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Article

Model to Balance an Acceptable Radon Level Indoors

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Abstract: A theoretical model is presented for balancing an acceptable radon concentration in indoor air. The infiltration of radon from the ground to the indoor air can be controlled by barriers or by lowering the air pressure at the lower zone of the ground slab. Indoor air with a radon concentration higher than that of outdoor air can further be controlled through the effective dilution of indoor air with outdoor air. The theory estimates the allowed radon infiltration from the ground to balance radon at an acceptable level indoors for a given ventilation rate, considering the radon contribution to the indoor air from indoor materials, building materials and the interior. A method using this theory is presented, identifying the necessary airtightness required for a radon barrier to balance the acceptable radon concentration for a building. Barriers include commercially used system solutions, such as bitumen-based radon blockers, wet-room membranes, reinforced fixed mortar pastes, and polyethene membranes. An acceptable indoor radon concentration of between 100 and 300 Bq/m³ in indoor air is used. Barriers are evaluated by their ability to prevent soil gas penetration from the ground in combination with their effect on the building durability, as barriers may create a far more vulnerable building.

Keywords: model; radon; soil gas; indoor materials; penetration; ventilation; indoor air quality



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1. Introduction

Radon-222 develops from the radioactive decay of radium-226 and has a half-life of 3.8 days. This gas seeps through the soil into buildings to interfere with radon derived from the atmosphere and building materials. If not diluted with outdoor air through ventilation, much higher human exposure levels can occur indoors than outdoors [1,2]. Thus, radon affects occupants through the indoor climate.

Radium is a decay product of uranium. Radium is a solid as uranium. Since uranium is one of the most common radioactive elements on Earth, radon will be present on Earth long into the future despite its short half-life.

The World Health Organization (WHO) recommends that states introduce requirements for the maximum radiation concentration from natural indoor-air sources. After determining that radon is responsible for 3% to 14% of lung cancer cases, the WHO recommended these requirements, depending on the average radon exposure in various countries [3]. The results indicate that radon is the second-leading cause of lung cancer (smoking tobacco is still the primary cause). Therefore, it is crucial to prevent radon from penetrating buildings. Since 2010, Danish building regulations have required that buildings be constructed to ensure that indoor radon levels remain below 100 Bq/m³ [4].

The radon level indoors in Danish dwellings built before 2018 is 105 Bq/m³. For dwellings built before 1995, the radon level is 106 Bq/m³. For dwellings built between 1996 and 2009, the radon level is 93 Bq/m³, and for dwellings built between 2010 and 2018, the radon level is 58 Bq/m³. Approximately 9% of dwellings built before 2018 have a radon level above 200 Bq/m³. In addition, 41% have a radon level above 100 Bq/m³ [5]. In comparison, the radon level in dwellings in Finland is 96 Bq/m³, in Sweden 108 Bq/m³ and in Norway 60 Bq/m³. In addition, the radon level in Germany is 50 Bq/m³, in France

66 Bq/m³ and in England 20 Bq/m³, [6]. In Sweden, Norway and Finland, the limit value for radon levels in newly built buildings is 200 Bq/m³. Norway requires that buildings for permanent residence must be able to activate measures to reduce the radon level, if the radon level exceeds 100 Bq/m³. In England (England, Wales, Scotland and Ireland) the authorities apply an action level of 200 Bq/m³ and a target level of 100 Bq/m³. In Germany, the radon level in a workplace must not exceed 300 Bq/m³ [7]. For other buildings, there is no requirement for the radon level in the indoor air [8]. However, new buildings should be planned and constructed so that the radon level does not exceed 100 Bq/m³.

Infiltration of radon from the ground to the indoor air can be prevented by barriers, such as membranes, or by lowering the air pressure at the lower zone of the ground slab or combining them.

Radon originates from the ground. Soil gas penetrates from the ground underneath a building and is the primary radon source in indoor air [9]. However, building materials can also contribute to the radon concentration in indoor air if they contain radium or the chemical elements uranium and thorium (e.g., granite and alum shale). The radon contributions to the indoor air from building materials used indoors are seldomly considered in balancing the radon concentration. Outdoor air and the atmosphere contain a low concentration of radon because the soil gas is diluted when reaching the ground surface.

When using barriers as a system solution to prevent radon from penetrating buildings, it is crucial to determine the airtightness of such barriers. Moreover, the barrier must be sufficiently airtight and have airtight joints at the corners, across floor-level changes, around barrier-penetrating pipes and against floor drains.

This paper presents a theoretical model for balancing an acceptable radon concentration in indoor air for a typical single-family building construction. The presented theory theoretically estimates the allowed radon infiltration from the ground to balance the radon at an acceptable level indoors for a given ventilation rate, considering the radon contribution to the indoor air from indoor materials, such as building materials and the interior.

However, the choice of a radon barrier must be made consistently with an acceptable change in the building physics. Using a barrier to prevent radon gas penetration from soil often causes a change in the building physics related to the moisture level in the building materials from the rising soil moisture.

Ideally, the indoor radon concentration is lowered to a balanced level that meets the national building regulations. However, for existing buildings, a higher indoor radon concentration might be considered acceptable, considering the expense of preventing a rise in the soil moisture level. Therefore, a barrier must be evaluated by its ability to prevent soil gas penetration from the ground and its influence on the overall moisture level in the affected building materials.

This paper demonstrates the theory used in practice to balance the indoor radon concentration at an acceptable level, using several different radon barriers, which were evaluated as single-system solutions. The barriers include system solutions based on various materials, such as bitumen-based radon blockers, wet-room membranes, reinforced fixed mortar pastes, and mortar and polyethylene membranes.

The barriers were tested using a modified version of the NBI 167/02 radon membrane airtightness test method [10], which determines the airtightness of a radon barrier used as a system solution. The assessment method was modified by providing a digital stirring and control system and introducing equipment to determine the overall mean air-pressure difference over the barrier. Barriers were identified to balance the indoor radon concentration between 100 and 300 Bq/m³ for a ventilation rate of between 0.5 and 4 h⁻¹. For these findings, the model considered a low initial radon contribution from indoor materials of around 40 Bq/m³ and higher contributions of around 1000 Bq/m³. Barriers managed the radon exposure from the ground of up to 800,000 Bq/m³ in the soil gas.

2. Balancing Radon Indoors

Indoor-air infiltration of radon from the ground must be prevented, and the radon that reaches the indoor air must be diluted to reach a balance of an acceptable radon concentration or a radon concentration at a lower level. An efficient way to avoid radon infiltration in a building is by making the ground slab airtight and lowering the air pressure at the lower zone of the ground slab, either as individual measures or by combining the two measures. If resulting in a higher radon concentration than that of the outdoor air, radon in the indoor air can be diluted with outdoor air and ventilated.

Methods to balance the indoor radon concentration comprise a combination of the three design criteria shown in Figure 1:

1. Making the ground slab airtight;
2. Lowering the air pressure at the lower zone of the ground slab;
3. Effectively diluting indoor air with outdoor air.

The indoor radon concentration can be balanced at an acceptable level using this method [11]. However, in contrast to new buildings, the three design criteria may not be implementable to influence the indoor radon concentration sufficiently for already-constructed buildings.

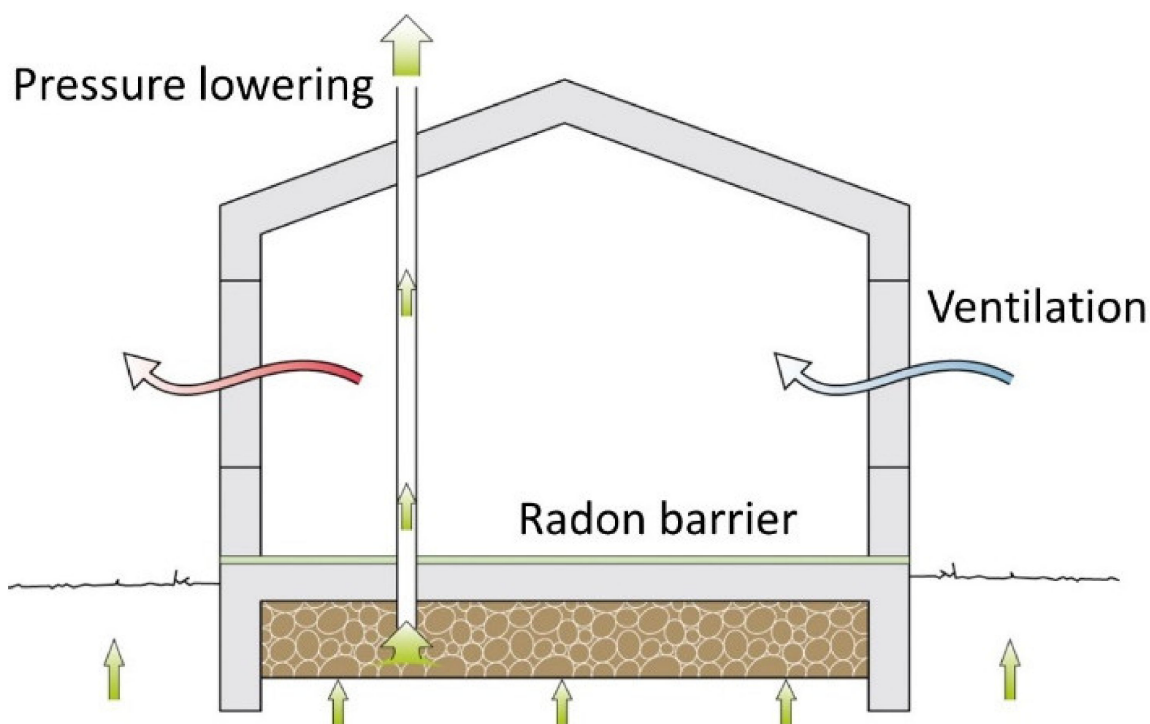


Figure 1. Design criteria to control the radon penetration and radon concentration in indoor air: 1. radon barrier—establishing a barrier preventing soil gas from penetrating from the ground; 2. pressure lowering—lowering the air pressure in the lower zone of the ground slab; and 3. ventilation—diluting indoor air with outdoor air.

3. Model for Balancing Radon Indoors

The theoretical model is based on a description of a detached single-family house with a ground area denoted by A , a ceiling height h and an air-change rate q . The indoor air is diluted with outdoor air with a radon concentration denoted by r and an indoor-air radon concentration denoted by R , as shown in Figure 2. Soil gas and the contribution from building materials and the interior are assumed to increase the indoor-air radon concentration. Therefore, the maximum penetration of soil gas with radon content (R_g)

and contribution from indoor materials (R_m) to maintain an acceptable indoor radon concentration were found using the equilibrium equation.

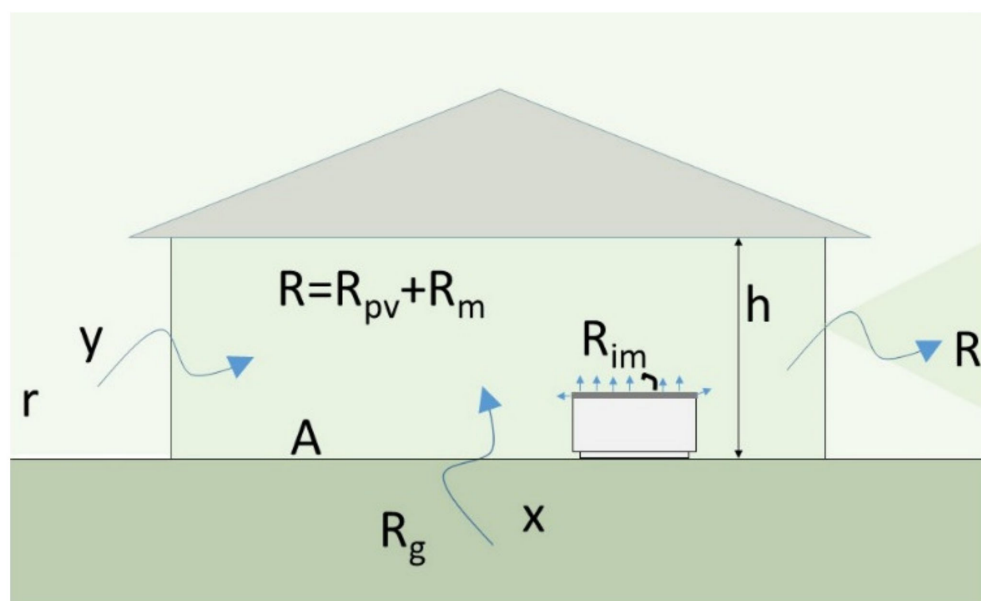


Figure 2. The equilibrium equation describes the equilibrium between the constant radon concentration in the indoor air (R), and the radon supply from soil gas (R_g), exterior air (r) and indoor materials (R_{im}) for a constant air-pressure difference between the interior and exterior over time.

Assuming the air-pressure difference between the interior and exterior of the building is constant over time, the equilibrium equation describes the static equilibrium of all internal and external system forces [12]. In the static case, the equilibrium equation is as follows:

$$K \cdot u = F, \quad (1)$$

where K denotes the stiffness matrix of the system, u is the vector with nodal displacements and F represents external forces.

The equilibrium equation describes the equilibrium between the constant radon concentration in the indoor air and the radon supply from soil gas, exterior air and indoor materials. The soil gas and exterior air are both assumed to have a constant but different radon concentrations. The contribution from indoor materials is assumed to follow the dilution equation. The radon contribution from indoor materials contributes to the indoor radon concentration and depends on the ventilation rate. The contribution to the indoor radon concentration from indoor materials reduces by 50% when the ventilation rate doubles. The equilibrium is given by Equations (2)–(4):

$$q \cdot A \cdot h \cdot R_{pv} = y \cdot r + x \cdot R_g, \quad (2)$$

where the indoor-air radon content, denoted as R , is the result of the radon contribution from soil gas, outdoor air (R_{pv}) and indoor materials (R_m):

$$R = R_{pv} + R_m. \quad (3)$$

The radon contribution from indoor materials (R_m) is described by the function F , where the contribution declines with the ventilation rate following the dilution equation:

$$R_m = F(R_{im}, q), \quad (4)$$

where R_{im} is the initial radon contribution from indoor materials. The radon content in the air outlet equals the indoor-air radon content provided from the three supply sources: the outdoor air, soil gas and indoor materials.

The equilibrium equation also describes the equilibrium between the indoor-air volume ventilated out of the building and the air supply volume needed from the soil gas and exterior air to stabilize the air-pressure difference over the building envelope over time. The equilibrium is given by Equation (5):

$$x + y = q \cdot A \cdot h. \quad (5)$$

The variables x and y are the only undefined variables in these equations (i.e., in Equations (2) and (5)). The air supply from the ventilation and the penetrating soil gas is equal to the building air outlet.

4. Quantifying the Contribution of Indoor Materials

The radon contribution from indoor materials is well known [13]. The contribution to the indoor-air radon content is related to the specific materials used in a building, contributing to the indoor radon concentration if the materials contain radium or the chemical elements uranium and thorium (e.g., granite and alum shale). The radon contribution to the indoor radon concentration from building materials is seldomly significant in well-ventilated buildings. However, if an acceptable indoor-air level of radon concentration is as low as 100 Bq/m^3 , or even lower, radon contributions from less polluting sources must be considered.

The contribution from indoor materials is theoretically described in this paper by the function F , where the contribution declines with the ventilation rate. The radon concentration from indoor materials is described by an initial contribution (R_{im}) that declines by 50% every time the ventilation rate is doubled, following the dilution equation [14].

The initial contribution (R_{im}) from indoor materials (R_m) must be defined. The presented theory defines the initial radon contribution to the indoor-air radon concentration and considers the contribution related to a very low air change q of 0.1 times per hour, as illustrated in Figure 3 and Table 1.

Table 1. Decline in the radon contribution to the indoor-air radon concentration from indoor materials. q is the air change per hour.

$q \text{ (h}^{-1}\text{)}$	$R_m \text{ (Bq/m}^3\text{)}$				
0.01	400.00	1000.00	5000.00	10,000.00	
0.05	80.00	200.00	1000.00	2000.00	
0.10 ¹	40.00	100.00	500.00	1000.00	
0.20	20.00	50.00	250.00	500.00	
0.40	10.00	25.00	125.00	250.00	
0.80	5.00	12.50	62.50	125.00	
1.60	2.50	6.25	31.25	62.50	
3.20	1.25	3.13	15.63	31.23	
6.40	0.63	1.56	7.81	15.63	
12.80	0.31	0.78	3.91	7.81	

¹ R_m is calculated for several different ventilation rates ranging from 0.01 h^{-1} to 12.8 h^{-1} . Initial radon contributions (R_{im}) of 40, 100, 500 and 1000 Bq/m^3 are shown. The initial radon contribution (R_{im}) is defined at the air change q equal to 0.1 times per hour.

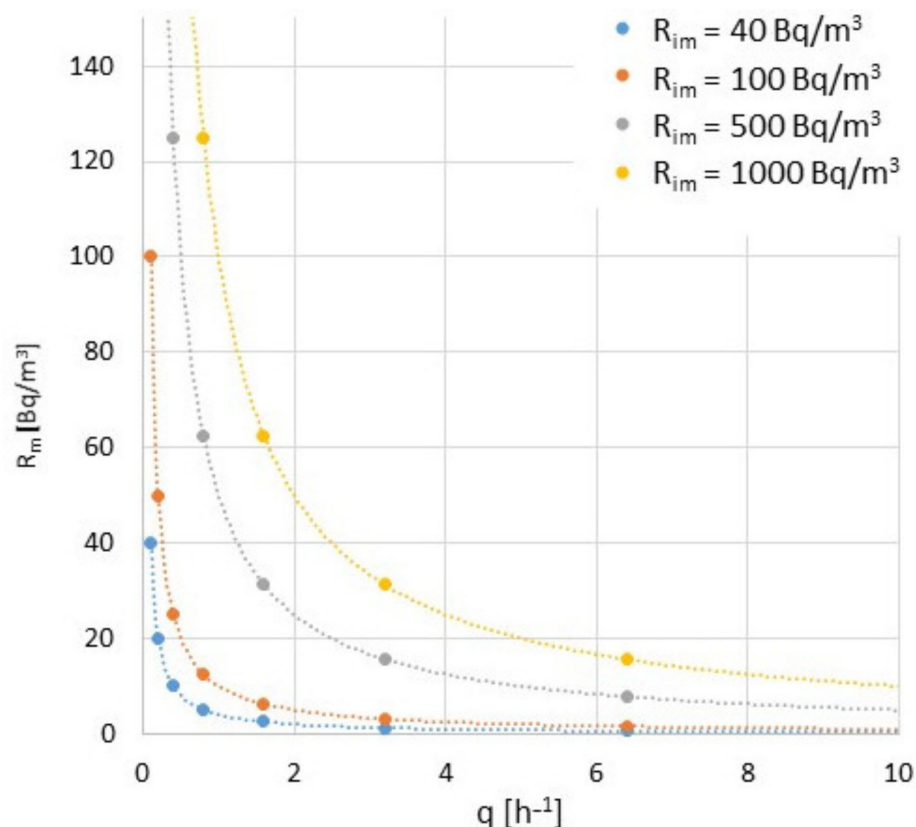


Figure 3. Radon contribution to the indoor-air radon concentration from indoor materials (R_m) described by the function F where the contribution declines by 50% every time the ventilation rate doubles, taking its starting contribution as the initial contribution (R_{im}) at an air-change rate q of 0.1 times per hour.

Although a ventilation rate of 0.1 h^{-1} is low, field studies show measurements of the ventilation rates in new detached single-family houses to be as low as 0.07 h^{-1} [15].

5. Balancing Radon Indoors

The presented theory can be used to determine the related values and requirements for the radon penetration from soil gas, the radon contribution from indoor materials and the radon concentration in outdoor air. The theory can also determine the ventilation rate to balance radon in indoor air at an acceptable level for a specific detached single-family house.

For a detached single-family house, the maximum penetration of soil gas to maintain an acceptable indoor radon concentration of 100 Bq/m^3 was determined for several radon exposures from soil gas. The radon concentration in soil gas varied from less than 1000 to $150,000 \text{ Bq/m}^3$. The ground area of the house was 100 m^2 with a ceiling height of 2.5 m. The air-change rate was 0.5 h^{-1} to maintain an acceptable indoor environment, equivalent to changing all the indoor air every two hours.

The initial radon contribution from indoor materials to the indoor radon concentration (R_{im}) was 40 Bq/m^3 , resulting in a radon contribution of 8 Bq/m^3 from indoor materials (R_m) to the indoor radon concentration (Figure 3 and Table 1). Indoor air was diluted with outdoor air with a radon concentration of 5 Bq/m^3 . The requirements to balance an acceptable indoor radon concentration R of 100 Bq/m^3 for the penetration of soil gas containing radon are listed in Figure 4.

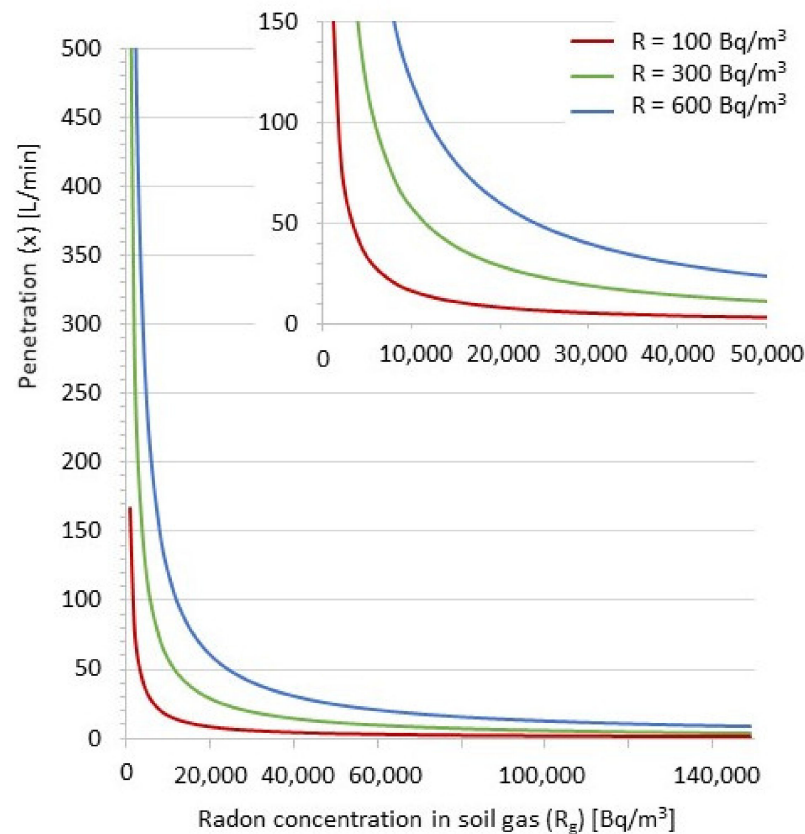


Figure 4. Soil gas penetration, balancing an acceptable radon concentration in indoor air of 100, 300, and 600 Bq/m³. Soil gas contains radon. Indoor air was diluted with outdoor air. Outdoor air contains 5 Bq/m³ radon. The air-change rate was 0.5 h⁻¹. The initial radon contribution from indoor materials (R_{im}) was 40 Bq/m³, providing a radon contribution from indoor materials (R_m) of 8 Bq/m³ to the radon indoor-air concentration. The house has a ground area of 100 m² and a ceiling height of 2.5 m.

Additionally, Figure 4 illustrates that the soil gas penetration for the same detached single-family house can increase to balance an acceptable radon indoor-air concentration R of 300 and 600 Bq/m³. Penetration was calculated in liters per minute. Less soil gas may penetrate the indoor air through the ground slab to balance an acceptable radon indoor-air level of 100, 300 and 600 Bq/m³ to increase the radon concentration in the soil gas. To reach a balance at a higher level of an acceptable radon concentration in the indoor air, a larger amount of radon penetrates indoor air through the ground slab, either through the increased penetration of soil gas or a higher radon concentration in the soil gas.

When balancing an acceptable indoor radon concentration of 100 Bq/m³ for a house, the maximum penetration of soil gas was found for several radon exposures from soil gas and for several initial radon contributions from indoor materials (R_{im}) with air-change rates of 0.5, 1.06 and 2.11 h⁻¹. For the initial radon contribution from indoor materials (R_{im}) of 237 Bq/m³, an indoor radon concentration R of 100 Bq/m³ can be balanced and kept with an air-change rate of 0.5 h⁻¹ if soil gas penetration containing radon is avoided. To further increase the initial radon contributions from indoor materials, the air-change rate must be increased to balance indoor radon at a concentration of 100 Bq/m³, still avoiding soil gas penetration containing radon. For the initial radon contribution from indoor materials of 500 Bq/m³, an air-change rate of 1.06 h⁻¹ is needed. For an initial radon contribution from indoor materials of 1000 Bq/m³, an air-change rate of 2.11 h⁻¹ is needed for balance at an acceptable radon indoor-air concentration R of 100 Bq/m³ (Figure 5). The ground slab must be airtight, and measures must be taken to lower the air pressure at its lower

zone to avoid soil gas penetration of the indoor air through the ground slab of a detached single-family house.

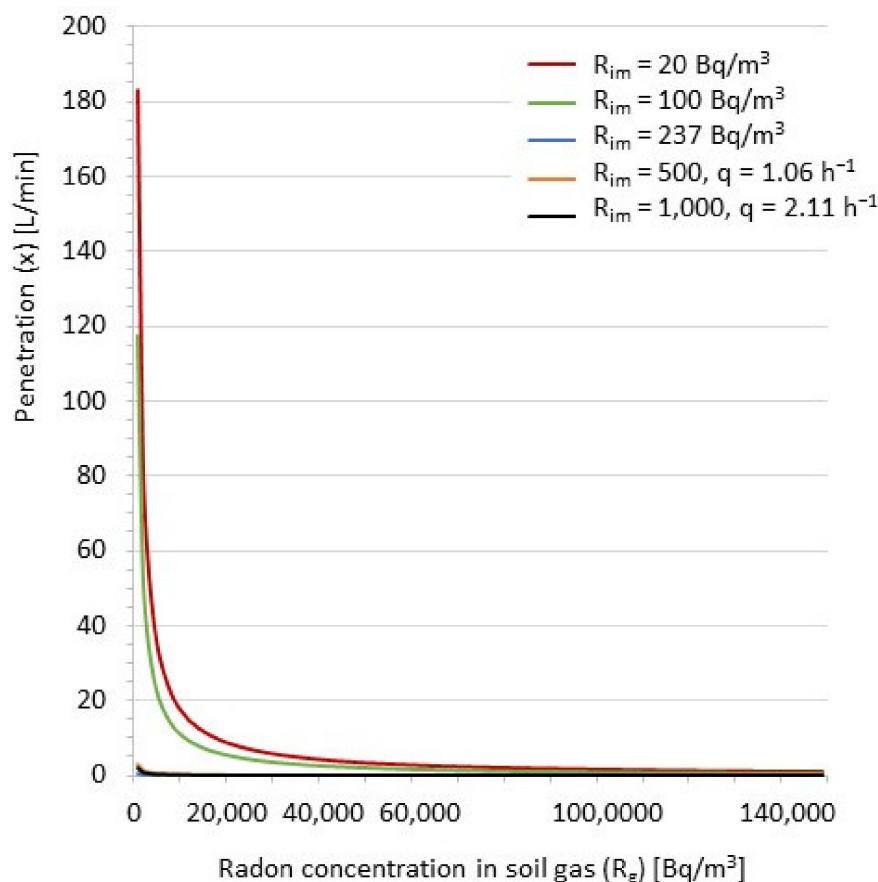


Figure 5. The allowed soil gas penetration with a given radon concentration balancing the radon indoor-air concentration at 100 Bq/m³ with increased initial radon contributions from indoor materials and an air-change rate starting from 20 Bq/m³ and 0.5 h⁻¹, respectively.

6. Controlling Soil Gas Penetration

Controlling the radon concentration via soil gas penetration through the ground slab is a key parameter for balancing the radon indoor-air concentration at an acceptable level. Measures that make the ground slab airtight or lower the air pressure at the lower zone of the ground slab can be used individually or combined. Making the ground slab airtight increases the effect of a pressure-lowering measurement at the lower slab zone. A measure reducing radon penetration to a predefined level can be reached using a barrier. The barrier choice depends on its ability to reduce infiltration. Ten radon barriers used as system solutions were tested with the modified version of the NBI 167/02 radon membrane, the airtightness test method [10], which determines the airtightness of a radon barrier used as a system solution.

6.1. Barriers

Ten barriers were tested as system solutions, which are denoted as Systems A through J, as shown in Table 2.

Table 2. Barrier systems tested.

System	Contents
A	A fixed mortar paste combined with acrylic sealant, also used as a wet-room membrane.
B	A firm bitumen-based radon blocker combined with a two-component floating sealant.
C	A reinforced fixed mortar paste combined with acrylic sealant.
D	A one-component floating membrane combined with edge reinforcements, epoxy and elastic pipe collars.
E	A two-component fixed mortar paste combined with edge reinforcements, epoxy and elastic pipe collars.
F	A foil system consisting of nonwovens filled with a two-component fixed mortar paste combined with edge reinforcements, epoxy and elastic pipe collars.
G	A polyethene membrane with solid tape joints, acrylic primer and elastic pipe collars.
H	A polyethene membrane with solid tape joints, acrylic adhesive, acrylic primer and elastic pipe collars.
I	A noise-reducing aluminum foil-coated subflooring with aluminum butyl tape joints, primer and elastic pipe collars.
J	A noise-reducing aluminum foil-coated subflooring with aluminum butyl tape joints, primer, elastic pipe collars and a one-component flow membrane.

Figure 6 illustrates mounting the test material inside the mock-up for System B. System B is a firm bitumen-based radon blocker combined with a two-component floating sealant. Figure 7 displays the mounting of the two-component fixed mortar paste combined with edge reinforcements, epoxy and elastic pipe collars, denoted as System E.

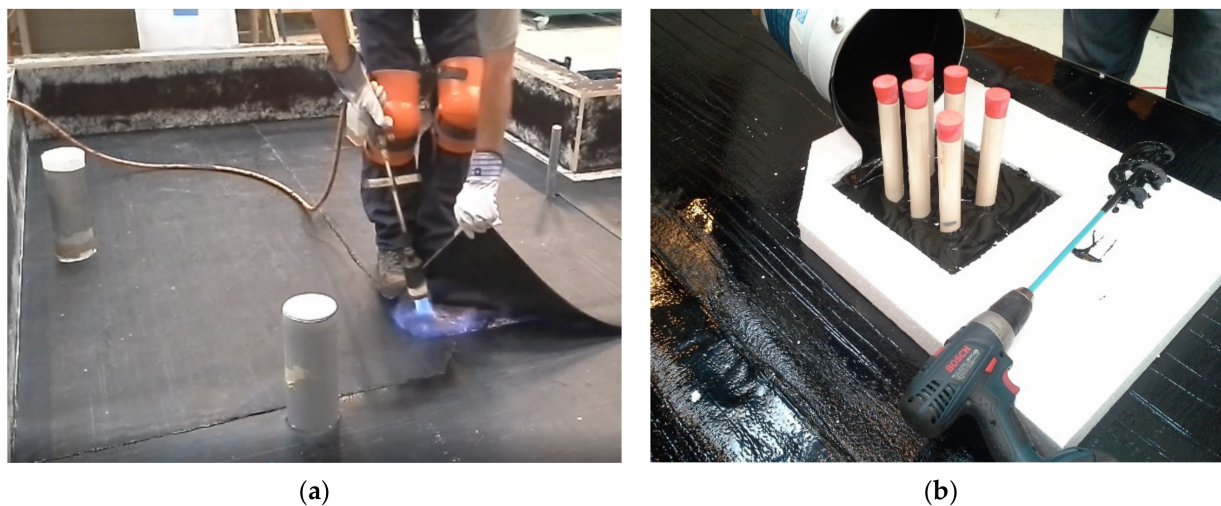


Figure 6. Mounting the test material inside the mock-up for System B, which is a firm bitumen-based radon blocker (a) combined with a two-component floating sealant (b).

The barriers were used as delivered, and the manufacturer mounted them inside the mock-up. The tests started 40 h after mounting the barrier to ensure a stress-free barrier and joints. The tests set no specific requirements for the indoor climate at the testing laboratory. However, the laboratory climate should be a dry tempered room with a temperature between 17 °C and 25 °C with relative humidity between 15% and 65%.



Figure 7. Mounting the test material inside the mock-up for System E, which is a two-component fixed mortar paste combined with edge reinforcements, epoxy and elastic pipe collars.

6.2. Test of Air Infiltration

The test determines the air penetration through a material evaluated for suitability as a radon barrier. The test evaluates how well a barrier prevents soil gas with radon from penetrating the indoor air. The barrier was mounted inside a mock-up, providing a stable basis with penetrating pipes, an elevation, and narrow-angled and wide-angled corners. The airtightness of the barrier was determined as the air penetration through the barrier and its joints for a difference in air pressure of 30 Pa, denoted as q_{30} . The difference in air pressure over the barrier is the difference in the air pressure between the air inside the mock-up (designed as a box) and in the surrounding test laboratory.

6.3. Measurement Setup

The test was conducted by mounting the test material inside a mock-up. After molding the test material, the mock-up was filled with pressure-firm thermal insulation using mineral wool. On top of the firm insulation, a test-material layer was mounted to seal the mock-up volume that holds the firm insulation enveloped by the test material. The constant airflow from the sealed mock-up was measured. The airflow provides a constant air-pressure difference.

6.4. Equipment

The barrier was mounted in a mock-up of laminated wooden boards 3.0 m long and wide and 0.3 m high with a notch of 1.0 by 1.0 m, with changed floor levels, penetrating pipes and floor drains (Figure 8). The air was extracted from the volume using a fan. The cavity of the mock-up was filled with pressure-firm thermal insulation material and enveloped by the test barrier material. The coherent airflow values and difference in air pressure between the air inside the mock-up and the surrounding test laboratory were systematically measured and logged.

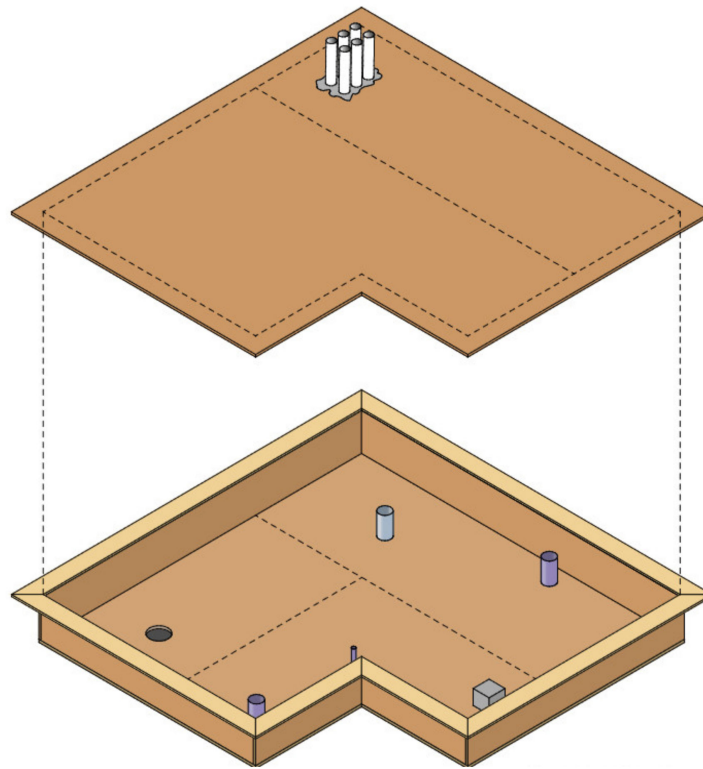


Figure 8. Sketch of mock-up measuring the barrier airtightness.

Using the program TECLOC3 from BlowerDoor GmbH, the data were logged by connecting a (1) computer to a unit measuring the pressure difference and (2) a fan. The fan was a Minneapolis micro leakage meter, type FD E51-767, which measured the airflow between 0.09 and $79 \text{ m}^3\text{h}^{-1}$. The fan was mounted on a disc with a circular hole to measure the airflow. Individual discs were mounted, and each had a circular hole of 3.8, 8.0, 20 or 45 mm. A computer controlled the fan to extract the air from the mock-up volume and measure the airflow, introducing predetermined differences in air pressure between the volume within the mock-up and the air in the surrounding test laboratory.

The mean value of the difference in air pressure between the volume within the mock-up and the air in the surrounding test laboratory was determined using five air-pressure difference measurement units mounted on the top layer of the test material. These units were used to calibrate the airflow pressure measurements because the air pressure within the mock-up was not homogeneously distributed.

Adding air infiltration through well-defined openings was necessary to measure the airtightness of the barriers with very low airflow in the lower ranges of the capacity of the micro leakage meter. The well-defined openings were added using discs with a 7, 10, 14 or 20 mm diameter. The airflow through the well-defined opening was subtracted from the measured airflow during data processing.

6.5. Processing Results

The airflow was measured at four air-pressure levels of 30, 50, 70 and 90 Pa controlled by the air-pressure measuring equipment mounted over the barrier system. At each pressure level, four measurements were performed using four different well-defined openings. For all 16 measurements, the opening areas, the individual air-pressure differences in the five air-pressure difference measurement units, and the airflow through the suction point were measured. The measurements were used to calculate the airflow in liters per minute for a 30-Pa mean pressure difference, denoted as q_{30} , over the barrier system, where q_{30} was determined for the individual barrier systems.

The airflow for a 30-Pa mean pressure difference over the barrier system comprises the soil gas penetration for a one-floor building with a ground area of 100 m² with a difference in air pressure over the building envelope of 1 to 4 Pa [4,9,10,16]. The highest allowed soil gas penetrations with a radon concentration not exceeding an acceptable level in the indoor air of 100, 200 and 300 Bq/m³ were determined. Soil gas penetration was determined as the intersection between the air balance indoors, given by the air-change rate and an acceptable radon concentration from Equations (2) and (3), an initial radon contribution from indoor materials of 40 Bq/m³ and the penetration of soil gas, q_{30} . For the calculations, indoor air was assumed to be diluted with outdoor air with a radon concentration of 5 Bq/m³ [17]. Additionally, the air-change rate in the building was set at 0.5 h⁻¹ [18]. Figure 9 presents the soil gas determination with a radon concentration not exceeding acceptable indoor-air levels of 100, 200 and 300 Bq/m³ for the System B and E barriers.

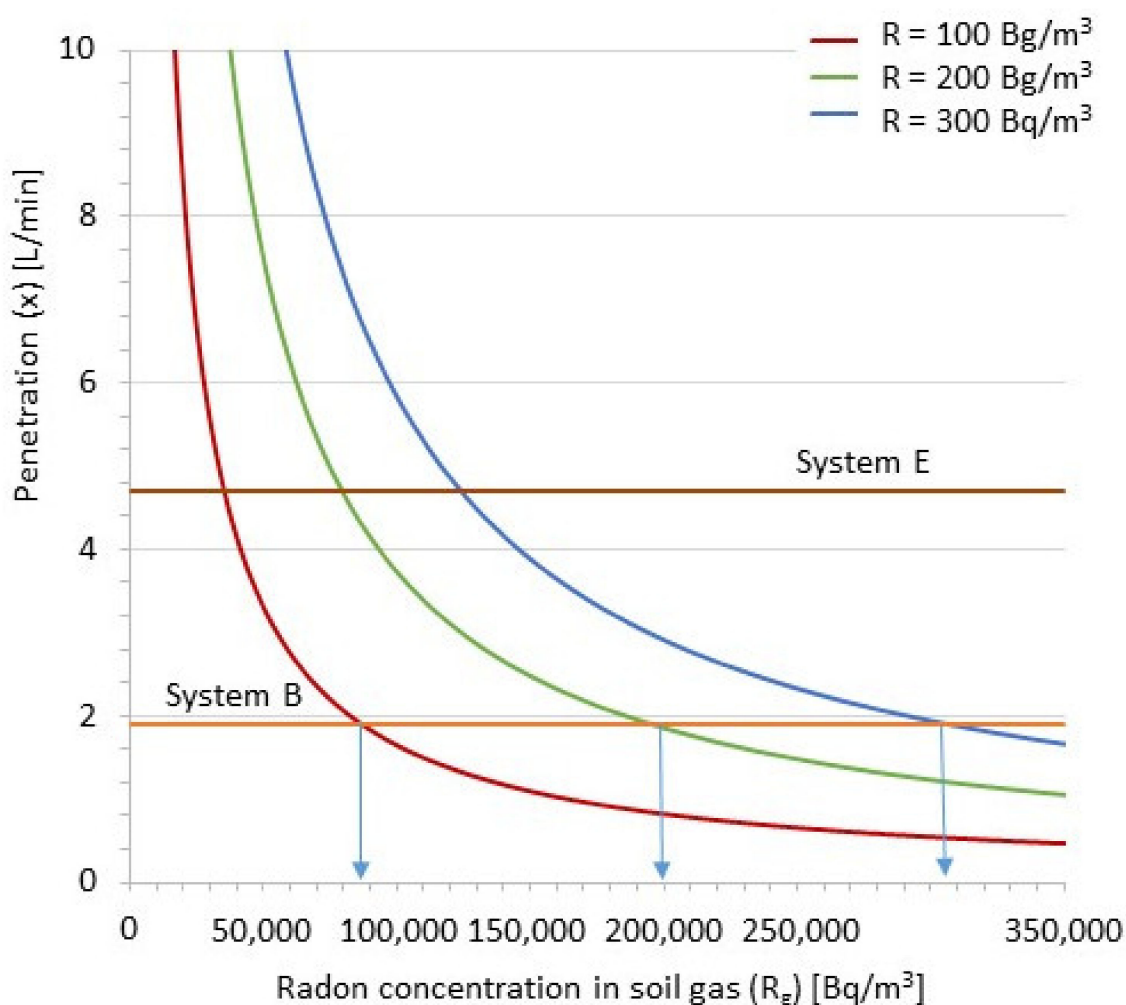


Figure 9. Radon barriers for System B and E, where the intersection between the horizontal line indicating the measured airtightness and the curves for reaching an acceptable radon indoor-air level of 100, 200 and 300 Bq/m³ provides the critical radon concentration in soil gas.

Figure 10 displays the soil gas determination with a radon concentration not exceeding an acceptable level in indoor air of 100 Bq/m³ for an air-change rate of 0.5, 1.0, 2.0 and 4.0 h⁻¹ for the System B and E barriers.

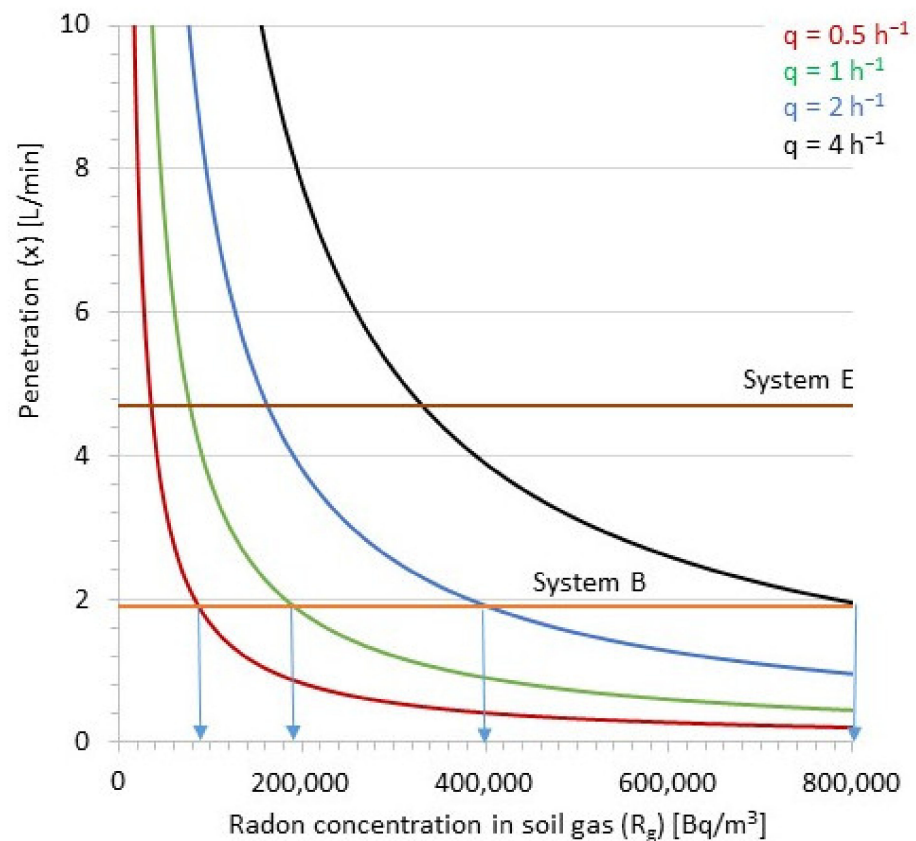


Figure 10. Radon barriers for System B and E, where the intersection between the horizontal line measuring the airtightness and the curves for the air-change rates provides the radon concentration in soil gas.

7. Results

The penetration rates and radon concentration in soil gas (Table 3) should not exceed 100, 200 and 300 Bq/m³ to reach an acceptable radon concentration in indoor air. For Table 3, the air-change rate was 0.5 h⁻¹, and the initial radon contributions from indoor materials (R_{im}) was 40 Bq/m³. Moreover, the penetration rates and radon concentration in soil gas to not exceed 100 Bq/m³ are listed in Table 4, where the air-change rates were 0.5, 1.0, 2.0 and 4.0 h⁻¹, and the initial radon contribution from indoor materials (R_{im}) was 40 Bq/m³.

Table 3. Maximum soil gas penetration to reach an indoor radon concentration of 100, 200 and 300 Bq/m³ for System A to J barriers. The air-change rate was 0.5 h⁻¹, and the initial radon contribution from indoor materials (R_{im}) was 40 Bq/m³. The airflow penetration rate (q_{30}) defines how well a barrier prevents soil gas penetration.

Barrier System	Airflow, Penetration Rate (q_{30}) (L/min)	R_g in Soil Gas		
		100 (Bq/m ³)	200 (Bq/m ³)	300 (Bq/m ³)
A	12.0	13,500	31,000	48,500
B	1.9	86,600	196,200	305,800
C	29.0	5700	12,900	20,100
D	4.8	34,400	77,600	121,000
E	4.7	35,000	79,400	123,700
F	12.6	13,000	29,500	46,000
G	132.0	1400	2800	4400
H	8.9	18,500	42,000	65,700
I	63.9	2600	5900	9100
J	16.6	9800	22,500	35,000

Table 4. Maximum soil gas penetration to reach an indoor-air radon concentration of 100 Bq/m³ for System A to J barriers. The air-change rate was 0.5, 1.0, 2.0 and 4.0 h⁻¹, and the initial radon contribution from indoor materials (R_{im}) was 40 Bq/m³. The airflow penetration rate (q_{30}) defines how well a barrier prevents soil gas penetration.

Barrier System	Airflow, Penetration Rate (q_{30}) (L/min)	R_g in Soil Gas			
		$q = 0.5$ (h ⁻¹)	$q = 1.0$ (h ⁻¹)	$q = 2.0$ (h ⁻¹)	$q = 4.0$ (h ⁻¹)
A	12.0	13,500	30,500	63,500	129,000
B	1.9	86,600	190,800	399,000	817,000
C	29.0	5700	12,500	26,200	53,500
D	4.8	34,400	75,500	158,000	323,000
E	4.7	35,000	77,200	161,300	330,000
F	12.6	13,000	29,000	60,500	123,000
G	132.0	1400	2700	5800	11,800
H	8.9	18,500	40,500	85,500	174,200
I	63.9	2600	5600	11,800	24,200
J	16.6	9800	22,000	45,500	94,000

8. Moisture Challenges

A radon barrier can easily be applied during building construction, creating a barrier to increase the ground slab airtightness within or above the ground slab. The barrier can even be mounted in the ground below the slab. This barrier can be applied in numerous ways with suitable fixation onto the materials and surfaces, combined with a moisture barrier that prevents ground moisture from reaching constructions above the foundation or the basement interior. Applying a radon barrier to an already-constructed building can affect the durability of the building, especially for heritage buildings, because measures may create a far more vulnerable building and change its robustness to withstanding moisture and user behavior.

The influence and change in moisture load and content of other building components and constructions must be considered when deciding on a radon barrier mounted on the ground slab or basement wall and floor. Thus, the changed water vapor diffusion and resulting rise in soil moisture load may create a more vulnerable building after mounting a radon barrier for construction. Special attention must be focused on the risk of mold growth, for example, in an air cavity behind a radon barrier that is not bonded to the underlayment.

Through diffusion, radon can penetrate the ground slab or basement wall and floor. The ability of gases, vapors and other minor molecules to penetrate the ground slab, basement wall and floor by diffusion depends on the individual permeability of the ground slab, basement wall and floor.

Diffusion through concrete is considered limited. Fixed mortar paste can reduce diffusion but cannot prevent penetration by diffusion. As the ability to limit diffusion is related to the density of the fixed mortar paste and the thickness of the mortar paste layer, even minor cracks can increase diffusion [19].

Investigations have found that radon diffusion through a typical concrete slab of 150 mm in thickness without cracks contributes to indoor radon by approximately 15 to 20 Bq/m³. For these investigations, an air-change rate of 0.5 h⁻¹ was provided in the building, and the radon content in the soil gas was 500,000 Bq/m³ [20].

In Denmark, the general radon content in soil gas is substantially lower, approximately 50,000 Bq/m³ [21]. In this case, the contribution by radon diffusion into the indoor air is substantially lower at approximately 2 Bq/m³.

Radon penetration through the ground slab, basement wall and floor by diffusion in buildings today represents a limited contribution to the overall indoor-air radon content, and the primary source is soil gas from the ground. However, a high indoor-air radon content can be observed in indoor air where the air-change rate is lower than 0.5 h⁻¹ due to the accumulation of radon from indoor materials.

9. Discussion

Soil gas penetrating through the ground slab is the primary source of radon in indoor air in most cases [11]. However, the contribution from indoor materials may affect the indoor-air radon content, resulting in an unacceptable level. Therefore, the (1) geological composition of the ground on which a building is situated, (2) radon concentration in soil gas, (3) soil gas penetration through the ground slab, (4) contribution from indoor materials and (5) air-change rate are used to set the indoor radon concentration level. Radon seeps into a building through soil gas penetration through cracks or other ground construction openings [22] and indoor materials. Therefore, it is essential to control soil gas penetration and balance the radon concentration indoors through ventilation.

Establishing a barrier that prevents soil gas penetration from the ground is an efficient way to prevent radon penetration. By avoiding soil gas penetration and lowering the air pressure in the lower zone of the ground slab, a barrier provides a more effective solution, providing a far better possibility of providing an air-change rate of 0.5 h^{-1} that balances the indoor radon concentration at an acceptable level. However, when combining the three mentioned design criteria, (1) making the ground slab airtight, (2) lowering the air pressure at the lower zone of the ground slab and (3) effectively diluting the indoor air with outdoor air, the radon concentration in indoor air can be robustly balanced and maintained at an acceptable level. If the air pressure in the lower zone of the ground slab cannot be lowered, the radon barrier choice is crucial for soil gas penetrating the indoor air.

The presented theory aids in combining the radon barrier choice and related necessary ventilation rate of the indoor air to balance the radon at an acceptable indoor concentration. The theory estimates the allowed radon infiltration from the ground to balance the radon at an acceptable indoor level for a given ventilation rate, considering the radon contribution to the indoor air from indoor materials. However, the moisture-level change in the building components must be considered when choosing the most suitable radon barrier, which depends on individual building physics.

The requirement for the airtightness of a radon barrier, the penetration rate (q_{30}), can be determined from the radon concentration in soil gas underneath a building. In certain cases, a diffusion-tight radon barrier can be used, and in others, a diffusion-open barrier is preferred. The barrier choice depends on the moisture level after mounting. It is crucial to choose a sufficiently airtight radon barrier to meet the requirements while contributing to the building physics.

From the theoretical processing of the test results combined with the radon contribution from indoor materials and the indoor-air ventilation rates, a radon barrier can be chosen based on the indoor radon concentration being balanced at an acceptable level and the radon content in the soil gas underneath a building. The theoretical processing demonstrates that, for an initial radon contribution from indoor materials (R_{im}) of up to 237 Bq/m^3 , an acceptable indoor radon concentration of 100 Bq/m^3 can be achieved with an air-change rate of 0.5 h^{-1} , controlling the soil gas penetration. However, at a radon contribution from materials of 237 Bq/m^3 , soil gas penetration containing radon must be avoided. An increased initial radon contribution from indoor materials means an increased ventilation rate is needed, balancing an acceptable indoor radon concentration of 100 Bq/m^3 . The ventilation rates of 1.06 and 2.11 h^{-1} are needed for radon contributions from indoor materials of 500 and 1000 Bq/m^3 , respectively, balancing an acceptable indoor radon concentration of 100 Bq/m^3 and avoiding soil gas penetration containing radon. Hence, in this study, the radon contribution from indoor materials was determined as the initial contribution at a ventilation rate of 0.1 h^{-1} . Avoiding soil gas penetration into the indoor air through the ground slab requires combined measures, including making the ground slab airtight and lowering the air pressure at the lower zone of the ground slab to a level that is even lower than the air pressure above the ground slab [23].

The theoretical test results indicate that the radon barrier in System B with the penetration rate (q_{30}) of 1.9 L/min can balance an acceptable radon concentration in indoor air that is less than or equal to 100 Bq/m^3 in a building on soil with a radon concentration of less

than or equal to $86,600 \text{ Bq/m}^3$. If the soil gas contains a concentration of between $86,600$ and $305,800 \text{ Bq/m}^3$, an acceptable indoor radon concentration can be balanced between 100 and 300 Bq/m^3 . For theoretical processing, it was assumed that indoor air was diluted with outdoor air with a radon concentration of 5 Bq/m^3 at an air-change rate of 0.5 h^{-1} and an initial radon contribution from indoor materials of 40 Bq/m^3 . However, by increasing the air-change rate to 1 , 2 , or 4 h^{-1} , an acceptable radon concentration in indoor air could be kept balanced at 100 Bq/m^3 or less in a building on soil with a radon concentration of $190,800$, $399,000$ and $817,000 \text{ Bq/m}^3$, respectively.

In terms of the testing barriers, it is vital to be aware of how the joints perform. These concerns are based on the performance of Systems G and H and Systems I and J, which are alike except for how the joints perform.

10. Conclusions

A model for theoretically balancing the radon concentration in indoor air was presented. The theory estimates the allowed radon infiltration from the ground to balance the radon at an acceptable indoor level for a given ventilation rate considering the radon contribution to the indoor air from indoor materials, such as building materials and the interior. The theory is useful for a typical building construction for a single-family house. Furthermore, the paper presents a theoretical processing method to balance the radon concentration indoors by combining the results from an improved testing method for determining the airtightness of a radon barrier assessed as a system solution [10]. Moreover, if appearing in the indoor air, a radon concentration above that of the outdoor air can be lowered by diluting the indoor air using outdoor air and ventilation. The model also demonstrates how the radon contribution from indoor materials influences the measures balancing the radon concentration indoor at an acceptable level.

Using the theoretical processing of the results determining the airtightness of the radon barriers as system solutions made it possible to choose a radon barrier with an acceptable radon concentration in indoor air and soil gas underneath a building with the ventilation rate and radon exposure from indoor materials. However, the acceptable radon concentration in indoor air could be compromised because a suitable radon barrier depends on the moisture-level change in the building after mounting the radon barrier. A radon barrier must contribute to the building physics, creating a more robust building. Further, the needed ventilation rate to achieve an acceptable radon concentration in indoor air could compromise the energy performance of the building.

The presented theory and theoretical processing method assumed that only soil gas, indoor materials and the atmosphere contain radon and that soil gas and indoor materials are the radon sources in indoor air. However, the contribution to the radon concentration in indoor air from indoor building materials is seldom significant. The contribution from indoor building materials is included in the theory, as materials contribute radon if they contain radium or the chemical elements uranium and thorium (e.g., granite and alum shale).

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