HUMAN HEALTH DAMAGES DUE TO INDOOR SOURCES OF RADON IN LIFE CYCLE ASSESSMENT OF DWELLINGS

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ABSTRACT

A methodology was developed to calculate health damages due to exposure to radon emitted to indoor air for use in dwelling life cycle assessment. Fate factors were calculated based on dose conversion factors and effective outgoing airflows. Effect factors were calculated from linear relationship between dose and cancer cases. Damage factors are expressed in terms of disability adjusted life years (DALYs). Health damages due to emissions of radon from building materials in the use phase appeared to be 0.7 – 520% of health damages associated with the rest of the life cycle of the same materials. Health damages due to the emissions of radon from building materials in the use phase of the Dutch reference dwelling are about 50% of the health damages associated with the rest of the life cycle of the same dwelling. This methodology allows for better evaluation of health impacts of building materials and provisions for ventilation.

KEYWORDS

life cycle assessment; indoor emissions; radon; health damages

INTRODUCTION

In life cycle assessment (LCA), several methods have been developed to simulate the impact of emissions of harmful components on human health (Hofstetter 1998, Goedkoop and Spriensma 1999, Frischknecht et al. 2000, Huijbregts et al. 2000). These methods take into account outdoor sources of contamination. A method to simulate the impact of indoor sources on human health due to indoor exposure is, however, still missing (Jönsson 2000, Reijnders and Huijbregts 2000). The reason for this absence is that LCAs usually do not take into account local effects of products on users (Jönsson 2000).

However, environmental comparisons and improvements for building products may be biased by excluding the impact of indoor air pollution. For instance, human health damage scores of concrete compared to wood may be underestimated by excluding indoor air emissions of radon. Another example is that the positive influence on human health of mechanical indoor air ventilation in buildings is not accounted for by disregarding impacts of indoor air pollution.

The impact of indoor radon exposure on human health may be an important factor for the LCA of dwellings, because people live in houses for a great part of their lives. The Dutch Health Council for instance estimated the number of casualties due to lung cancer as a result of exposure to radon in the Netherlands at 800 per year (Gezondheidsraad 2002). In a review of radiation exposure in the Netherlands, it appears that nearly 50% of the total average annual dose per capita of the Dutch population originates from radon or gamma radiation from building materials (Eleveld 2003). Apparently, the exclusion of indoor exposure to radioactive elements originating from building materials leads to an underestimation of the human health risks in the life cycle assessment of dwellings.

This paper presents a methodology to calculate characterisation factors for radon emitted from building materials. The characterisation factors are calculated for a Dutch reference dwelling (Novem 1998, W/E Adviseurs 1999). Fate, effects and damages are incorporated in the characterisation factor calculations (Goedkoop and Spriensma 1999). Fate factors of radon are calculated using an indoor airflow and exposure model for dwellings. Exposure in both indoor and outdoor environment is considered. Effect factors are calculated using epidemiological data for ionising radiation (Frischknecht et al. 2000). Damages to human health are expressed in disability adjusted life years (DALYs) (Hofstetter 1998, Goedkoop and Spriensma 1999, Frischknecht et al. 2000).

METHODS AND SIMULATION

Calculation procedure

In the LCA methodology, characterisation factors can be used to calculate the combined environmental damage occurring in the life cycle of a product (Heijungs and Hofstetter 1996). For radon emitted from building products, characterisation factors can be used to link the total amount of radon exhaled during the lifetime of the building material to human health damage. The damage score for the use phase of building material p as a result of emission of radon can then be calculated by:

$$DS_{p,u} = \sum_r M_{r,p} \cdot Q_r \qquad (1)$$

where $DS_{p,u}$ is the damage score associated with the use phase of building material p (DALY·kg$_p^{-1}$); $M_{r,p}$ is the total amount of radon exhaled during the lifetime of building material p (Bq·kg$_p^{-1}$); and Q_r is the characterisation factor of radon (DALY·Bq^{-1}).

As the calculations regard damage to human health, the characterisation factors for radon can be calculated by (Goedkoop and Spriensma 1999):

$$Q_r = \sum_j \left(F_{r,j} \cdot \sum_k E_{r,k,j} \cdot D_{r,k} \right) \qquad (2)$$

where F_r is the fate factor of radon for impact category j (Sv·Bq^{-1}); $E_{r,k,j}$ is the effect factor of radon for impact category j for human health damage category k (cases·Sv^{-1}); and $D_{r,k}$ is the damage factor of radon for human health damage category k (DALY·case^{-1}).

The characterisation factors are calculated for a Dutch reference dwelling (Novem 1998, W/E Adviseurs 1999). It is assumed that this two-floor single-family row house is occupied by three persons. The walls between the dwellings and the floors are made of concrete, and the façades are made of sand-lime bricks and clay bricks. The windows are double paned.

Parameter values used in this methodology are given in Table 4.

Fate factor

Fate factors for radon emitted to outdoor air are commonly calculated with multimedia fate models (Dreicer et al. 1995). For the indoor environment, these models cannot be use, because the transport routes inside the dwelling differ from those outside.

To calculate exposure to radon emitted indoors, the dwelling is divided into compartments, generally consisting of one floor. In Figure 1, an overview of the compartments in the house is given. It is assumed that the activity concentrations in the rooms of one compartment are similar. As convective transport has the dominating effect on concentrations in dwellings (Nazaroff et al. 1985), diffusive transport is not included in the fate factor calculations. Furthermore, in these calculations average Dutch meteorological conditions and ventilation behaviour are assumed.

The human dose in indoor air as a result of radon exhaled from building material p situated in dwelling compartment a can be calculated by:

$$F_{Rn,a,i} = \frac{CF_d}{f_{e,a}} \cdot N_a \qquad (3)$$

where $F_{Rn,a,i}$ is the fate factor, representing the conversion of the emission of radon to the indoor air of compartment a to dose received by the occupants (Sv·Bq^{-1}); CF_d is the dose conversion factor (Sv·y^{-1}·Bq^{-1}·m^3); $f_{e,a}$ is the effective outgoing airflow for an emission to compartment a (m^3·y^{-1}); and N_a is the number of persons living in the dwelling (-).

Exposure to radon in both indoor and outdoor air are taken into account. The fate factor for the dose received in outdoor air as a result of radon emitted in compartment a can be calculated by:

$$F_{Rn,a,o} = F_{Rn,a,i \to o} \cdot F_{Rn,o,o} \qquad (4)$$

where $F_{Rn,a,o}$ is the fate factor representing the conversion of an emission of radon to the indoor air of compartment a to dose received in outdoor air (Sv·Bq^{-1}); $F_{Rn,a,i \to o}$ represents the fraction of radon exhaled to compartment a that is transported from indoor air to outdoor air (-); and $F_{Rn,o,o}$ represents the conversion of the presence of radon in outdoor air to dose received by all humans (Sv·Bq^{-1}).

Because radon has a relatively high half-life (3.8 days) in view of the ventilation rate, it is assumed that $F_{Rn,a,i \to o}$ approaches 1. $F_{Rn,o,o}$ is equal to $1.6 \cdot 10^{-11}$ Sv·Bq^{-1} (Goedkoop and Spriensma 1999).

Effective outgoing airflows

The effective outgoing airflow $f_{e,a}$ is the weighed sum of the airflows leaving all compartments regarding an emission in compartment a. It reflects the radon transport between the compartments and the time fraction the occupants spend in the compartments.

The vertical airflows through the floors from compartment a to compartment b (from crawlspace to first floor, or from first floor to second floor) can be calculated by (Waitz et al. 1996):

$$f_{ab} = \frac{of_b^2 \cdot \Delta p_{ba}}{n_b \pi \cdot 8\eta \cdot Lf_b} \cdot A_f \qquad (5)$$

where f_{ab} is the airflow from compartment a to compartment b (m^3·y^{-1}); of_b is the fraction of openings in the floor of compartment b (-); ΔP_{ba} is the air pressure difference between compartment b and compartment a (Pa); n_b is the number of gaps in the floor of compartment b per floor area (m^{-2}); h is the dynamic viscosity of air (Pa·y); Lf_b is the floor thickness of compartment b (m); and A_f is the floor area (m^2).

The calculation of the airflows between outdoor and indoor space is based on the Bernoulli equation. It is calculated by (ASHRAE 1997):

$$f_{oa} = c_{sy} \cdot Cd \cdot Ac_{oa} \cdot \sqrt{\left(2 \cdot \left|\Delta p_{oa}\right|\right) / \rho} \qquad (6)$$

where f_{oa} is the airflow between outdoor air and compartment a ($m^3 \cdot y^{-1}$); c_{sy} is the conversion coefficient from seconds to year ($s \cdot y^{-1}$); Cd is the discharge coefficient for the openings between outdoor air and compartment a (-); Ac_{oa} is the cross-sectional area of the openings between outdoor air and compartment a (m^2); ΔP_{oa} is the pressure difference between outdoor air and compartment a (Pa); and ρ is the air density ($kg \cdot m^{-3}$).

The airflows between outdoor and indoor space are calculated separately for all façades of the dwelling. At the façade on the windward side, the airflow is generally from outside to inside, and at the leeward side and on the sides generally the reverse is true. It is assumed that A_{coa} is equal to the effective air leakage area $A_{L,oa}$ (ASHRAE 1997).

The pressure difference between outdoor air and compartment a consists of two parts:

$$\Delta p_{oa} = \Delta p_{s,oa} + p_{w,oa} \tag{7}$$

where $\Delta p_{s,oa}$ is the pressure difference between outdoor air and compartment a due to stack effect (Pa); and $p_{w,oa}$ is the wind pressure on the surface between outdoor air and compartment a (Pa).

The pressure difference between outdoor air and compartment a due to stack effect, $\Delta p_{s,oa}$ can be calculated by:

$$\Delta p_{s,oa} = \rho \cdot g \cdot (H_{oa} - H_{NPL}) \cdot (T_{i,oa} - T_o) / T_o \tag{8}$$

where g is the gravity constant ($m \cdot s^{-2}$); H_{oa} is the average height of connection oa (m); H_{NPL} is the height of neutral pressure level (m); $T_{i,oa}$ is the indoor temperature for connection oa (K); and T_o is the outdoor temperature (K).

The wind pressure on the surface between outdoor air and compartment a, $p_{w,oa}$ can be calculated by:

$$p_{w,oa} = ½ \cdot Cp_{oa} \cdot \rho \cdot V^2 \tag{9}$$

where Cp_{oa} is the wind surface pressure coefficient for connection oa (-); and V is the wind speed ($m \cdot s^{-1}$). The wind surface pressure coefficient depends on the angle between the surface between outdoor air and compartment a and is given for several angles (ASHRAE 1997).

Based on the airflows defined above, the total ventilation rates of the different compartments can be calculated by:

$$vr_c = f_{oc} \tag{10}$$

$$vr_1 = f_{o1} + f_{c1} \tag{11}$$

$$vr_2 = f_{o2} + f_{12} \tag{12}$$

where vr_c is the total ventilation rate of the crawl space ($m^3 \cdot y^{-1}$); f_{oc} is the airflow from outside to the crawl space ($m^3 \cdot y^{-1}$); vr_1 is the total ventilation rate of the first floor ($m^3 \cdot y^{-1}$); f_{o1} is the airflow from outside to the first floor ($m^3 \cdot y^{-1}$); vr_2 is the total ventilation rate of the second floor ($m^3 \cdot y^{-1}$); and f_{o2} is the airflow from outside to the second floor ($m^3 \cdot y^{-1}$). The airflows f_{oc}, f_{o1} and f_{o2} are calculated using formula (6).

The effective outgoing airflows can then be calculated as follows:

$$f_{e,c} = \frac{vr_c}{t_c + t_1 \cdot \frac{f_{c1}}{vr_1} + t_2 \cdot \frac{f_{c1}}{vr_1} \cdot \frac{f_{12}}{vr_2}} \tag{13}$$

$$f_{e,1} = \frac{vr_1}{t_1 + t_2 \cdot \frac{f_{12}}{vr_2}} \tag{14}$$

$$f_{e,2} = \frac{vr_2}{t_2} \tag{15}$$

where $f_{e,c}$ is the effective outgoing airflow of an emission to the crawl space (-); t_c is the time fraction spent in the crawl space (-); t_1 is the time fraction spent in the first floor (-); t_2 is the time fraction spent in the second floor (-); $f_{e,1}$ is the effective outgoing airflow of an emission to the first floor (-); and $f_{e,2}$ is the effective outgoing airflow of an emission to the second floor (-).

Effect factors

The effect factor for radioactive exposure is calculated by (ICRP 1993):

$$E_{r,k} = c_k \tag{16}$$

where $E_{r,k}$ is the effect factor of radon for human health damage due to the effects of ionising radiation on tissue or organ k ($cases \cdot Sv^{-1}$); and c_k is the number of cases of cancers affecting tissue or organ k due to a dose of radiation ($cases \cdot Sv^{-1}$). The values of c_k used here are those given by Frischknecht et al. (2000).

Damage factor

The disability adjusted life years (DALY) concept has been developed by the World Health Organisation (Murray and Lopez 1996), and has been adjusted for use in LCA (Hofstetter 1998).

For all affected tissues or organs, the calculation of the damage factor regarding human health is the same:

$$D_{r,k} = DALY_{r,k} \tag{17}$$

where $D_{r,k}$ is the damage factor of radon for human health damage to tissue or organ k ($y \cdot case^{-1}$); and $DALY_{r,k}$ is the disability adjusted life years of radon per incidence case to tissue or organ k ($y \cdot case^{-1}$).

In the Eco-Indicator 99 methodology, 13 tissues and organs are considered (Goedkoop and Spriensma 1999). For clarity, only the combined effect and damage factors for radioactive pollutants are calculated. The value of the combined effect and damage factors is 1.5 DALY·Sv^{-1} for all radioactive pollutants (Frischknecht et al. 2000).

Radon emissions from building materials

Emissions of and exposures to contaminants occur in all phases of the dwelling life cycle. This is illustrated in Figure 2. In this study, a division is made between emissions occurring in the use phase and emissions occurring in the rest of the dwelling life cycle. In the use phase, building materials emit contaminants directly to both indoor air (indicated as indoor emissions) and outdoor air (indicated as outdoor emissions; examples of outdoor sources are outdoor constructions, roofs and façades). Indoor emissions lead to indoor exposure and to outdoor exposure when the substances are transported to outdoor air by ventilation. Outdoor emissions lead only to outdoor exposure. In this article, health damage scores due to indoor and outdoor emissions of radon occurring in the use phase of a number of building materials applied in the Dutch reference dwelling (Novem 1998, W/E Adviseurs 1999) are calculated.

In the rest of the life cycle, emissions of substances (not limited to radon) take place to outdoor air only. These emissions lead to outdoor exposure. Damage scores associated with the rest of the life cycle of the same materials are calculated by standard LCA methodology (Guinée et al. 2001).

The total amount of radon exhaled during the lifetime of building material *p* can be calculated by:

$$M_{Rn,p} = ER_{Rn,p} \cdot LT_p \cdot df_p \tag{18}$$

where $ER_{Rn,p}$ is the radon exhalation rate of building material *p* (Bq·kg$_p^{-1}$·y^{-1}); LT_p is the lifetime of building material *p* (y); and df_p is the distribution factor for building material *p* (-).

The distribution factor df_p reflects the distribution of the emissions over the compartments. When a building material is applied in a wall between two compartments (e.g. the floor between the first and second floor), half of the radon emission is attributed to one of the compartments and half to the other. When a building material is applied in a wall between a compartment and outdoor space, half of the radon emission is attributed to the compartment and half of the concentration is regarded as an emission directly to outdoor air.

For five common building material categories, average total radon exhalation rates were derived (Table 1). The radon exhalation rates are given using a distribution factor df_p of 1 and a dwelling lifetime LT_p of 75 year, unless stated otherwise.

Material input for dwelling

The total amounts of building materials present in the reference dwelling are given in the dwelling LCA tool Ecoquantum (W/E Adviseurs 1999). In the calculations performed in this paper, multiple applications of materials (e.g. replacements for maintenance) and losses during building or maintenance are included. The materials lost in this way do not emit radon to the indoor air during the use phase, so for these materials only the damage to human health associated with the rest of the life cycle is taken into account. The distribution factors *df* are also take into account by assigning a value of 0.5 to the amounts of material for both compartments when a material is applied in a construction separating two compartments. For materials applied in the soil (sand, piles and outdoor drains), we assume that the emission to outdoor air during the use phase is negligible. The lifetime of the dwelling is assumed to be 75 years.

RESULTS AND DISCUSSION

Characterisation factors

The fate factors, effect factors and damage factors are combined to calculate characterisation factors (Eq. (2)). The results are given in Table 2. The characterisation factors for radon emitted to the first and second floor have the same order of magnitude. The characterisation factors for emissions of radon to the crawl space and to the outdoor air are a factor of 10 lower.

Damage scores of materials

Using the characterisation factors calculated with Eq. (2) and the radon emissions as given in Table 1, the damage scores of building materials as a result of the emission of radon to the different compartments are calculated. The results are given in Figure 3. Health damages due to emissions of radon from building materials in the use phase appeared to be 0.7 – 520% of the damage to human health associated with the rest of the life cycle of the same materials. For gypsum, the damage score associated with the rest of the life cycle is a factor of 10 higher than the damage score due to emissions of radon during the use phase. For cellular concrete, this is a factor of 3. For the other building materials, these are within the same order of magnitude.

Dwelling level

In Table 3, the total damages to human health due to the emissions of radon occurring in the use phase of the reference dwelling and health damages associated with the rest of the life cycle of the same reference dwelling are given. The damage to human health due to the emissions of radon occurring in the use phase of the reference dwelling is about 50% of the damage to human health associated with the rest of the life cycle of the same dwelling.

DISCUSSION

Regarding the damage scores presented here, it should be noted that there are several factors causing uncertainties in the characterisation factors for radon and for the damage scores of the building materials. Uncertainties in the intake fraction calculations are caused by the use of average airflow characteristics and time fractions spent in the different compartments, which may differ due to differences in occupant behaviour. For the effect factor, the uncertainties in the epidemiological data are the main source of uncertainty (Frischknecht et al. 2000). The damage factors are calculated taking account of the duration of a disease or a period of life lost due to premature death, and weighing the severity of disease. As to the matter of duration, the main source of uncertainty is the uncertainty that occurs in the epidemiological data used to determine the years living disabled and years of life lost. As to weighing the severity of diseases, the subjectivity thereof is another source of uncertainty (Hofstetter 1998).

For the damage scores of the building materials, the use of average emission rates of radon from building materials is a cause of uncertainty. The application of finishing materials like wallpaper or paint might decrease the radon exhalation from the building material under the finish (e.g. Van Dijk and De Jong 1989). Further, pressure differences between indoor and outdoor air caused by wind or mechanical ventilation might influence the emission rate of radon. This has not been taken into account in the current analysis. On a dwelling level, average materials input have been used, causing an uncertainty as well.

The indoor air model can be tested against empirical data only to a limited extend. An important element in such tests is the comparison of calculated and measured indoor activity concentrations of radon. From a preliminary study, it appeared that the concentrations of radon in the reference dwelling calculated with this methodology are roughly the same as the concentrations found in a national survey in the Netherlands (Stoop et al. 1998).

CONCLUSIONS

In this paper, damages to human health have been calculated for emission of radon to the indoor air of a single-family row house, based on a novel methodology for the calculation of fate factors for emissions to indoor air. These damages have been compared with the health damages associated with the rest of the dwelling life cycle.

From these results, it appears that damages to human health due to indoor emissions of radon from building materials cannot be neglected without causing a significant underestimation of total human health damages for the majority of building materials applied at the first and second floor, up to a factor of 5 for bricks, cement, mortar and ceramics. On a dwelling level, the corresponding underestimation is a factor of 0.5. Measures to improve the health of the occupants by improving the indoor air quality result in a lower environmental impact when indoor emissions of radon are taken into account.

For other dwellings, building materials or pollutants, damage scores can be calculated using the methodology described in this paper. These damage scores can be used as an addition to standard LCA methodology when simulating the environmental impact of dwellings.

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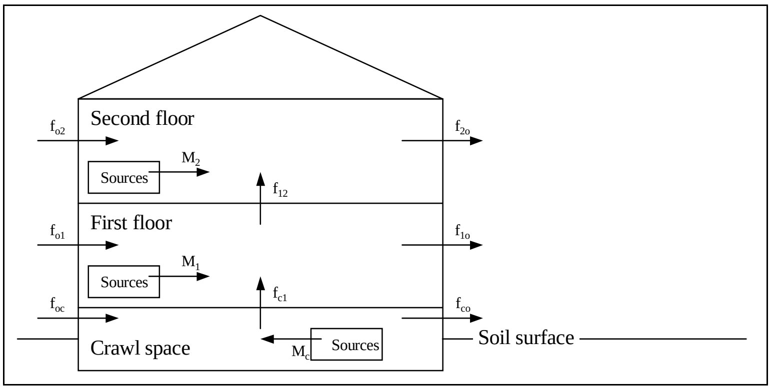

Figure 1 Overview of the different compartments of the single-family row house

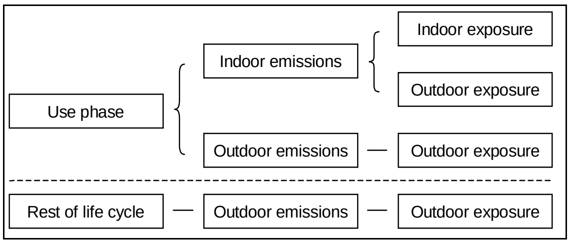

Figure 2: Life cycle phases of dwellings, emissions and exposures

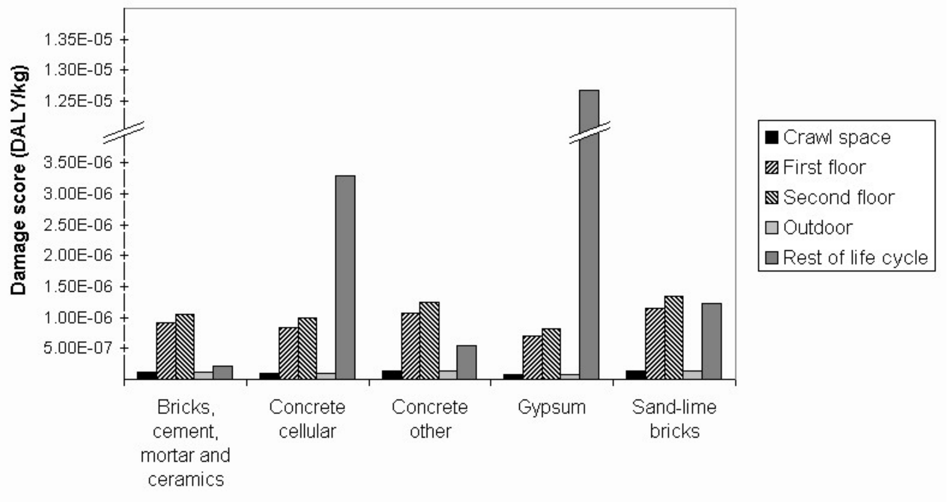

Figure 3 Damage score of building materials due to the emission of radon to the compartments of the house

Table 1: Average total radon exhalation of common building material categories($Bq \cdot kg_p^{-1}$)(Bosmans 1996)

MATERIAL CATEGORY	**TOTAL RADON EXHALATION DURING LIFETIME**
Bricks, cement, mortar and ceramics[a]	$4.7 \cdot 10^3$
Concrete cellular[b]	$4.3 \cdot 10^3$
Concrete other[c]	$5.5 \cdot 10^3$
Gypsum[d]	$3.6 \cdot 10^3$
Sand-lime bricks[e]	$5.9 \cdot 10^3$

[a] ρ (density) = 1498 $kg \cdot m^{-3}$; thickness = 0.05 m; [b] ρ = 593 $kg \cdot m^{-3}$; thickness = 0.10 m; [c] ρ = 2375 $kg \cdot m^{-3}$; thickness = 0.20 m; [d] ρ = 843 $kg \cdot m^{-3}$; thickness = 0.07 m, lifetime = 60 y; [e] ρ = 1748 $kg \cdot m^{-3}$; thickness = 0.08 m

Table 2 Fate factors, effect factors× damage factors and characterisation factors for radon

COMPARTMENT	**FATE FACTOR** ($Sv \cdot Bq^{-1}$)		**EFFECT FACTOR × DAMAGE FACTOR** ($DALY \cdot Sv^{-1}$)	**CHARACTERISATION FACTOR** ($DALY \cdot Bq^{-1}$)
	Indoor exposure	Outdoor exposure		
Crawlspace	$5.4 \cdot 10^{-14}$	$1.6 \cdot 10^{-11}$	1.5	$2.4 \cdot 10^{-11}$
First floor	$1.1 \cdot 10^{-10}$	$1.6 \cdot 10^{-11}$	1.5	$1.9 \cdot 10^{-10}$
Second floor	$1.3 \cdot 10^{-10}$	$1.6 \cdot 10^{-11}$	1.5	$2.3 \cdot 10^{-10}$
Outdoor	0	$1.6 \cdot 10^{-11}$	1.5	$2.4 \cdot 10^{-11}$

Table 3 Total damage to human health for the reference dwelling

	DAMAGE SCORE (y)	**FRACTION**
Due to emission of radon in the use phase		
Crawl space	$2.2 \cdot 10^{-3}$	0.6%
First floor	$4.1 \cdot 10^{-2}$	11.2%
Second floor	$7.8 \cdot 10^{-2}$	21.0%
Outdoor[a]	$2.4 \cdot 10^{-3}$	0.7%
Total	$\mathbf{1.2 \cdot 10^{-1}}$	**33.5%**
Associated with rest of life cycle	$\mathbf{2.5 \cdot 10^{-1}}$	**66.5%**

[a] Materials emitting only to outdoor air (e.g. outdoor constructions, part of façades and roofs)

Table 4 (Assumed) value for several general parameters

STANDARD PARAMETER	**DENOTATION**	**VALUE**	**LITERATURE**
c_{sy}	Seconds per year	$31557600\ \text{s}\cdot\text{y}^{-1}$	
g	Gravity constant	$9.81\ \text{m}\cdot\text{s}^{-2}$	
η	Dynamic viscosity of air	$6.8\cdot10^{-13}\ \text{Pa}\cdot\text{y}$	
ρ	Air density (273 K)	$1.29\ \text{kg}\cdot\text{m}^{-3}$	
BUILDING-SPECIFIC PARAMETER	**DENOTATION**	**ASSUMED VALUE**	**LITERATURE**
A_f	Floor area	$39\ \text{m}^2$	[a]
Ac_{oc}	Cross-sectional area of openings between outdoor and crawl space	$0.0102\ \text{m}^2$	[b,c]
Ac_{co}	Cross-sectional area of openings between crawl space and outdoor	$0.0102\ \text{m}^2$	[b,c]
Ac_{o1}	Cross-sectional area of openings between outdoor and first floor	$0.00214\ \text{m}^2$	[b,c]
Ac_{1o}	Cross-sectional area of openings between first floor and outdoor	$0.00206\ \text{m}^2$	[b,c]
Ac_{o2}	Cross-sectional area of openings between outdoor and second floor	$0.00105\ \text{m}^2$	[b,c]
Ac_{2o}	Cross-sectional area of openings between second floor and outdoor	$0.00105\ \text{m}^2$	[b,c]
H_c	Average height of crawl space	-0.05 m	
H_1	Average height of first floor	1.26 m	
H_2	Average height of second floor	3.77 m	
H_{NPL}	Height of neutral pressure level	2.51 m	
Lf_1	Floor thickness of first floor	0.23 m	[a]
Lf_2	Floor thickness of second floor	0.23 m	[a]
n_1	Number of gaps in floor of first floor	10	[d]
n_2	Number of gaps in floor of second floor	10	[d]
of_1	Fraction of openings in floor of first floor	$1.28\cdot10^{-5}$	[a,d]
of_2	Fraction of openings in floor of second floor	$1.28\cdot10^{-5}$	[a.d]
ΔP_{1c}	Air pressure difference between first floor and crawl space	4 Pa	
ΔP_{21}	Air pressure difference between second floor and first floor	4 Pa	
OCCUPANT-DEPENDENT PARAMETER	**DENOTATION**	**ASSUMED VALUE**	**LITERATURE**
N_a	Number of people living in dwelling	3	
t_c	Time fraction spent in crawl space	0	
t_1	Time fraction spent in first floor	0.5	
t_2	Time fraction spent in second floor	0.3	
METEOROLOGICAL PARAMETER	**DENOTATION**	**ASSUMED VALUE**	**LITERATURE**
Cp_{oc}, Cp_{o1}, Cp_{o2}	Wind surface pressure coefficient	0.7	[b]
Cp_{co}, Cp_{1o}, Cp_{2o}	Wind surface pressure coefficient	-0.14	[b]
$T_{i,c}$	Indoor temperature in crawl space	289 K	
$T_{i,1}$	Indoor temperature in first floor	293 K	
$T_{i,2}$	Indoor temperature in second floor	292 K	
T_o	Outdoor temperature	288 K	
V	Wind speed	$5\ \text{m}\cdot\text{s}^{-1}$	
OTHER PARAMETER	**DENOTATION**	**(ASSUMED) VALUE**	**LITERATURE**
Cd	Discharge coefficient	1	[b]
CF_d	Dose conversion factor	$2.1\cdot10^{-5}\ \text{Sv}\cdot\text{y}^{-1}\cdot\text{Bq}^{-1}\cdot\text{m}^3$	[e]
LT_p	Default lifetime of products	75 y	
[a] Novem 1998; [b] ASHRAE 1997; [c] W/E Adviseurs 1999; [d] Waitz et al. 1996; [e] Schaap et al. 1998			