How to Ensure Low Radon Concentrations in Indoor Environments

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How to ensure low radon concentrations in indoor environments

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SUMMARY:
This paper focuses on methods for measuring radon levels in the indoor air in buildings as well as on concrete solutions that can be carried out in the building to prevent radon leakage and to lower the radon concentration in the indoor air of new buildings. The radon provision in the new Danish Building Regulations from 2010 has been tightened as a result of new recommendations from the World Health Organization. Radon can cause lung cancer and it is not known whether there is a lower limit for its harmfulness. It is therefore important to reduce the radon concentration as much as possible in new buildings. The airtightness is a major factor when dealing with radon in buildings. Above the ground it is important to build airtight in compliance with energy requirements and against the ground it is important to prevent radon from seeping into the building. There is a direct connection between a building construction being airtight against the ground and the concentration of radon in the indoor air.

1. Introduction

1.1 Radon and health risks

In September 2009 the World Health Organization recommended that requirements to the maximum concentration of radon in the indoor air should be tightened from 200 Bq/m^3 to 100 Bq/m^3. 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 (Zeeb & Shannoun 2009). 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 (Zeeb & Shannoun 2009). If people spend their whole life in a house with an average radon concentration in the indoor air exceeding 200 Bq/m^3, their of 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 (Andersen et al 1997). Therefore it is crucial to prevent radon from leaking 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.

1.2 Regulations and guidelines

In Denmark the recommendation by the World Health Organization has resulted in a tightened radon provision in the new Danish Building Regulations that came into force 30 June 2010. The Danish Building Regulations stipulate a maximum level of 100 Bq/m^3 in the indoor air in all new buildings. For existing buildings, simple and cheap actions are recommended if concentrations range between 100 Bq/m^3 and 200 Bq/m^3 in the indoor air; however if the concentration of radon in the indoor air exceeds 200 Bq/m^{3,} immediate intervention is necessary and more efficient efforts and improvements are recommended in order to lower the concentration of radon in the indoor air (Erhvervs- og Byggestyrelsen 2010). In 2008 measurements of radon concentrations made in Danish detached houses, built on ground with high radon levels, showed that 1% of these houses have radon concentrations in the indoor air above 200 Bq/m^3, and 7% have concentrations above 100 Bq/m^3 (Bovbjerg Jensen & Gunnarsen 2008).

1.3 Radon in buildings

Radon is a radioactive noble gas that develops as a result of the decay chains of uranium and thorium (Clavensjö 2004). When radon decays into different radon daughters, it generates alpha, beta and gamma radiation. It is the radiation from the radon daughters that is harmful to human beings. Radon originates in the ground, from building materials and water. However, the levels of radiation are quite different for the different sources. The ground is the primary source of radon in Denmark (Erhvervs- og Byggestyrelsen. 2007). Therefore the geological character of the ground, on which a building is situated, sets the level for how high the radon concentration of the indoor rooms can become. Radon penetrates into a building both as a result of diffusion through building materials and by air seeping from the ground chased by convection and advection through cracks or other unforeseen openings in the construction (Lehmann et al 2001). Therefore it is of great importance to ensure an airtight building envelope against the ground in new buildings. Radon is without colour, smell, taste and sound and can therefore only be detected through measures (Clavensjö 2004). Ensuring a good quality of the indoor air includes a focus on radon, and measurements of the radon concentration in the indoor air.

2. Measuring methods

It is possible to measure radon concentrations by applying momentary, continuous and integrated methods. As radon concentrations can vary widely between hours, days and months, the most reflective result of a measurement is the mean-value for a year (Hagberg et al 2009). In Denmark the trace-film method, which is an integrated measuring method, is recommended for this end (Sundhedsstyrelsen 2010).

A mean-value for a year can be achieved by measuring for at least two, and preferably three, months during the heating season (Hagberg et al 2009). This gives a mean-value for the whole period of time in which the measuring has taken place and can be converted into a yearly mean-value. In Denmark the most common measuring equipments for integrated measuring is a dosimeter. Dosimeters register alpha-decay radiation through etches on a film that are processed and analysed in a laboratory (Clavensjö 2004). For measuring, the dosimeter should be placed so as to reflect the general conditions of the users of the building. The measuring should therefore be carried out in two 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 measuring equipment should be placed in a spot where the conditions are representative of the users' conditions. Therefore it should not be placed in strong draft or near a heat source – i.e. not near a door, window, radiator, TV, in direct sunlight etc (Hagberg et al 2009) (Valdbjørn Rasmussen & Wraber 2010).

3. Performance

An efficient way to avoid radon that penetrates into a building and to control the concentration of radon in the indoor air is to combine three different methods, see Figure 1:

1. A radon shell, either as a) an airtight shell within the building envelope facing the ground or as b) a radon shell underneath the ground of the building
2. Pressure lowering of the zone underneath the ground of the building
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 failures occur in the radon shell (Valdbjørn Rasmussen 2010).

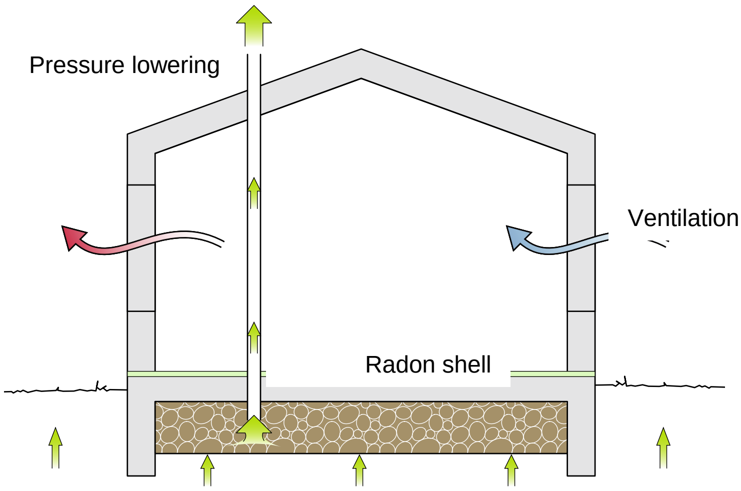

Figure 1. By combining three initiatives the radon penetration and concentration indoors can be controlled. 1) Establishing a shield that prevents radon from penetrating into the building. 2) Lowering the pressure difference over the building envelope facing the ground. 3) Diluting the indoor air in the building with outdoor air.

3.1 Radon shell

It is important to create a radon shell as an airtight shell within the building envelope facing the 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 the joints between the materials should be airtight and the materials used for the joints should therefore be airtight and suitable for fixation onto the used materials and surfaces.

3.1.1 Airtightness of materials

Some materials are considered to be airtight in themselves and therefore able to prevent radon leakage, i.e. plaster work without cracks and liquid membranes based on 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 larger than 1600 kg/m^3 and a thickness larger than 100 mm. The concrete slab in the ground is often cast on site. The concrete slab is considered to be sufficiently tight to constitute an airtight shell against ground-air with radon, if it is made of at least 100 mm 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 slab.

Membranes made of polyethylene are also considered to be airtight 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 i.e. sharp objects. Membranes can be made more robust by choosing a thicker membrane or a membrane with reinforcement. A membrane can also be protected with a cloth of fibre-textile.

3.1.2 Airtightness of constructions

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 of the ground deck. As the lightweight concrete blocks are not considered to be airtight, the airtight plane should be established with a membrane. It is an advantage to use moulded corners, i.e. 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 façade, together with the moisture protection and fix it to the top of the foundation, as shown in Figure 2 and Figure 3. Membranes should be tightly fixed to the surfaces and have a suitable size. Surfaces should be clean to ensure good fixation.

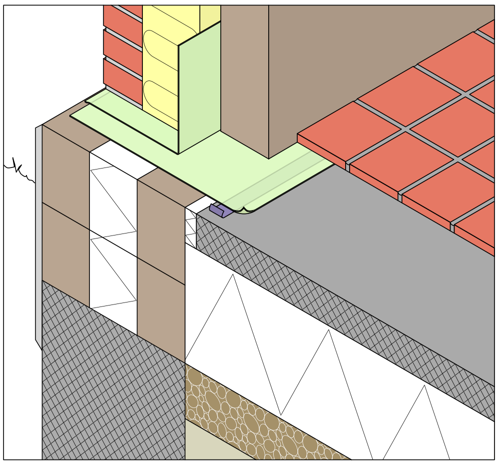

Figure 2. The membrane and the top of the foundation are level, which makes it simple to handle the membrane. It is extended approx. 50 mm above the concrete slab to prevent leakage between the tiles and the slab. The membrane is glued to the concrete slab, extended to the façade and glued to the foundation, if necessary.

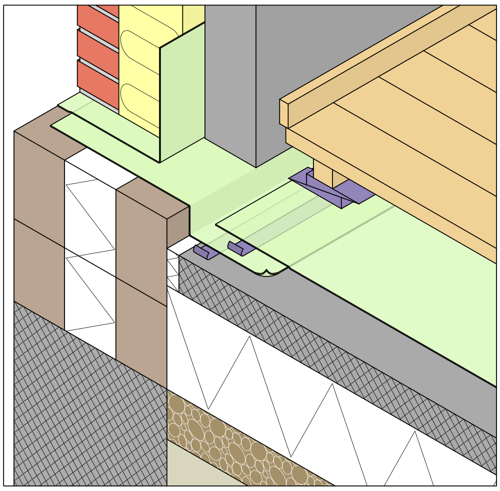

Figure 3. The membrane is extended to the façade and is glued to the foundation, if necessary. The membrane is joined with the membrane laid out on the concrete slab and is protection both against moisture and radon. The membranes should be joined on a steady surface unless something else is recommended by the producer. The joints should be glued meticulously and the membranes should have a generous overlap, 100-150 mm. The joint should fix the overlap, be even and glued to the concrete slab.

Ground decks should be tight against penetration from ground air at interior walls. The foundation underneath load-bearing and non-load-bearing interior walls on ground deck can be variously constructed. Load-bearing interior walls should normally have their own foundation, see Figure 4. A membrane ensures tightness against ground air. The membrane can either be fixed to the top of the concrete slab or be extended underneath the slab on each side of the foundation. If the membrane covers the full extension of the concrete slab, it constitutes both moisture protection and tightness against radon. Such a membrane should therefore be joined with membranes, if any, covering foundations, including foundations supporting interior walls. All joints should be airtight

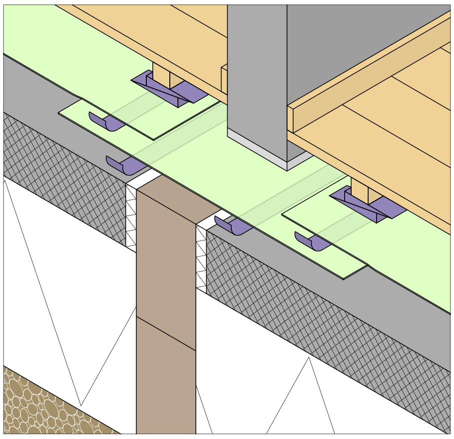

Figure 4. Load-bearing interior walls should have their own foundation. The membrane is laid out under the wall and is tightly joined with a membrane on the concrete slab. These membranes work as protection against penetration by ground air as well as moisture to a moisture-sensitive floor cladding.

Radon can be stopped by using a membrane underneath the ground deck 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 being seeping in between 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 sensitive earth-layer underneath the foundation, the membrane can be placed in a sand pad under the building, see Figure 5.

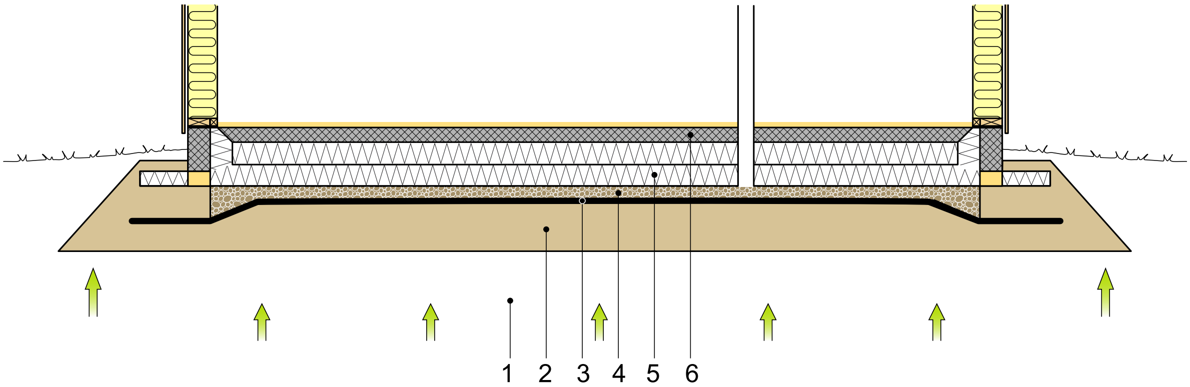

Figure 5. Shallow foundations should have exterior terrain insulation and protection against rats and other vermin.1. Radon-containing soil. 2. Sand pad. 3. Radon protecting membrane. 4. Capillary break layer. 5. Insulation. 6. Concrete.

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. Under the ground deck the membrane is placed underneath a layer of high permeability, which can be used for pressure equalisation across the floor construction. The membrane should have a downward sloping gradient towards the exterior of the building so as to prevent moisture problems. Penetration 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 ensured with tight joints and connections.

3.2 Pressure lowering of the zone underneath the ground deck of the building

The most effective way of preventing radon from seeping into a building is considered to be a radon suction system. The pressure difference can be up to 10 MPa between the interior of the building and underneath the ground deck. This pressure difference can be equalised by establishing a connection between the atmosphere and a highly permeable layer underneath the building, such as the capillary break layer. In such a construction the pressure difference will be lower and the leakage of ground air into the building will therefore also decrease. The radon suction system can either be passive or active – i.e. creating suction through the stack effect only or creating suction using mechanical ventilation. If the capillary break layer is made of a rigid insulation material, it is therefore necessary to establish a radon suction layer of high permeability towards the ground. In this case the pressure equalisation is established by placing a permeable layer of i.e. shingles, pebbles or coated ceramic pellets that is pressure equalised through i.e. a pipe leading above the roof. The pipe can be lead directly into the radon suction layer or the connection can be established through a radon suction pit. This means that the pipe is lead into a small cavity in the radon suction layer and from there the suction effect is spread throughout the radon suction layer. This construction decreases the risk of blockage of the pipe. Radon suction pits can be differently constructed. It can be a prefabricated unit, such as a plastic container with holes and a prepared connection 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 Figure 6. The brick container is built at the end of the vent pipe. If the pressure underneath the building is lower than the pressure inside of the building, there is a risk of warm, moist air being drawn down through the floor construction where it is cooled down, which could result in mould growth in organic material.

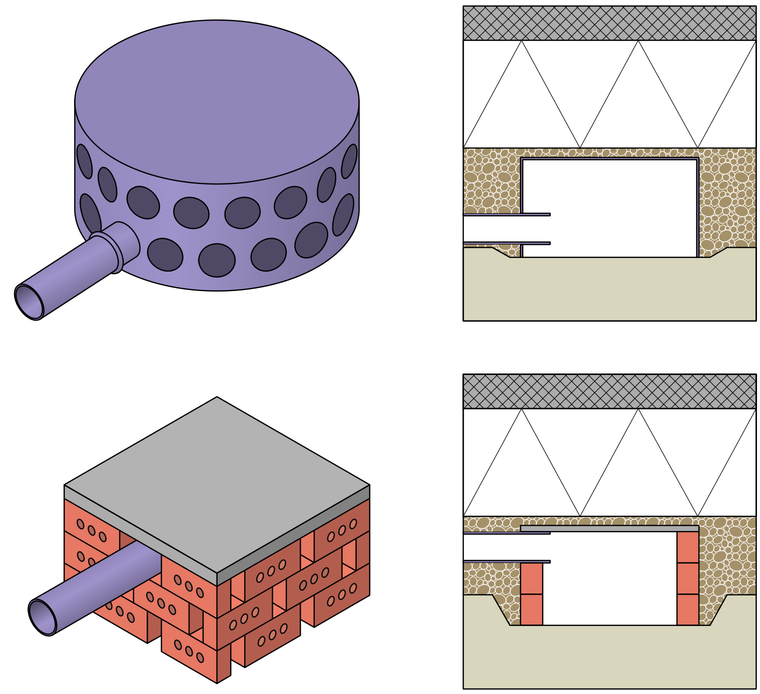

Figure 6. Detail of radon suction pit. The upper device is a prefabricated unit and the lower is an on-site built cavity surrounded by perforated bricks. Radon-containing ground air seeps into the cavities and is lead out through the exhaust pipe. It is important the holes to the cavities remain open.

3.3 Creating efficient dilution indoors with outdoor air

Dilution of the indoor air with outside air will lower the radon level in the building. The inflow can therefore be increased in order to decrease the radon level. An increase in ventilation, for example through a mechanical exhaust device, can however result in a further decrease in the pressure inside the building, which in turn can cause an increased leakage of radon into the building. Venting, through the regular opening of windows etc., will reduce the radon levels of the indoor air. However, the reduction will only last while the venting takes place. As soon as the venting stops, the radon levels will rise again. Venting can also be established through vents in the exterior walls. They will ensure a constant inflow of outdoor air to the building. Mechanical ventilation will also reduce the radon levels of the indoor air. 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 diminish the low pressure in the building (Valdbjørn Rasmussen 2010).

4. Discussion

The tightening of the radon provisions incorporated in the new Danish Building Regulation is caused by the new guidelines issued by the World Health Organization that stipulate a maximum level of 100 Bq/m^3 in new building. This tightening is a result of the facts 1) that radon is the second-largest cause for lung cancer and 2) that 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 below ground and the lowering of the pressure underneath the ground deck of the building, radon is prevented from seeping into the building either by diffusion or through convection. However, as houses get more airtight, a larger part of the radon in a building originates from 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 are again tightened. The air change should be balanced with the energy requirements in force to achieve both satisfactory radon concentration and energy consumption. Should new knowledge of the adverse health effects of radon be gained, it would be useful to be able to control and adjust the radon suction system and the ventilation system in new buildings. This could for example be a passive radon suction system that is prepared for later active suction through the connection to an extractor 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 of the building decreases in relation to the surroundings. The radon concentration will also depend on to which extent the house is inhibited 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 heating period. For this end it is recommended to use integrated measuring methods in Denmark. Air penetration through unforeseen leaks 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 towards soil on site as well as during the design phase. However, the public good requires implementation of airtight constructions towards soil in existing buildings.

5. Conclusions

Radon is a gas without colour or smell and it is therefore necessary to measure it in order to determine the radon concentration 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 simple and it provides a yearly mean-value as the result. This is important when valuing the general state of a building, as the level of the radon concentration can vary widely during a day, a month and a year.

There is no lower limit for when the radon concentration is low enough to be harmless for human beings. Therefore it is crucial to prevent radon from seeping into new buildings and to dilute the indoor air with air from outdoors so as to reduce the radiation that might accumulate however low the concentration might be. Through the combination of three methods, high levels of radon in the indoor air can effectively be prevented:

1. A radon shell, either as a) an airtight shell within the building envelope facing the ground or as b) a radon membrane underneath the ground of the building
2. Lowering the pressure of the zone underneath the ground of the building
3. Effective dilution of the indoor air of the building with air from outdoors.

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 membrane. 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 of human beings.

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