APPLICABILITY OF VARIOUS INSULATING MATERIALS FOR RADON BARRIERS

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The effectiveness of various insulating materials for limiting radon entry into houses has been investigated experimentally in 90 existing houses and in laboratory conditions. Each material has been evaluated according to several aspects - placeability, durability, tear resistance and diffusion properties. The results of the radon diffusion coefficients measurement in more than 80 insulating materials are summarized. We have found out that great differences exist in diffusion properties, because the diffusion coefficient varies within four orders from $10^{-13}$ m²/s to $10^{-10}$ m²/s. A methodological approach is proposed in order to identify the minimal thickness of radon-proof membranes in dependence on building and soil characteristics. General guidelines for selection of radon-proof insulation and the principles of application are presented.

Key words: Radon, $^{222}$Rn, diffusion, radon mitigation, membranes

INTRODUCTION

Dampproof or waterproof insulation placed over the entire surface of the floors and basement walls in contact with the soil can prevent radon from entering buildings from the soil. Our experience confirm that some kinds of the above mentioned insulation can be considered as one of the most effective radon reduction systems for new houses (Jiránek, 1996). Application of membranes into existing houses is less suitable, because any wall and floor coverings and thermal insulation panels in the floors must be removed before the insulation is applied. Usually it is also impossible to install insulation behind existing walls and thus radon-rich air from the ground may sometimes be drawn up vertically through the wall into the dwelling (Clavensjö, Akerblom, 1994). This effect may substantially reduce the resulting effectiveness of the insulation.

Building markets throughout the world offer a large number of various waterproof and dampproof insulating materials, that can be used also as radon barriers. However, due to the lack of information, the correct selection of radon-proof insulation from the total amount of materials is very difficult.

EXPERIMENTAL METHODS

To give an answer to the question of what kind of insulation can be considered radon-proof we have studied the most important mechanical and physical properties of insulating materials as well as their diffusion properties by means of the radon diffusion coefficient.
Determination of radon diffusion coefficients was based on the measurement of the radon flux through the tested material placed between two cylindrical containers. Radon concentration of approximately 100 MBq/m³ is maintained in the lower container. Radon may diffuse through the tested material to the upper container that is permanently ventilated. After reaching the relaxation time (usually after 10 - 15 days), steady-state of the system is reached (i.e. there is a steady-state radon concentration profile in the tested material). In this time the upper container is closed and the radon flux to the upper container is measured and the diffusion coefficient evaluated from Fick’s law. Detailed description of the measuring method has been presented by Hůlka and Jiránek, 1997.

RESULTS

Mechanical and physical properties of insulating materials

Our previous investigation of 90 single family houses (Jiránek, 1997) has confirmed that the presence of insulation and the quality of insulation play a crucial role in ensuring of low radon concentration inside homes. The quality of insulation is influenced mainly by the chemical composition determining its mechanical and physical properties and other important features such as durability, resistance to soil corrosion, etc. Presented work has been therefore focused on the identification of the most important factors that must be considered and which we have summarized in the following paragraphs.

Bitumen membranes. The great advantage of bitumen membranes results from the fact that they can be installed fully adhered to the construction without generating of an air gap within which radon can be transported to the untight places in the insulation. Bitumen membranes are usually produced with the reinforcing fabric. Fabrics based on paper boards, rag boards or jute hessian, which are moisture-absorbents, are not recommended for radon-proof insulation because long-term exposure to moisture leads to their decay. The preference should be given to membranes with moisture-resisting fabrics made of mineral, glass or synthetic fibres in the form of mats or clothes. The best fabrics as far as elongation and workability concerns are polyester fabrics.

Membranes based on oxidated asphalt. The resistance to soil corrosion as well as to weathering is very poor. Cold flexibility is limited by 0 °C (membranes must not be applied below 5 °C) and thermal stability by 70 °C. The highest value of elongation is only 2 - 5 % (without the reinforcing fabric). As a result of ageing or due to the exposure to lower temperatures, membranes based on this type of asphalt become brittle and rapid-setting.

Membranes based on plastomeric bitumen. These membranes have longer durability, higher resistance to ageing and to higher temperatures (up to 140 °C). Membranes are flexible up to -15 °C and their elongation is approximately 50 %. However this elongation is permanent, i.e. membranes cannot return to their initial length.

Membranes based on elastomeric bitumen. Their properties are analogous with plastomeric bitumen membranes, however, they have higher flexibility (up to -35 °C) and elastic elongation. On the other hand, thermal stability is lower (only 100 °C).

Plastic membranes. Among the merits of plastic membranes compared to bitumen ones belong better mechanical and physical properties, longer durability, higher elongation and only one layer
application. On the other hand, the foils are installed loose laid, which may help radon to move from the soil into the dwelling.

**PVC foils.** Dimensional stability ensuring that corrugation of foils does not occur during the hot-air welding is the most important property of PVC foils. Appropriate softness and flexibility, even during lower temperatures (up to -35°C), result in good workability. Due to high tensile strength and high elongation (200 - 400 %) PVC foils are required for complicated insulating works. Geotextile matting must be laid beneath and above the foil. Direct contact of PVC foils with bitumen membranes and an expanded polystyrene or polyurethane must be avoided.

**HDPE foils.** Among the positives of HDPE foils belongs long durability caused primarily by high resistance to soil corrosion and by outstanding mechanical and tear resistance. On the other hand, high hardness, lower flexibility and enormous thermal expansivity lead to worse placeability. This makes the foils less suitable for substructures with a complicated shape - with a lot of corners, edges, etc. As a result of thermal expansivity, permanent corrugation of foils appears during the hot-air welding. It is not necessary to protect HDPE foils against puncturing by geotextile matting.

**LDPE foils.** Compared to HDPE foils, flexibility and placeability of LDPE foils is better. Higher softness demands an appropriate protection of foils from both sides. Corrugation is usually minimal.

**RADON DIFFUSION COEFFICIENTS**

The results of the radon diffusion coefficient D measurement realized by the Faculty of Civil Engineering of the Czech Technical University in Prague and by the National Radiation Protection Institute in more than 80 insulating materials available throughout Europe are summarized in Figure 1. Generalizing results obtained up to now we have found out that for the most often used insulation the diffusion coefficient varies between $10^{-15}$ m$^2$/s and $10^{-10}$ m$^2$/s.

The lowest values of the radon diffusion coefficient D were obtained for polypropylene foils. In HDPE foils with dimples the coefficient varies in the range $1.10^{-12}$ and $5.10^{-12}$ m$^2$/s. Radon diffusion coefficients for HDPE and PVC foils and plastomeric or elastomeric bitumen membranes were measured between the orders of $5.10^{-12}$ and $10.10^{-12}$ m$^2$/s. In the range $1.10^{-11}$ and $2.5.10^{-11}$ m$^2$/s the coefficients for bitumen membranes made of oxidated asphalt, recycled PVC and LDPE or ECB membranes were found. The highest values of D were discovered for rubber foils made of EPDM, where the coefficient D increases up to the order of $10^{-10}$ m$^2$/s.

**DIMENSIONING OF RADON - PROOF INSULATION**

As far as the minimal thickness of the radon-proof insulation concerns, the situation differs from country to country. In the UK (BRE report, 1992) the diffusion through membranes is ignored and thus the minimal produceable thickness is recommended (generally a PE membrane 0,3 mm). In accordance with Keller (1993) from Germany a material can be considered radon-proof only if its thickness is at least three times the radon diffusion length in it. This approach is based only on the properties of the insulation itself. According to this rule the PE membrane should be at least 2 mm thick ($D = 1.10^{-12}$ m$^2$/s), which differes from the UK considerably. In the Czech Republic we use a more complex method, that takes into account all accessible parameters of buildings, foundation soils and the insulation.
Our method is derived from the fact that radon-proof insulation must minimalize the radon supply rate $J_s$ (Bq/h) from the soil into the interior. Under steady-state conditions the maximum value for $J_s$ can be found from the equation (1) ensuring that the indoor radon concentration will be below the limit value $C_{lim}$

$$J_s \leq C_{lim} \cdot V \cdot n$$  \hspace{1cm} (1)

where $V$ is the interior air volume (m$^3$) and $n$ is the air exchange rate (h$^{-1}$).

In practice both convection and diffusion contribute to the radon supply rate. Since the radon transport through cracks, untight joints and pipe penetrations is usually much more greater than the diffusion through unfaulted insulation, the significant reduction in the interior radon concentration can be achieved only by the significant reduction of the radon penetration through leaky places and defects. Every design that aims to be sufficient must, therefore, ensure that the convective flow of soil gas will be close to zero (i.e. all joints between foils or membranes and all openings around utility entrances must be carefully sealed, etc.). Since whatever insulation in the thinnest producable thickness can stop the convective flow, the formula for the minimal thickness of insulation has to be derived from the diffusive term.

In a correct design we can consider the convective transport to be negligible and thus it is possible to suppose that the radon supply rate is created only by the diffusion through insulation. Based on this simplification the condition for the highest permissible radon exhalation rate from the insulation $E_{lim}$ can be derived, from equation (1), where $C_{lim}$ was replaced by $C_{dif} = 10\% \cdot C_{lim}$. The value of $C_{dif}$ means that the importance of the diffusion was reduced to the estimated $10\%$ and the remaining $90\%$ of $C_{lim}$ is reserved for the accidentally occurring convection. Our estimate of $C_{dif}$ is consistent with the range $4 - 50\%$ presented by Holub and Killoran (1994) in which the upper limit of $50\%$ for the diffusion component has been found for a substructure without insulation. The highest permissible radon exhalation rate can thus be calculated for each house from equation (2)

$$E_{lim} = \frac{C_{dif} \cdot V \cdot n}{A_f + A_w}$$  \hspace{1cm} (2)

where $V$ is the interior air volume (m$^3$), $n$ is the air exchange rate (h$^{-1}$), $A_f$ is the floor area in direct contact with the soil (m$^2$), $A_w$ is the area of the basement walls in direct contact with the soil (m$^2$) and $C_{dif}$ is $10\%$ of the highest permissible radon concentration indoors (in the Czech Republic 20 Bq/m$^3$ for new buildings and 40 Bq/m$^3$ for existing buildings).

Detailed design of radon-proof insulation (i.e. thickness, number of layers, sort of insulation etc.) in dependence on real geological and building characteristics is based on the condition that the radon exhalation rate $E$ from the real insulation in a real house must be less or equal to the highest permissible radon exhalation rate $E_{lim}$ calculated for that house.

$$E \leq E_{lim}$$  \hspace{1cm} (3)

$$E = \alpha \cdot l \cdot \lambda \cdot C_s \frac{1}{\sinh(d/l)}$$  \hspace{1cm} (4)
where \( C_S \) is the radon concentration in the soil gas (Bq/m\(^3\)), \( \lambda \) is the radon decay constant (0.00756 h\(^{-1}\)), \( d \) is the thickness of the radon-proof insulation (m), \( l \) is the radon diffusion length in the insulation \( l = (D/\lambda)^{1/2} \) (m), \( D \) is the radon diffusion coefficient in the insulation (m\(^2\)/h) and \( \alpha_1 \) is the safety factor, that should eliminate the inaccuracies arising during the soil gas radon concentration measurements and the possible increase of the radon concentration beneath the completed house in comparison with the radon concentration \( C_S \) measured on the unbuilt area. Values of \( \alpha_1 \) have been estimated according to the soil permeability (for highly permeable soils \( \alpha_1 = 10 \), for soils with medium permeability \( \alpha_1 = 4.3 \) and for low permeable soils \( \alpha_1 = 3 \)).

On the assumption that the insulation is homogeneous, its minimal thickness can be calculated from equation (5) obtained after the replacement of \( E \) in equation (4) by \( E_{\text{lim}} \) from equation (2).

\[
d \geq l \cdot \text{arcsinh} \left( \frac{\alpha_1 \cdot l \cdot \lambda \cdot C_S}{E_{\text{lim}}} \right) \quad (\text{m})
\]

DISCUSSION

The principle of designing according to the above mentioned method, which is also incorporated into the Czech Standard ČSN 730601 „Protection of buildings against radon from the soil“, can be identified from Figure 2 in which the thickness of the insulation with \( D = 1 \cdot 10^{-11} \) m\(^2\)/s is plotted against the soil gas radon concentration and soil permeability. It can be seen that the thickness increases proportionally to the radon concentration in the soil and soil permeability. It is obvious that the lower the radon concentration in the soil, the greater the overdimensioning of the radon insulation designed according to the formula \( d = 3l \).

The thickness of the insulation in dependence on the radon diffusion coefficient \( D \), soil permeability and the house type is plotted in Figure 3. From this Figure it is clear that the thickness of the insulation with \( D \) of order of \( 10^{-12} \) m\(^2\)/s can be only several tenths of one millimeter, even in the areas with high radon concentration in the soil. Such small thickness is hardly producable and applicable due to sensitivity to puncturing and thus thicker insulation must be in practice used. This may lead to uneconomic and inefficient overdimensioning.

On the other hand, the applicability of the insulation with \( D \) of order of \( 10^{-10} \) m\(^2\)/s will be very strongly dependent on building characteristics and the radon concentration in the soil. Since radon barriers made of such insulation must be thicker (several milimeters), the insulation must be placed in two or three layers. It can be seen that rubber foils made of EPDM with \( D \) around \( 2.45 \cdot 10^{-10} \) m\(^2\)/s are too permeable to be used for radon-proof insulation.

This clearly leads to the conclusion that the optimal value of \( D \) lies in the interval \( 5 \cdot 10^{-12} \) to \( 1 \cdot 10^{-11} \) m\(^2\)/s. This interval corresponds with the production thickness of the most frequently used insulating materials, that is 1 or 2 mm for plastic foils and 3 or 4 mm for bitumen membranes (which in addition can be applied in two or three layers).
CONCLUSION

Realized experiments show that radon-proof insulation can create an effective barrier against radon, preferably in new buildings. A method has been developed for the evaluation of the minimal thickness of radon-proof membranes in dependence on the building and soil characteristics and the radon diffusion coefficient in the insulation. The results indicate that the method can be useful in examining the effectiveness of the insulation and in optimising its design. The possibility of over or underdimensioning is thus very strongly reduced. Basic mechanical and physical properties of insulating materials have been summarized in order to decide whether the insulation meets the general guidelines for selection that we have expressed into the following aspects:

1. The durability of the insulation must be equalled with the expected lifetime of the building. The reason is that the insulation after its incorporation into the building substructure will be inaccessible, it means that the future maintenance and repair works are hardly feasible and always complicated and very costly.
2. The insulation must be resistant to the soil corrosion caused primarily by microbiological agents and chemical compounds occurring in the soil.
3. The insulation must be capable to withstand (without being punctured) permissible movements of the building substructure to which it is applied. Materials with higher elongation are less sensitive to puncturing. On the other hand, transfer of tensile forces from the substructure to the insulation can be reduced by placing the insulation between two sheets of geotextile matting.
4. Complete insulating systems should be preferred to pure and simple insulating materials. Complete systems with extra components for external and internal corners, edges and prefabricated „top hat“ sections for sealing around pipe entries ensure higher quality and airtightness of details.
5. Particular attention should be given to the placeability. Some insulation must not be applied at temperatures below 5°C, some materials are difficult to seal in adverse weather, etc.
6. The insulation must eliminate the convective flow of soil gas containing radon and minimize radon transport by diffusion. Optimal values for the radon diffusion coefficient should be within the range $5 \times 10^{-12} \text{ m}^2/\text{s}$ and $1 \times 10^{-11} \text{ m}^2/\text{s}$.

During the application following instructions should be considered:

- Surfaces on which the radon-proof insulation will be applied, must satisfy the conditions presented by the producers of the insulation. A dry, clean and smooth surface is usually required.
- Before the insulation is applied, any visible through cracks and other leakage points in the slabs or basement walls should be sealed.
- The insulation must be installed to the entire area of the structures in direct contact with the soil. Careful attention should be given to ensuring the integrity in the horizontal, vertical and stepped plane. Radon-proof insulation should be laid fully adhered to the construction.
- Particular attention must be taken to the jointing in order to ensure continuity.
- It is advisable to keep the number of penetrations to a minimum. Any penetration through the insulation must be properly sealed. „Top hat“ sections should be used for sealing around pipe entries.
- Before the insulation is covered, it is necessary to check its integrity and airtightness. Any accidental perforations must be repaired.
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REFERENCES


Radon diffusion coefficient $D \times 10^{-12} \text{ m}^2/\text{s}$

Legend: BM - bitumen membranes made of oxidated asphalt, MBM - BM made of modified asphalt, HDPE - high density polyethylene foils, HDPE-D - HDPE foils with dimples, LDPE - low density polyethylene foils, CPE - chlorinated polyethylene, PVC - flexible polyvinylchloride foils, RPVC - foils made from recycled PVC, PP - polypropylene foils, FPP - flexible PP, ECB - ethylene copolymer bitumen, EPDM - ethylene propylene dien monomer, MAC - modified asphalt coating

Figure 1: Radon diffusion coefficients
Figure 2: The thickness of the insulation with $D = 1.10^{-11}$ m$^2$/s plotted against the soil gas radon concentration, soil permeability and the type of a house.
Figure 3: The thickness of the insulation in dependence on the radon diffusion coefficient $D$, soil permeability and the house type (for $C_s = 100 \text{ kBq/m}^3$)