TESTING AND DESIGN OF RADON RESISTING MEMBRANES BASED ON THE EXPERIENCE FROM THE CZECH REPUBLIC

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ABSTRACT

Testing of barrier properties of insulating materials against radon is usually based on the measurement of the radon diffusion coefficient. Presented report summarizes results of radon diffusion coefficients measurements in more than 120 insulating materials obtained throughout Europe. All measurements were performed by the Faculty of Civil Engineering of the Czech Technical University and by the National Radiation Protection Institute. We have found out that great differences exist in diffusion properties, because the diffusion coefficients vary within eight orders from 10^{-15} m^2/s to 10^{-8} m^2/s. Various possibilities of application of the radon diffusion coefficient for the design of radon barrier materials are discussed. Setting strict limits for maximal radon diffusion coefficient or minimal thickness of membranes results in significant reduction of the amount of materials that can be used for protection against radon. Calculation of the membrane thickness based on the radon diffusion coefficient and particular soil conditions and building characteristics seems to be the most effective and convenient approach.

TESTING OF MEMBRANES AND OBTAINED RESULTS

Testing of barrier properties of insulating materials against radon is usually based on the measurement of the proportionality coefficient *D* in equation (1) describing one dimensional radon distribution in the tested material:

$$\frac{\partial C_{(x,t)}}{\partial t} = D.\frac{\partial C_{(x,t)}}{\partial x} - \lambda.C_{(x,t)} \qquad (1)$$

where $C_{(x,t)}$ is a radon concentration (Bq/m^3) and λ is the radon decay constant (2,1.10^{-6} s^{-1}). Since the proportionality coefficient *D* (m^2.s^{-1}) expresses the diffusive properties of radon in the material, it is mostly known as the radon diffusion coefficient [3, 5]. However in the literature we can also find other names for this parameter, such as permeability [1], or permeation coefficient [4]. It is important to stress that not only diffusion, but also other physical processes, such as solubility of radon in the tested material and adsorption of radon on the tested material are included in the radon diffusion coefficient.

Measurement of the radon diffusion coefficient on commercial basis started in the Czech Republic in 1995. Up to now a quite excellent database of results is available. This enables to make some general requirements considering the applicability of the radon diffusion coefficient for the design of radon-proof membranes. Czech method for the determination of the radon diffusion coefficient is based on the measurement of the radon flux through the tested material placed between two cylindrical containers. Detailed description of the measuring method has been presented in [6].

The results of the radon diffusion coefficient D measurements realized by the Faculty of Civil Engineering of the Czech Technical University in Prague and by the National Radiation Protection Institute in 126 insulating materials available throughout Europe are summarized in Fig. 1. On x-axis materials are grouped into categories according to the chemical composition. The amount of tested materials in each category is printed in parentheses behind the names of categories. This enables us to identify the most frequently used materials among which belong:

bitumen membranes with Al foils, PVC-P, HDPE and LDPE membranes, polymer modified bitumen compositions and membranes made of modified bitumen.

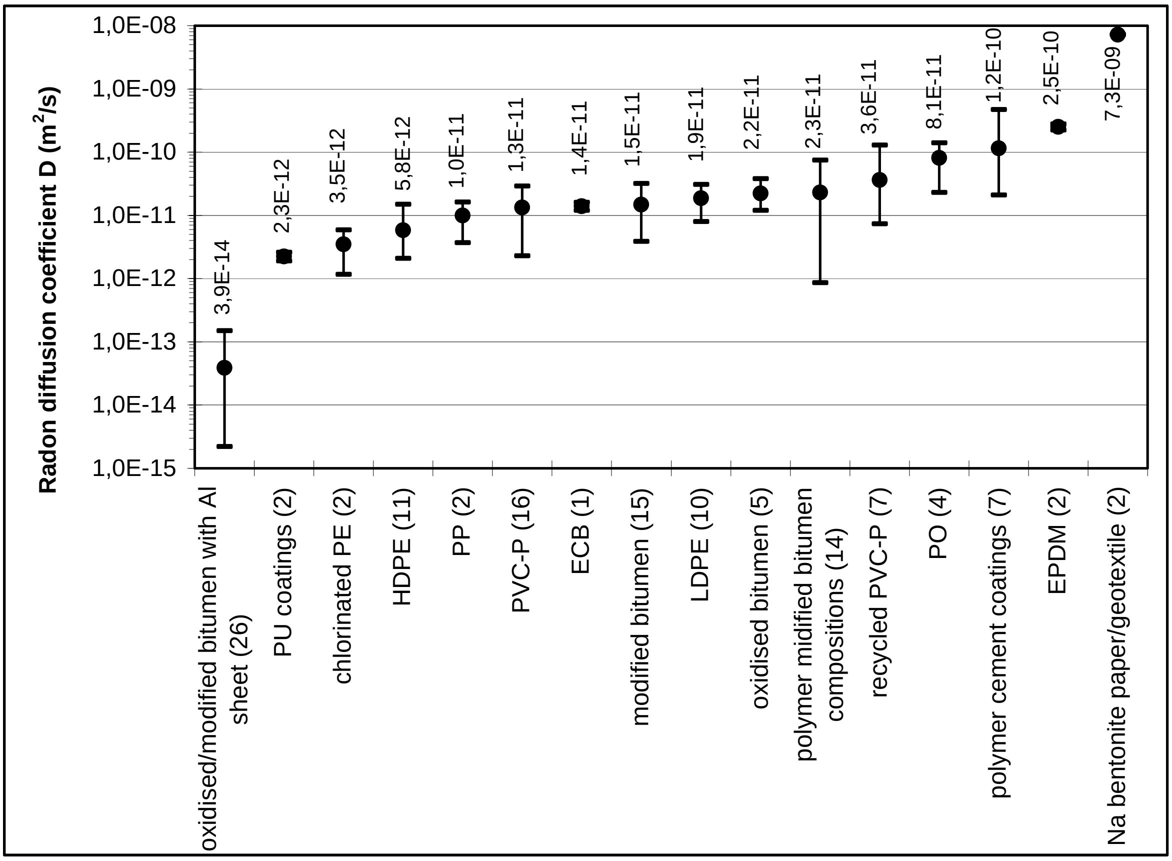

Fig. 1. Summary of the radon diffusion coefficient measurements realized in 126 materials. On x-axis materials are registered with respect to rising order of their diffusion coefficients (HDPE - high density polyethylene, LDPE - low density polyethylene, PVC-P - flexible polyvinyl chloride, PP - polypropylene, PO – polyolefin, PU – polyurethane, ECB - ethylene copolymer bitumen, EPDM - ethylene propylene dien monomer)

Fig. 1 shows very clearly that in common insulating materials used for protection of houses against radon the diffusion coefficients vary within eight orders from 10^{-15} m^2/s to 10^{-8} m^2/s. The lowest values were obtained for bitumen membranes with Al foils no matter whether the bitumen was modified or not. On the other hand the highest values of the radon diffusion coefficient were discovered for sodium bentonite placed between paper or geotextile sheets, rubber membranes made of EPDM, polymer cement coatings and polyolefin membranes. Polyolefin category covers other polymers than EPDM, LDPE, HDPE and PP, i.e. it is a group of relatively new materials, which are still in development. Radon diffusion coefficient for the majority of materials varies in the range 3.10^{-12} and 3.10^{-11} m^2/s.

From Fig.1 it is evident that relatively long scatter lines were obtained for two material categories – for bitumen membranes with Al foils and for polymer modified bitumen compositions. In case of membranes with Al foils it is caused by different thickness of Al foils, which usually varies between 0,006 mm and 0,08 mm. However in the category of bitumen compositions it is a result of different chemical composition of each material. It means that on the lower end of the scatter line materials with very good barrier properties can be found, but on the upper end there are materials, which could be hardly considered as radon-proof. Since the mean value lies close to the upper end, we can assume that majority of these materials will not work satisfactorily.

From Fig. 1 we can also see the effect of recycling on the increase of the radon diffusion coefficient. In membranes made of recycled PVC-P the radon diffusion coefficient is in average three times greater compared to non-recycled flexible PVC membranes.

Radon diffusion coefficient in polyethylene membranes is influenced very strongly by the density of polyethylene, which is apparent from Fig. 2. As we can see radon diffusion coefficient decreases with the increasing density. Correlation between these properties can be used by producers for preparing of appropriate chemical composition of polyethylene membranes, so that production costs, hardness of the membrane and diffusion properties will be in balance.

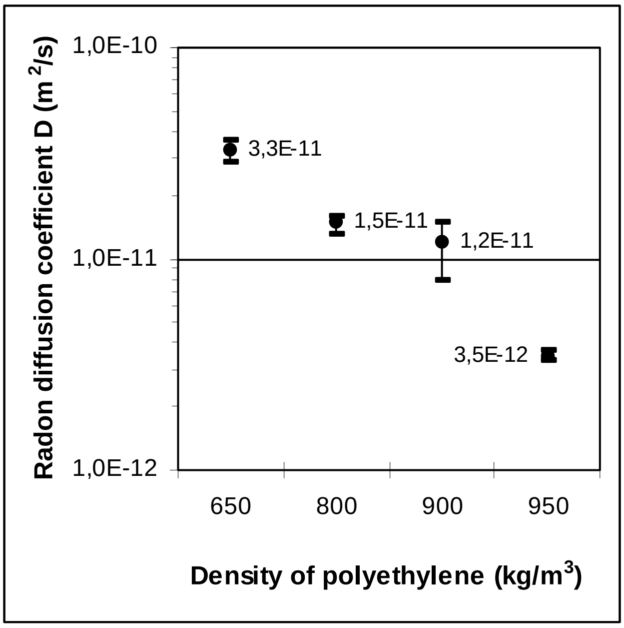

Fig. 2. Radon diffusion coefficient in polyethylene membranes plotted as a function of the density of polyethylene (membranes with the density lower than 920 kg/m^3 are foamed LDPE membranes)

DESIGN OF RADON-PROOF MEMBRANES

Radon diffusion coefficient has been found in several countries (Czech Republic, Germany, Spain, Netherlands, Ireland, etc.) as a suitable parameter for the design of radon-proof membranes. However the application of this parameter differs from country to country. In general we can find three different approaches how to use the diffusion coefficient for the design of membranes:

1. the radon diffusion coefficient of the radon-proof membrane must be below the strict limit value,
2. the thickness of the radon-proof membrane must be at least three times greater than the radon diffusion length l [3] calculated as $l = (D/\lambda)^{1/2}$,
3. the thickness of the membrane is calculated for each house [7, 8, 9] according to the radon diffusion coefficient in the membrane, radon concentration in the soil on the building site and house parameters (ventilation rate, area in contact with the soil).

Limit for the maximal value of the radon diffusion coefficient

The main problem connected with this approach is how to choose correctly the limit value. To be safe and reliable under all circumstances (for all types of houses and radon concentrations in the soil) it should be rather lower than higher. However the lower the limit will be, the more materials will be of no use. This is in contradiction with our experience that for nearly each material conditions can be found, under which it can be applied.

This approach has another consequence. Since a great number of common waterproofing materials with radon diffusion coefficients above the limit value should not be used, it could be a tendency to solve the protection against radon preferably by materials with Al foils. This is from the technical point of view meaningless, because membranes with Al foils have very low elongation and therefore they can very easily loose their barrier properties by destroying of the Al foil.

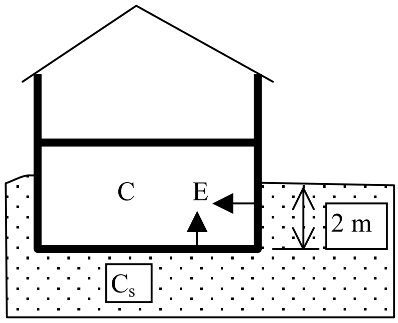

Fig. 3. Sketch of the house from the example

The situation can be very clearly illustrated by an example. Let's consider a new single-family house with habitable rooms in the basement (Fig. 3). The floor area of the house A_f is 100 m^2 and the area of the basement walls in contact with the soil A_w is 80 m^2. The outdoor – indoor ventilation rate n is assumed to be 0,3 h^{-1} and the volume of air V in the basement 260 m^3. Indoor radon concentration C in the basement caused by diffusion through the membrane can be calculated from equation (2):

$$C = \frac{E.(A_f + A_w)}{n.V} \qquad \text{(Bq/m}^3\text{)} \qquad (2)$$

where E is the radon exhalation rate from the membrane that can be found from equation (3):

$$E = \frac{l.\lambda.C_s}{\sinh(d/l)} \qquad \text{(Bq/m}^2\text{.h)} \qquad (3)$$

where d is the thickness of the membrane (m), C_s is the radon concentration in the soil gas (Bq/m^3), λ is the radon decay constant (0,00756 h^{-1}) and l is the radon diffusion length in the insulation $l = (D/\lambda)^{1/2}$ (m).

The results of calculation are presented in Fig. 4, where the radon concentration in the basement is plotted against the radon diffusion coefficient for different combinations of the soil gas radon concentration and the membrane thickness. For safety reasons higher concentrations and lower thicknesses were introduced into the calculation. Under consideration that indoor radon concentration should not exceed the reference level, which is in nearly all European countries 200 Bq/m^3 for new houses and 400 Bq/m^3 for existing houses, the radon diffusion coefficient should be lower than 2.10^{-11} m^2.s^{-1}. Assuming that at least 60 % of indoor radon concentration is caused by convection of soil air through untight places in the membrane, the maximum value of the radon diffusion coefficient should be 1.10^{-11} m^2.s^{-1}. If we compare this finding with the summary of radon diffusion coefficients in Fig. 1, only materials based on Al foils, HDPE, PP and PU remain for application.

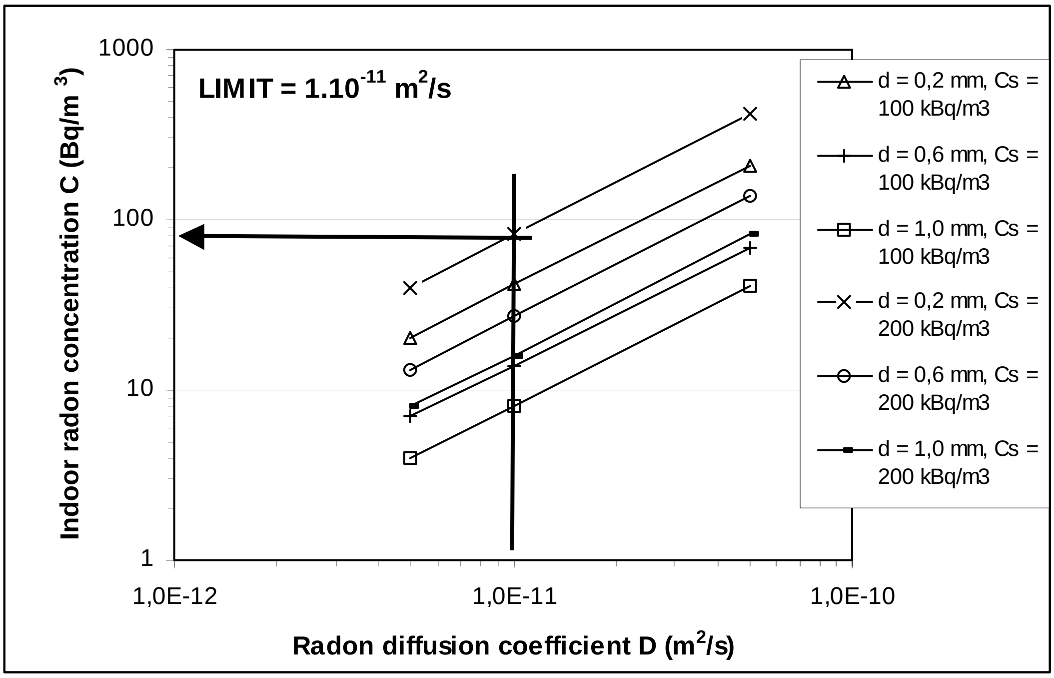

Fig. 4. Indoor radon concentration calculated for the house from the example. For chosen parameters diffusion through the membrane of D = 1.10^{-11} $m^2.s^{-1}$ will be responsible for indoor radon concentration 80 Bq/m^3, i.e. 40 % of the reference level 200 Bq/m^3.

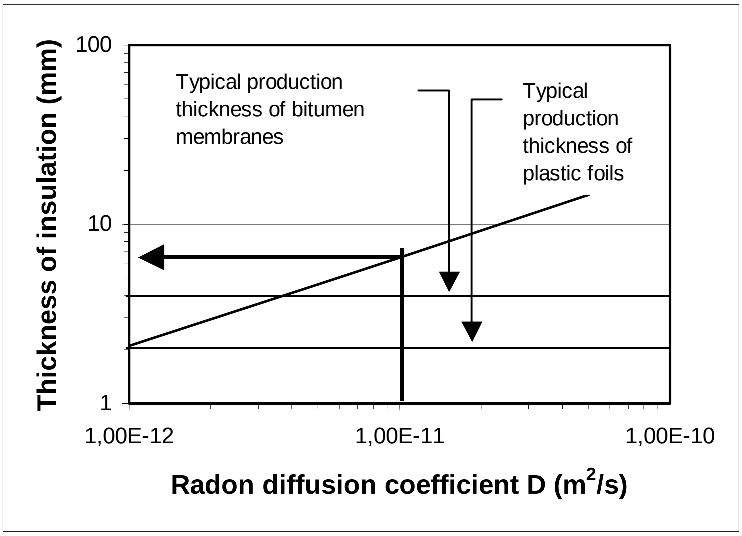

Fig. 5. Thickness of the radon-proof membrane calculated according to formula d = 3l. In this case the thickness of the membrane of D = 1.10^{-11} $m^2.s^{-1}$ should be at least 6,5 mm (for all types of houses and radon concentrations in the soil).

Limit for the minimal thickness of the membrane

Limits for the minimal thickness of membranes are derived from the assumption that most radon atoms will decay before they pass through the insulation, if the thickness of the insulation is greater than the diffusion length. However the condition that the insulation thickness should be at least three times greater than the diffusion length [3] leads to the enormous thickness of membranes. The required thickness exceeds the production thickness, if the radon diffusion coefficient is higher than 1.10^{-12} $m^2.s^{-1}$ in case of plastic membranes or 4.10^{-12} $m^2.s^{-1}$ in case of bitumen membranes. Situation is illustrated in Fig. 5. Consequently this approach can be also considered as a condition for the highest value of the radon diffusion coefficient, because insulation of greater thickness than is the production thickness is applicable only in few cases (in site prepared coatings, two layers of bitumen membranes). In fact the requirement $d \geq 3l$ is more strict than the previously described limit for D and will be met by a considerably smaller group of materials. In addition measurements of indoor radon concentration realized by the National Radiation Protection Institute in new houses confirm that even materials of significantly lower thickness can create a sufficient protection against radon.

Calculation of the membrane thickness

Under the conditions that the insulation is placed over the entire area of structures in direct contact with the soil, all joints between sheets are airtight and any penetration of utility entries through the insulation is properly sealed, we can consider the convective transport of radon to be negligible. Therefore it is possible to assume that the radon supply rate into the house with continuous tanking is created only by the diffusion through insulation. Based on this simplification the highest permissible radon exhalation rate into the house, E_{lim}, can be expressed by equation (4):

$$E_{\mathrm{lim}} = \frac{C_{dif}.V.n}{A_f + A_w} \qquad (\mathrm{Bq/m^2h}) \qquad (4)$$

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 a fraction of the reference level for indoor radon concentration C_{ref} caused by diffusion. The value of C_{dif} can be estimated, for example according to the Czech standard ČSN 730601 as 10% [9]. This means that the importance of the diffusion is reduced to 10 % of C_{ref} and the remaining 90 % of C_{ref} is reserved for the accidentally occurring convection. Our estimate of C_{dif} is consistent with the range of 4 - 50 % presented by Holub and Killoran [2]. An upper limit of 50 % for the diffusion component has been found for substructures without insulation.

The thickness of the radon-proof insulation can then be found in dependence on real geological and building characteristics from the condition that the radon exhalation rate E from the real insulation in a real house calculated according to equation (5), must be less or equal to the highest permissible radon exhalation rate E_{lim} calculated for that house, i.e. $E \leq E_{lim}$.

$$E = \alpha_1.l.\lambda.C_S \frac{1}{\sinh(d/l)} \qquad (\mathrm{Bq/m^2h}) \qquad (5)$$

where C_s is the radon concentration in the soil gas (Bq/m^3) measured on the building site, λ 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 α_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 α_1 can be estimated according to the soil permeability (for highly permeable soils α_1 = 7, for soils with medium permeability α_1 = 3 and for low permeable soils α_1 = 2,1).

On the assumption that the insulation is homogeneous, its minimal thickness can be calculated from equation (6) obtained after the replacement of E in the equation (5) by E_{lim} from equation (4).

$$d \geq l.\mathrm{arcsinh}\frac{\alpha_1.l.\lambda.C_s.(A_f + A_w)}{C_{dif}.n.V} \qquad (\mathrm{m}) \qquad (6)$$

The great advantage of this approach is that the design of the radon-proof membrane can be fitted according to particular conditions (soil and building characteristics). The possibility of under- or over-dimensioning is thus strongly reduced.

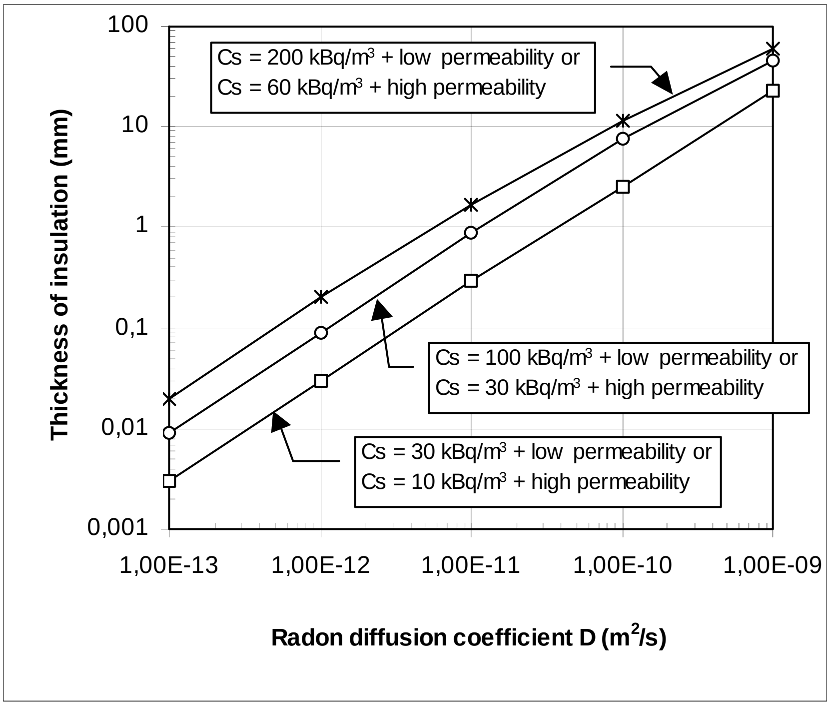

Fig. 6. Thickness of the insulation calculated according to the equation (6) for different values of D and various combinations of soil gas radon concentration and soil permeability. The influence of the soil permeability is introduced by the safety factor α_1 that increases proportionally with the permeability. Chart is valid for the house with habitable rooms in the basement according to the previously described example.

The principle of designing according to this method can be identified from Fig. 6 in which the thickness of the insulation is plotted as a function of the radon diffusion coefficient and various combinations of soil gas radon concentration and soil permeability. It is clear that the thickness of the insulation with D lower than 10^{-12} m^2/s can be only several tenths of one millimetre, even in the areas with high radon concentration in the soil. Such small thickness is hardly produceable and applicable due to sensitivity to puncturing and thus thicker insulation must be in practice used. 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. Membranes with D above 1.10^{-10} $m^2.s^{-1}$ are too permeable to be used for radon-proof insulation.

This clearly leads to the conclusion that the optimal value of the diffusion coefficient lies in the interval 5.10^{-12} to 5.10^{-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).

COCLUSIONS

Radon diffusion coefficient seems to be a convenient parameter for testing of radon-proof membranes and thus measurement of this parameter should be required in any insulating material that aims to act as a radon barrier.

Based on the experience from the Czech Republic controlling applicability of membranes by setting strict limits for the maximal value of the radon diffusion coefficient or the minimal thickness of the membrane is not a convenient approach. It seems to be reasonable to replace strict limits by the real design of the insulation in dependence on particular building and soil characteristics. Radon diffusion coefficient plays a crucial role in this design, because it enables to calculate the membrane thickness and the radon exhalation rate from the membrane.

In countries, where radon prone areas are classified according to indoor radon data and where measurements of the radon concentration in the soil gas are not so common, evaluation of C_s can be a problem. However it can be overcome, if we realize that in fact radon prone areas substitute real soil gas concentrations. Therefore an appropriate value of the radon concentration in the soil can be added to the each type of the radon prone area. The uncertainty of this procedure can be covered by the safety factor α_1.

Design of radon resisting membranes should be more complex. It should be stressed that barrier properties of membranes should be in balance with other very important properties such as durability, flexibility, buildability, chemical resistance, etc.

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