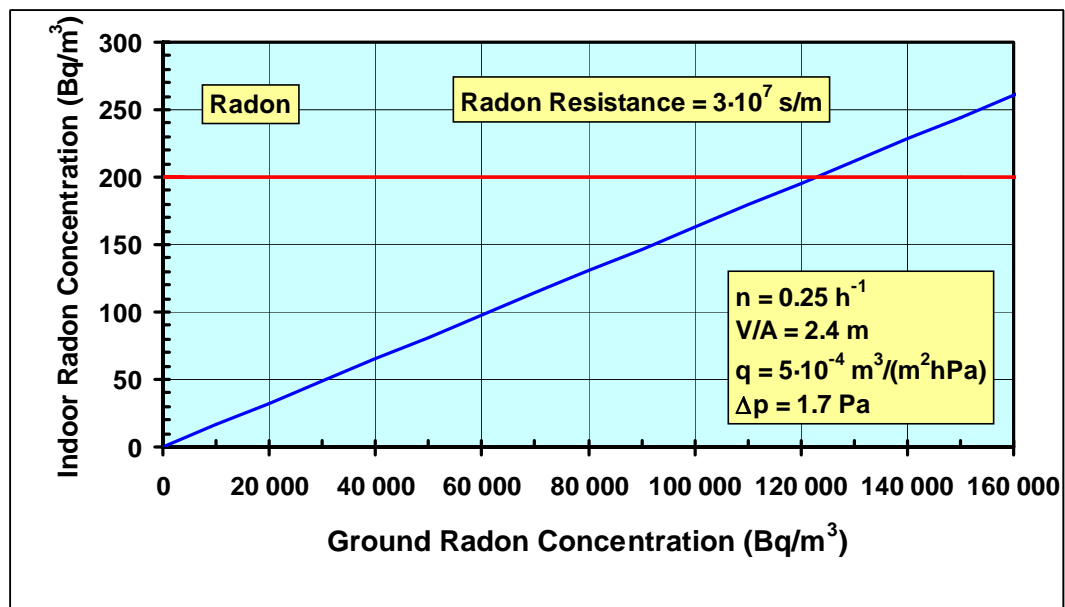
Fig.15. Radon concentration in indoor air versus radon concentration in ground for selected values of radon resistance in radon barrier, number of air changes per hour, building volume/area towards ground ratio, air permeance of ground and air pressure difference between outdoor ground and indoor at ground level.

Fig.16. Radon concentration in indoor air versus number of air changes per hour for selected values of radon concentration in ground, radon resistance in radon barrier, building volume/area towards ground ratio, air permeance of ground and air pressure difference between outdoor ground and indoor at ground level.
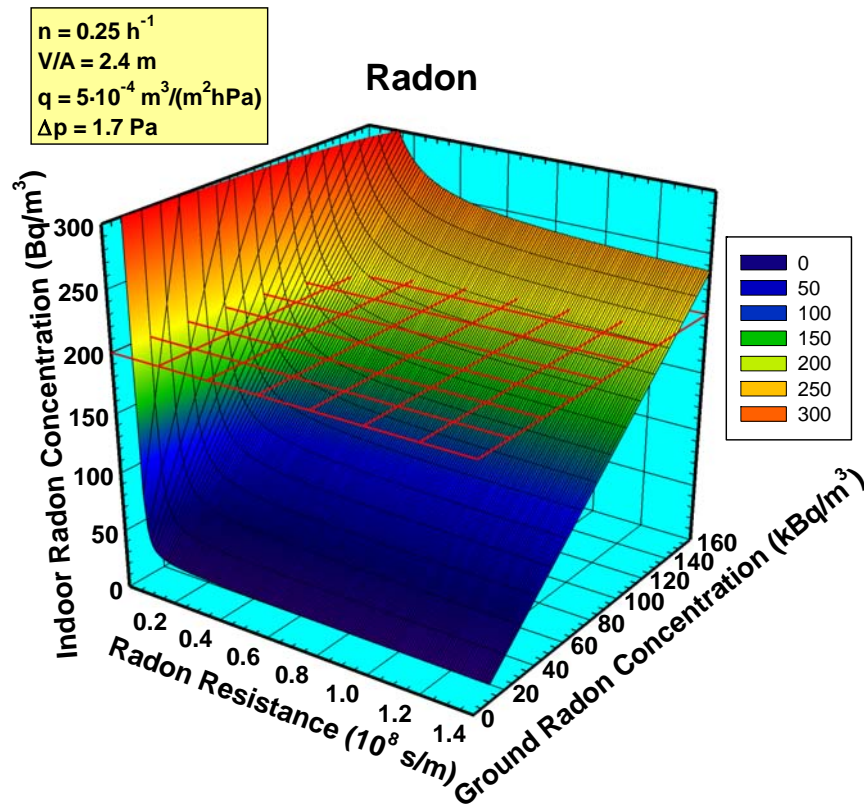
Fig.17. Radon concentration in indoor air versus radon resistance in radon barrier and radon concentration in ground for selected values of number of air changes per hour, building volume/area towards ground ratio, air permeance of ground and air pressure difference between outdoor ground and indoor at ground level.

In the graphical presentations in figs.18-20 the following values have been chosen: $C_e = 0$, $C_m = 0$, $v = 0$, $C_g = 100\ 000$ Bq/m^3, $R = 3 \cdot 10^7$ s/m, $n = 0.25$ h^{-1} and $V/A = 2.4$ m. The radon resistance value of $R = 3 \cdot 10^7$ 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 polyolefin products). Figure 18 shows within this model that the radon concentration in indoor air C_a increases linearly with increasing air permeance q, whereas fig.19 shows that C_a increases linearly with increasing pressure difference Δp (eqs.2-3, mathematically in eq.3 since normally $(P + q\Delta p)A/(nV) \ll 1$). 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 three dimensional plot in fig.20, where the other parameters are kept constant.

Note that 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 here.
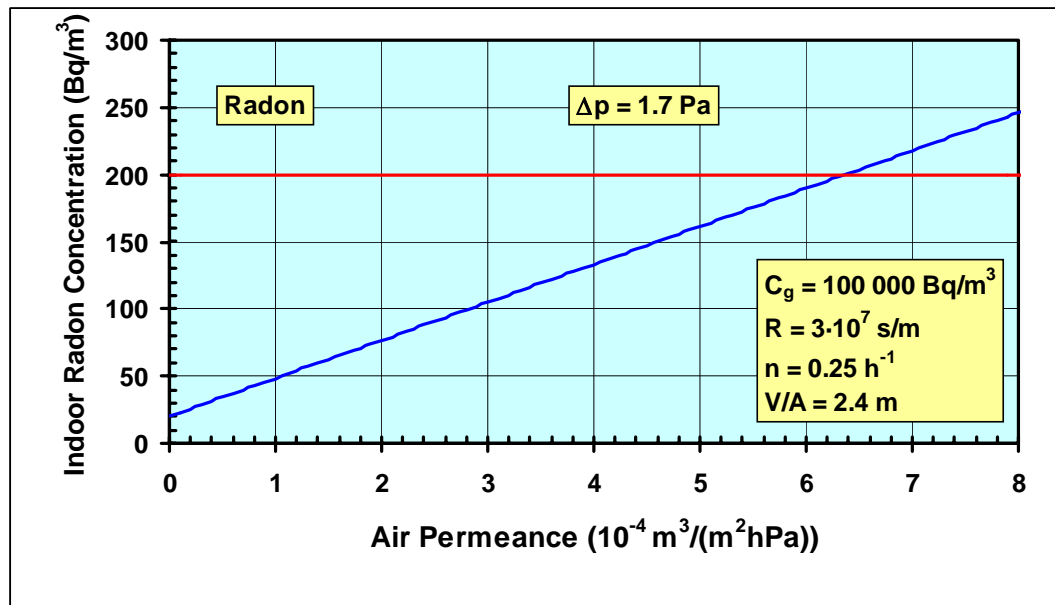
Fig.18. Radon concentration in indoor air versus air permeance of ground for selected values of radon concentration in ground, radon resistance, number of air changes per hour, building volume/area towards ground ratio and air pressure difference between outdoor ground and indoor at ground level. Note that n including air infiltration, exfiltration and ventilation from the walls and the roof is influenced by q and Δp, and will affect the shape of the C_a vs. q curve, which is not included here.
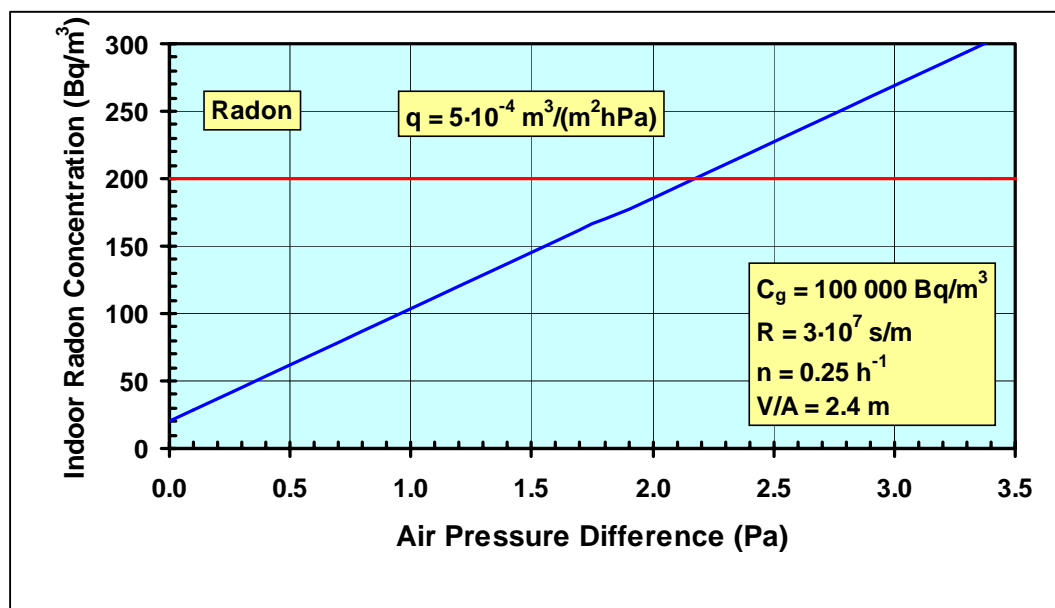

Fig.19. Radon concentration in indoor air versus air pressure difference between outdoor ground and indoor at ground level for selected values of radon concentration in ground, radon resistance, number of air changes per hour, building volume/area towards ground ratio and air permeance of from ground. Note that n including air infiltration, exfiltration and ventilation from the walls and the roof is influenced by Δp and q, and will affect the shape of the C_a vs. Δp curve, which is not included here.
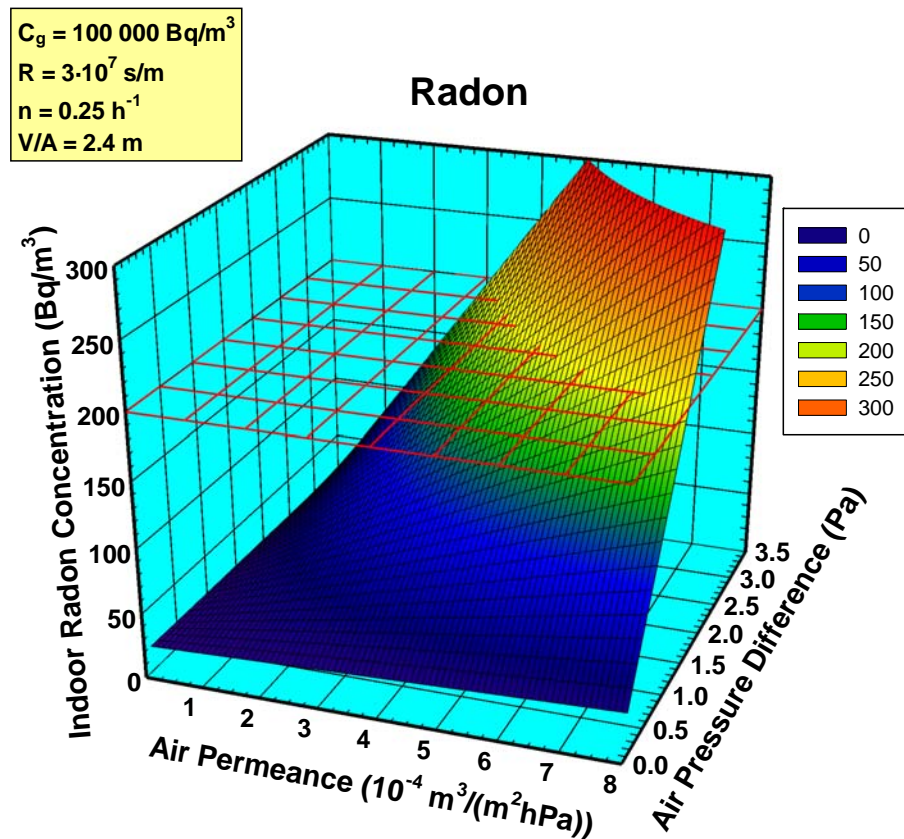
Fig.20. Radon concentration in indoor air versus air permeance of ground and air pressure difference between outdoor ground and indoor at ground level for selected values of radon concentration in ground, radon resistance, number of air changes per hour and building volume/area towards ground ratio. Note n including air infiltration, exfiltration and ventilation from the walls and the roof is influenced by q and Δp, and will affect the shape of the C_a vs. q and C_a vs. Δp curves, which is not included here.

A comparison between the significance of radon resistance in radon barrier and air leakage in connection with radon barrier, is given as a three dimensional graphical plot in fig.21, i.e. visualizing if or when the radon transport into the building is radon diffusion dominant or air leakage dominant.

By incorporating various, including realistic, values in a spreadsheet version of the indoor air radon concentration model presented in eqs.1, 3, 4 and 5, valuable information about the different parameters' influence on the radon level inside buildings is gained. Hence, the given model may be utilized as a tool for studying what measures or actions should be carried out in order to obtain satisfactory low radon levels inside the buildings in question.

Thus, 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.
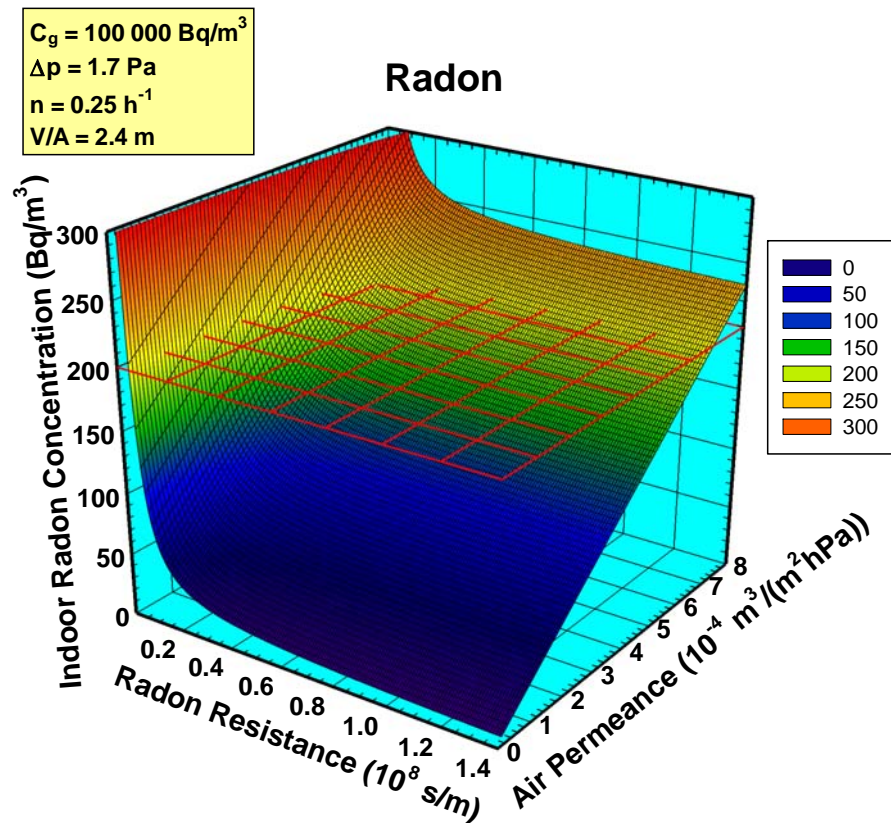
Fig.21. Radon concentration in indoor air versus radon resistance in radon barrier and air permeance of ground for selected values of radon concentration in ground, air pressure difference between outdoor ground and indoor at ground level, number of air changes per hour and building volume/area towards ground ratio.

8. Conclusions

Our study has focused on implementation of radon barriers as preventive measures against radon in dwellings. 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 assorted feed-throughs. The radon barriers will have to be combined with stable and continuous mechanical ventilation of the indoor air by ensuring that the air exchange rate is sufficient and that the ventilation system balances/reduces the pressure differences between the indoor air and the surroundings. Based on various parameters a simplified model for calculating the radon concentration in indoor air has been developed. Characteristic 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 in order 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 something in between 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.

Acknowledgements

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.

- H. Arvela, "Seasonal Variation in Radon Concentration of 3000 Dwellings with Model Comparisons", *Radiation Protection Dosimetry*, **59**, 33-42, 1995.

- *Byggeindustrien*, no. 1, page 47, 2009.

- 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.

- G. Dubois, "An Overview of Radon Surveys in Europe", EUR 21892 EU, *European Commission*, 2005.

- O. Ennemoser, W. Ambach, P. Brunner, P. Schneider, W. Oberaigner, F. Purtscheller, V. Stingl and G. Keller, "Unusually High Indoor Radon Concentrations from a Giant Rock Slide", *The Science of the Total Environment*, **151**, 235-240, 1994.

- O. Ennemoser, S. M. G. Giacomuzzi, P. Brunner, P. Schneider, V. Stingl, F. Purtscheller and W. Ambach, "Radon Measurements in Soil to Predict Indoor Radon Concentrations in New Buildings in an Area with Unusually High Radon Levels", *The Science of the Total Environment*, **162**, 209-213, 1995.

- L. 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.

- R. B. Gammage, C. S. Dudney, D. L. Wilson, R. J. Saultz and B. C. Bauer, "Subterranean Transport of Radon and Elevated Indoor Radon in Hilly Karst Terrains", *Atmospheric Environment*, **26A**, 2237-2246, 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.

- C. L. Jensen, T. Strand, G. B. Ramberg, L. Ruden and K. Ånestad, "The Norwegian Radon Mapping and Remediation Program", IRPA 11, 23–28 May 2004, paper 6a61, http://www.irpa11.com, 2004.

- G. Jönsson, "Radon Gas – Where From and What to Do?", *Radiation Measurements*, **25**, 537-546, 1995.

- G. Jönsson, "The Nuclear Track Detector – A Tool in Radon Measurements", *Radiation Measurements*, **28**, 695-698, 1997.

- 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.

- NORDIC, "Naturally Occurring Radioactivity in the Nordic Countries – Recommendations", *The Radiation Protection Authorities of Denmark, Finland, Iceland, Norway and Sweden*, ISBN 91-89230-00-0, 2000.

- A. L. Rudjord, I. Finne and T. Strand, "Study of Factors Affecting Indoor Radon in Norwegian Dwellings", To be submitted for publication in *Journal of Radiological Protection*, 2009.

- *SINTEF Byggforsk Kunnskapssystemer*, 520.706, "Sikring mot radon ved nybygging" (SINTEF Building and Infrastructure Building Research Design Sheet, 520.706, "Protection against radon for new building constructions"), 2006.

- *SINTEF Byggforsk Kunnskapssystemer*, 701.706, "Tiltak mot radon i eksisterende bygninger" (SINTEF Building and Infrastructure Building Research Design Sheet, 701.706, "Safety measures against radon in existing buildings"), 2006.

- T. Strand, B. M. R. Green and P. R. Lomas, "Radon in Norwegian Dwellings", *Radiation Protection Dosimetry*, 45 (1/4), 503-508, 1992.

- 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.

- 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 Sediements", *Science of the Total Environment*, **389**, 418-428, 2008.

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

- *World Health Organization*, WHO Handbook on Indoor Radon, WHO, 2009.