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Modelling radon transport in Dutch dwellings

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CONTENTS

SAMENVATTING

Met aan elkaar gekoppelde computermodellen zijn de radonconcentraties en de externe bestraling door nucliden van de ^{238}U-reeks berekend voor een representatieve Nederlandse tussenwoning. Er is een analyse gemaakt van het effect van wijzigingen in parameterwaarden die veranderingen in bouwpraktijk gedurende de laatste decennia simuleren.

De luchtdichtheid van de bouwschil en de verdeling van luchtlekken over buitenmuren, dak en begane grondvloer vormen een eerste groep variabelen die de totale luchtverversing, stromingspatronen en radonconcentraties in belangrijke mate beïnvloeden. Bij een ventilatievoud voor de woonkamer, typisch voor nieuwe, luchtdichte woningen ($< 1\ h^{-1}$) is de radonconcentratie meestal hoger dan 20 Bq m^{-3}. Concentraties zijn meestal lager dan 20 Bq m^{-3} bij ventilatievouden karakteristiek voor oudere woningen ($> 1\ h^{-1}$). De bijdrage van radon afkomstig uit de bodem aan de radonconcentratie in de woonkamer varieert van meer dan 70% in oude woningen tot minder dan 30% in nieuwe en is sterk afhankelijk van de luchtdichtheid van de begane grondvloer.

Deuren en ventilatieroosters openen of sluiten en de mechanische ventilatiesnelheid wijzigen vormen een tweede groep factoren, samen te vatten onder de noemer 'bewonersgedrag', die de radonconcentratie in huis beïnvloeden. In nieuwe, luchtdichte woningen is het relatief belang van bewonersgedrag voor de radonconcentratie aanzienlijk groter dan in oude woningen. Mechanische ventilatie stelt een ondergrens aan het ventilatievoud van nieuwe woningen en bijgevolg een bovengrens aan de radonconcentratie.

De radonrelevante kenmerken van de bouwmaterialen vormen de derde groep variabelen waarvoor de invloed op de radonconcentratie bepaald is. Vervanging van hout door beton voor vloeren heeft de radonproductie in woningen sterk doen wijzigen. In de woonkamer van nieuwe woningen draagt de radonproductie uit bouwmaterialen 5 tot 10 maal meer bij aan de totale radonconcentratie dan in oude woningen. Een 50% lager ventilatievoud en een 5 maal hogere radonproductie verklaren dit verschil.

De derde groep variabelen is tevens basis voor de interpretatie van de externe bestraling in nieuwe en oude woningen. De aanwezigheid van betonnen vloeren leidt tot een hogere aanstraling vanuit de bouwmaterialen maar ook tot een betere afscherming van de aanstraling vanuit de bodem. De gemiddelde externe bestraling op de begane grondvloer van nieuwe woningen wijkt bijgevolg nauwelijks af van die in oude woningen. Wijzigingen in de bouwpraktijk hebben dus gemiddeld genomen geleid tot een hogere radonconcentratie in de woonkamer en niet tot een wijziging in de externe bestraling.

SUMMARY

Radon concentrations and external exposure by nuclides of the ^{238}U decay chain were quantified for a typical Dutch town house using a series of interconnected computer models. Also studied was the effect of changes in a variety of parameters representing changes in building practices over the past decades.

The airtightness of the building shell and the distribution of leaks over outer walls, roof and ground floor comprised the first set of parameters having a major effect on total air flow, flow pattern and radon concentration. A ventilation rate for the living room that is typical for airtight new dwellings (< 1 h^{-1}) will usually result in radon concentrations of more than 20 Bq m^{-3}. Concentrations were found to be generally lower than 20 Bq m^{-3} for ventilation rates typical for old dwellings (> 1 h^{-1}). The contribution of soil radon to the radon level in the living room ranged from more than 70% in old dwellings to less than 30% in new ones and depended highly on the leakage area of the ground floor.

Opening air inlets or inner doors and changing the mechanical ventilation rate, which may be summarised as 'habits of the occupant', comprise the second set of factors affecting indoor radon. In new, airtight dwellings the relative effect of this behaviour was considerably larger than in old ones. In new dwellings the mechanical ventilation set a lower limit to the ventilation rate and thus an upper limit to the radon level.

The radon-relevant characteristics of the building materials make up the third group of parameters, the importance of which is quantified. Substitution of wood by concrete for the construction of floors was found to greatly affect the radon source strength in dwellings. The contribution of the radon production in the living room to the total radon concentration of this room is 5–10 times higher in new dwellings than in old ones. This change is partly explained by ventilation rate which was at least 50% lower in new dwellings and partly by radon production which was five times higher.

The third group of parameters is also used to interpret the external exposure in old and new dwellings. The presence of concrete floors will increase exposure from the building itself and shield external radiation from the underlying soil. As a result, the dose rate averaged over the total area of the ground floor of a new dwelling hardly differs from that of an old one. On average changes in building practices thus clearly enhanced the radon concentration in the living room without affecting external exposure.

1. Introduction

The actual average radon level in Dutch dwellings is about 23 Bq m^{-3} [1], which is low in comparison with levels in other (European) countries [2]. The average concentration in dwellings built since 1980 (28 Bq m^{-3}), however, was observed to be 50% higher than in dwellings built before 1970 (19 Bq m^{-3}). The Dutch policy on indoor radon aims at preserving the actual favourable situation [3]. Implementation of regulations to realise this goal requires insight into the processes governing the observed changes in radon level. Additional insight may be acquired through experimental studies [e.g. 4, 5, 6, 7] and theoretical calculations, both separately or in combination [8, 9].

The study reported here focuses on theoretical calculations. It is designed to model radon transport in typical Dutch dwellings and aims to describe the relative importance of the different factors determining the indoor radon concentration. Questions to be dealt with relate to the relative importance for indoor radon of:

- the soil under the dwelling,
- the characteristics of the building materials,
- airtightness and distribution of leaks over walls and floors, and
- open windows, air inlets or inner doors and changing the mechanical ventilation rate (summarised as 'habits of the occupant')

The accent is on the simulation of radon levels in *newly* built dwellings, considering that intended regulations for new dwellings will be of a more binding character than those for existing ones. Some calculations are made for old dwellings for comparison's sake, however, and to estimate the effect of practices which were standard in the past but hardly applied in new dwellings, such as the use of natural ventilation systems and wood for floors.

A proper evaluation of the effectiveness of regulations, however, has to be based on estimates of the total indoor absorbed dose. The dose from the gamma rays emitted by nuclides of the ^{238}U decay chain present in the building materials and soil is also estimated as a first step.

The report begins with a brief presentation of the models (chapter 2) and the scenarios studied (chapter 3). Responses to major issues are presented in the subsequent chapters (4–7). Conclusions and recommendations are found in chapter 8.

2. Structure of the model

In this study, estimates of the indoor absorbed dose have been based on calculations using a series of interconnected models (Figure 1). Each model provides results for a specific segment of the chain linking source to dose. An integrative database was developed for handling data exchange between the various models, for calculating the total dose and for data interpolation. These models are managed and run by different operators: COMIS – used to calculate pressure differences and air flows in the dwelling and managed by TNO-Bouw (Delft); RAETRAP – used to estimate pressure-dependent exhalation from building materials and soil and managed by KVI (Groningen); MARMER – used to calculate external exposure from soil and building materials, and the integrating mass balance equation model managed by RIVM. RIVM was also responsible for data handling and data exchange. The structure for this model was chosen to maximize the input of know-how in the different relevant fields of expertise. Background information on the organisational form of the overall model was reported on elsewhere [10].

The structure and function of each of the models is discussed in the subsequent sections. First, the various segments from which the dose due to indoor radon arises are discussed, and then the model used to calculate the external exposure is presented. Pressure differences, air flows and radon concentrations at equilibrium are estimated with the segments on indoor radon. As pressure differences are continuously changing, the real flows and concentrations will be a mixture of the various, sometimes never occurring, equilibrium situations. The current approach, however, has been chosen to allow for a transparent identification and comparison of relevant variables.

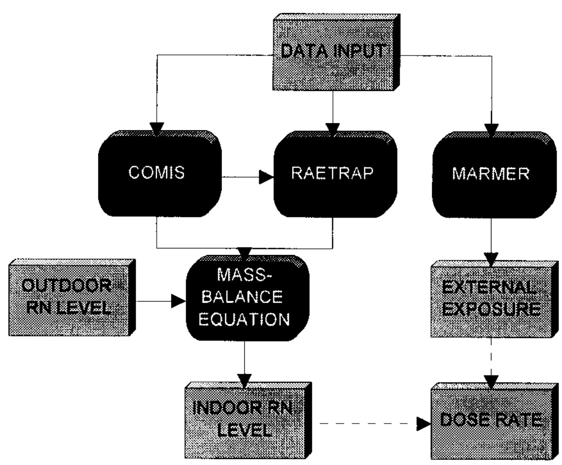


Figure 1: Simplified scheme of the various interconnected models.

2.1 Modelling air flow and pressure differences

Whereas the characteristics of soil and building materials determine the size of the radon source, radon decay and ventilation determine its removal. As the rate of removal by radon decay is negligible compared to removal by ventilation, decay is not taken into account in the model estimations. Three types of ventilation are distinguished [11, 12], each of which can be modelled in COMIS (Conjunction of Multizone Infiltration Specialists) [13]: uncontrolled leakage of air into the building (through cracks and openings), natural ventilation through open air inlets and doors, and mechanical ventilation. The model generates air flows within the house and pressures (dPs) over different walls.

A building is modelled by pressure nodes that are interconnected with airflow paths (links). Each node represents a space with uniform pressure conditions inside or outside the building; the interconnections correspond to impediments (e.g. closed doors) to air flow. Pressure coefficients, relating wind velocity to wind pressure, can be attributed to external nodes. Not only wind effects, but also buoyancy, resulting from temperature and air composition differences, and fans are taken into account. COMIS allows the user to define schedules describing changes in the indoor temperature distribution, fan operation, opening of air inlets and doors, and weather data. COMIS substitutes the originally selected ventilation model, VENCON [10].

2.2 Modelling radon exhalation

The source strength, i.e. the radon exhalation from the soil under the dwelling and from its walls and floors, is modelled with RAETRAP [14]. The walls, floors and soil are defined as a number of homogeneous layers, such as the inner and outer face of the cavity wall and the cavity filling. Each layer is characterized by factors like its thickness, radium concentration, radon emanation and diffusion coefficients, porosity and water saturation. Pressure-driven transport, mainly through the soil, is quantified for dPs, estimated by the COMIS model. The selection of dPs used as input of RAETRAP is based on both range and frequency distribution of the COMIS values.

2.3 The outdoor radon concentration

Combining the source strength, as calculated with RAETRAP, and the air flows from COMIS results in the radon concentration caused by the indoor sources (see 2.4). The radon concentration in outdoor air has to be superimposed on the concentration generated by these indoor sources. Several variables, however, such as soil type and meteorology affect the outdoor radon concentration. Therefore the outdoor concentration has to be attuned to the meteorological state and soil characteristics used in the scenario at issue. We preferred not to estimate the outdoor radon concentration from model calculations planned when the model was designed [10]. Instead location-specific, and wind-speed and wind-direction dependent data, were selected from a thorough analysis of a vast database on measurements of radon daughter levels in outdoor air [15].

2.4 The integrative module

The radon concentration in each node (see 2.1) is derived from all air flows entering and leaving (output of COMIS) and the exhalation rate of the sources contributing to the radon concentration of each of the flows (output of RAETRAP). The radon concentration at equilibrium is calculated, which means that input via all flows entering equals the loss in all air leaving each of the nodes. Calculations were made for a variety of meteorological conditions, ventilation regimes and building characteristics; these are specified in chapter 3. It is doubtful whether the estimated steady-state radon concentrations will be observed in the field. Continuously changing weather conditions and irregular and unremitting actions of the inhabitant will prevent development of steady-state concentrations. However, weighing and averaging individual results for a given dwelling is considered to provide its yearly averaged radon concentration. The results were checked by comparing the mass balance of the air flows and the radon balance for each zone.

2.5 Estimating external exposure

The computer package MARMER [16, 17, 18, 19, 20] was used to calculate the dose rate from external radiation. MARMER calculates, for example, dose rate using the point-kernel shielding model. According to this model, the dose rate due to the unscattered radiation is calculated by use of a *kernel*. This *kernel* is a function of the distance between source point and dose point and the shielding properties of the medium between these points. The contribution due to scattered radiation is taken into account by use of a build-up factor, which is a function of the atomic number of the shielding material, the thickness of the shield (commonly measured in mean free paths) and the energy of the unscattered radiation. For a source that cannot be considered as a point source and one which also has a continuous energy spectrum, e.g. a wall, this kernel-build-up function has to be integrated over energy (the photon energies emitted by the radionuclide considered) and source volume (the building material). MARMER substitutes the originally selected ventilation model, EXPO [10].

3. Input of the model

An extensive number of variables had to be quantified before the various models could be run. To structure their listing the most important variables were grouped around a number of items: the weather conditions to which the dwelling is exposed, the dwelling's floor plan, and its airtightness and ventilation regime, the building materials used in the dwelling and the characteristics of the underlying soil.

3.1 Weather conditions

A frequency distribution of the hourly means for wind direction, wind velocity and temperature observed in De Bilt over the period April 1995–March 1996, was used to select 30 combinations of wind velocity, wind direction and temperature (Table 1). Most combinations with a very low occurrence were discarded; however, some of the more extreme weather conditions – such as a temperature of -5 °C and 8 m s^{-1} wind velocity – were maintained to get insight into their effect on total infiltration and pressure distribution. The occurrence of each weather condition is given in Appendix 2. Wind velocities were measured at a height of 10 m and corrected by TNO to velocities at a height of 9 m, being the top of the dwelling.

Table 1: Weather conditions

run no.	wind direction (degrees)	wind velocity (m s^{-1})	temperature (°C)
1-3	–	0	-5, 1, 18
4-12	45	2, 5, 8	1, 10, 18
13-18	135	2, 5	1, 10, 18
19-24	225	2, 5	1, 10, 18
25-30	315	2, 5	1, 10, 18

3.2 Pressure distribution around the dwelling

The pressure distribution around a dwelling is usually described by a dimensionless pressure coefficient (Cp) (Table 2), which is the ratio of the surface pressure and the dynamic pressure in the undisturbed flow pattern at a reference height.

Table 2: Cp values for four wind directions and for front wall, back wall and roof

	45°	135°	225°	315°
front wall	0.10	-0.12	-0.12	0.10
back wall	-0.12	-0.10	0.10	-0.19
roof	-0.30	-0.30	-0.30	-0.30

3.3 Floor plan

In 1996 the radon concentration was measured in 1404 houses located across the Netherlands. All houses investigated were built in the period of 1985 to 1993. The set-up and results of this research were reported in [21] and [1], respectively. To facilitate modelling of the radon concentration and validation of model estimates with measurements, a common type of dwelling was selected as the 'reference dwelling' from those investigated in this national radon survey.

The 'reference dwelling' is a town house built in 1988 on a normal, sheltered location. The type of house selected, an enclosed town house, 8.9 m high and with a floor plan of 40.8 m^2, is found throughout the country. It has a total volume of 247 m^3 (Appendix 3). A crawl space (about 25 m^3) is present, but no cellar. The house has three floors connected by a staircase: a through lounge, an open kitchen and an entrance hall with toilet on the ground floor, three bedrooms and a bathroom on the second floor and an attic on the third floor. This 'reference dwelling' was used to design the 'model dwelling'.

Sections 3.4–3.8 describe two major versions of the model dwelling. The first one represents the actual building practices and is called the 'new dwelling' (N). The second one represents practices which were common up to the early sixties and is called the 'old dwelling' (O). Differences between both building periods relate mainly to the ventilation mechanisms, the building materials applied and the airtightness of the building [26, 28]. The floor plan of the old and the new dwelling, however, is the same.

3.4 Airtightness and ventilation: new dwellings (N)

In the context of this report a new dwelling is one in which concrete is used for the floors and a number of the walls (see 3.7). Furthermore, it has a mechanical ventilation system and a relatively airtight building shell. Both the airtightness and the flow rate of the mechanical ventilation system of this new dwelling are varied to study the relative importance of these factors.

The airtightness is defined as the amount of air leaving the building, given a pressure difference of 10 Pa over the building shell while all outer doors and air inlets are kept closed and all inner doors open [$q_v(10)$ in $dm^3\ s^{-1}$]. Van der Wal *et al.* [22] and Sherman [23] exemplify measurements of this parameter by pressurisation.

According to Dutch legislation new buildings should meet certain requirements for airtightness of the building shell [24]. These requirements are specified in a Dutch Standard [25]. The leakage of the building shell of a dwelling of 500 m^3 must be less than 200 $dm^3\ s^{-1}$ given a pressure of 10 Pa. In practice, $q_v(10)$ decreased from about 500 $dm^3\ s^{-1}$ before 1970 to less than 100 $dm^3\ s^{-1}$ after 1985 [26]. In 1992 [24] a minimum airtightness for the ground floor [$q_v(1) = 20\ 10^{-3}\ dm^3\ s^{-1}\ m^{-2}$] was set down. Measured infiltration through basement floors in dwellings from 1980–1990 was often higher than this value and shows a large variation [4, 20].

A range of realistic $q_v(10)$ values is chosen for the model estimations (Table 3). Dwelling N_4 represents a dwelling with a $q_v(10)$ comparable to the official maximum. Dwellings N_1-N_3 represent newly built dwellings with a lower $q_v(10)$ value, which can be found in practice. Dwelling O will be discussed elsewhere (3.5). The leaks in the building shell are divided among the roof, outer walls (including front and back doors, and air inlets) and ground floor, taking account of measured data and legal limits [27]. No leaks to neighbouring dwellings are assumed as these houses are considered similar to the dwelling, with similar pressure differences.

Table 3: Infiltration rates (pressure difference of 10 Pa) in different construction elements and total leakage area for new and old dwelling versions

dwelling code*	$q_v(10)$	roof	walls	floor	total leakage area
	$dm^3\ s^{-1}$	$dm^3\ s^{-1}$	$dm^3\ s^{-1}$	$dm^3\ s^{-1}$	cm^2
N_4	200	110	50	40	280
N_3	100	32	29	39	181
N_2	81	32	29	20	139
N_1	72	32	29	11	121
O	484	228	131	126	902

* N_4, N_3, N_2 and N_1= new dwelling with mechanical ventilation and various concrete construction elements, and with decreasing leakage area of the building shell; O= old dwelling with natural ventilation and without concrete construction elements

The airtightness relates to the effective leakage area of the building shell, the type of air flow through the cracks and openings, and to the air density [12]. The total surface area of the leaks of the new dwelling ranges from 121 to 280 cm^2, which is in the range observed for houses built in the Netherlands between 1980 (800 cm^2) and 1990 (150 cm^2).

The leakage area on the ground floor is 240 cm^2 in dwelling O (see 3.5) and, at most, 56 cm^2 in dwelling N. The leaks in the ground floor can be attributed to cracks and leaks around pipes and the crawl space hatch. No leaks are present on the other floors of dwelling N. The total leakage area on ground floors in the Netherlands generally varies between 6 and 200 cm^2.

The links between different zones in the dwelling are characterized by their surface area and net height. A schematic diagram of the house and the links between the different zones is given in Figure 2. Leakage through inside walls is considered negligible compared to the air flow through doorways or chinks along the doors. Large openings to neighbouring houses may exist in the crawl space.

The ventilation system has a fan installed in the attic and an outlet on the roof. It extracts air from the kitchen, the toilet and the bathroom. Estimates were made for two flow rates of the mechanical ventilation (21 and 42 $dm^3\ s^{-1}$). Air inlets and inner doors are either closed all together or partly opened. The air inlets are located at the top of the window frames. When air inlets are open (in living room, bedrooms, and attic) inner doors are closed, and when doors are open (in living room and bedrooms) air inlets are closed. The surface area of an air inlet is 70 cm^2; the surface area of all air inlets is 490 cm^2. This area is about 50% of the uncontrolled leakage area of dwelling O and four times that of dwelling N_1.

Altogether, 14 combinations simulating differences in habits of the occupant were studied (Table 4).

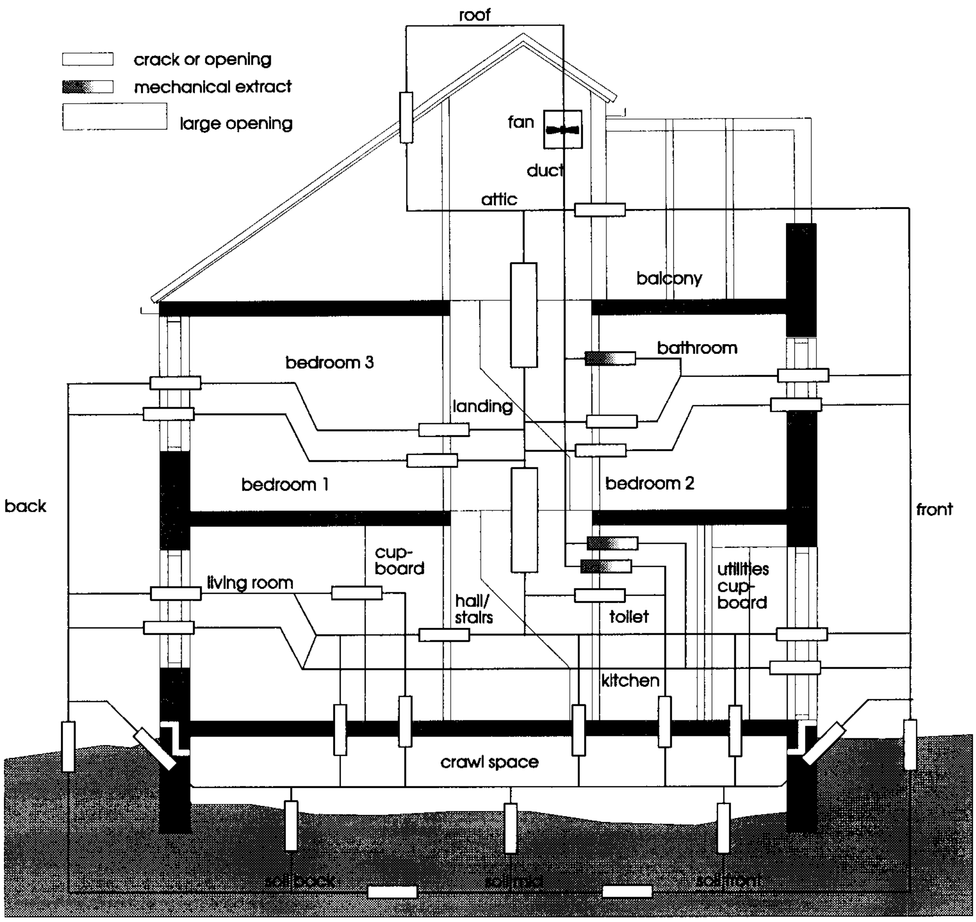


Figure 2: Scheme of the dwelling and links between the different zones as used in the simulations with COMIS.

3.5 Airtightness and ventilation: old dwellings (O)

The total surface area of the leaks and thus the airtightness of the dwelling depends heavily on building and insulation practices, which have changed considerably over the past few decades. Furthermore, old houses have natural ventilation rather than mechanical ventilation. To simulate the consequences of these changes on the radon level and on the role of its sources, a dwelling was composed with a relatively large leakage area in the building shell (about 900 cm^2) and natural ventilation only [$q_v(10)$ of about 484 $dm^3\ s^{-1}$] (Table 3).

The leakage area of the ground floor of dwelling O is about four times that of dwelling N to simulate the presence of wooden floors. The leakage area of the other floors is either zero or 6 cm^2 per 10 m^2. The leakage area of the roof and the outer walls is also enlarged. Floor plan and location of walls, doors and air inlets were kept unchanged, as well as the characteristics of the air inlets and doors. Altogether, five combinations simulating differences in habits of the occupant were studied (Table 4).

Table 4: Airtightness and ventilation in the various versions of the dwelling

dwelling code*	ventilation natural	mechanical (dm^3 s^{-1}) 21	mechanical (dm^3 s^{-1}) 42	air inlets open	inner doors open	cracks in floors
N_x†		×				
N_{xw}†		×		×		
N_{xd}†		×			×	
N_4		×				
N_{4w}		×		×		
N_{4h}			×			
N_{4wh}			×	×		
N_{4dh}			×		×	
O	×					
O_c	×					×
O_{cd}	×				×	×
O_{cw}	×			×		×

* N = new dwelling with mechanical ventilation and various concrete construction elements, where there is increasing leakage area in the building shell; O= old dwelling with natural ventilation and without concrete construction elements; d and w= doors and air inlets open; c= cracks in floors of first and second floors; h= high mechanical ventilation rate.

† $N_x = N_1$, N_2 and N_3 (see Table 3)

3.6 Zones and indoor temperature

The volume (m^3) and temperature (°C) of each zone are used as input for the COMIS model.

A central heating system using radiators is present in the new as well as in the old dwelling. Indoor temperatures in the various zones of the new dwelling are the same as in those of the old dwelling. The indoor temperature is to some extent related to the weather conditions. Temperatures in some of the zones will be lower in winter than in summer. Therefore indoor and outdoor temperatures relate to each other in the various model runs (Table 5). Temperature variation is largest in the crawl space and smallest in the bathroom and living room.

Temperatures measured in the crawl space of Dutch dwellings were slightly higher than those used in our calculations: 6.4–7.9 °C at an outdoor temperature of -5.9 °C and 12.4–12.9 °C at +5 °C [4]. This difference is thought not to have a large effect on the air flow from the crawl space to the living room [27].

Measurements showed that increased ventilation of the crawl space resulted in a lower crawl space temperature, but not in a higher air flow from the crawl space to the living room. In other studies the stack effect was not found to significantly affect indoor-soil pressure differences driving air flow [11].

Table 5: The four temperature combinations for which calculations are made

zone	temperature (°C)			
outdoors	-5	1	10	18
soil + crawl space	5	5	10	10
living room + bathroom	18	18	20	20
hall/stairs + ventil. canal	17	17	19	19
toilet	16	16	18	18
landing	16	16	18.5	18.5
bedrooms + attic	15	15	18	18

3.7 Building materials: what and where?

The walls and floors are described as one or more homogeneous layers of one building material. The thickness of each layer and the type of material are given in Table 6. Most walls and floors are modelled as simple composites, not adding any wallpaper, paint or floor cover, since their effect on radon exhalation is hard to quantify or negligible. One combination of building materials represents present-day building practices (N) and another one the old fraction of the building stock (O). The combinations were selected on the basis of the trends described by De Graaf [28] and information on building characteristics collected during the two Dutch surveys on radon in dwellings [1, 29]. More details of the layers are given in Appendix 4.

Table 6: Characteristics of the construction elements and building materials representing the present and past situations

construction element		material	density (kg m^{-3})	^{226}Ra (Bq kg^{-1})	surface area (m^2)	thickness (m)	volume (m^3)
bearing side walls	N*	concrete	2400	20	110	0.2	22.0
	O*	brick	1700	40	110	0.1	11.0
cavity wall front	N/i*	concrete	2400	20	19	0.1	1.9
	N/e*	brick	1700	40	19	0.1	1.9
	O/i,e	brick	1700	40	19	0.1	1.9
cavity wall back	N/i	concrete	2400	20	16	0.1	1.6
	N/e	brick	1700	40	16	0.1	1.6
	O/i,e	brick	1700	40	16	0.1	1.6
floors	N	concrete	2400	20	118	0.22	26.0
	O	wood	600	10	118	0.03	3.6
inner walls		gypsum	960	10	43	0.07	3.0

* N, O= present and past situation; i, e= inner and outer face of the wall

The outer walls of dwelling N, representative of present-day building practices, are cavity walls with an outer face of brick masonry and an inner face of concrete. The insulation material in the cavity (10 cm) is considered neither to contain radium nor to affect radon transport. The bearing walls, i.e. those between the neighbouring houses, and all floors are made of concrete, whereas most inner walls are made of gypsum blocks. All frames and doors are made of wood. The house has an insulated gabled roof covered with tiles. In the dwelling representing the old fraction of the housing stock (O), wooden floors are present instead of concrete ones, and bearing and outer walls are made of bricks. Data on sand-lime brick will occassionally be given (e.g. in Table 9), though they are not used in (the comparison of) dwellings O and N.

3.8 Building materials: radon-related characteristics

When indoor radon originates entirely from building materials, the radon concentration C (in Bq m^{-3}) in a zone can be described as

$$C = \frac{E * S}{V * \lambda} \qquad (1)$$

with
E = exhalation rate (Bq h^{-1} m^{-2})
S = surface area (m^2)
V = volume of the zone (m^3)
λ = ventilation rate (h^{-1}).

The radon exhalation rate of a building material depends on its radium concentration (see 3.7), on its physical characteristics, such as porosity and density, and on the pressure difference over the construction element in which the material is used. The physical characteristics of the materials given by Put and Van der Graaf are used [30] (see Appendix 5). The pressure differences are generated by the COMIS model (2.1). Out of the generated range of pressure differences a representative selection was made for each of the construction elements.

The total amount of radium in a certain material gives a first and rough indication of the contribution of this material to the total radon concentration in the building. Concrete, bricks and gypsum blocks contribute about 90%, 10% and 1%, respectively, to the total amount of 2.8 MBq ^{226}Ra found in the new dwelling. In the old dwelling the total amount of radium is about 1.3 MBq. The difference between 'old' and 'new' is mainly due to the use of wood instead of concrete for the floors in the old house.

3.9 Soil

For estimating the radon exhalation from soil, a sandy soil with a radium level of 25 Bq kg^{-1} is used, which is the average radium concentration in Dutch soils [1].

Pressure over the soil column (and thus radon exhalation from the soil below a dwelling) varies with changing meteorological conditions and differs between the front and the back wall of the dwelling. Estimates are derived using the model COMIS (see 2.1), in which the soil below the dwelling is subdivided into three compartments situated side-by-side. Radon exhalation from the side compartments is assumed to be the result of the pressure over a soil column of 3 m with a surface area of 10 m^2. Radon will escape from the middle compartment with a surface area of 21 m^2 as a result of diffusion only.

3.10 Outdoor radon concentrations

The outdoor radon concentration depends on weather conditions (especially wind direction and wind speed). The values selected for each combination of meteorological conditions given in section 3.1 vary between 0.7 and 4.3 Bq m^{-3} [15].

4. Pressures and Ventilation

This chapter describes results of calculations using COMIS such as pressures over walls and air flows. Data on radon exhalation from building materials and soil, and on radon production in the dwelling, which are generated with RAETRAP, will be given in Chapter 5. The results of Chapters 4 and 5 are used to calculate indoor radon levels in Chapter 6.

Wind pressure and temperature differences lead to pressure differences over the various construction elements of a dwelling, the variation of which is discussed in 4.1. The total infiltration resulting from these pressure differences is presented in 4.2 and air flows between the various zones in 4.3–4.4.

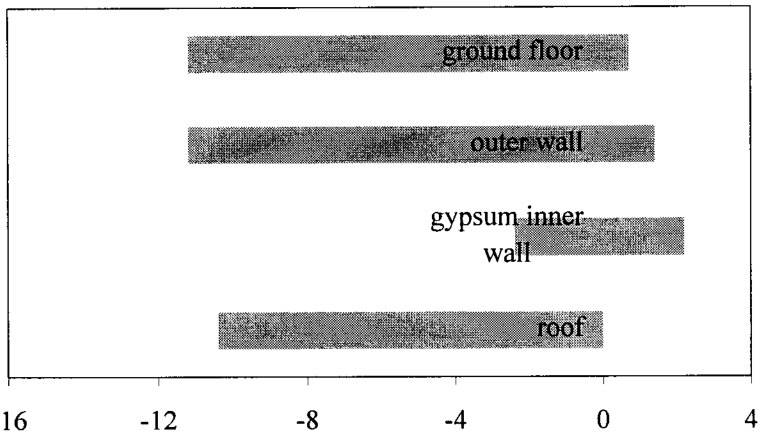


Figure 3: Distribution of pressure differences (dPs) for different construction elements of an old dwelling with natural ventilation (O).

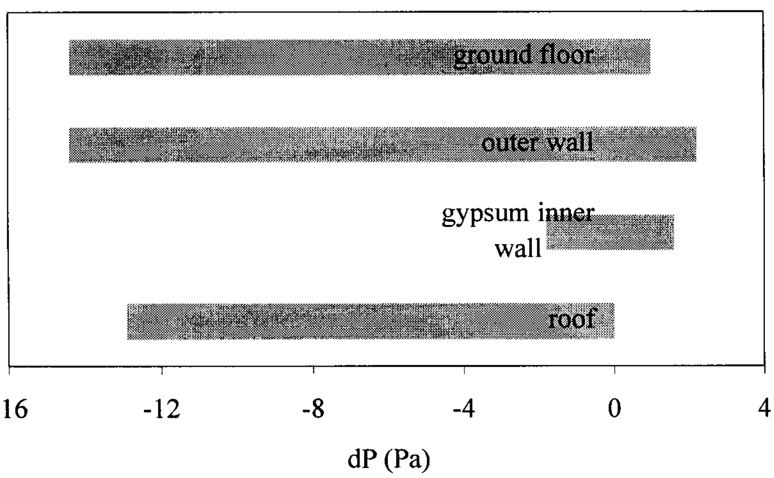


Figure 4: Distribution of dPs for different construction elements of a new dwelling when mechanical ventilation rate is high (N_{4h}).

4.1 Wind pressure and pressure differences

COMIS generates the pressures in the different zones of the dwelling as well as pressure differences over walls between zones. More than 95% of the results are between -7 and 0 Pa. The interior of the structure is usually depressurized relative to the ambient atmosphere and air will flow from outside to inside through e.g. cracks and openings [31]. The pressure differences over the outer walls and roof are generally more variable than those over the inner walls. Furthermore, the range in a dwelling with an open shell (Figure 3) is smaller than in one with a tight shell and mechanical ventilation (Figure 4).

The small indoor–outdoor pressure differences are created by the stack effect, wind interaction with the building shell, ventilation and air-conditioning systems, and result in pressure-driven air flow (advection). Field measurements generally produce values varying between zero and -5 Pa [11, 31], which is in agreement with values generated by COMIS. Temperature differences and ventilation practices play an important role in indoor pressure gradients and thus in indoor air flows. The effect of varying pressure differences on radon exhalation from building materials will be discussed in Chapter 5.

4.2 Total infiltration and ventilation rate

The total infiltration into a dwelling ($m^3\ h^{-1}$) not only depends on pressure differences between inside and outside, but also on how airtight the building shell is (uncontrolled leakage), opening of air inlets (natural ventilation) and mechanical ventilation. This relationship can be described as

$$Q = E(\Delta P)^n \qquad (2)$$

with
Q = air flow ($m^3\ h^{-1}$)
E = airtightness ($m^3\ h^{-1}\ Pa^{-n}$)
ΔP = average pressure difference across the shell (Pa)
n = exponent related to the type of air flow ($0.5 < n < 1.0$)

Total infiltration affects the indoor radon concentration through dilution. Other aspects, however, such as exhalation from building materials and indoor circulation, must also be taken into account in drawing conclusions on the radon concentrations in each of the zones. Given the fact that the various versions of the dwelling studied in this report have the same volume, the flows can also be expressed and compared as ventilation rates, since

$$\lambda = Q/V \qquad (3)$$

with
λ = the ventilation rate (h^{-1})
V = dwelling volume (m^3)

Of the ventilation rates for 30 combinations of weather conditions, the most variation was found for dwelling O (0.21 - 3.9 h^{-1}). The least variation was observed for the most airtight version of dwelling N, i.e. N_1 (0.28 - 2.8 h^{-1}).

Table 7: The yearly averaged total ventilation rates for different ventilation strategies and various versions of the dwelling

†dwelling version	$q_v(10)$	*leakage on floor area	mech. vent.	ventilation rate		
				air inlets open	doors open	all closed
	($dm^3\ s^{-1}$)	(cm^2)	($dm^3\ s^{-1}$)	(h^{-1})	(h^{-1})	(h^{-1})
N_1	72	18	21	0.86	0.55	0.55
N_2	82	35	21	0.86	0.55	0.55
N_3	100	71	21	0.85	0.55	0.55
N_4	200	71	21	1.18	-	0.83
N_{4h}	200	71	42	1.34	0.94	0.94
O_c	484	174	-	1.75	1.52	1.46

†For information on the dwellings see Tables 3 and 4.
* = leakage on ground floor as a whole

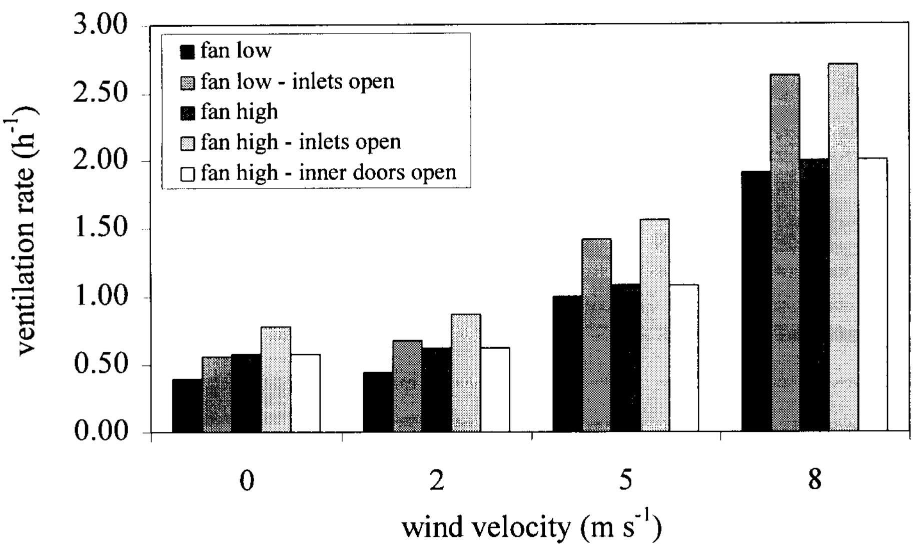


Figure 5: Average ventilation rate of dwelling N_4 versus wind velocity for five ventilation strategies as based on the results for outdoor temperatures of 1°C and 18 °C. Wind direction is 45°

The relative occurrence of the 30 combinations of weather conditions used in the calculations was used as weighting factor to derive yearly averaged ventilation rates from data as given in Appendix 6. Generally, increasing the airtightness of a building will lower the yearly averaged ventilation rate (Table 7). Reducing the leakage area of the ground floor alone ($N_3 \rightarrow N_1$) will result in negligible changes of the average ventilation rate. Increasing the leakage area of the walls ($N_3 \rightarrow N_4$, air inlets closed) resulted in an almost proportional increase of the average ventilation rate. Opening the air inlets caused a 40–50% increase in average ventilation rate and is more effective than doubling the mechanical ventilation rate. The latter action led to an increase of 10–20%. The relative effect of opening the air inlets increased with increasing airtightness (compare open and closed inlets for N_1, N_4 and O). Opening inner doors affects internal circulation but hardly total infiltration and ventilation rate.

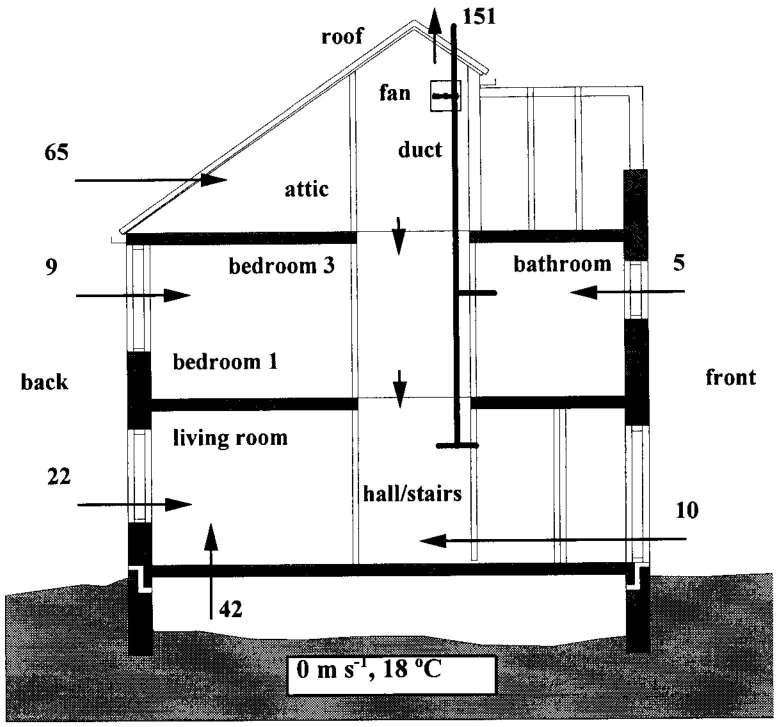


Figure 6: Air flows (m^3 h^{-1}) through dwelling N_{4h} with small temperature differences between outside and inside and no wind.

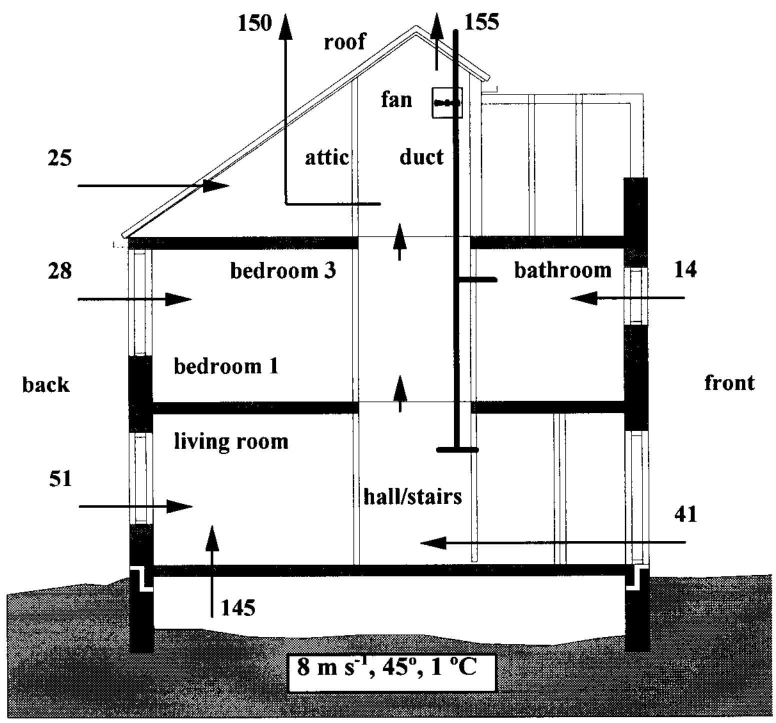


Figure 7: Air flows (m^3 h^{-1}) through dwelling N_{4h} where wind velocity is high and outdoor temperature low.

A wind velocity of 5 m s^{-1} can be considered as a mean for the Netherlands. The ventilation rates at this velocity as given in Figure 5 roughly correspond to the yearly averaged values of N_4 in Table 7.

Mechanical ventilation sets the lower limit of the ventilation rate [32]. Mechanical ventilation rates of 21 and 42 dm^3 s^{-1} result in a ventilation rate of 0.28 and 0.56 h^{-1}, respectively. The relative contribution of the mechanical ventilation in the total ventilation rate increases with increasing airtightness (Table 7) [26] and with decreasing wind velocity (Figure 5). As long as wind-driven infiltration is lower than the exhaust flow rate of the fan, the mechanical ventilation system will steer internal flows. Figure 6 and Figure 7 show an example of how flows change when the infiltration doubles due to changed weather conditions. When there is no wind, the mechanical ventilation system regulates the flows entirely. Where there is high wind pressure, mechanical ventilation contributes about 50% to the flows through the dwelling.

Generally, the effect of the weather is similar for the different variants of the dwelling: changes in wind velocity cause infiltration to change by a factor of four. The modelled variations in temperature cause changes of less than 30% (Figure 8). These results reflect measured changes in infiltration [11, 33], which show the effect of temperature to be generally much smaller than that of wind velocity. The lowest ventilation rates were found at low wind velocity, high outdoor temperature (18 °C) and low mechanical ventilation rate. Differences in ventilation rates between the houses increased with wind velocity. At high velocity, ventilation rates in dwelling O were shown to be up to 1.5 times higher than in dwelling N_4 and up to three times higher than in dwelling N_1. The last version of dwelling N corresponds to dwellings built at the present in the Netherlands, where the ventilation rate is far below 1 h^{-1} most of the time.

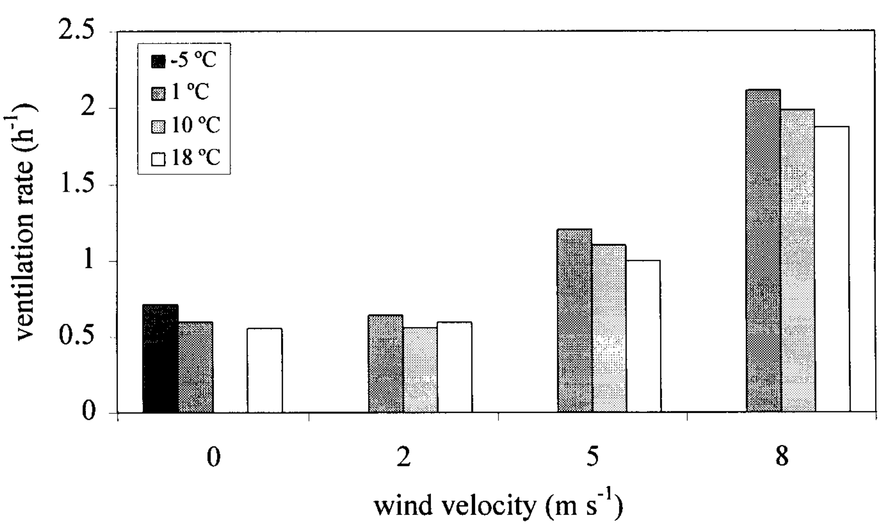


Figure 8: Ventilation rate of dwelling N_{4wh} versus outdoor temperature and wind velocity averaged over four wind directions.

Andersen *et al.* [34] observed an average air exchange rate in Danish houses of

0.37 h^{-1} (0.16–0.96 h^{-1}), which is below the minimum of 0.5 h^{-1} laid down by Danish law. Cavallo *et al.* [35] found air exchange rates between 0.25 and 0.4 h^{-1} with closed air inlets and about 1.0 h^{-1} with open air inlets in US dwellings with natural ventilation. Ventilation rates measured in Dutch dwellings with closed air inlets and ventilation openings in the winter averaged 1.2 h^{-1} (1.05–1.35 h^{-1}) for mechanically ventilated houses renovated in the eighties and 0.6 h^{-1} (0.3–0.9 h^{-1}) for naturally ventilated older houses [22]. The lower and upper boundaries of the yearly averaged ventilation rate of recently built dwellings (as derived from the second national survey on indoor radon [1]) are about 0.3 and 1 h^{-1}, respectively. These values are derived from the air flows measured in the living room. The upper boundary is derived assuming that 1) the exchange of air between the living room and other zones can be ignored and 2) the average flow is about the same for each of the zones. The lower boundary is based on the assumption that exchange between the various zones in the dwelling is so intensive that inner walls seem to be absent. For the lower boundary, measurements would represent the total infiltration was measured. Dwellings studied in the second survey on radon were built between 1985 and 1993.

The average ventilation rates from our model calculations for dwelling N correspond fairly well with recent Dutch field measurements [1], being of the same order of magnitude as for comparable dwellings studied abroad. The model estimates on old dwellings, however, tend to be higher than the above-mentioned measurements. This may be due to the fact that the measurements of Van der Wal *et al.* [22] were carried out in winter, resulting in relatively low ventilation rates.

4.3 Crawl space ventilation

As a thorough discussion of the observations for each zone and for all versions of the modelled dwelling is not within the scope of this study, the presentation of data is restricted to two zones. This section presents data on the crawl space, which is considered to be a potentially important source of indoor radon. The next section supplies data on the living room.

Table 8: Air flow (m^3 h^{-1}) through the crawl space of dwelling N_4 for three wind velocities (A), four ventilation strategies (B), and as a function of increasing airtightness of the building shell (C)

(A)		2 m s^{-1}	5 m s^{-1}	8 m s^{-1}
total air flow		64	142	245

(B)	N_{4h}	N_{4wh}	N_4	N_{4w}
yearly averaged total air flow	123	105	114	101

(C)	N_4	N_3	N_2	N_1
air flow at a wind velocity of 5 m s^{-1}	142	107	93	86

Wind velocity has the largest influence on the total amount of air entering and leaving the crawl space (Table 8A). It easily causes fluctuations of up to a factor of four. It enhances both the flow through the crawl space and that towards the ground floor. Low outdoor temperatures will cause an additional increase of the air flow through the crawl space. When changing the mechanical ventilation rate the quantity of air withdrawn from the crawl space and as a result its total ventilation rate are slightly changed (Table 8B). A 75% reduction in the leakage area of the ground floor will significantly reduce the air flow from the crawl space into the dwelling (see 4.4). As a result, the total ventilation in the crawl space may decrease by about a factor of two (Table 8C). Since the air inlets to the crawl space of dwelling O are about twice as large as those of dwelling N, its air flow will also be larger, on average, 190 $m^3 h^{-1}$. Air flows through the crawl space are markedly higher than measured during the national radon survey [1].

4.4 Air flows to the living room

The air flowing to the living room comes mainly from outside and the crawl space (Figure 9). The average contribution of air from the hall to the total air flow of the living room is less than 20% when inner doors are closed, although it may be higher under specific weather conditions. The hall contributes more than 80% to the air flow into the living room when inner doors are open.

Opening air inlets of the living room results in a larger total air flow, a larger flow from outdoors to the living room, and a smaller flow from the crawl space (Figure 9). Increasing the mechanical ventilation rate without changing the surface area of leaks results in a larger total inflow, but hardly changes the distribution between the zones of origin. Enlarging the leakage area of the ground floor leads to a larger total infiltration of the living room and a larger flow from the crawl space to the living room (Figure 10). Enlarging the leakage area of the ground floor hardly affected total infiltration of the dwelling.

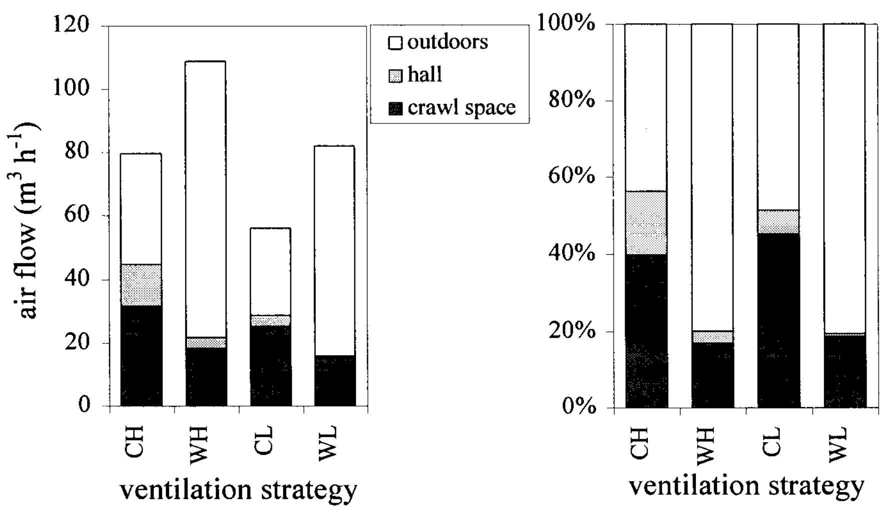


Figure 9: Absolute (left) and relative (right) contribution of three zones to the air flow through the living room in dwelling N_4 with closed (C) or open air inlets (W) and high (H) or low mechanical ventilation rate (L).

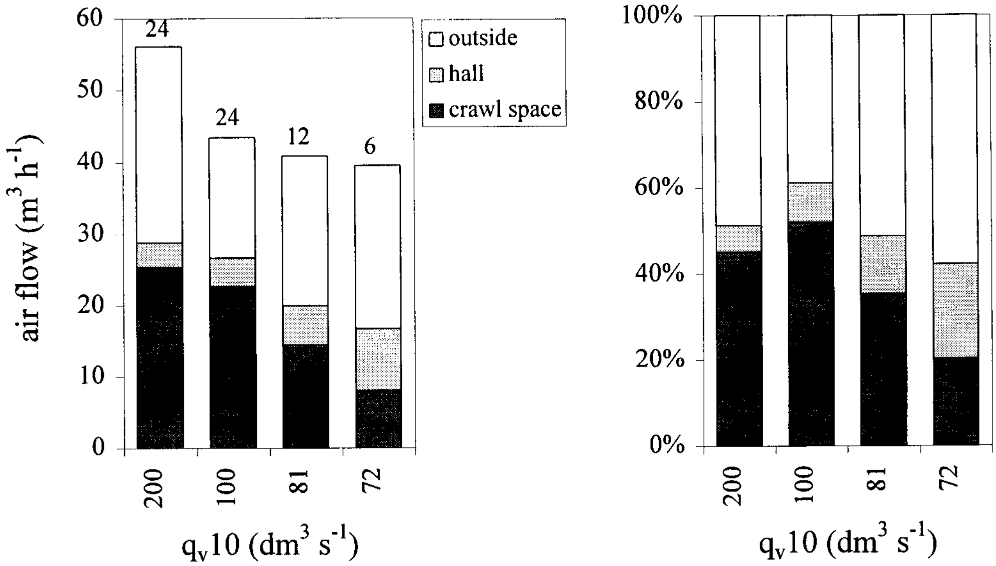


Figure 10: Absolute (left) and relative (right) contribution of three zones to the air flow through the living room in a closed dwelling N as the airtightness of the building shell increases (the leakage area in cm^2 on the ground floor shown above bars)

Changes in weather conditions cause a four-fold change in the flow from outside to the living room of dwelling N_4 (Figure 11). The same effect was observed for the crawl space (see 4.3). Furthermore, Figure 11 shows that the flow from outside to the living room for a given ventilation strategy is linearly related to the flow originating from the crawl space. Closing air inlets not only causes a 50% decrease in the flow from outdoors to the living room, but also a 50% increase in the flow coming from the crawl space, as already demonstrated in Figure 9.

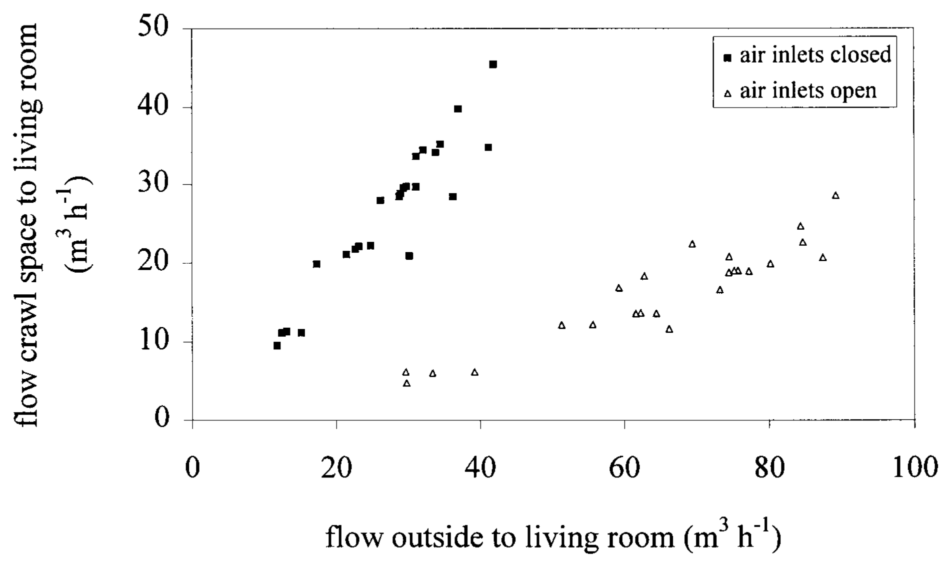


Figure 11: Flow from outdoors and crawl space to the living room of dwelling N_4 for 30 weather conditions and two ventilation strategies.

5. EXHALATION AND PRODUCTION BY SOIL AND BUILDING MATERIALS

5.1 Exhalation from soil and building materials

The radon exhalation from different walls, floors and soil was calculated for various pressures using the model RAETRAP. Exhalation from the concrete floors and walls is about the same, 2.38 mBq m^{-2} s^{-1} and 2.22 mBq m^{-2} s^{-1} respectively. Exhalation is far higher than that obtained for other materials and construction elements (Table 9). The effect of pressure differences on the radon exhalation from building materials apart from wood is negligible. The total quantity of radon originating from wooden floors is, however, insignificant compared to that from other construction elements.

The results for concrete, gypsum and sand-lime brick are in the range measured by Intron [36], yielding 0.7–2.9 mBq m^{-2} s^{-1}, 0.06–0.17 mBq m^{-2} s^{-1} and 0.2–0.6 mBq m^2 s^{-1} respectively. The values estimated with the model are 2–4 times higher than the values measured by Van Dijk & De Jong [37] yielding values of 0.6–1.0 mBq m^{-2} s^{-1} for concrete, 0.08 mBq m^{-2} s^{-1} for bricks and 0.09 mBq m^{-2} s^{-1} for gypsum. The bulk density, thickness and ^{226}Ra concentration mentioned by these authors correspond well to those in our model. The emanation fraction, however, is often somewhat lower.

Table 9: Exhalation of different sources on the inside at a dP of zero Pa and the relative effect of given changes in pressure difference on exhalation relative to the exhalation at the lowest pressure

source	thickness (m)	exhalation top (mBq m^{-2} s^{-1})	dP range (Pa)	decrease (%)
soil	1.1	9.0	-	
soil	3.0	21.1	-5 - +5	24.2
roof	0.14	0.11	-13 - 0	8.1
gypsum wall	0.07	0.42	-2.5 - +2.5	0.5
outer wall (1) *	0.3	1.64	-15 - +2.5	0.6
outer wall (2) *	0.3	0.41	-15 - +2.5	4.4
[outer wall (3) *	0.3	0.82	-15 - +2.5	5.7]
[sand-lime bricks	0.1	0.38	-2.5 - +2.5	4.4]
concrete floor	0.22	2.38	-15 - +15	0.8
wooden floor (a)	0.02	0.04	-15 - +15	49.6
wooden floor (b)	0.24	0.05	-15 - +15	36.2
inner wall (1) ✧	0.2	2.22	–	
inner wall (2) ✧	0.2	0.87	–	

* cavity wall with outer face of brick masonry and inner face of concrete (1), brick masonry (2) and sand-lime bricks (3)

✧ 20 cm of concrete (1) or sand-lime brick covered with 1 cm plaster on both sides (2)

Radon exhalation from the soil is much higher than from building materials and varies with pressure. Radon exhalation from a soil column of 3 m containing 25 Bq kg^{-1} of ^{226}Ra varies between 18.2 and 24 mBq m^{-2} s^{-1} at dPs of 5 and -5 Pa, respectively (Table 9). The average length of the soil column contributing to the radon level in the crawl space is hard to estimate, but greatly affects the exhalation non-linearly. The same holds for the moisture content of the soil column. Pressure differences considerably affect radon exhalation from soil and thus may affect the radon concentration in the dwelling by changing the radon concentration in the crawl space.

Assuming a dry soil column of 3 m maximizes the radon exhalation for the middle compartment of the soil. In the Netherlands the water table will often be above -3 m, which reduces the permeability and the exhalation from the saturated column [12].

A large number of parameters are used to estimate radon exhalation (see Appendix 5) [14]. Discrepancies in exhalation rates are probably caused by differences in parameters such as ^{226}Ra content, emanation fraction, thickness and porosity [38, 39]. Differences for these parameters may explain the difference between the model estimations presented in Table 8 and quoted measurements. Because of the low permeability of most building materials, it is often assumed that advective transport of radon produced in building materials will be of minor importance and diffusion the only transport mechanism [38]. The model estimations reflect these assumptions: the exhalation rate is relatively insensitive to pressure differences.

As the total volume of concrete within a new dwelling is larger than that of the other building materials (Table 6) and as its radon exhalation rate is much higher (Table 9), concrete contributes most to the total radon exhalation in the dwelling. Changes in dPs over floors and walls hardly alter radon exhalation. Weather conditions and ventilation will thus affect radon concentrations more likely through changes in dP-driven air flow than through changes in exhalation. However, the weather conditions may affect the radon concentration in the dwelling by changing the radon exhalation from the soil.

5.2 Radon production in the dwelling

Radon production in the dwelling depends on the building materials used and on the characteristics of the underlying soil. Radon production from building materials is relatively constant as exhalation does not vary much with weather conditions (see 5.1). Exhalation from all building materials resulted in an entry rate of 3.2 kBq h^{-1} for dwelling N and 0.6 kBq h^{-1} for dwelling O. Radon production per zone is highly variable and depends on the materials and the surface area of the walls (Table 10). Average radon production in the living room is 0.9 kBq h^{-1} for dwelling N and 0.2 kBq h^{-1} for dwelling O, where wood substitutes for concrete in floors and ceiling.

Using the radon production of the soil (Table 9) and the surface area of the crawl space (40.8 m^2), the radon entry rate from the underlying soil varies between 3.5 and 2.7 kBq h^{-1}. The average entry rate for both dwellings is 3 kBq h^{-1}.

A radon entry rate from building materials of 1-3 kBq h^{-1} was estimated in a study of Danish single-family houses [34]. It is slightly lower than the value estimated for dwelling N. Based on measurements of air flows and radon concentrations Stoop *et al.* [1] estimated the average radon source strength in the living room of new Dutch dwellings to have a maximum of 1.9 kBq h^{-1}. Using average surface areas of building materials in sample dwellings and radon exhalations measured in the lab, they calculated an entry rate of 0.3 to 1.1 kBq h^{-1}. The estimate for the living room of dwelling N (0.9 kBq h^{-1}) fits into this range.

Table 10: Average radon production in building materials in different zones of the new (N) and old (O) dwellings

	average total production ($Bq\ h^{-1}$)		average production per volume ($Bq\ h^{-1}\ m^{-3}$)	
	dwelling N	dwelling O	dwelling N	dwelling O
living	872	159	11.4	2.1
attic	445	94	7.3	1.6
crawl space*	450	45	18.4	1.8
hall/stairs	156	46	10.6	3.1
toilet	47	18	19.3	7.2
cupboard	46	9	28.9	5.8
landing	121	34	19.8	5.6
bedroom 1	345	77	11.6	2.6
bedroom 2	271	57	11.9	2.5
bedroom 3	284	62	14.9	3.2
bathroom	182	41	13.5	3.1
total	3219	642	–	–

* production from building materials only. The average production of the soil is about 3000 Bq h^{-1}.

6. INDOOR RADON CONCENTRATIONS

Indoor radon concentrations are determined by various sources. Soil and building materials are the major sources, the overall size of which was given in the previous sections. Outdoor air contributes to a minor extent. How this radon is distributed among the different zones of the dwelling depends on the production site, and on the size and direction of the air flows in the dwelling. It is obvious that the radon efflux is entirely determined by the ventilation.

In this chapter we will first summarize the estimates of the average radon concentrations in both dwellings and major differences between them. Subsequently, we will discuss in more detail the contribution of the crawl space to the indoor radon concentrations, radon in relation to the ventilation of the living room and the relative importance of the different sources of radon for the radon concentration in the living room.

6.1 Average indoor radon concentrations

The average radon concentration in the various zones varies between 14 and 123 Bq m^{-3} in dwelling N and between 5 and 31 Bq m^{-3} in dwelling O. Average concentrations in the living room vary between 18.7 and 54.5 and between 9.6 and 16.1, respectively (Table 11).

Table 11: Average ^{222}Rn concentration in the living room for different ventilation strategies

dwelling type	air inlets open (Bq m^{-3})	inner doors open (Bq m^{-3})	all closed (Bq m^{-3})
O_c	9.6	14.8	13.2–16.1
N_{4h}	18.7	31.8	32.2
N_4	23.2	nd*	40.2
N_3	26.6	51.7	51.9
N_2	24.2	54.5	53.2
N_1	21.4	51.8	51.4

*nd= not determined

The radon concentration is less variable in dwelling O than in dwelling N and the average is much lower. Differences in radon production (see 5.2), airtightness of the building shell (Table 3) and variability in the ventilation rate (Table 7) are major causes of these differences between O and N. The estimated concentrations for the living room correspond quite well with the concentrations mentioned in Stoop *et al.* [1] for the period of 1950–1970 (17–19 Bq m^{-3}) and for the period after 1980 (28–31 Bq m^{-3}).

6.2 Radon concentration in the crawl space

Average radon concentrations in the crawl space vary between 40.2 and 101 Bq m^{-3} in dwelling N, and between 26 and 29 Bq m^{-3} in dwelling O. Soilborne radon contributes to about 80% of the radon concentration in the crawl space for dwelling N and to about 90% in dwelling O. The average radon production in the crawl space of both dwellings differs by less than 15 % (Table 10). Differences in concentrations are thus mainly determined by the quantity of air flowing through the crawl space. A difference of factor 2 in surface area of the air inlets of the crawl space and to a minor extent differences in the ventilation regime of the dwelling explain the difference in flow rate (see 4.3).

Table 12: Average radon concentration in the crawl space of N_4 for three wind velocities (A), four ventilation strategies (B) and as a function of increasing airtightness of the building shell (C)

(A)		$2\ m\ s^{-1}$	$5\ m\ s^{-1}$	$8\ m\ s^{-1}$
radon concentration (Bq m^{-3})		64.8	26.0	10.5

(B)	N_{4h}	N_{4wh}	N_4	N_{4w}
radon concentration (Bq m^{-3})	40.2	50.0	46.5	53.4

(C)	N_4	N_3	N_2	N_1
radon concentration (Bq m^{-3})	46.5	52.1	69.6	82.7

Wind velocity has the largest effect on the radon concentration in the crawl space. When the velocity increases from 2 to 8 m s^{-1}, the air flow through the crawl space increases by a factor of four (Table 8), causing an 85% decrease in radon level (Table 12). The ventilation regimes with open air inlets in the living room show a lower total air flow through the crawl space and a higher radon concentration. This is explained by a decreased air flow from the crawl space to the ground floor when air inlets are open. Reducing the leakage area of the ground floor by 75% increases the radon concentration of the crawl space by a factor of about two. The net result of reducing the leakage area on the ground floor on the radon entry from the crawl space will thus depend on the ratio of the flow reduction and the increase in radon concentration in the crawl space. This will be discussed in the next section.

6.3 Indoor radon concentrations and soil gas radon

From the data on radon production (see 5.2) it is obvious that in dwelling N, 50% of all indoor radon at most is soilborne and in dwelling O this can reach 90%. The contribution of soilborne radon to the radon concentration of a zone depends on the amount which enters the building and on the zone considered.

Radon exhalation from the soil is set at zero to estimate the contribution of soilborne radon to the radon concentrations of various zones. The relative contribution of soil gas radon to the indoor radon concentration is generally larger in dwelling O than in dwelling N (Table 13). Between 30% and 43% of the radon in the living room of dwelling N_4 comes from the soil; in dwelling O this is 54% to 70%. A higher relative contribution in dwelling O can be attributed to larger leaks in the ground floor and a smaller production from building materials. We will come back to the importance of soil gas radon for the radon level in the living room when discussing calculations for this zone (see 6.5).

Table 13: Relative contribution of soilborne radon to the radon concentration of the living room for various ventilation strategies for dwellings N_4 and O

dwelling	soil contribution	dwelling	soil contribution
N_{4h}	0.42	O	0.61
N_4	0.39	O_c	0.62
N_{4dh}	0.43	O_c'	0.63
N_{4wh}	0.32	O_{cd}	0.70
N_{4w}	0.30	O_{cw}	0.54

The contribution of the soilborne radon generally decreases with floor level. Similar results were obtained by Albering *et al.* [40], who indicated that there is a gradient in indoor air radon concentration from basement to upper floor level. Some zones, such as the bedrooms show a smaller percentage of radon originating from the soil than the other zones on the same floor level, which can be attributed to the relatively small exchange with neighbouring zones when doors are closed (Table 14). Zones with a high exchange, such as the landing and the attic, show a relatively large contribution in the crawl space.

Table 14: Relative contribution of soilborne radon in various zones of dwellings N_4 and O_c when doors and air inlets are closed

	N_4	O_c		N_4	O_c
crawl space	0.81	0.87	landing	0.36	0.70
hall	0.39	0.78	bedrooms	0.00	0.11
toilet	0.69	0.78	bathroom	0.29	0.47
living	0.39	0.62	attic	0.34	0.67

6.4 Radon concentration in the living room and ventilation

Dilution with outdoor air is generally considered as an important mechanism in reducing radon concentrations inside [41]. Generally, air flow from outside contributes the most to the total air flow into the living room (Figure 9) and the radon concentration in the living room clearly relates to this component of total air flow (Figure 12 and Figure 13). When the infiltration is low ($< 0.3\ h^{-1}$) radon concentrations of 50 Bq m^{-3} and higher are observed, whereas at ventilation rates above 1.2 h^{-1}, radon concentrations are generally lower than 20 Bq m^{-3} for both dwellings. Variations in the radon concentration of the living room at a given infiltration are related to changing contributions of other sources as the radon production by the building materials in the living room is constant.

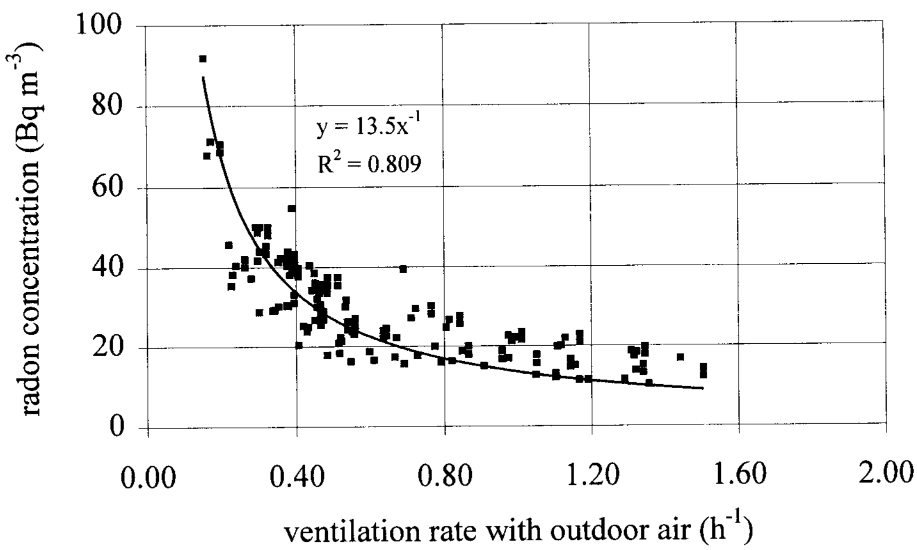


Figure 12: Radon concentration in the living room of dwelling N_4 as a function of ventilation with outdoor air for all weather conditions and ventilation strategies

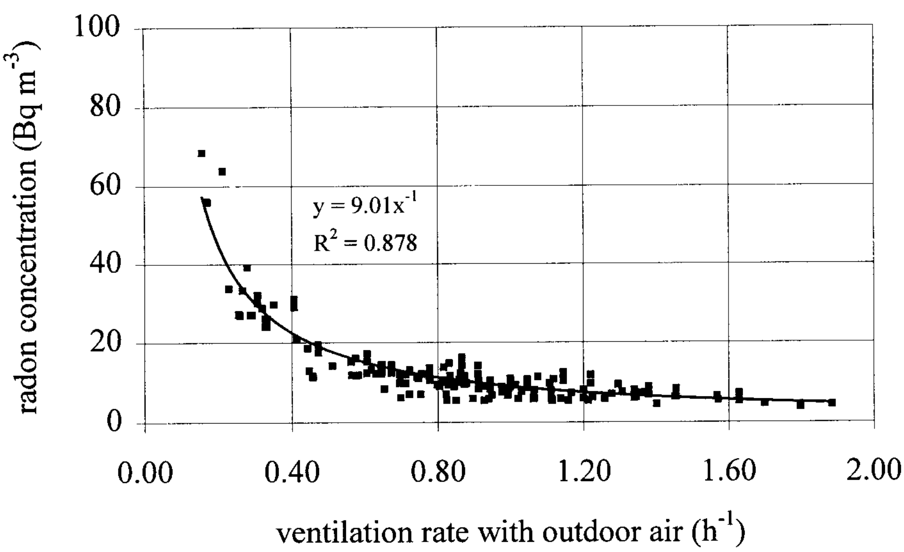


Figure 13: Radon concentration in the living room of dwelling O as a function of ventilation with outdoor air for all weather conditions and ventilation strategies.

When radon enters at a fixed rate [41], for example, through exhalation from building materials, the concentration can be described by the equation:

$$C = \frac{S_v}{V * \lambda} \qquad (4)$$

in which

- C = radon concentration (Bq m^{-3})
- S_v = radon entry rate (Bq h^{-1})
- V = volume of the zone (m^3)
- λ = ventilation rate (h^{-1}).

Fitting this equation to the data results in $C = 13.5/\lambda$ ($R^2 = 0.809$) for the dwelling N_4 and in $C = 9.01/\lambda$ ($R^2 = 0.878$) for dwelling O. The corresponding radon entry rates in the living room ($V = 76.5\ m^3$) are 1033 Bq h^{-1} and 689 Bq h^{-1}, respectively. The radon entry rate is thus higher for dwelling N_4 than for dwelling O. The radon production from the building materials in the living room is very different for each dwelling, i.e. 872 and 159 Bq h^{-1}, respectively (see 5.2), and is a main reason for the difference in entry rate. The largest difference between estimated entry rate and radon production from building materials in the living room is for dwelling O. Obviously radon production in dwelling O is less important in determining the radon concentration than in dwelling N. Radon entry from other sources such as the crawl space thus plays a more significant role in dwelling O.

6.5 Sources of radon in the living room

The radon concentration in a specific zone depends on its production from the building materials in that zone, and on the exchange between neighbouring zones (air flows from and radon concentration in neighbouring zones). The contribution of each source to the radon concentration in the living room was determined for a variety of situations. Radon in the air flowing from zone X (e.g. crawl space) via zone Y (e.g. hall) into the living room is attributed to zone Y. In this section the relative effect of changes in ventilation strategy, in airtightness of the building shell or the ground floor and in building materials for the average relative importance of the various sources of radon in the living room will be discussed. The variation induced by changing weather conditions will be discussed in the next section.

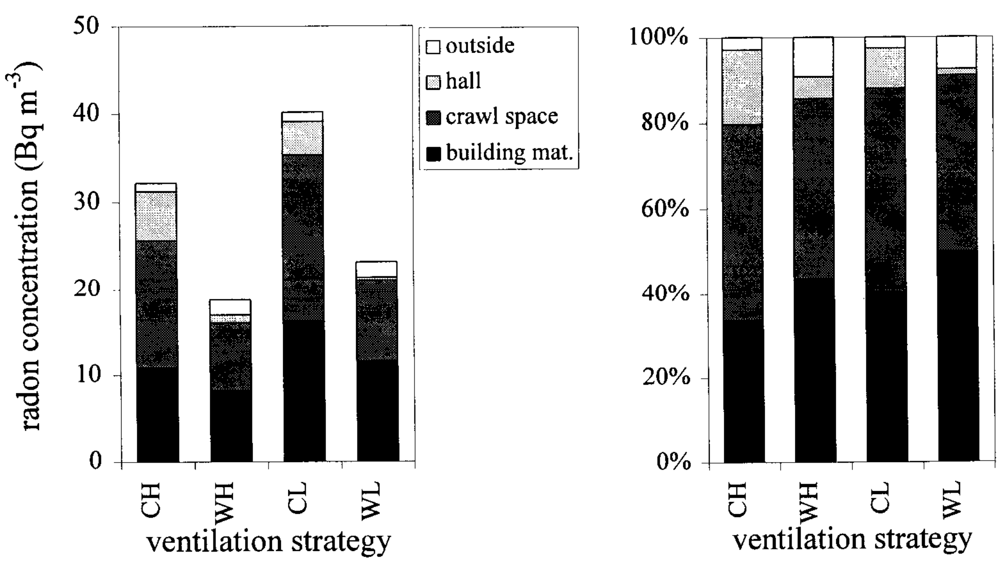


Figure 14: Absolute (left) and relative (right) contribution of four radon sources to the radon concentration in the living room in dwelling N_4 with closed (C) or open air inlets (W) and high (H) or low mechanical ventilation rate (L).

Opening all air inlets cause an increase in the leakage area of the building shell of dwelling N_4 from about 200 to 690 cm^2, which results in a larger infiltration (see Figure 9) and a 40% decrease in radon concentration irrespective of the rate of mechanical ventilation (Figure 14). And increasing the mechanical ventilation rate reduces the average radon concentration in the living room by 20%.

The average relative contributions of outdoor air and production increase by opening the air inlets (from 3 to 9 % and from 37 to 47 %, respectively), whereas contributions in the crawl space and the hall decrease from 48 to 42% and from 13 to 3 %. The smaller contribution in the crawl space is more likely due to a smaller flow towards the living room than to a lower radon concentration in the crawl space (see Table 8 and Table 12). When air inlets are opened, the fan will furthermore withdraw less air from the hall and more from outdoors, explaining a decreased contribution from the hall (and other zones in the dwelling).

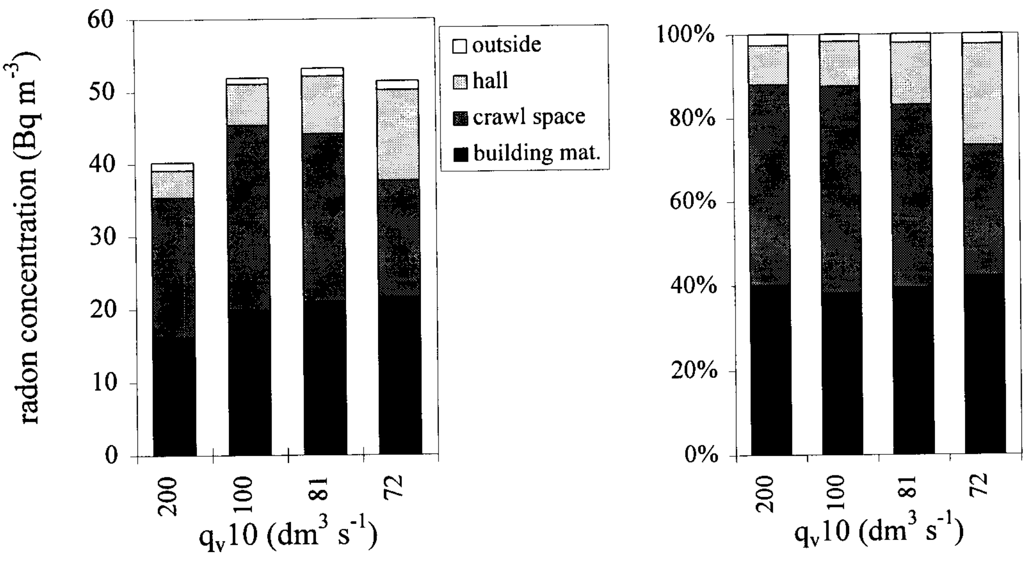


Figure 15: Absolute (left) and relative (right) contribution of four radon sources to the radon concentration in the living room in dwelling N with closed air inlets as the airtightness of the building shell increases.

Increasing the $q_v(10)$ (from 100 to 200 $dm^3\ s^{-1}$), but maintaining the floor leakage area at 70 cm^2 results in a 20 % lower radon concentration in the living room (Figure 15). However, this hardly affects the relative importance of the various sources.

Reducing the leakage area of the floor in the living room from 24 cm^2 to 12 cm^2 and subsequently to 6 cm^2 resulted in limited changes in the radon concentration in the living room; however, the contribution of the various sources markedly changed. That in the crawl space decreased from 49 to 31%, reflecting the net effect of a decreased air flow from and an increased radon concentration in the crawl space. A decreasing contribution from the crawl space is compensated by a larger one from the hall reflecting a comparable shift in air flows (Figure 10). As a result of the smaller air flow through the living room (Figure 10) the contribution of the radon production from the building materials increased slightly (from 38 to 40%).

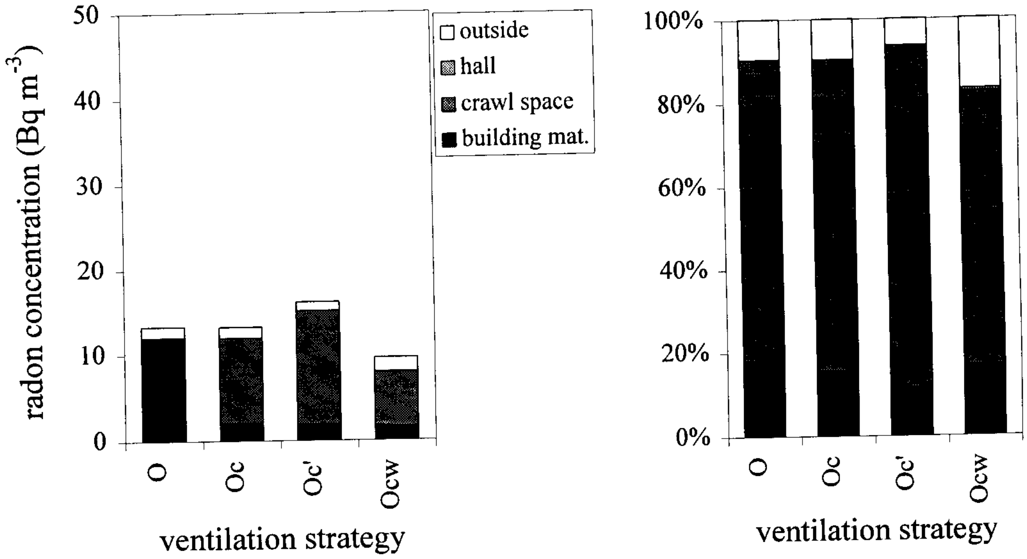


Figure 16: Absolute (left) and relative (right) contribution of four sources of radon to radon levels in the living room of dwelling O for various ventilation strategies.

The average radon concentration in the living room of dwelling O (Figure 16) is considerably lower than that of dwelling N. The lower concentration is due to the higher average ventilation rate (Table 7), the lower ^{226}Ra content of the building materials of dwelling O (Table 6) and the lower input of radon from the crawl space (see 4.3 and 6.2). If dwelling N has a comparable ventilation rate for the living room (N_{4wh}= WH in Figure 14) to dwelling O (O or O_c), the concentration in dwelling O still is about 30% lower, a difference which is mainly due to a difference in radon production from the building materials of the living room.

The crawl space is the major source of radon in the living room for all versions of dwelling O. In dwelling N the absolute contribution of radon from the crawl space is, however, mostly larger than in dwelling O. This is different from what is observed in the field [1]. This difference is most probably due to a still somewhat unrealistic distribution of leaks over the building shell. Contributions from the crawl space seem to be comparable to or smaller than those for dwelling O in calculations for the most airtight versions of dwelling N (N_1 and N_2) when air inlets are open.

The contribution from the hall is negligible in dwelling O (Figure 16). A larger contribution of radon from the hall in dwelling N compared to O is the combined effect of a more airtight building shell and the presence of a fan extracting air from the hall when air inlets are closed.

6.6 Variations induced by changing weather conditions

The average effect of a changing ventilation strategy or airtightness has been documented in the previous section. Variations induced by changing weather conditions will be dealt with in this section. Radon concentrations vary between 10 and 160 Bq m^{-3} in the crawl space of dwelling $N_{4(w)}$ and between 18 and 90 Bq m^{-3} in its living room as a result of changes in weather conditions (Figure 17). Radon concentrations in the crawl space and the living room have been positively correlated. Analysis of underlying data shows that this correlation can be mainly attributed to correlated changes in ventilation rate – driven by wind velocity – and not to a higher flux from crawl space to living room at high radon levels in the crawl space. Closing the air inlets enhances the flux from the crawl space (see Figure 11), resulting in a steeper slope for this ventilation strategy.

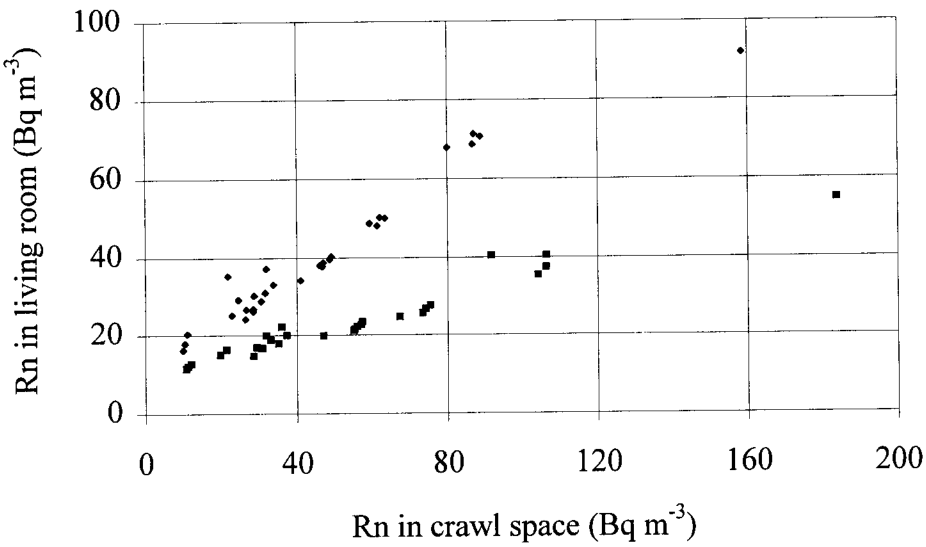


Figure 17: Relationship between the radon concentration in the living room and in the crawl space of dwelling N_4 when air inlets are open(■) or closed(♦).

Changes in weather conditions not only induce a five-fold change in radon level in the living room but also marked changes in the relative contribution of the various sources of radon (Figure 18). Variation in radon concentration decreased with increased mechanical ventilation in most zones, but increased with opening of the air inlets. Variation was shown to be higher in the old dwelling than in the new dwelling. The increased variation can be attributed to the relatively larger contribution of the uncontrolled infiltration in the old compared to the new dwelling, and a larger contribution of natural ventilation in the dwellings with open air inlets.

Weather conditions characterized by low wind velocities and high temperatures (0 or 2 m s^{-1}, 18 °C as on the left-hand side of Figure 18) result in a relatively low ventilation rate, the lower limit of which is set by the mechanical ventilation system. Under these conditions the mechanical ventilation system in the living room generates an air flow from the hall to the living room and thus a contribution from that zone. The air flow from the crawl space is low under these circumstances, but its radon concentration is high, which still results in a considerable contribution from the crawl space.

High wind velocities (right hand side of Figure 18) result in lower radon levels in the crawl space but larger flows towards the living room. As a result, the contribution from the crawl space will decrease slightly with increasing wind velocity . The relative contribution of radon produced from the building materials of the living room increases from 24% at low wind velocity to about 65% at the highest velocity.

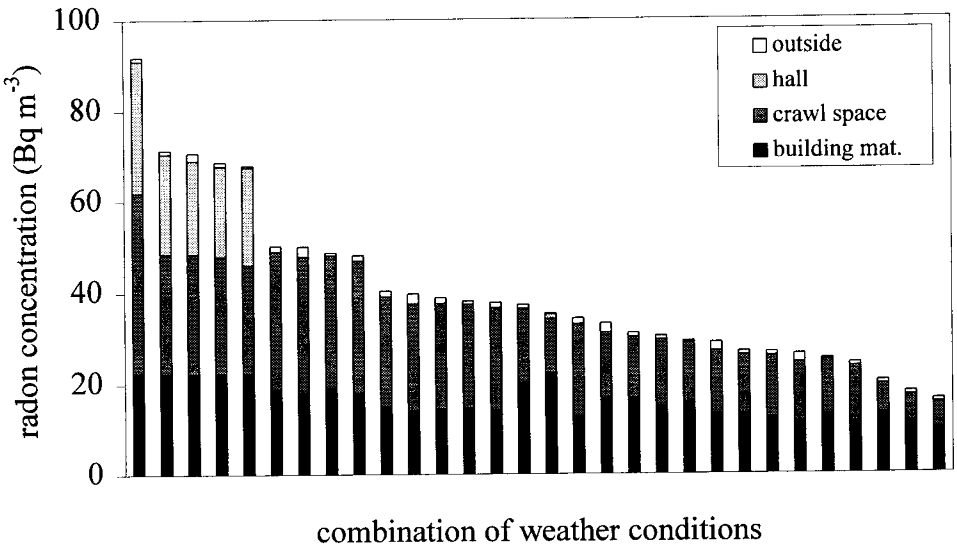


Figure 18: Contribution of four sources to the radon concentration in the living room of dwelling N_4 for 30 combinations of weather conditions arranged from the highest to the lowest radon concentration. The selection roughly equals increasing wind velocity.

6.7 Differences between zones

Differences in radon concentration between zones are largest when air inlets are open (N_{4w}, N_{4wh}, O_{cw}), and smallest when inner doors are open (N_{4dh}, O_{cd}). Radon concentrations in the living room of dwelling N_4 vary by a factor of five irrespective of the air inlets being open (e.g. Figure 18). Variation in the radon concentration in the bedrooms, however, may increase from 8-fold to 18-fold when air inlets are opened. This may be attributed to the fact that a mechanical ventilation, which sets the lower limit of air flow, is present in the living room but not in the bedrooms. Infiltration into the bedrooms is largely determined by uncontrolled entry through cracks and openings and by controlled exchange through open doors or open inlets. Opening the air inlets reduces the radon concentration in zones with air inlets, whereas there is still a build-up of radon in neighbouring zones with closed doors and closed air inlets. In contrast, opening inner doors increases circulation resulting in comparable concentrations in connected zones. These differences are not reflected in the average concentrations, which showed larger differences between the zones when air inlets were closed (Figure 19). It thus is difficult to generalize on the ventilation strategy resulting in the lowest concentrations, as it entirely depends on the zone considered, and more specifically, on the air flux to and from that zone (Table 15). The results indicate the negative effects of increasing airtightness on infiltration and thus on radon concentration. Especially in airtight dwellings, a combination of mechanical ventilation and opening the air inlets will be necessary to reduce radon concentrations in the various zones.

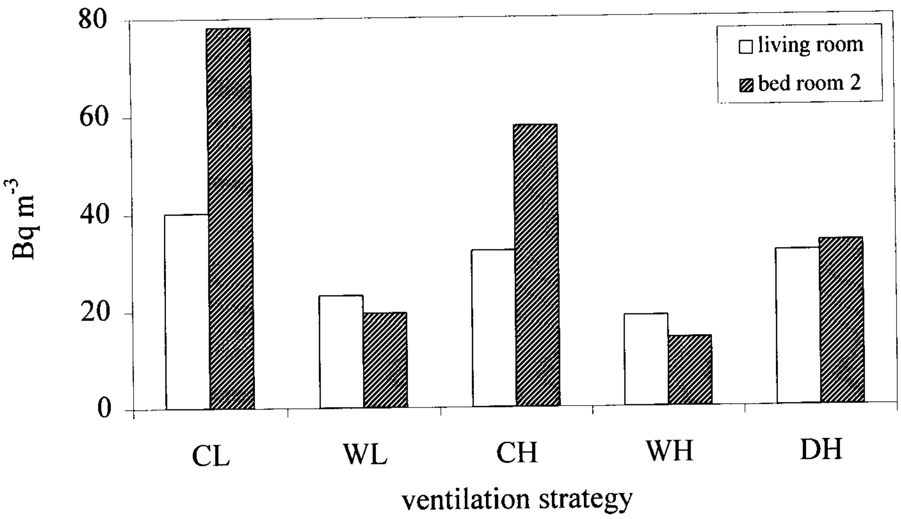


Figure 19: Average radon concentration in the bedroom and the living room of dwelling N_4 where air inlets or inner doors are open (W and D) or closed(C), and when the ventilation rate is high (H) or low (L).

Table 15 shows the large effect of weather conditions on the radon concentration in the hall. At high wind velocity air flow through the hall is about one and a half times larger than under conditions without wind. However, total air flow in the hall is mainly determined by exchange with the landing. Air flow from outdoors increases by 4-9-fold which reflect the 2-9-fold reduction in radon concentration (see also Figure 7 for CH).

The effect of mechanical ventilation on radon concentration is mainly visible in the meteorological conditions without wind and 18 °C. When mechanical ventilation is low (CL, WL) net exchange with the landing is low and air flow from outdoors is reduced by 25-40%. Radon concentrations are almost two-fold higher when the mechanical ventilation rate is low (CL, WL).

High mechanical ventilation does not result in lower concentrations at high infiltration (NE wind 8 m s^{-1}; temperature 1 °C) but opening the air inlets does. In this situation total air flow does not differ much from the other situations, but air flow from the living room (with open air inlets) is much higher and air flow from the crawl space is much lower than when air inlets are closed. The radon concentration in the air from the living room is low compared to that for air-inlet closed conditions.

In general, the model results show that (mechanical) ventilation is an important tool in setting the lower limit to the ventilation rate and thus in limiting the build-up of radon. However, if the natural inflow of air is not large enough, air may be attracted from neighbouring zones with higher radon concentrations.

Table 15: Radon concentration, relative pressure and air flow in the hall of dwelling N_4 for two combinations of weather conditions, when air inlets or inner doors are open (W and D) or closed (C) and when the ventilation rate is high (H) or low (L)

ventilation strategy	no wind, 18 °C			NE wind 8 m s^{-1}, 1 °C		
	radon conc. (Bq m^{-3})	pressure (Pa)	air flow (m^3 h^{-1})	radon conc. (Bq m^{-3})	pressure (Pa)	air flow (m^3 h^{-1})
CH	35.2	-1	153.3	14.5	-10.4	232.8
CL	68.1	-0.4	133.9	12.3	-9.4	246.0
WL	77.2	-0.2	126.0	9.4	-6.1	237.0
WH	42.5	-0.3	138.0	8.8	-6.3	237.0
DH	43.3	-1.1	435.0	15.2	-10.3	525.0

7. EXTERNAL RADIATION EXPOSURE

The volumes and materials constituting the walls, floor and ceiling were digitized, using the floor plan and list of building materials from Chapter 3 to facilitate the calculation of the dose rate in the living area on the ground floor of the model house. Exhalation of ^{222}Rn from the building materials, i.e. a gradient of the remaining ^{222}Rn and decay products, was not considered. As major contributors to the dose rate from external radiation, ^{214}Pb and ^{214}Bi were selected for the calculation. However, these radionuclides only contribute some 20-30% to the external dose from building materials. Other radionuclides of importance are ^{40}K and some radionuclides from the ^{232}Th series. Because the focus is on radon, these will not be further considered here.

Two cases were evaluated:

(a) a dwelling where the main inner walls, floors and ceilings are made of concrete, the outer walls at the back and the front of the house of brick and the secondary inner walls of gypsum or aerated concrete blocks (dwelling N) and

(b) a dwelling where all main walls are brick, floors and ceilings wood and secondary inner walls, gypsum or aerated concrete blocks (dwelling O).

Because of the structure of a dwelling (windows, doors, staircase, crawl space, cavities etc.) the ground floor was partitioned into a large number of smaller more uniform building blocks to support the Monte Carlo integration over the total source volume. In addition to the building materials, the soil outside and below the house, and the air inside, outside and in the crawl space were also taken into account. However, the air was not incorporated as a source volume, i.e. external radiation from radionuclides in the air was not calculated. Furthermore, the dose equivalent rate was calculated for a height of 1 m above ground, which is a standard height for human exposure in an external radiation field and for a large number of locations on the ground floor; this makes a more general evaluation easier.

Figure 20 presents the results of dwelling N. Several observations can be made (see also Table 16). As might be expected, the proximity of windows and doors reduces the dose rate considerably, even when external radiation from the soil outside is taken into account. In contrast, the concrete walls give rise to higher than average dose rates. The secondary inner walls (bottom right in the figure) result in lower than average dose rates due to their lower content of radioactivity and because they act as a shield for the external radiation from the main, concrete, walls. The smaller patches near the walls and in the centre of the living room are not significant in view of the standard deviation (up to 2 nSv h^{-1} in these patches against less than 1 nSv h^{-1} everywhere else) in the dose rate due to the limited number of Monte Carlo simulations. The average dose rate over the total area of the ground floor is 19.5 ±1.3 nSv h^{-1}.

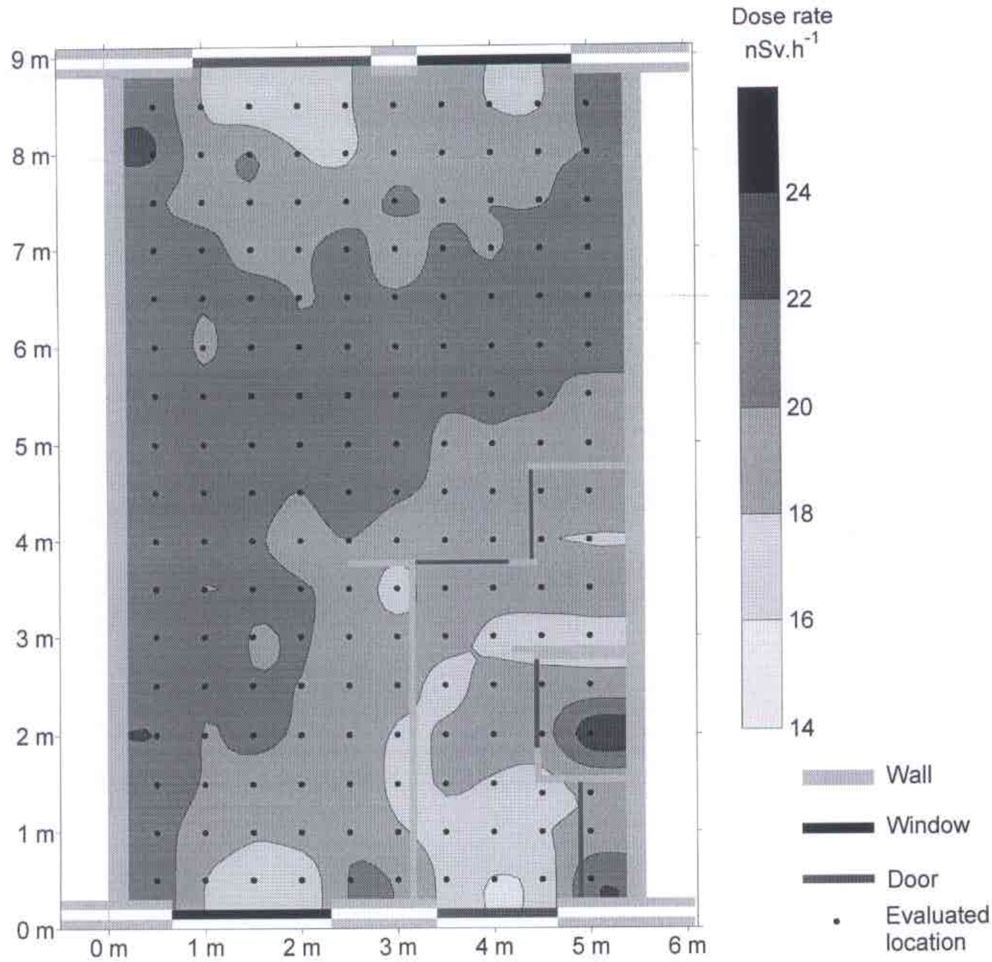


Figure 20: Dose equivalent rate 1 m above the ground floor of dwelling N due to external radiation from ^{214}Pb and ^{214}Bi in the building materials as modelled with MARMER. Values to the right of the figure represent the scale (m).

Results of dwelling O are presented in Figure 21 (see also Table 16). The effect of the wooden floor and ceiling on the dose rate is conspicuous. In contrast, the brick walls give rise to higher than average dose rates. However, they affect dose rate only up to 1 m into the room. The secondary inner walls are almost invisible, as far as dose rate is concerned because their content of radioactivity matches that of the floor and ceiling. The smaller dark patches near the walls are again not significant in view of the standard deviation (up to 2 nSv h^{-1} in these patches against less than 0.5 nSv h^{-1} everywhere else) in the dose rate due to the limited number of Monte Carlo simulations. One other interesting observation pertains to the effect of the soil. The absolute contribution from soil, as far as external radiation from radon decay products is concerned, is fairly constant throughout the house. This means that the floor does not shield this radiation and dose rate inside the house is affected by the soil beneath it. The average dose rate over the total area of the ground floor is 17.4±3.3 nSv h^{-1}.

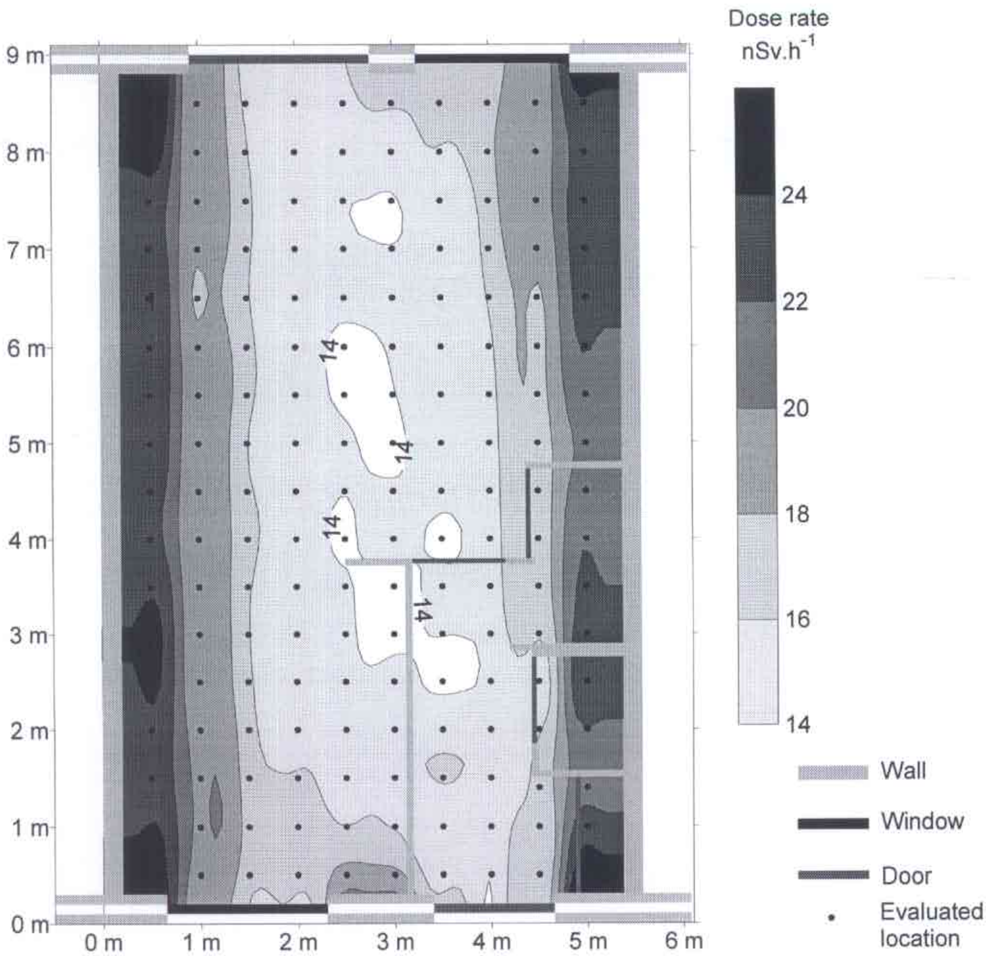
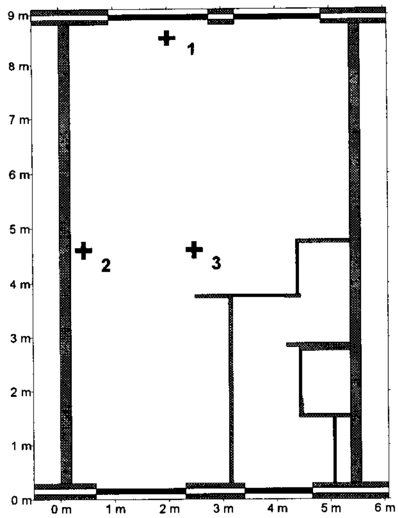


Figure 21: Dose equivalent rate 1 m above the ground floor of dwelling O due to external radiation from ^{214}Pb and ^{214}Bi in the building materials as modelled with MARMER. Values to the right of the figure represent the scale (m).

Table 16: Major dose-contributing constructions for three locations indicated in the accompanying figure

location	dwelling N	dwelling O
1	32% floor	30% left wall
	25% ceiling	18% inner wall back
	14% left wall	17% soil
	13% outer wall back	15% outer wall back
	8% right wall	15% right wall
	7% inner wall back	
2	43% left wall	75% left wall
	27% floor	9% soil
	21% ceiling	7% right wall
3	39% floor	36% left wall
	29% ceiling	24% right wall
	15% left wall	19% soil
	9% right wall	



Supplement to Table 16. The back of the dwelling is the top of the figure.

The major difference between the two cases evaluated is the impact of floor and ceiling, first because they contain more radioactivity in the case of concrete, and second, because for concrete they shield the external radiation from the soil beneath the house. For new dwellings soil is not expected to be of any importance for dose rate indoors due to external radiation. It can be concluded that the dose rate averaged over the total area of the ground floor of dwelling N is about 10% higher than that of dwelling O.

8. Discussion, conclusions and recommendations

The database system designed to communicate between various submodels on external irradiation and radon transport in dwellings proved to be a valuable tool for the analysis and management of the large data sets generated in these modelling exercises. Communication between scientists of various disciplines, such as structural engineers and applied nuclear physicists, was improved by choosing integration of submodels operated by specialists in the field.

Furthermore, the integrated model proved to be useful to identify the relative importance of the different factors determining radon transport in dwellings, to simulate observed trends in indoor radon concentration and to compare exposure to radon with external irradiation. Conclusions on each of these aspects will be discussed in the following sections.

8.1 Factors determining radon transport and concentration

Uncontrolled leakage

Ventilation, a first major factor determining radon transport and concentrations, is a combination of three components, the distinction of which has been demonstrated to be important: uncontrolled leakage, related to the airtightness of the building shell, natural ventilation through doors and windows and mechanical ventilation. Both natural and mechanical ventilation depend on occupational behaviour.

It is well known that increasing the energy efficiency and thus airtightness of buildings will generally lead to higher concentrations of pollutants such as radon [22, 42]. An increase in radon concentrations in relation to increased airtightness of new buildings was already observed by Put *et al.* in 1985 [29]. In new airtight dwellings, variations in radon concentration induced by changes in weather conditions will also be less than in old dwellings because of a decreased influence of uncontrolled leakage.

Furthermore, the distribution of leaks over the building shell has been shown to be very important. Model estimations by De Gids & Phaff [32] demonstrate that a distribution of 20:80 between walls and roof has resulted in an infiltration almost twice as high as the distribution of 10:90. The distribution of leaks was demonstrated in this study to be especially important for the flow of radon from crawl space to living room. Cracks in other floors than the ground floor hardly affect indoor radon levels, explained by the fact that 1) differences in average radon level between rooms are low and 2) the resulting additional flows between rooms are small compared to regular flows via interconnecting doors and the staircase.

As a result of the increased airtightness during the last two decades the infiltration from the crawl space has decreased, resulting in a lower contribution from the soil to the indoor radon concentration. The total ventilation of the crawl space has decreased as well, resulting in higher radon concentrations. The results indicate that care should be taken not to increase the airtightness of the walls and the roof relative to that of the ground floor.

Natural ventilation

It is obvious that the ventilation behaviour of the inhabitants has a major influence on the pollutant concentrations [32, 22]. Our results show that as a result of the increased airtightness, the relative influence of occupant behaviour on ventilation, i.e. by opening air inlets and doors or by changing the mechanical ventilation rate, has increased considerably. The model simulations indicate the range of possible indoor radon concentrations which may be observed in reality due to different ventilation strategies. Air inflow, however, also depends heavily on weather conditions. This is obvious from the fact that the highest indoor radon concentrations occur when the time-averaged indoor/outdoor pressure difference is zero. Air exchange is therefore very small, whether air inlets and doors are opened or not.

Furthermore, air inflow mainly affects the radon concentration in zones in which air inlets are present. Air exchange with neighbouring zones (e.g. through cracks) is critical in determining the radon concentration in zones in which no air inlet is present. Open inner doors tend to increase internal circulation, as measured by De Gids and Phaff [32], for example, and to level out radon concentrations throughout the dwelling [8]. However, this does not change the total amount of radon inside the model dwelling as open doors do not affect the total ventilation rate.

Mechanical ventilation

Mechanical ventilation is shown to set the lower limit to the ventilation rate and dictates the air flow pattern when natural ventilation is low, which is apparent from measurements also [32]. Cornelissen and De Gids [26] indicated that air flow due to mechanical ventilation decreased only slightly with decreasing airtightness of the building shell, whereas natural ventilation showed a large decrease. Furthermore, increasing the mechanical ventilation rate will reduce the radon level but does not affect the relative importance of the various sources of radon.

Our data also show large differences between the different zones of the model dwelling related to the presence of a fan. The effect of mechanical ventilation in zones without exhaust is negligible. Ventilation of such zones is entirely dictated by the uncontrolled ventilation through cracks and the controlled ventilation through opening air inlets or doors.

Building materials

Pressure differences have relatively small effects on radon exhalation from building materials, resulting in stable radon production rates in the various zones. The calculations with RAETRAP were thus limited to generating an order of magnitude of the source terms in each zone.

The total radon production by the building materials of the new dwelling was about five-fold that of the old dwelling. This may be mainly attributed to the presence of concrete floors instead of wooden floors. The contribution of radon produced in the living room to the total radon concentration in this room is 5–10 times higher in dwelling N than in dwelling O. This change is partly explained by the difference in average ventilation rate between dwellings N and O of about a factor of two and partly by a five times higher radon production in dwelling N.

The model simulations thus suggest the use of other building materials as a potential major cause of the observed increase in the radon level in Dutch dwellings. This conclusion complements the conclusion drawn from the interpretation of the results of the second Dutch national survey on indoor radon [1]. Stoop *et al.* stressed especially the importance of improved insulation for the observed trend.

8.2 Model simulations versus surveys

Measured trends of the radon level in Dutch dwellings [1] could be roughly simulated with the selected set of models. The yearly averaged indoor radon level for each of the modelled dwellings is a weighted average of the multitude of values reported in this study. The average for the simulations on past building practices (dwelling 'O') is estimated to be below 20 Bq m^{-3}. For most of the new airtight dwellings (N_l), the yearly average is between 20 Bq m^{-3} and 50 Bq m^{-3}. The radon concentration in a dwelling with open air inlets and/or open outer doors was not calculated in this study. However, when estimating a yearly averaged indoor radon level from model calculations this value should be taken into account.

The computed average radon level for dwelling O was slightly below measured values for old dwellings. The relative contribution of the source 'crawl space' was somewhat higher for this dwelling than estimated in past studies [43]. Selection of average airtightness for old dwellings, considered to be an upper limit [$q_v(10) = 484$ dm^3 s^{-1}], can be considered as a major explanation for these deviations. Model estimates of the indoor radon level and of the relative importance of the crawl space as a source of indoor radon for new dwellings (N) are somewhat higher than measured averages. Deviations can be explained by the choice of relatively high levels for the airtightness of the ground floor [$q_v(10) \geq 11$ dm^3 s^{-1}].

The model shows an increased airtightness of the building shell, and more specifically, a ground floor airtightness causing a decrease in the relative importance of the crawl space as a source of indoor radon. The absolute change is expected to be low, which is not in agreement with previous estimates based on laboratory and field measurements [43, 1].

8.3 Radon dose versus external irradiation

An increased airtightness of the building shell in combination with increased use of concrete as a building material is suggested as being the cause of a long-term increase in the average radon concentration [1]. The potential effect of both factors was illustrated in this study. Furthermore, the shift in building materials applied explains the difference in external exposure between old and new dwellings. The presence of concrete floors will increase exposure from the building itself and shield external radiation from the underlying soil. As a result, the dose rate averaged over the total area of the ground floor of a new dwelling hardly differs from that of an old one. On average, changes in building practices have thus clearly enhanced the radon concentration in the living room without affecting external exposure.

8.4 Recommendations for future research

Further attention should be given to the discrepancy between measured and calculated air flow through the crawl space, and measured and calculated contributions of crawl-space radon to the radon level in the living room.

The simulations on external irradiation should be completed with estimates for parts of the dwelling other than the ground floor so as to describe the overall occurring variation and to allow for a correct quantification of the average indoor external irradiation by nuclides from the ^{238}U decay chain. Furthermore, it is advisory to model external irradiation from ^{40}K and the ^{232}Th decay chain to make a proper comparison between exposure to radon and external irradiation.

A more detailed comparison with field measurements and other model estimates has to be subject of the follow-up of this study.

Finally, comparable simulations for other standard or prescribed dwelling concepts should give information on expected radon levels in various types of new dwellings.

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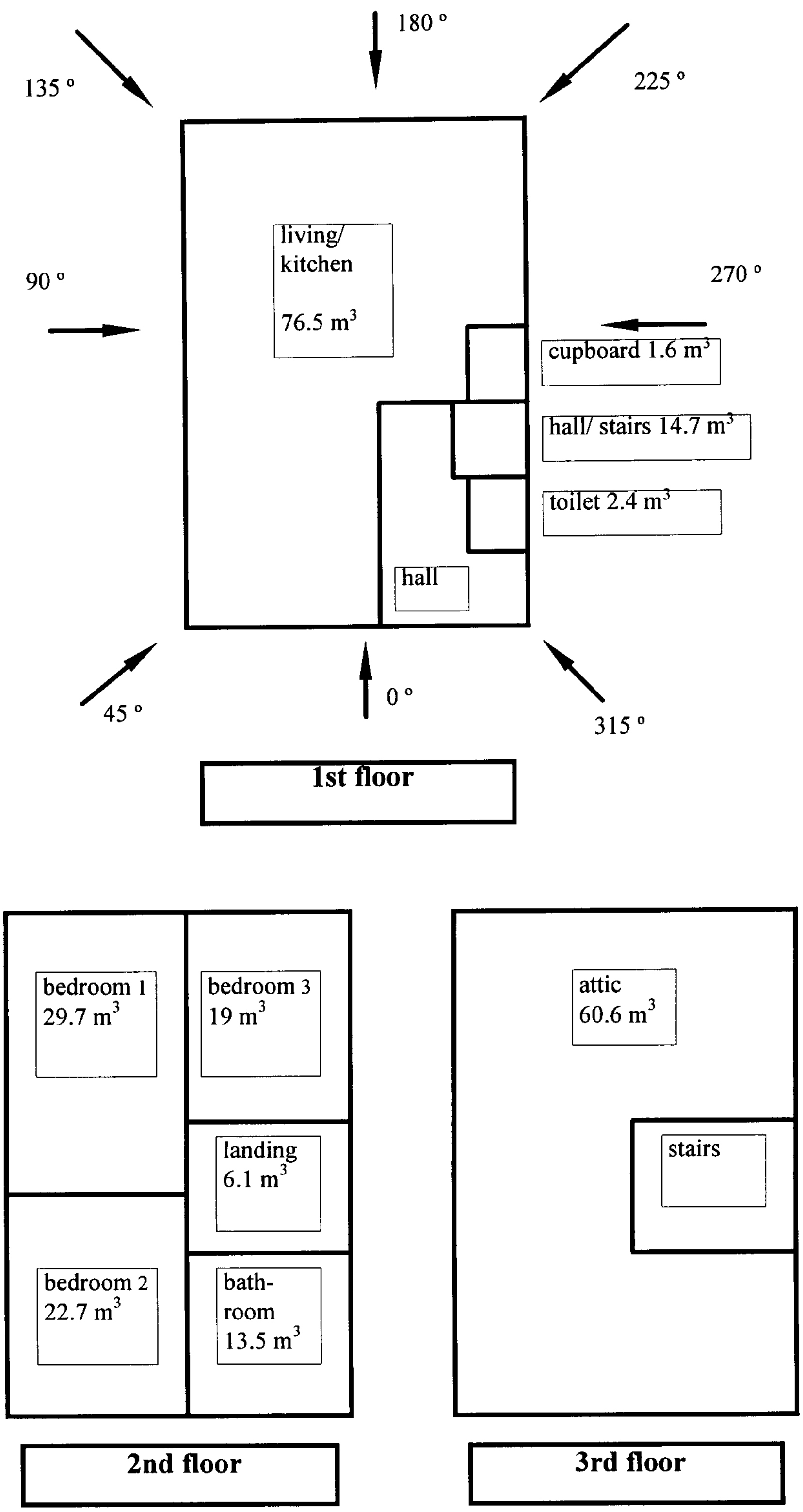
APPENDIX 1: MAILING LIST

1 - 10	Directoraat-Generaal Milieubeheer, directie Stoffen, Veiligheid en Straling
11	plv. Directeur-Generaal Milieubeheer
12 - 16	Novem, drs. R. Wismeijer
17 - 21	Kernfysisch Versneller Instituut, Groningen
22 - 26	TNO-Bouw, Delft
27	Depot van Nederlandse publicaties en Nederlandse bibliografie
28	Directie RIVM
29	Directeur Sector Stoffen en Risico's (IV)
30	Hoofd van het Laboratorium voor Stralingsonderzoek
31	Hoofd van het Laboratorium voor Water- en Drinkwateronderzoek
32	Hoofd van het Laboratorium voor Bodem- en Grondwateronderzoek
33	Bibliotheek van het Laboratorium voor Stralingsonderzoek
34 - 40	Auteurs
41	Hoofd afdeling Voorlichting & Public Relations
42	Bureau Rapportenregistratie
43	Bibliotheek RIVM
44 - 53	Bureau Rapportenbeheer
54 - 63	Reserve-exemplaren LSO

APPENDIX 2: WEATHER CONDITIONS

run no.	wind direction (degrees)	wind velocity ($m\ s^{-1}$)	temperature (°C)	occurrence (%)
1	-	0	-5	0.6
2	-	0	1	2.8
3	-	0	18	6.4
4	45	2	1	3.2
5	45	2	10	2
6	45	2	18	2.7
7	45	5	1	7.3
8	45	5	10	2.6
9	45	5	18	5.8
10	45	8	1	4
11	45	8	10	0.4
12	45	8	18	0.6
13	135	2	1	3.9
14	135	2	10	3.2
15	135	2	18	1.9
16	135	5	1	6.3
17	135	5	10	4
18	135	5	18	3.1
19	225	2	1	1.3
20	225	2	10	2.9
21	225	2	18	1.9
22	225	5	1	1.9
23	225	5	10	6.9
24	225	5	18	5.5
25	315	2	1	2.4
26	315	2	10	2.6
27	315	2	18	2.3
28	315	5	1	1.7
29	315	5	10	5.4
30	315	5	18	4.3

APPENDIX 3: THE MODEL HOUSE



APPENDIX 4: WALL AND FLOOR LAYERS

	layer no.	thickness (m)	material
soil 1	1	1.1	sand dry
soil 2	1	3	sand dry 8 Bq kg^{-1}
soil 3	1	3	sand dry 25 Bq kg^{-1}
roof	3	0.02	wood
roof	2	0.1	cavity space
roof	1	0.02	roof tile
gypsum wall	1	0.07	gypsum
outer wall 1	3	0.1	concrete
outer wall 1	2	0.1	cavity space
outer wall 1	1	0.1	brick
outer wall 2	3	0.1	sand-lime bricks
outer wall 2	2	0.1	cavity space
outer wall 2	1	0.1	brick
outer wall 3	4	0.01	gypsum
outer wall 3	3	0.1	sand-lime bricks
outer wall 3	2	0.1	cavity space
outer wall 3	1	0.1	brick
sand-lime bricks	1	0.1	sand-lime bricks
floor 1	1	0.22	concrete
floor 2	1	0.02	wood
floor 3	3	0.02	wood
floor 3	2	0.2	cavity space
floor 3	1	0.02	gypsum
side wall (1)	1	0.2	concrete
side wall (2)	3	0.01	gypsum
side wall (2)	2	0.2	sand-lime bricks
side wall (2)	1	0.01	gypsum

APPENDIX 5: RADON EXHALATION

material	density ($kg\ m^{-3}$)	porosity	permeability (m^2)	water saturated fraction
brick	1700	0.20	$1\ 10^{-14}$	0.30
concrete	2400	0.30	$5\ 10^{-16}$	0.00
roof tiles	1700	0.20	$1\ 10^{-14}$	0.30
gypsum	960	0.40	$1\ 10^{-13}$	0.00
wood	600	0.40	$1\ 10^{-13}$	0.00
sand-lime bricks	1800	0.24	$1\ 10^{-13}$	0.20
cavity space	1	1.0	$1\ 10^{-4}$	0.00
sand dry	1600	0.40	$9.7\ 10^{-12}$	0.00
sand 50/50	1600	0.40	$4.6\ 10^{-12}$	0.50
sand wet	1600	0.40	$6\ 10^{-17}$	1.00

material	^{226}Ra ($Bq\ kg^{-1}$)	emanation coeff.	diff.coeff. ($10^{-7}\ m^2\ s^{-1}$)
brick	40	0.03	$5\ 10^{-8}$
concrete	20	0.25	$5\ 10^{-8}$
roof tiles	40	0.03	$5\ 10^{-8}$
gypsum	10	0.60	$3\ 10^{-6}$
wood	10	0.36	$1\ 10^{-7}$
sand-lime bricks	10	0.20	$5\ 10^{-7}$
cavity space	0	0.00	$1.2\ 10^{-5}$
sand dry	25	0.20	$7.7\ 10^{-6}$
sand 50/50	25	0.20	$1.4\ 10^{-6}$
sand wet	25	0.20	$3.7\ 10^{-9}$

The air viscosity, the radon absorption coefficient and the distribution coefficient of ^{226}Ra and ^{222}Rn used in the estimation of the radon exhalation rate are 1.77×10^{-5} Pa s, zero, 10^{20} and 0.26 respectively.

APPENDIX 6: TOTAL INFILTRATION RATES, NEW DWELLING

ventilation regime	N_{4h} [a]	N_4 [a]	N_{4w} [a]	N_{4wh} [a]	N_{4dh} [a]
meteo combination no.			ventilation rate (h^{-1})		
1	0.71	0.62	0.97	1.14	0.72
2	0.60	0.51	0.82	1.00	0.60
3	0.56	0.28	0.30	0.56	0.56
4	0.65	0.55	0.85	1.02	0.65
5	0.56	0.42	0.66	0.81	0.56
6	0.59	0.34	0.51	0.72	0.60
7	1.18	1.10	1.47	1.66	1.18
8	1.09	1.00	1.40	1.56	1.09
9	0.98	0.90	1.36	1.45	0.98
10	2.11	2.02	2.71	2.80	2.12
11	1.99	1.90	2.61	2.67	1.99
12	1.87	1.79	2.53	2.60	1.88
13	0.64	0.55	0.88	1.06	0.64
14	0.56	0.42	0.71	0.87	0.56
15	0.59	0.34	0.47	0.69	0.60
16	1.16	1.07	1.53	1.69	1.16
17	1.07	0.98	1.37	1.52	1.07
18	0.96	0.88	1.21	1.39	0.96
19	0.64	0.55	0.88	1.06	0.64
20	0.56	0.42	0.71	0.87	0.56
21	0.59	0.34	0.47	0.69	0.60
22	1.16	1.07	1.53	1.69	1.16
23	1.07	0.98	1.37	1.52	1.07
24	0.96	0.88	1.21	1.39	0.96
25	0.65	0.55	0.85	1.02	0.64
26	0.57	0.44	0.68	0.82	0.57
27	0.62	0.37	0.54	0.73	0.62
28	1.31	1.23	1.66	1.83	1.32
29	1.21	1.13	1.60	1.74	1.21
30	1.10	1.02	1.56	1.64	1.10

[a] Symbols are described in Table 4