

Design Criteria for Achieving Acceptable Indoor Radon Concentration

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Abstract—Design criteria for achieving an acceptable indoor radon concentration are presented in this paper. The paper suggests three design criteria. These criteria have to be considered at the early stage of the building design phase to meet the latest recommendations from the World Health Organization in most countries. The three design criteria are; first, establishing a radon barrier facing the ground; second, lowering the air pressure in the lower zone of the slab on ground facing downwards; third, diluting the indoor air with outdoor air. The first two criteria can prevent radon from infiltrating from the ground, and the third criteria can dilute the indoor air. By combining these three criteria, the indoor radon concentration can be lowered achieving an acceptable level. In addition, a cheap and reliable method for measuring the radon concentration in the indoor air is described. The provision on radon in the Danish Building Regulations complies with the latest recommendations from the World Health Organization. Radon can cause lung cancer and it is not known whether there is a lower limit for when it is not harmful to human beings. Therefore, it is important to reduce the radon concentration as much as possible in buildings. Airtightness is an important factor when dealing with buildings. It is important to avoid air leakages in the building envelope both facing the atmosphere, e.g. in compliance with energy requirements, but also facing the ground, to meet the requirements to ensure and control the indoor environment. Infiltration of air from the ground underneath a building is the main providing source of radon to the indoor air.

Keywords—Radon, natural radiation, barrier, pressure lowering, ventilation.

I. INTRODUCTION

THE World Health Organization recommends states to introduce requirements to the maximum concentration of radiation from natural sources in the indoor air. The recommendation, of introducing such requirements to the indoor air in states, is new. The new recommendations are a result of the World Health Organization's evaluation of radon as being responsible for 3-14% of lung cancer incidents, depending on the average radon exposure in different countries [1]. These results show radon as being the second-largest cause of lung cancer (smoking is still the principal cause). Radon exposure must be taken seriously in the fight against radon-induced lung cancer due to the large number of people that is exposed daily in buildings and especially in residential buildings [1]. If people spend their whole life in a house with an average radon concentration in the indoor air exceeding 200 Bq/m³, their risk of getting lung cancer is higher than 1%. This is far too high and higher than what in other contexts is

acceptable for a single-factor risk [2]. Therefore, it is crucial to prevent radon from infiltrating into buildings. Accurate methods are needed for detecting radon in the indoor air as well as methods for providing cheap and effective solutions to prevent radon from polluting the indoor air.

A. Regulations and Guidelines

In Denmark, the recommendation by the World Health Organization has resulted in a tightened provision on radon in the Danish Building Regulations. The Danish Building Regulations stipulate a maximum level of 100 Bq/m³ in the indoor air in all buildings constructed after 2010. For buildings constructed before 2010, simple and cheap actions are recommended if the concentration of radon is between 100 Bq/m³ and 200 Bq/m³ in the indoor air; however, if the concentration of radon in the indoor air exceeds 200 Bq/m³, immediate intervention is necessary and more efficient efforts and improvements are recommended in order to lower the concentration of radon in the indoor air [3]. In 2008, measurements of the radon concentration of the indoor air were made in Danish detached houses build between 2001 and 2007. These buildings were built on ground at locations with a high radon content in the ground. Results showed that 1% of these houses had radon concentrations in the indoor air above 200 Bq/m³, and 7% had concentrations in the indoor air above 100 Bq/m³ [4].

B. Radon in Buildings

Radon is a radioactive noble gas that develops as a result of the decay chains of uranium and thorium [5]. When radon decays into different radon daughters, it generates a radioactive radiation. It is the radioactive radiation from the radon daughters that is harmful to human beings. Radon originates in the ground, from building materials and water. However, the level of radioactive radiation is quite different for the different sources. The ground is the primary source of radon in Denmark [6]. Therefore, the geological composition of the ground, on which a building is situated, sets the level for how high the indoor radon concentration can become. Radon infiltrates into a building both as a result of diffusion through building materials and by air infiltrating from the ground chased by convection and advection through cracks or other unforeseen openings in the ground construction [7]. Infiltration from diffusion through building materials and from water is far lower than the amount provided from air infiltrating from the ground. Therefore, it is of great importance to ensure an airtight building

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envelope towards the ground or by other means to avoid infiltration of air from the ground. Methods for avoiding radon infiltration are far the easiest and cheapest to implement when constructing the building. Radon is without colour, smell, taste and sound and can therefore only be detected through measurements [5]. Ensuring a good quality of the indoor air includes a focus on radon, and hence measurements of the radon concentration in the indoor air.

II. MEASURING METHODS

It is possible to measure the radon concentration in the indoor air by applying momentary, continuous and integrated methods. As the radon concentration can vary widely between hours, days and months, the most accurate result of a measurement is the mean value for a year [8]. In Denmark the trace-film method, which is an integrated measuring method, is recommended [9].

A year mean value of the indoor radon concentration can be achieved by measuring for at least two, and preferably three, months during the winter season when the building is heated [8]. Measurements can provide a mean value for the measured period of time and be converted into a yearly mean value. In Denmark, the most common measuring equipment for integrated measuring is a dosimeter. Dosimeters register alpha-decay radiation through etches on a film that are processed and analysed in a laboratory [5]. When measuring, the dosimeter should be placed so as to reflect the general indoor air conditions of the users of the building. The measuring should therefore be carried out in rooms that are frequently used for longer periods of time, such as a sitting-room or a bedroom. In buildings with several storeys, it is necessary to measure on all floors. In each room the measurements should take place at a spot where the conditions are representative of the users' conditions. Therefore, measures should not take place at locations with a strong draught or near a heat source – i.e. not near a door, window, radiator, TV or in direct sunlight etc. [8], [10].

III. PERFORMANCE

An efficient way to avoid radon infiltrating into a building and to control the concentration of radon in the indoor air is to combine the three design criteria, described by:

- 1) A radon barrier, either as a) an airtight concrete slab or as b) a radon barrier placed in or underneath the slab on ground
- 2) Lowering the air pressure of the air at the lower zone of the slab on ground
- 3) Effective dilution of the indoor air with outdoor air, see Fig. 1.

In this way, the radon concentration in the indoor air of a building can be controlled and kept at an acceptable level even if failures occur in the radon barrier [11].

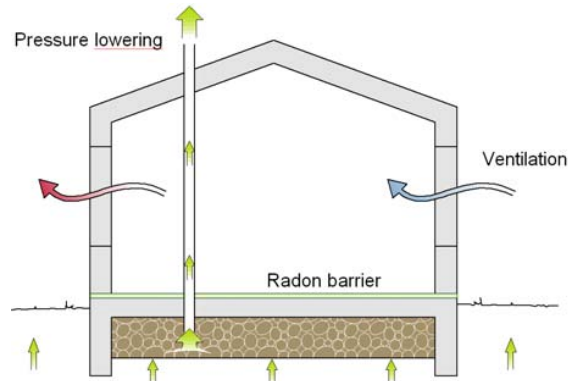


Fig. 1 By combining three design criteria, the radon infiltration and concentration of radon in the indoor air can be controlled. 1) Establishing an airtight barrier that prevents air infiltration from the ground. 2) Lowering the air pressure of the air in the lower zone of the slab on ground. 3) Diluting the indoor air with outdoor air

IV. RADON BARRIER

It is important to create a radon barrier as an airtight barrier within the slab on ground or in the ground below the slab on ground. This can be done in various ways and with various materials. The general requirement for the materials used is that they should be sufficiently airtight and remain so during the life-time of the building. Furthermore, joints should be airtight and the materials used for the joints should be airtight and suitable for fixation onto the used materials and surfaces.

A. Materials Used as Radon Barrier

Some materials are considered to be sufficiently airtight in themselves and therefore able to prevent radon infiltration, e.g. fiber reinforced plaster work without cracks and liquid membranes based on epoxy, asphalt, bitumen and hydraulically solidifying materials. The tightening is proportional with the thickness of the layer and is product-specific. Brick work, concrete and lightweight concrete are also considered to be tight in relation to radon if they have no cracks, a density higher than 1600 kg/m³ and a thickness larger than 100 mm. The concrete slab on the ground is often cast on site. The concrete slab is considered to be sufficiently tight to constitute a radon barrier, if it is made with a thickness of at least 100 mm of the quality concrete 20 MPa or better, with a shrink reinforcement of 5 mm reinforcing steel per 150 mm in both directions placed in the centre of the concrete slab and covering an area of no more than 30 m². A large concrete slab can consist of a number of smaller concrete slabs with airtight joints.

Membranes made of polyethylene are also considered to be a radon barrier if they are thicker than 0.2 mm. This kind of membrane is quite sensitive during subsequent work and should be protected from perforation by e.g. sharp objects. By choosing a thicker membrane or a membrane with reinforcement, more robust membranes can be achieved. A membrane can also be protected with a cloth of fibre textile.

B. Constructions as Radon Barrier

The exterior wall and the ground deck meet at the foundation.

A foundation can for example be constructed of lightweight concrete blocks with insulation in the middle of the blocks and between the blocks and the concrete slab on ground. As the lightweight concrete blocks are not considered to be airtight, the radon barrier must be established at such locations e.g. by using a membrane. It is an advantage to use moulded corners, e.g. of polyethylene, as corner solutions and at exterior doors, and liquid membranes on larger surfaces to avoid joints. The membrane should be extended at least to the outer side of the heavy back wall. It is also a possibility to extend the membrane to the facade, together with the moisture protection and fix it on to the top of the foundation, as shown in Figs. 2 and 3. Membranes should be tightly fixed to the surfaces and have a suitable size. Surfaces should be clean to ensure good fixation.

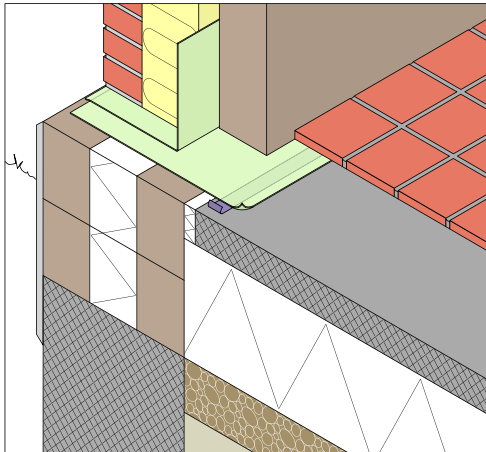


Fig. 2 The membrane and the top of the foundation are levelled, which makes it simple to handle the membrane. The membrane is extended approx. 50 mm on to the concrete slab to prevent infiltration between the foundation block and the concrete slab. The membrane is glued to the concrete slab, extended to the facade and glued on to the foundation block

Slabs on ground should be tight against infiltration by air from the ground at interior walls. The foundation underneath load-bearing and non-load-bearing interior walls on the slab on ground can be variously constructed. Load-bearing interior walls normally have their own foundation, see Fig. 4. A membrane ensures tightness against air from the ground. The membrane can be fixed either to the top of the concrete slab or be extended underneath the concrete slab on either side of the inner wall foundation. If the membrane covers the full extension of the concrete slab, it constitutes both moisture protection and tightness against air and radon infiltration from the ground.

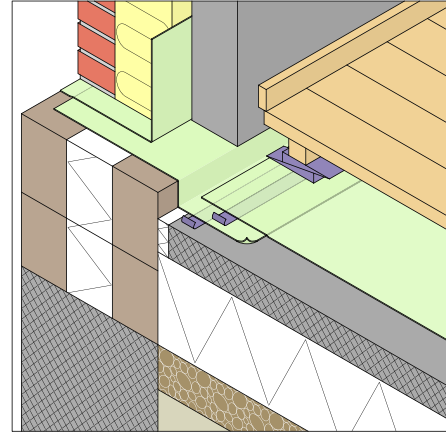


Fig. 3 The membrane is extended to the facade and is fixed on to the foundation. The membrane is joined with the membrane laid out on the concrete slab and protects both against moisture and air, radon, infiltration from the ground. The membranes are joined on a steady surface. The joints are glued meticulously and the membranes have a generous overlap, 100-150 mm.

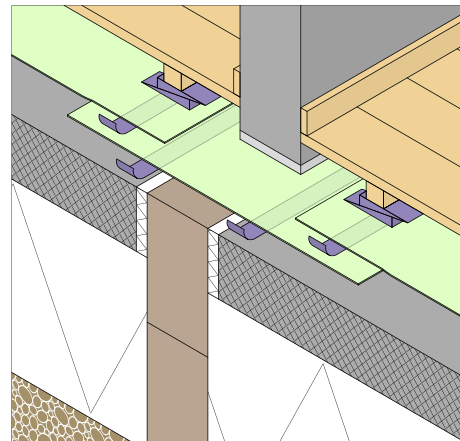


Fig. 4 Load-bearing interior walls that has its own foundation. The membrane is laid out under the wall and is tightly joined with a membrane laid out on the concrete slab

C. Completely Covering Radon Barrier

A radon barrier can also be established by using a membrane within the floor construction. A membrane can be placed inside the insulating layer covering the ground surface of the building and located not lower than half way into the insulating layer. A polyethylene membrane can be used. It is an advantage to use moulded corners, e.g. of polyethylene. The membrane should be extended at least past the outer side of the heavy back wall. It is also a possibility to extend the membrane to the facade, together with the moisture protection and to fix it on to the top of the foundation, as shown in Fig. 5. Membranes should be tightly fixed to the surfaces and have an appropriate size. Surfaces should be clean to ensure good fixation. The membrane needs to cover foundations, including foundations supporting interior walls. All joints should be airtight.



Fig. 5 Continuous radon barrier placed within the insulation layer covering the ground surface of a building. The membrane is extended to the outer side of the exterior wall and covers foundations, including foundations supporting interior walls

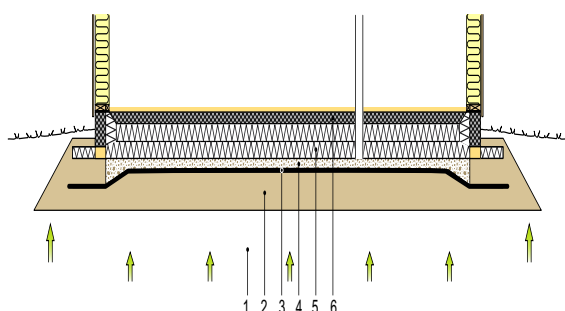


Fig. 6 Shallow foundations should have exterior terrain insulation and protection against rats and other vermin. 1. Radon-containing soil. 2. Sand pad. 3. Radon protecting membrane. 4. Capillary-breaking layer. 5. Insulation. 6. Concrete

D. Radon Barrier Underneath the Slab on Ground

Radon from the ground can also be stopped before approaching the foundation by using a membrane underneath the slab on ground of the building. The membrane can be made of asphalt, aluminium foil or reinforced polyethylene. It should be tight in the full extension of the building and be extended further out so as to prevent radon from infiltrating in between the foundation of the building and the membrane. In case the membrane is laid out in lengths, it is important to ensure airtight joints through generous overlaps and meticulous gluing or welding. When using shallow foundations with exterior ground insulation of the frost susceptible soil underneath the foundation, the membrane can be placed in a sand pad under the building, see Fig. 6. It is furthermore important to ensure that the exterior ground insulation is robust enough to remain intact throughout the life-time of the building and to provide a sturdy protection against rats and other vermin. Below the slab on ground, the membrane is placed underneath a layer of high permeability, which can be used for pressure lowering of the lower zone of the slab on ground across the floor construction if necessary. The membrane should have a downward sloping gradient towards the exterior of the building so as to prevent moisture problems. Penetrating of the membrane can be avoided by leading technical installations above the membrane.

Should it be necessary to penetrate the membrane, airtightness has to be re-established with tight joints and connections.

V. PRESSURE LOWERING OF THE LOWER ZONE OF THE SLAB ON GROUND

The air pressure at the lower zone of the slab on ground can be lowered and hence reduce the infiltration of air from the ground. The air pressure difference between the indoor air pressure of the building and that underneath the concrete slab can be as high as 10 Pa. This air pressure difference can be lowered or equalised by establishing a connection between the atmosphere and a highly permeable layer located in the lower zone of the slab on ground. The highly permeable layer facing the ground can be as such as the capillary-breaking layer. Lowering the air pressure difference decrease the infiltration of ground air. The capillary-braking layer constitutes in such a case the radon suction layer. However, by lowering the air pressure in the radon suction layer to a pressure lower than the air pressure inside, the airflow is changed towards the capillary-braking layer. In some cases, there is a risk of warm, moist air being drawn down through the floor construction where it is cooled down, which can result in mould growth in organic material. The suction can be either passive or active – e.g. creating suction through the stack effect only or creating suction by means of mechanical ventilation.

If the capillary-breaking layer is made of a rigid insulation material, it is necessary to establish a layer of high permeability towards the ground where the suction can be connected to. In such a system, the pressure lowering can be established by placing a permeable layer of e.g. shingles, pebbles, coated ceramic pellets or a sub-slab suctioning system [12], as the radon suction layer, that are depressurised through e.g. a vent pipe lead above the roof. The vent pipe can be led directly into the radon suction layer or the connection can be established through a radon suction pit. This means that the vent pipe is led into a small cavity in the radon suction layer and from there the suction effect is spread throughout the permeable layer serving as a radon suction layer. This construction decreases the risk of blockage of the vent pipe. A radon suction pit can be differently constructed. It can be a prefabricated unit, such as a metal tube closed at the bottom and with holes at the lower end and ready to connect to a vent pipe, a plastic container with holes and ready to connect to a vent pipe, or it can be made of perforated bricks that are laid out to allow a flow of air into it from the radon suction layer, see Figs. 7 and 8.

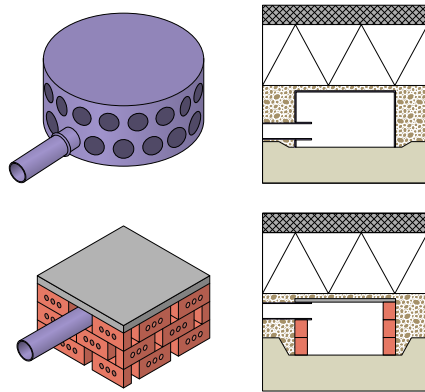


Fig. 7 Detail of radon suction pit. The upper device is a prefabricated unit and the lower is an on-site built cavity surrounded by perforated bricks

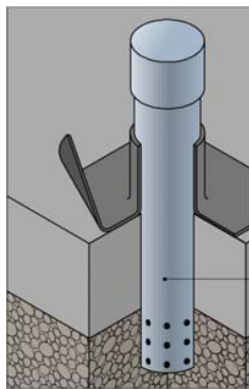


Fig. 8 Detail of radon suction pit. A prefabricated unit shown with a lid on top to be removed when connected with a vent pipe

VI. EFFECTIVE DILUTION OF INDOOR AIR WITH OUTDOOR AIR

Dilution of the indoor air with outdoor air can lower the radon level in the building. The inflow of outdoor air can be increased in order to decrease the radon concentration in the indoor air. Increased ventilation, for example by means of a mechanical exhaust device, can however result in a further decrease of the air pressure inside the building compared to the air pressure outside/underneath the building, which in turn can cause increased infiltration of radon into the building from the ground. Venting, through the regular opening of windows etc., will reduce the radon concentration of the indoor air. However, the reduction will only last while the venting takes place. As soon as the venting stops, the radon concentration in the indoor air will rise again. Venting can also be established through vents in the exterior walls. They can ensure a constant inflow of outdoor air to the building. Mechanical ventilation can also reduce the radon concentration of the indoor air if a constant inflow of outdoor air is ensured. The ventilation can be simple, using only mechanical exhaust device, or it can be a balanced system, using both mechanical injection and exhaust devices. Both the use of vents in exterior walls and a balanced ventilation system can equalise the indoor air pressure with the outdoor air pressure [11].

VII. DISCUSSION

The tightening of the radon provisions incorporated in the Danish Building Regulation took place as a result of the guidelines issued by the World Health Organization which stipulate a maximum level of 100 Bq/m^3 in new buildings. This tightening was a result of the facts that 1) radon is the second-largest cause of lung cancer and 2) it is not known how low the radon concentration should be in order to be harmless to human beings. By focusing on the airtightness of the construction facing the ground and the lowering of the pressure underneath the concrete slab, radon is prevented from infiltrating into the building through convection and advection. However, as buildings get more airtight, a larger part of the radon in a building originates from diffusion and building materials. It is therefore important to ensure sufficient ventilation in order to lower the radon concentration in the future if new knowledge is gained and the provisions in the Danish Building Regulations should again be tightened. The air change should be balanced with the energy requirements in force to achieve both a satisfactory radon concentration and energy consumption. Should new knowledge of the adverse health effects of radon be gained, that result in tightened guidelines issued by the World Health Organization, it would be useful to be able to control and adjust the radon suction system and the ventilation system to meet the new risk assessment of radon exposure on human beings. This could for example be a passive radon suction system that is prepared for later active suction through the connection to an exhaust fan. The radon concentration will shift according to wind conditions and outdoor temperature. The radon transport from the ground to the interior of the building increases, as the pressure inside the building decreases in relation to its surroundings. The radon concentration will also depend on to what extent the building is inhabited and used; if doors and windows are opened and closed. Therefore, it is necessary to measure the radon concentration for a longer period of time to ensure a representative result. The measuring should take place over at least two months, and preferably three months, during the winter period, when buildings are heated. It is therefore recommended to use integrated measuring methods in Denmark. Air infiltration through unforeseen cracks in the construction against soil can easily be prevented by using airtight materials and by ensuring that all joints are made airtight through the use of membranes. It is crucial that the joints between building components maintain their airtight properties during the lifetime of the construction and that they are not damaged or decompose during their service life. This entails a great deal of focus on how to establish the airtight construction facing the ground on site as well as during the design phase. By taking advantage of the three design criteria an acceptable radon concentration of the indoor air can be achieved, which are based on; first, establishing a radon barrier facing the ground; second, lowering the air pressure in the lower zone of the slab on ground; third, dilution of the indoor air with outdoor air.

VIII. CONCLUSION

Radon is a gas without colour or smell and it is therefore necessary to measure it in order to determine the radon concentration of the indoor air of a building. There are three different measuring methods; integrated, continuous, and momentary measuring. Integrated measuring with a dosimeter is the most commonly used method in Denmark. It is cheap and simple and it provides a yearly mean value as the result. The yearly mean value is important when evaluating the general state of a building, as the level of the radon concentration of the indoor air can vary widely during a day, a month and a year.

There is no lower limit for when the radon concentration of the indoor air is low enough to be harmless for human beings. Therefore, it is crucial in the building design phase to include design criteria for achieving acceptable and low radon concentration of the indoor air. Through the combination of three design criteria, an acceptable level of radon in the indoor air can effectively be achieved:

- 1) A radon barrier, either as a) an airtight concrete slab or as b) a radon barrier placed in or underneath the slab on ground
- 2) Lowering the air pressure of the air at the lower zone of the slab on ground
- 3) Effective dilution of the indoor air in the building with outdoor air.

In this way, the radon concentration in the indoor air of a building can be controlled and kept at an acceptable level even if minor failures occur in the radon barrier. It is also important to consider possibilities of adjustments of the radon concentration in the future, as the provision of the Danish Building Regulations may again be tightened as a result of new knowledge about the effects of radon exposure on human beings.

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