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Součinitel difuze radonu – stanovení a použití pro návrh protiradonových izolací

Determining and applying the Radon Diffusion Coefficient for dimensioning radon-proof insulations

SUMMARY

This lecture gives a brief overview of theoretical aspects of radon diffusion through waterproofing materials and of measuring methods used for determining the radon diffusion coefficient in these materials. I have been working on these topics at the Department of Building Structures since 1995. The work has been supported by two grants of the Czech Science Foundation, No. P103/95/1306 and No. P104/11/1101, and by a grant from the State Office for Nuclear Safety under the title "Development and optimization of experimental and calculation procedures for analysing the transport of radon through radon-proof insulations".

Research in this area was initially motivated by the fact that no theoretical work had been done and no practical experience was available in the Czech Republic on radon transport through waterproofing materials. Even in other parts of the world, this field of research was only in the initial stages. We developed the first method (K124/02/95) for determining the radon diffusion coefficient jointly with colleagues from the National Radiation Protection Institute (NRPI) in 1995. The applicability of this method was limited by the need to create stationary conditions during the measurement phase. A new methodology (K124/01/09), developed in 2009, again in cooperation with NRPI, is more versatile, because it allows the radon diffusion coefficient to be determined under non-stationary conditions. A description of these two methods, which were accredited by the Czech Accreditation Institute soon after they were established, is provided in section 2.

For a better understanding of radon diffusion through waterproof materials, we have developed two numerical models, IterRn and TransRn. These models are based on the solution of a one-dimensional time-dependent differential equation for radon diffusion. The models can update and extend our knowledge about radon transport processes and about the diffusive properties of various insulating materials. The fundamental correlations, e.g. between the radon distribution within the tested sample and the thickness of the sample or its radon diffusion coefficient, are discussed in section 3.

Since 1995, we have determined the radon diffusion coefficients of more than 500 waterproofings of different chemical compositions. A comparison of the results for different material variants, together with comments explaining the differences, is presented in section 4. Section 4 also shows that the radon diffusion coefficient can be used effectively as an indicator of the radon-tightness of joints between preformed membranes.

A method that I have developed for dimensioning radon-proof membranes uses the radon diffusion coefficient for calculating the minimal thickness of the insulation. In addition, the method takes into account the radon risk of the foundation soils and the parameters of the building (the area in contact with the soil, and the ventilation rate). The principle behind this method, and a correlation with methods applied in other countries, is provided in section 5. At the end of section 5, I introduce the principle for a quite new approach to the dimensioning of radon-proof membranes, which is based on the radon resistance of the insulation. The aim of this new method is to create a proposal for unifying the approaches used across Europe.

SOUHRN

Tato přednáška uvádí stručný přehled teorie difuze radonu hydroizolačními materiály a metod používaných ke stanovení součinitele difuze radonu v těchto materiálech. Na katedře Konstrukcí pozemních staveb se těmto tématům věnuji od roku 1995. Práce byla podpořena dvěma granty GAČR P103/95/1306 a P104/11/1101 a grantem Státního úřadu pro jadernou bezpečnost s názvem “Vývoj a optimalizace experimentálních a výpočetních postupů pro analýzu transportu radonu protiradonovými izolacemi”.

Výzkum v této oblasti byl motivován skutečností, že o transportu radonu hydroizolacemi nebyla v ČR vypracována žádná teoretická práce a chyběly i praktické zkušenosti. I v ostatních částech světa byl tento výzkum v počátcích. První metodu pro stanovení součinitele difuze radonu (K124/02/95) jsme vyvinuli společně se Státním ústavem radiačních ochrany (SÚRO) v.v.i. v roce 1995. Použitelnost této metody je omezena tím, že měření musí probíhat za stacionárních podmínek. Nová metoda (K124/01/09), vyvinutá v roce 2009 opět ve spolupráci se SÚRO v.v.i., je již univerzální, neboť umožňuje stanovit součinitel difuze radonu i za nestacionárních podmínek. Popis obou dvou metod, které byly brzy po svém zavedení akreditovány ČIA, je uveden v kapitole 2.

Pro lepší pochopení procesu difuze radonu hydroizolačními materiály jsme vytvořili dva numerické modely IterRn a TransRn, které jsou založeny na řešení diferenciální rovnice popisující jednodimenzionální časově proměnnou difuzi radonu. Modely mohou upřesnit a rozšířit naše znalosti o transportu radonu a difuzních vlastnostech různých hydroizolačních materiálů. Základní vztahy, jako například mezi distribucí radonu uvnitř zkoušeného vzorku a tloušťkou vzorku nebo jeho součinitelem difuze, jsou rozebrány v kapitole 3.

Od roku 1995 jsme stanovili součinitel difuze radonu ve více než 500 hydroizolačních materiálech o různém chemickém složení. Porovnání výsledků pro různé materiálové varianty spolu s komentářem vysvětlujícím příčiny některých rozdílů je obsahem kapitoly 4. Tatáž kapitola také ukazuje, že součinitel difuze radonu může být efektivně použit jako indikátor těsnosti spojů hydroizolačních pásů a fólií.

Metoda, kterou jsem vyvinul pro dimenzování protiradonových izolací, používá součinitel difuze radonu pro výpočet tloušťky izolace. Metoda dále zohledňuje kategorii radonového rizika stavebního pozemku a parametry chráněné budovy (plocha v kontaktu s podložím a intenzita větrání). Princip metody a její porovnání s metodami používanými v jiných státech je popsáno v kapitole 5. V závěru kapitoly 5 představuji princip nového přístupu k dimenzování protiradonových izolací, který je založen na tzv. radonovém odporu izolace. Cílem této nové metody je vytvoření návrhu unifikace postupů používaných v Evropě.

Klíčová slova

radon, koncentrace radonu, numerické modelování, měřící metody, součinitel difuze, protiradonová izolace, dimenzování izolace, radonový odpor

Keywords

radon, radon concentration, numerical modelling, measurement methods, diffusion coefficient, radon-proof insulation, dimensioning of insulation, radon resistance

CONTENTS

1 INTRODUCTION

Radon in buildings is considered to be the most important indoor air pollutant, with harmful effects on the health of the general population. Inhaling radon and its short-living decay products increases the risk of lung cancer. In many countries, the levels of indoor radon concentration are therefore regulated. The radon dose in dwellings can be effectively reduced by reducing the transport of radon from the soil into buildings.

Some waterproof materials applied for protecting buildings against soil moisture or underground water can also prevent soil radon from entering buildings. In many countries, suitable waterproof materials are therefore considered as a basic measure for protecting new buildings against radon [2], [9]. In the Czech Republic, continuous insulation has been required as a radon barrier in all houses built in radon-prone areas since 1995 [3]. The barrier properties of waterproof materials against radon penetration are usually expressed in terms of the radon diffusion coefficient. Measurements of this parameter started at the Faculty of Civil Engineering of the Czech Technical University in 1995. Results obtained up to now indicate that there are great differences in diffusion properties. Depending on the chemical composition, the radon diffusion coefficients in waterproofing materials widely used for protecting houses vary within eight orders of magnitude, from 10^{-15} m^2/s to 10^{-8} m^2/s [18].

The radon diffusion coefficient is used in some countries for dimensioning radon-proof insulations. Although the application principles differ from country to country, the radon diffusion coefficient has been found to be a suitable parameter for selecting effective radon barriers from among the waterproofing materials available on the construction market. However, there is currently no standardized technique for determining this coefficient. As a consequence of this impractical situation, different test protocols with extraordinarily different results can be found for the same waterproof material.

International comparative measurements of the radon diffusion coefficient in waterproof materials organized jointly in 2009 and 2010 by the Faculty of Civil Engineering of the Czech Technical University in Prague and the National Radiation Protection Institute in Prague showed that the differences between the results of particular laboratories for the same material were as high as two orders of magnitude [34]. This provided the impulse for us to start investigating the causes. Detailed time-dependent numerical analysis of different measuring procedures was performed by our IterRn and TransRn universal numerical models. These models determine the radon diffusion coefficient from any data set obtained by all known measuring modes used throughout Europe. Our analysis showed that the differences can mainly be attributed to three parameters - insufficient duration of the tests, insufficient radon concentration to which the samples are exposed, and the use of steady state calculation procedures for data measured under non-steady state conditions [35].

In an attempt to increase the accuracy of the tests, to ensure reproducibility and repeatability of the test results, and to simplify interpretation of the results, we have developed a unified test method that has become the basis for an international ISO standard [12].

2 DETERMINING THE RADON DIFFUSION COEFFICIENT OF WATERPROOFING MATERIALS

2.1 Basic principles

We define the radon diffusion coefficient as the proportionality coefficient *D* in equation (2.1) describing the one-dimensional radon distribution in a tested material [17]:

$$\frac{\partial C_{(x,t)}}{\partial t} = D.\frac{\partial^2 C_{(x,t)}}{\partial x^2} - \lambda.C_{(x,t)} \tag{2.1}$$

where $C_{(x,t)}$ is the radon concentration (Bq/m^3) and λ is the radon decay constant (2,1.10^{-6} s^{-1}). It is important to stress that not only diffusion but also other physical processes, such as the solubility of radon in the tested material and the adsorption of radon on the tested material are included in the radon diffusion coefficient.

The radon diffusion coefficient represents the amount of radon penetrating per unit of time through a sample 1 m in thickness with an area of 1 m^2 during a radon concentration gradient of 1 Bq/m^3. The radon diffusion coefficient is a material property that depends mainly on its chemical composition, and that is independent of the thickness of the material. If a homogeneous material is produced in different thicknesses, the value of this coefficient measured for one thickness is valid for all thicknesses. However, if a layered material is produced in different thicknesses, the radon diffusion coefficient must be determined separately for each thickness.

Most methods for determining the radon diffusion coefficient are based on the same principle [5], [6], [8], [14], [28], [29], [31], [37]. A sample of a radon-proof membrane is placed between two air-tight containers and the joint is carefully sealed (Fig. 2.1). The source container is connected to an efficient radon source, which is able to generate very high radon concentration in the container in a short time from the beginning of the measurement. Radon subsequently diffuses through the sample to the receiver container. The increase in radon concentration is measured in the source container and also in the receiver container. Using an appropriate mathematical process (either an analytical process for measurements performed under stationary conditions, or a numerical process for measurements under non-stationary conditions), the radon diffusion coefficient is subsequently calculated from the time-dependent courses of the radon concentrations in the two containers.

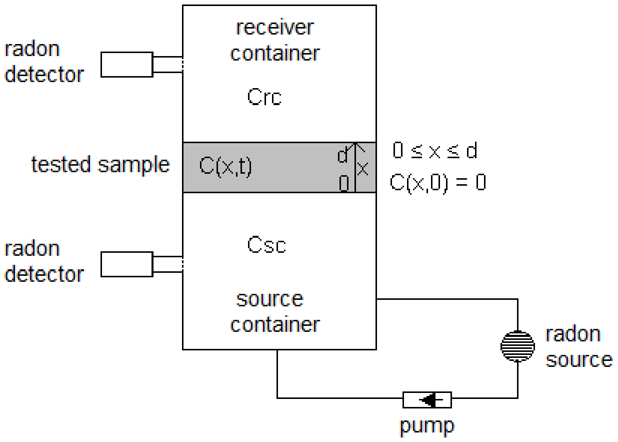

Fig. 2.1 - Typical arrangement of the measuring device (C_{sc}, C_{rc} – radon concentrations in the source and receiver containers, $C_{(x,t)}$ – Rn concentration within the tested sample).

It can be seen that the whole determination process consists of two separate parts: the first part involves measuring the radon concentrations on both sides of the tested sample, and the second part involves calculating the radon diffusion coefficient using mathematical processing of the measured data.

The main problems in the first phase (measurement) are as follows: determining the time that is needed to establish steady-state radon diffusion through the sample; and determining the minimum radon concentration in the source container that is needed to develop a sufficiently high (i.e. well detectable) radon concentration in the receiver container. In the second step of the determination procedure (calculation), the usual source of errors lies in the universal use of simple numerical techniques which are, however, valid (and accurate enough) only in certain conditions.

2.2 Determining the radon diffusion coefficient under stationary radon diffusion established during ventilation of the receiver container – the K124/02/95 method

After placing the sample between the source and receiver containers, the source container is connected to the radon source, which is able to create a radon concentration of up to 100 MBq/m^3 within this container. Radon diffuses through the tested material to the receiver container, which is continuously ventilated in order to hold the radon concentration in the receiver container at values close to 0 Bq/m^3. After the steady state of the system has been established (i.e. when there is a steady state radon concentration profile in the tested material), the ventilation of the receiver container is stopped and the subsequent increase in radon concentration in the receiver container is measured [11], [17]. The test procedure is presented in Fig. 2.2.

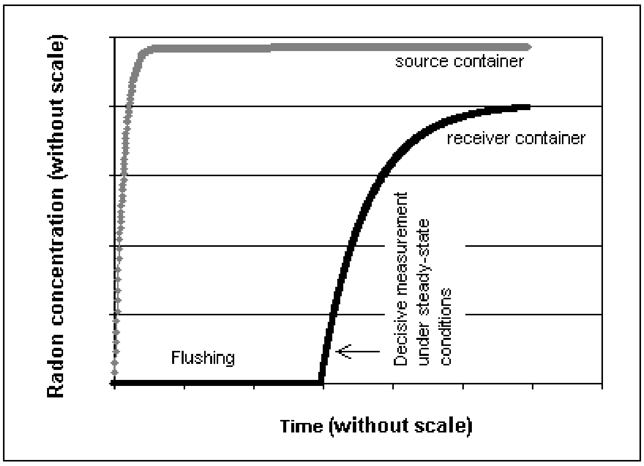

Fig. 2.2 - Test procedure according to the K124/02/95 method

In practice, the measuring system comprises 4 container pairs (source + receiver) connected to each other and to the radon source through the source containers in a serial circuit. The radon concentrations in the containers are measured by extracting air samples and introduction them into the Lucas cells. The measuring system is shown in Fig. 2.3.

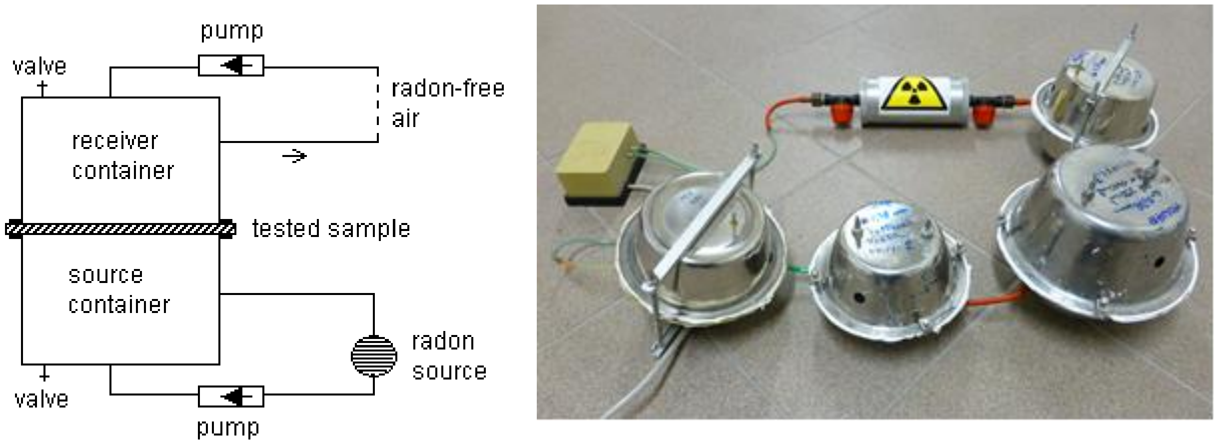

Fig. 2.3 – Schematic drawing of the measurement system and a photograph showing several pairs of containers connected to the radon source in a serial circuit.

Assuming steady state conditions, equation (2.1) changes into:

$$D \cdot \frac{\partial^2 C_{(\mathrm{x})}}{\partial x^2} - \lambda . C_{(\mathrm{x})} = 0 \qquad (2.2)$$

The solution of equation (2.2) for constant radon concentration in the source container and zero concentration in the receiver container provides the following equation for stationary distribution of the radon concentration in the tested sample:

$$C_{(x)} = C_{sc} . \frac{e^{-(x-d)/l} - e^{(x-d)/l}}{e^{d/l} - e^{-d/l}} \ [\mathrm{Bq/m^3}] \qquad (2.3)$$

where C_{sc} is the radon concentration in the source container [Bq/m^3], $C_{(x)}$ is the radon concentration at depth x in the tested sample [Bq/m^3], d is the thickness of the sample [m], and l is the radon diffusion length in the sample [m].

The radon exhalation rate E_{rc} from the tested material to the receiver container is:

$$E_{rc} = -D \frac{dC_{(x)}}{dx} = \frac{2.C_{sc}.l.\lambda}{e^{d/l} - e^{-d/l}} \qquad [\mathrm{Bq/m^2.s}] \qquad (2.4)$$

Immediately after ventilation is stopped, the radon concentration in the receiver container begins to increase. During the first few hours, the radon concentration in the receiver container is still low, so the back diffusion can be neglected and the growth of the radon concentration in the receiver container can be described by equation (2.5) and in linear approximation by equation (2.6):

$$C_{rc(t)} = \frac{A \cdot E_{rc}}{V.\lambda} .(1 - e^{-\lambda t}) \qquad [\mathrm{Bq/m^3}] \qquad (2.5)$$

where E_{rc} is the radon exhalation rate [Bq/m^2.s], A is the area of the tested sample [m^2], V is the volume of the receiver container [m^3], λ is the radon decay constant [2,1.10^{-6} s^{-1}], and t is time [s]. The radon leakage rate from the receiver container is assumed to be negligible.

$$C_{rc(t)} = \frac{A \cdot E_{rc}}{V} .t \qquad [\mathrm{Bq/m^3}] \qquad (2.6)$$

The radon exhalation rate into receiver container E_{rc} is calculated from equations (2.5) or (2.6) in dependence on the known curve of the increase in radon concentration in the receiver container.

Using equation (2.4), the radon diffusion length l is calculated iteratively from

$$\frac{E_{rc}}{2.C_{sc}} = \frac{l.\lambda}{e^{d/l} - e^{-d/l}} \tag{2.7}$$

And finally the radon diffusion coefficient D is derived from

$$D = l^2.\lambda \qquad [\mathrm{m^2/s}] \tag{2.8}$$

The great advantages of this method lie in the simplicity of the measurement phase, the possibility to measure several samples at the same time with a single measurement device, low measurement costs, and a simple calculation procedure. Disadvantages are the need to create stationary conditions, the longer measurement time, and complications in ensuring zero concentration in the receiver container (in the case of thin, permeable samples it may be difficult to ensure that the radon concentration in the receiver container is close to 0 Bq/m^3).

2.3 Determining the radon diffusion coefficient under non-stationary radon diffusion – the K124/01/09 method

After the sample has been placed between the source and receiver containers, both containers are closed and radon is admitted into the source container. The decisive measurements of the radon concentrations in the two containers begin at this moment (Fig. 2.4).

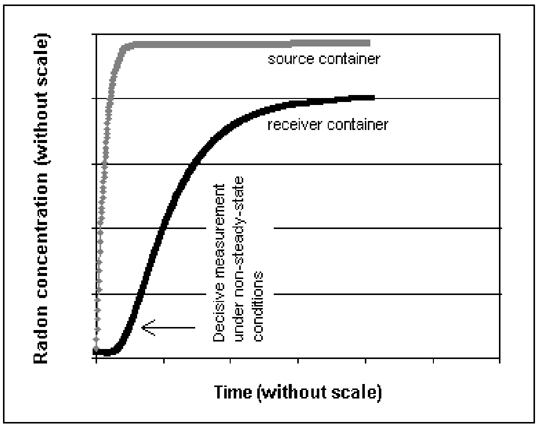

Fig. 2.4 - Test procedure according to the K124/01/09 method

This measurement principle was introduced in 2006, when a new measuring device was developed for continuous monitoring of radon concentrations on both sides of the sample, and a new computer program was developed for analysing the radon concentration curves measured in the containers [13], [14], [22], [24]. The new device is able to measure radon concentrations continuously, using ionisation chambers that serve at the same time as containers. The chambers operate in the current mode, and thanks to their very fast response the changes in radon concentrations can be monitored in 5-minute intervals. This device can therefore provide very precise records of time-dependent radon concentration curves. This is considered to be the main advantage of the new measuring device in comparison with the former device. A schematic drawing of the measuring device is presented in Fig. 2.5.

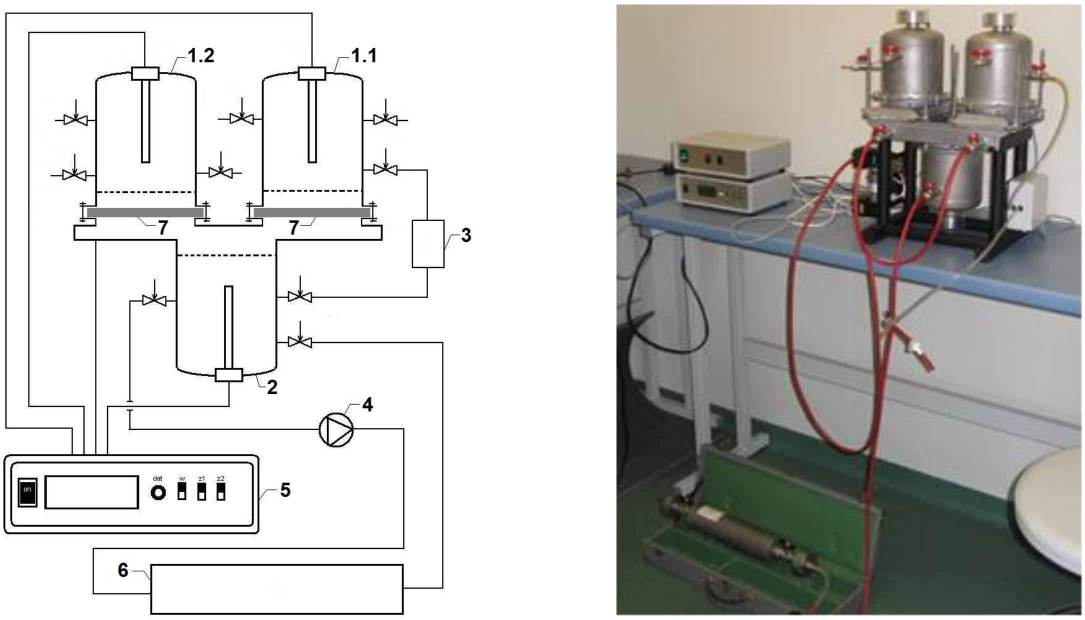

Fig. 2.5 - Schematic drawing of the new device (1.1, 1.2 – receiver containers, 2 – source container, 3 - pressure difference sensor, 4 - pump, 5 – control and operation unit, 6 – radon source, 7 – tested sample), and a photograph of the device.

We developed the IterRn numerical computer program, which is based on the FEM solution of equation (2.1), to determine the radon diffusion coefficient from the measured radon concentration curves. The IterRn software [24], [36] uses standard MS Windows procedures and dialogs to create, save, read and edit the data files. The results of the measurements can either be entered one-by-one into the input boxes on the main window of the program or they can be read directly from the record of the measurements (a simple text file with values separated by commas). The IterRn program is able to find the most appropriate value of the radon diffusion coefficient in the tested material from the inserted radon concentration curves in the source and receiver containers.

The radon diffusion coefficient is determined by an iterative procedure based on repeated numerical solutions of Equation (2.1). During this calculation, the radon diffusion coefficient value as the variable in the numerical solution gradually grows from the assumed lower limit to the assumed upper limit. The final radon diffusion coefficient is the value that results in the numerical solution of Equation (2.1) for which the differences between the calculated concentration and the measured concentration in the receiver container are minimal.

In the numerical solution of Equation (2.1), the time-dependent boundary conditions on both surfaces of the tested sample are expressed according to:

$$-D\frac{\partial C}{\partial x} = h \cdot \left(C_{\mathrm{s}} - C_{a}\right), \qquad (2.9)$$

where h is the radon transfer coefficient [m/s], C_s is the radon concentration on the surface of the sample [Bq/m^3], and C_{a} refers either to the radon concentration in the source container C_{sc} or to the radon concentration in the receiver container C_{rc}. In the calculation process, the radon concentration in the source container C_{sc} is always taken in accordance with the measured values. The initial radon concentration in the receiver container $C_{\mathrm{rc,0}}$ at the beginning of the calculation at time $t = 0$ is considered to be the concentration measured at that time. In the following time steps of the numerical solution, the radon concentration in the receiver container is calculated according to the equation:

$$C_{rc,i} = C_{rc,i-1}.e^{-(\lambda+n).\Delta t} + \frac{E_{rc,i-1}.A}{V.(\lambda+n)}.(1-e^{-(\lambda+n).\Delta t}) \, , \qquad (2.10)$$

where *Δt* is the time difference between time steps *(i)* and *(i-1)* [s] and n is the radon leakage from the receiver container [1/s]. Knowledge of the radon leakage can be important, especially in cases when there are some leaks in the sealing between the sample and the receiver container.

It is certainly more precise to calculate the radon diffusion coefficient using the IterRn model, because it uses the input data describing the whole time-dependent measuring process, and not only the final hypothetical “steady state” or a chosen part with linear changes in the radon concentrations in the two containers. The main advantages of this method are that it minimizes the uncertainties of the radon concentration measurements, it automatizes the radon measurements, and it shortens the measurement time (it is not necessary to wait for the steady state to be established). However, the fact that the containers serve as radon detectors increases the measurement costs and reduces the number of samples that can be measured at the same time.

2.4 Methods used in other countries

At least 11 measurement techniques for determining the radon diffusion coefficient of waterproof materials are available in various countries nowadays. An overview of these techniques is presented in [35]. However, there is currently no standardized method for determining this coefficient. As a result of this impractical situation, different test protocols providing extraordinarily different results can be found for the same waterproof material. International comparative measurements of the radon diffusion coefficient in waterproof materials, organized jointly in 2009 and 2010 by the National Radiation Protection Institute in Prague and the Faculty of Civil Engineering of the Czech Technical University in Prague, showed that the differences between laboratories were as high as two orders of magnitude [34].

An international comparison confirmed that the factors responsible for these differences are [35]: inappropriate mathematical processing of the measured data, different boundary conditions under which the tests are carried out (stationary or non-stationary), insufficient duration of the tests, insufficient radon concentration to which the samples are exposed, different measuring techniques, etc.

Most methods determine the radon diffusion coefficient from radon concentrations measured immediately after the beginning of the test (within no more than 10 days) using stationary mathematical techniques. This type of approach does not take into account that sufficient time, usually within the range from 10 to 20 days, is needed to reach stationary conditions (see section 3). The use of simple steady state calculation procedures leads to inaccuracies in the value of the radon diffusion coefficient derived from non-steady data. If it is not convenient to wait until steady state conditions are established, complex numerical modelling is the only way to ensure sufficient accuracy of the result.

2.5 Standardizing the method for determining the radon diffusion coefficient

In an attempt to increase the accuracy of the tests, to ensure reproducibility and repeatability of the test results, and to simplify the interpretation of the results, the Faculty of Civil Engineering of the Czech Technical University, in cooperation with the National Radiation

Protection Institute in Prague, developed a unified methodology for determining the radon diffusion coefficient. This methodology was accepted as a basis for the international ISO standard that is currently being drafted [20], [12].

This standard should ensure that the tests are carried out under the same conditions in all laboratories. It specifies the minimum radon concentration to which the samples shall be exposed, the minimum duration of the test, and correct mathematical processing of the measured data depending on whether the measurement was carried out under stationary conditions or under non-stationary conditions.

3 PARAMETERS INFLUENCING RADON DIFFUSION THROUGH WATERPROOFING MATERIALS

In addition to the IterRn software, we have developed the TransRn numerical computer program [36], which calculates the radon distribution within a material, the radon exhalation rate from a material, and the radon concentration in the receiver container for the known radon diffusion coefficient and radon concentration in the source container. TransRn software is also based on the FEM solution of equation (2.1), which describes one-dimensional time-dependent radon diffusion through the tested material. Both programs have been successfully verified by comparing their results with the analytical solution of simple transport cases.

The TransRn model can be used for deep analyses of transient radon diffusion through the measured sample. It is essential to understand the complex radon transfer processes within the measuring device and also within the measured sample in order to make measurements with a high level of accuracy. The fundamental correlations, e.g. between the radon distribution within the tested sample and the thickness of the sample or its radon diffusion coefficient, can be studied by means of the TransRn tool. This tool can also help the user to assess the minimum duration of the decisive measurement and the minimum radon concentration in the source container to which the sample is to be exposed. The following results of several model analyses show some significant dependencies and general relations between the physical quantities involved in the radon diffusion process [35].

3.1 Radon distribution within a radon-proof membrane

The radon concentration profile within the tested waterproof membrane generally has the shape of an exponential function. It is only in some special cases, e.g. for very thin membranes with the radon diffusion coefficient close to the order 10^{-10} m^2/s or higher, that the radon distribution can be almost linear. However, this is not a typical situation, because membranes with such a high radon diffusion coefficient are too permeable for use as efficient radon-proof barriers. Time-dependent changes in radon concentration within a polymeric membrane 1 mm in thickness with $D = 1.10^{-12}$ m^2/s (a typical representative of waterproof membranes) are presented in Figure 3.1. In the calculations, it was assumed that the radon concentration in the source container either has a stable value of 10 MBq/m^3, or increases at a rate of 50 kBq/m^3 per day, and the steady state concentration in the source container of 10 MBq/m^3 is attained at time t = 200 hours after radon has been admitted into the source container. The figure confirms the exponential shape of the radon concentration profile within the membrane, even in the steady state. In addition, it is evident that the time needed to establish the steady state profile is proportional to the rate of increase in the radon concentration in the source container.

3.2 Radon concentration in the receiver container

If the decisive measurement of the radon concentration in the receiver container starts immediately after radon has been admitted into the source container, the initial part of the build-up curve is not linear. This is because, at the beginning of the test, the membrane is not fully saturated with radon and hence the radon exhalation rate from the membrane into the receiver container is not steady. The significance of this non-linear shape increases as the thickness of the membrane increases and the radon diffusion coefficient decreases. Another important factor influencing the initial shape of the curve is the rate of the increase in radon concentration in the source container. The effect of all of these factors is shown in Fig. 3.2. The figure indicates that the initial non-linear part can be observed within the first 1 to 10 days after the test has commenced. A linear approximation of the measured data in this phase, especially if the duration of the test is short, can lead to serious mistakes and to underestimation of the diffusion coefficient.

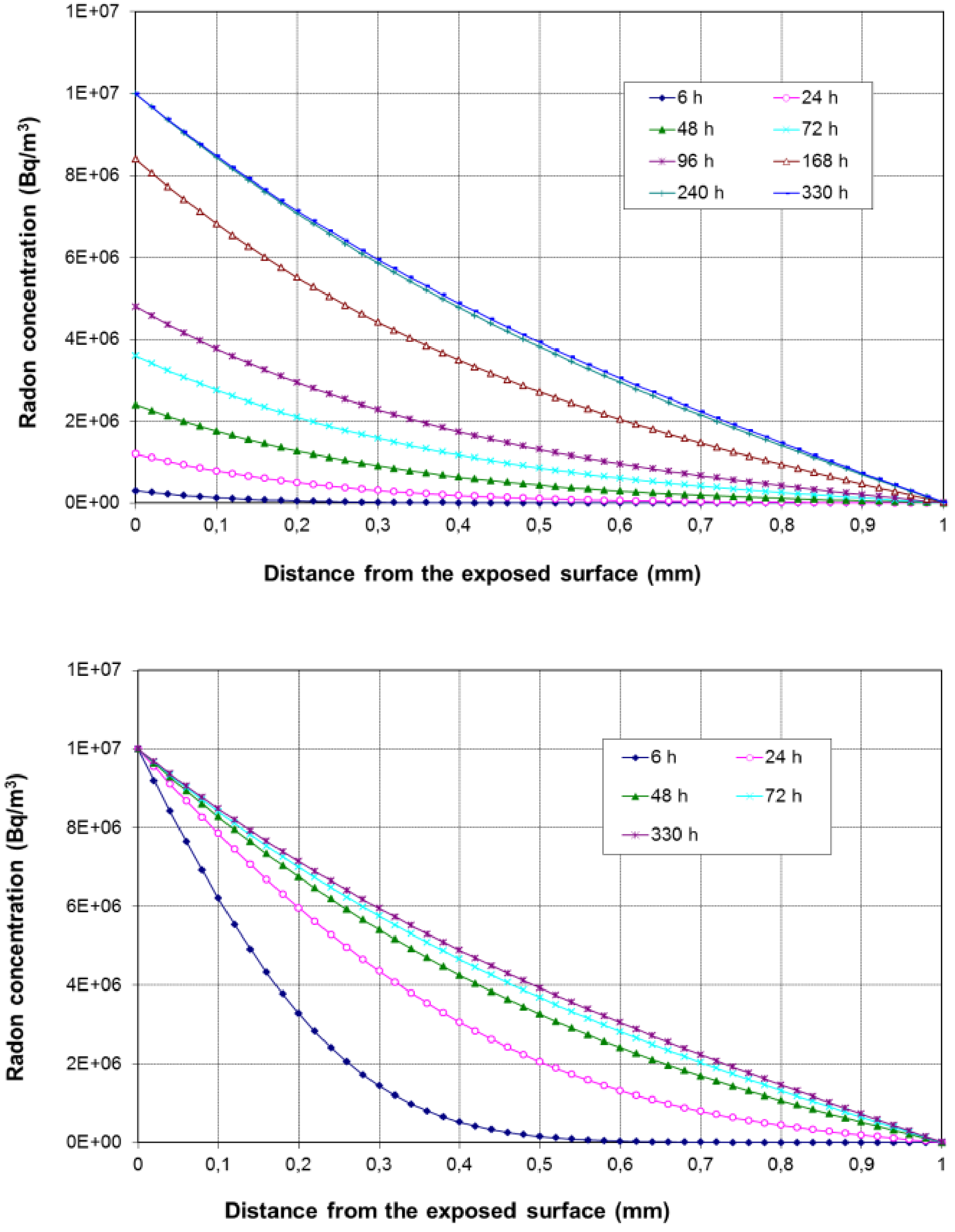

Fig. 3.1 - Radon distribution within a membrane of $D = 1.10^{-12}$ m^2/s for gradually increasing radon concentration in the source container (upper figure) and the steady state radon concentration in the source container of 10 MBq/m^3 (lower figure).

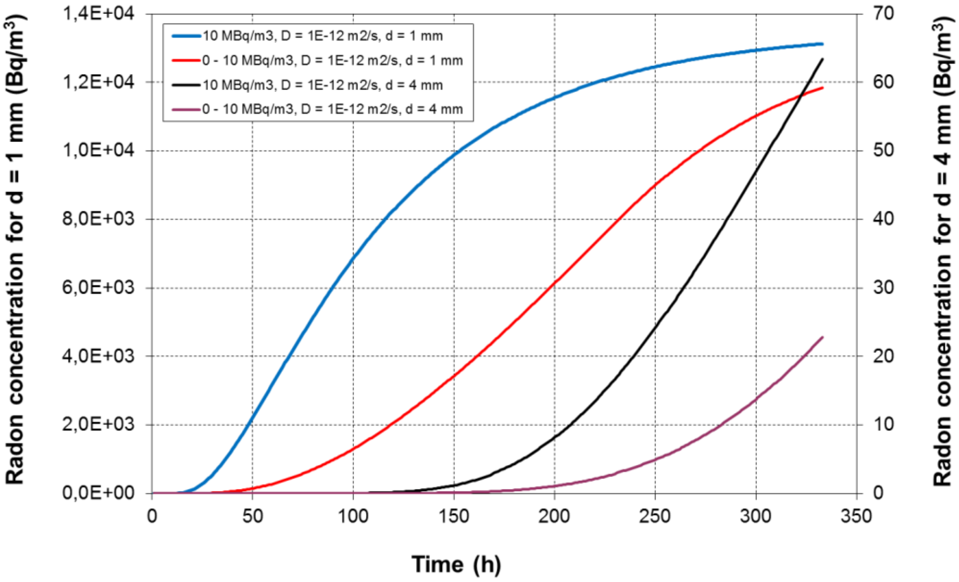

Fig. 3.2 - The shape of the built-up curves of the radon concentration in the receiver container for D = 1.10^{-12} m^2/s in dependence on the thickness of the membrane and the rate of increase in the radon concentration in the source container. It was assumed that the samples are exposed either to the steady state radon concentration in the source container of 10 MBq/m^3, or to a gradual increase in the radon concentration in the source container at a rate of 50 kBq/m^3 per day.

3.3 Radon concentration in the source container

Another important factor that may result in significant errors is low radon concentration in the source container that cannot generate sufficiently high radon concentration (i.e. well detectable by the measurement technique that is applied) in the receiver container. Correct prediction of the minimum radon concentration in the source container is a crucial prerequisite for ensuring that the measurement uncertainties will be as low as possible. For a typical representative of the waterproof membranes mentioned above, Fig. 3.3 shows how the radon concentration in the receiver container is influenced by the radon concentration in the source container. It can be seen, for example, that for a membrane with a radon diffusion coefficient of 1.10^{-12} m^2/s and 1 mm in thickness, exposed to concentrations of 100 kBq/m^3 or 500 kBq/m^3, respectively, it takes 80 hours or 37 hours for the radon concentration in the receiver container to reach 50 Bq/m^3. If we consider that a value of 1 kBq/m^3 in the receiver container in the steady state provides well detectable concentrations in the receiver container even at the beginning of the measurements, this membrane should be exposed to a concentration of at least 750 kBq/m^3. The thickness of the membrane has a major influence on this assessment. For a membrane with the same radon diffusion coefficient but four times greater thickness (4 mm), the radon concentration in the source container must be more than 10 times higher (see Fig. 3.2 – for 10 MBq/m^3 in the source container, the radon concentration in the receiver container reaches 50 Bq/m^3 after a period of 307 hours).

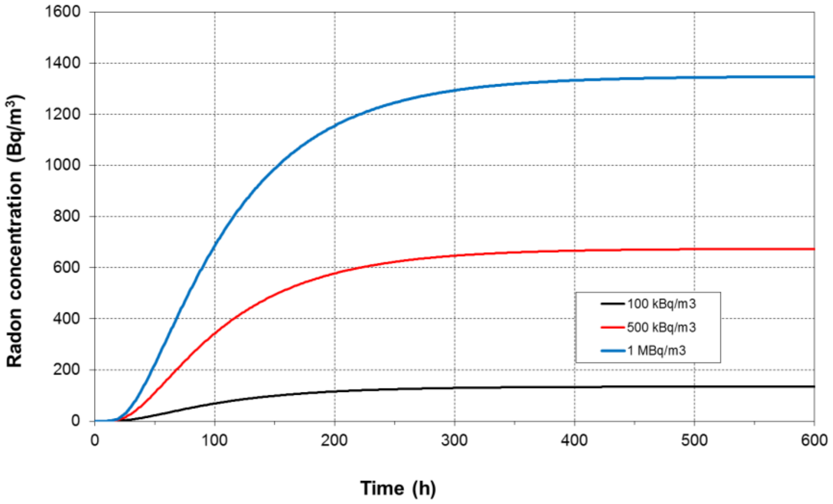

Fig. 3.3 - Radon concentration in the receiver container for a membrane 1 mm in thickness with D = 1.10^{-12} m^2/s in dependence on the steady state Rn concentration in the source container.

Numerical modelling can thus be used for predicting the minimal radon concentration in the source container for various types of measured membranes (in dependence on their thicknesses and their estimated radon diffusion coefficients). Such predictions ensure that the radon concentration in the receiver container will be detectable by the measurement technique that is applied, and the measurement uncertainties will be as low as possible. If we assume that 1 kBq/m^3 is a well-detectable radon concentration value in the receiver container, the minimum radon concentration in the source container can be predicted from Fig. 3.4. It can be seen that, for this assumption, the radon concentration in the source container should be, for example, 0,5 MBq/m^3 for a membrane 1,0 mm in thickness, if its estimated radon diffusion coefficient is around $1 \cdot 10^{-12}$ m^2/s. The influence of the thickness of the membrane is highly important in this assessment; for the same estimated radon diffusion coefficient and 4 times greater thickness (4.0 mm), the source radon concentration must be at least 100 times higher (50 MBq/m^3).

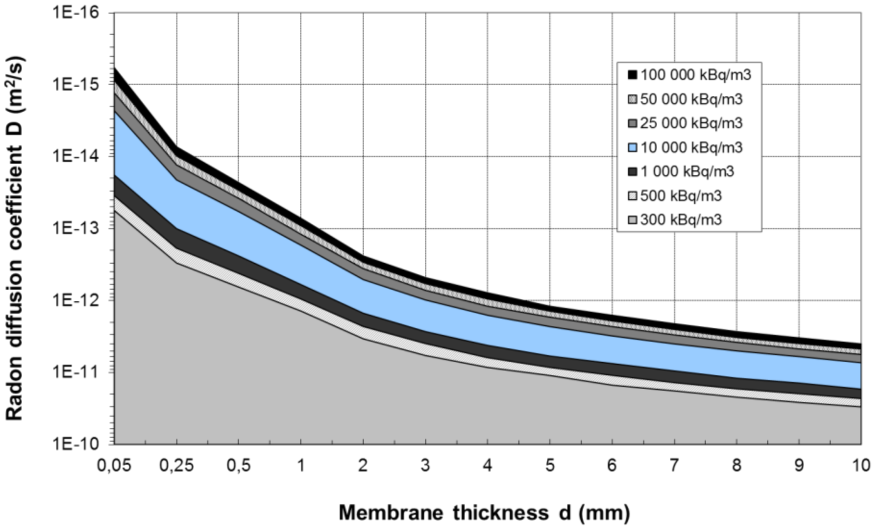

Fig. 3.4 - Minimum radon concentration in the source container ensuring minimum radon concentration in the receiver container of 1000 Bq/m^3.

4 RESULTS OF DETERMINING THE RADON DIFFUSION COEFFICIENT IN WATERPROOFING MATERIALS

4.1 Overview of results

The results of radon diffusion coefficient measurements carried out by the Faculty of Civil Engineering of the Czech Technical University in Prague in cooperation with the National Radiation Protection Institute in 360 insulating materials available throughout Europe are summarized in Fig. 4.1, where the materials are grouped into several categories according to their chemical composition [18]. For each category, the minimum, maximum and mean values are presented. Since at least 2 samples in the case of prefabricated membranes and at least 3 samples in the case of paints or coatings are required for testing by our method, Fig. 4.1 makes use of data obtained from more than 780 different samples.

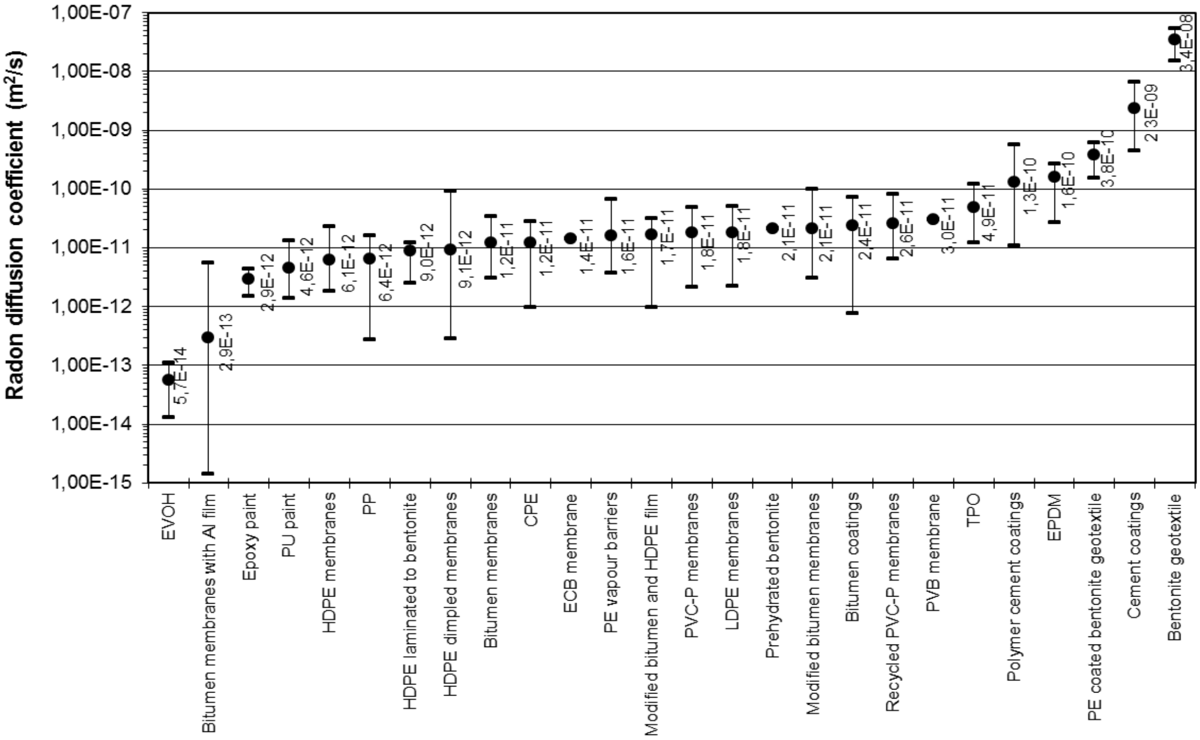

Fig. 4.1 - Radon diffusion coefficients of various waterproof materials measured according to the K124/02/95 method

Fig. 4.1 shows very clearly that in widely-used insulating materials applied for protecting houses against radon the diffusion coefficients vary within eight orders of magnitude, from 10^{-15} m^2/s to 10^{-8} m^2/s. The lowest values were obtained for bitumen membranes with an Al carrier film, irrespective of whether the bitumen was modified, and for EVOH membranes. The highest radon diffusion coefficient values were observed for sodium bentonite membranes, rubber membranes made of EPDM, and polymer cement coatings. The radon diffusion coefficients for waterproofings widely used for protecting houses, i.e. PVC, HDPE, LDPE, polypropylene and bitumen membranes, vary in the range from 3.10^{-12} to 3.10^{-11} m^2/s.

The relatively large differences between the minimum and maximum values (long error bars) are caused by the fact that widely-used membranes produced for the building industry are not composed of pure polymers. They contain various fillers, additives, softening agents, UV stabilisers, colours, reinforcing fabrics, etc. Even materials of the same chemical origin contain different types and different amounts of these admixtures. In addition, the content of these additives can vary with time (even for products sold under the same name) due to changes in the production phase caused by changes in technology, or due to the introduction of new additives. The detailed composition of membranes is usually not known, because producers consider this data as restricted.

4.2 Polymeric membranes

Fig. 4.1 indicates that the radon diffusion coefficients of LDPE membranes are approximately 3 times higher than those of HDPE membranes (HDPE has stronger intermolecular forces and a higher degree of crystallinity). Since the results for polyethylene vapour barriers are very close to the LDPE membrane values, it can be assumed that they have an LDPE origin. It is evident that forming dimpled membranes from flat HDPE membranes by moulding results in greater dispersion of the data. This can probably be attributed to a loss of uniform thickness, because the membrane usually becomes thinner around the edges of the dimples. The ratio between the thinner and thicker parts of the membrane, which is influenced in each case by the number and the shape of the dimples, affects the radon transport through the membrane and thus the value of the diffusion coefficient.

The radon diffusion coefficient in polyethylene membranes is very strongly influenced by the density of the polyethylene, see Fig. 4.2. The radon diffusion coefficient decreases with increasing density. The correlation between these properties can be used by producers for preparing polyethylene membranes with an appropriate chemical composition, so that production costs, diffusion properties and other important parameters will be in balance.

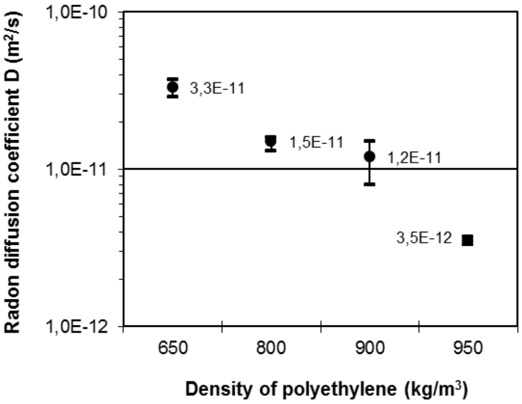

Fig. 4.2 - Radon diffusion coefficients of PE membranes plotted as a function of the density of the polyethylene (membranes with density lower than 920 kg/m^3 are foamed LDPE membranes).

Fig. 4.1 also shows that the radon diffusion coefficients for membranes made of recycled PVC are slightly higher (the increase is 10% for the medians and 44% for the means) than for membranes made of non-recycled flexible PVC. In addition, the interval between the first quartile and the third quartile is 26% wider, which means that the results are less reliable. The correlation with polyethylene membranes shows that the barrier properties of PVC membranes are comparable with those of LDPE, and are approximately 3,5 times worse than the barrier properties of HDPE.

From the group of polymeric membranes, the lowest values (within the order of 10^{-14} m^2/s) were discovered for EVOH membranes, which can therefore be considered very effective radon barriers. However, rubber membranes made of EPDM can hardly be considered as radon-proof materials, because their radon diffusion coefficient (usually of the order of 10^{-10} m^2/s) is too high to satisfy the requirements set by the building regulations or by the technical standards in various countries. The values for polypropylene membranes correspond to the values obtained for HDPE membranes, with the exception of the length of the error bars. The difference between the minimum and maximum values in the case of HDPE membranes is only one order of magnitude, while in the case of polypropylene membranes it is two orders of magnitude. This indicates that the diffusive properties of polypropylene may differ considerably. The radon diffusion coefficient values for thermoplastic polyolefins lie between the values for polypropylene and EPDM membranes. This can be explained by the chemical composition of TPO membranes. They are blends of polypropylene or polyethylene and elastomeric rubbers such as EPDM, EPR (ethylene propylene rubber), SEBS (Styrene-ethylene-butadiene-styrene), etc. Though the amount of EPDM in TPO polymers is usually much lower than the amount of polypropylene, it increases the diffusion coefficient by approximately one order of magnitude compared to pure polypropylene.

4.3 Bitumen materials

Generally, oxidized bitumen membranes have lower diffusion coefficients than modified bitumen membranes. The difference in the medians between these two categories is as high as 44%, and can be attributed to rubber styrene-butadiene-styrene, which is the most frequently-used modification agent. The diffusion properties of this type of rubber are similar as for EPDM. Fig. 4.1 also shows relatively long error bars for two material categories – for bitumen membranes with an Al carrier, and for polymer-modified bitumen coatings. In the case of membranes with Al carriers, this is caused by the differing thicknesses of the Al films, which usually vary between 0,006 mm and 0,08 mm. However, in the category of bitumen coatings this results from the different chemical composition of each material. This means that materials with very good barrier properties can be found at the lower end of the error bar, while at the upper end there are materials that can hardly be considered as radon-proof. Since the median lies close to the upper end, we can assume that most of these materials will not work satisfactorily. It should be noted that it is not permitted to apply bitumen membranes with an Al carrier for radon barriers in the Czech Republic, even if they have a very low radon diffusion coefficient. Such low values are conditioned by the integrity and the continuity of the Al carrier. In practical applications, it is almost impossible to avoid damage to the Al film, because it has very low tear resistance and almost no elongation.

4.4 Other materials

The group of other materials includes epoxy and polyurethane paints, cement coatings and several types of bentonite membranes. In the case of both paints, the low radon diffusion coefficients confirm very good barrier properties. However, cement coatings are extremely permeable to radon and thus they cannot serve as radon barriers. If polymers (usually acrylic, styrene-acrylic or silicone resins) are added into these coatings, the resulting product has a diffusion coefficient that is one order of magnitude lower, i.e. comparable with EPDM membranes. The long error bar can be explained by the different polymer cement ratio, which can vary from 0,05 to 0,2.

Irrespective of whether it is placed between two geotextiles (known as a geo-synthetic clay liner) or between kraft boards, the dry form of sodium bentonite is one order of magnitude more permeable to radon than cement coatings. Prehydration of bentonite decreases the diffusion coefficient by three orders of magnitude, see Fig. 4.1. However, it should be stressed that the measurement conditions differ considerably from real application conditions. When wet, bentonite expands several times and begins to behave like a gel, penetrating into pores and cracks in the substrate to which it is applied. This situation cannot be imitated while measuring the radon diffusion coefficient. It is clear that bentonite materials cannot perform everlasting protection against radon, because when the subsoil dries out the barrier properties of the bentonite are lost. This drawback can be eliminated by combining bentonite with a polyethylene layer. If a thin, usually non-continuous, polyethylene coat is applied directly to the geotextile, the decrease in the radon diffusion coefficient is not sufficient, but if bentonite is laminated directly to the valuable HDPE membrane, the radon diffusion coefficient is influenced primarily by the quality of the HDPE.

4.5 The radon diffusion coefficient as an indicator of the radon-tightness of joints

The effectiveness of radon-proof insulations depends very strongly on the radon-tightness of the joints between the preformed membranes. To be sure that the particular sealing technology provides a radon-tight bond between preformed membranes, the radon-tightness of the joints needs to be checked. The radon diffusion coefficient can also be used for these purposes [32]. When it is measured at the place where two sheets of membranes are joined, and the resulting value is considerably higher than the value for the membrane, it can be assumed that the joint leaks. Special laboratory OL124 of the Department of Building Structures has detected 4 types of leaky joints, which are introduced in Fig. 4.3 and are described below.

Generally, various self-adhesive tapes applied for sealing joints between rigid polymeric membranes more than 1 mm in thickness usually do not provide sufficient radon-tightness. Leakages especially occur when this sealing technology is used for sealing joints of dimpled membranes. It is almost impossible to form airtight joints between dimpled membranes (Tab. 4.1). This led in 2006 to a ban on the use of membranes of this type as radon barriers in the Czech Republic.

Tab. 4.1 - Radon diffusion coefficients of an HDPE dimpled membrane and an overlap joint sealed with a self-adhesive tape inside the overlap

HDPE dimpled membrane	$(4,1 \pm 0,1).10^{-12}$
Overlap joint sealed with a self-adhesive tape	$(7,4 \pm 0,7).10^{-10}$

Other problematic joints are those between self-adhesive bitumen membranes, if the top surface of these membranes is sanded. The self-adhesive underface adheres only to the upper grains of sand without filling the air gaps between the lower-positioned grains, through which radon can easily penetrate. The significance of this transport is illustrated by Tab. 4.2, which presents the differences between the radon diffusion coefficient values determined for a membrane itself, a torched joint, and a self-adhesive overlap joint. As a consequence of this finding, joints between these types of self-adhesive membranes should also be sealed by torching.

If a permeable surface coating in the form of fleece or geotextile is provided on one or both sides of the membrane, it is usually not possible to create radon-tight joints between these types of membranes. Self-adhesive tapes or adhesives applied inside the overlaps do not penetrate through the whole permeable coating. They adhere to the surface fibres only. Tab. 4.3 documents that radon can penetrate through the gaps between more deeply-positioned fibres. For the same reason, bentonite membranes with an impermeable polymer coating on one side cannot be joined using adhesives applied inside the overlaps, because radon would penetrate through the bentonite. The only way to join them in an air-tight manner is to use self-adhesive tapes pasted on the polymer coatings over the overlap.

Tab. 4.2 - Radon diffusion coefficients of SBS-modified bitumen membranes, overlap joints sealed by torching and self-adhesive overlap joints

SBS modified bitumen membrane reinforced with an Al foil	$(4,9 \pm 0,5).10^{-14}$
Overlap joint sealed by torching	$(5,1 \pm 0,5).10^{-14}$
Self-adhesive overlap joint	$(4,3 \pm 0,4).10^{-10}$
SBS modified bitumen membrane reinforced with polyester fabric	$(7,1 \pm 0,2).10^{-12}$
Overlap joint sealed by torching	$(8,6 \pm 1,0).10^{-12}$
Self-adhesive overlap joint	$1,2.10^{-8}$ - $1,7.10^{-11}$

Tab. 4.3 - Radon diffusion coefficients of a polymeric membrane with a geotextile coating on both sides and a joint sealed with a self-adhesive tape inside the overlap

Polymeric membrane with a geotextile coating on both sides	$(1,0 \pm 0,1).10^{-12}$
Joint sealed with a self-adhesive tape inside the overlap	$(1,5 \pm 0,2).10^{-9}$

Polymeric membranes are sometimes reinforced with a regular mesh made of glass or synthetic fibres. If the membrane is thin, the reinforcing mesh protrudes on the surface of the membrane. An uneven surface makes joining difficult and problematic, because leaks may arise along protruding reinforcing fibres. Hot air welding, which is considered to be the most reliable sealing technology for polymeric membranes, may in this case even worsen the result. Welding can be responsible for damage to the thin polymeric coating around the reinforcing fibres. If this occurs, radon is transported directly through the reinforcing mesh (see Tab. 4.4).

Tab. 4.4 - Radon diffusion coefficients of a polymeric membrane reinforced with a protruding regular mesh of fibres and an overlap joint sealed by hot air welding

Polymeric membrane with a protruding reinforcing mesh	$(7,6 \pm 0,8).10^{-12}$
Joint sealed by hot air welding	$2,6.10^{-10}$ – $4,7.10^{-11}$

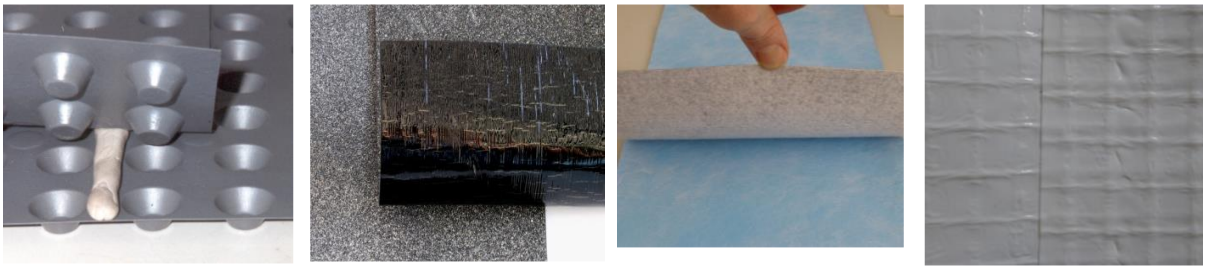

Fig. 4.3 - Examples of leaky joints – sealing tape applied inside the overlap of dimpled membranes, a joint between self-adhesive bitumen membranes, adhesive inside the overlap of polymeric membranes coated on both sides with a fleece or geotextile, and a welded joint between polymeric membranes with a protruding reinforcing mesh

5 APPLYING THE RADON DIFFUSION COEFFICIENT FOR DIMENSIONING RADON-PROOF INSULATIONS

5.1 The Czech approach

In 1995, I developed a general methodology for calculating the minimal thickness of radon-proof insulations [15], [16], [19], [25]. My approach takes into account all parameters that may affect the thickness of the insulation, i.e. the parameters of the membrane (the radon diffusion coefficient), the parameters of the building site (the soil gas radon concentration and soil permeability) and the parameters of the building (the area of the structures in contact with the soil, the interior air volume and the ventilation rate). The principle of the calculation is based on the following theory.

The minimal thickness of a radon-proof insulation can be derived from the fact that the insulation must minimize 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 equation (5.1), ensuring that the indoor radon concentration will be below the reference (limit) value C_{lim}

$$J_s \leq C_{lim}.V.n \quad \text{(Bq/h)} \qquad (5.1)$$

where V is the interior air volume [m^3] and n is the ventilation rate [h^{-1}].

In practice, both convection and diffusion contribute to the radon supply rate. Since the convective transport of radon through cracks, untight joints and pipe penetrations is usually significantly greater than radon diffusion through undamaged insulation, we assume that radon diffusion can be responsible for not more than 10% of the indoor radon concentration. This assumption is consistent with the range of 4 - 50% presented by Holub and Killoran [10], in which the upper limit of 50% for the diffusion component was found for a substructure without insulation.

The convective part of the radon supply rate cannot be used to find the thickness of the insulation, because convection is eliminated by even the thinnest insulation applied continuously. The formula for an appropriate thickness of the insulation must therefore be derived from the diffusive part.

On the basis of these considerations, the condition for the highest permissible radon exhalation rate from the insulation E_{lim} can be derived from equation (5.1), in which C_{lim} has been replaced by C_{dif} = 10% C_{lim}. The value of C_{dif} means that the importance of diffusion has been reduced to the estimated 10% and the remaining 90% of C_{lim} is reserved for accidentally occurring convection. The highest permissible radon exhalation rate can thus be calculated for each house from equation (5.2)

$$E_{\lim} = \frac{C_{dif}.V.n}{A_f + A_w} \quad \text{(Bq/m}^2\text{h)} \qquad (5.2)$$

where V is the interior air volume [m^3], n is the ventilation rate [h^{-1}], A_f and A_w are the areas of floors and 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).

The thickness of the radon-proof insulation can then be found in dependence on the 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 (5.3), must be less than or equal to the highest permissible radon exhalation rate E_{lim} calculated for that house, i.e. $E \leq E_{lim}$.

$$E = \alpha_1 . l . \lambda . C_S \frac{1}{\sinh(d/l)} \qquad (\mathrm{Bq/m^2h}) \qquad (5.3)$$

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 cover any inaccuracies arising during the soil gas radon concentration measurements and any increase in the radon concentration beneath the completed house in comparison with the radon concentration C_s measured on the unbuilt area. Values of α_1 are estimated according to the soil permeability (for highly permeable soils α_1 = 7, for soils with medium permeability α_1 = 3, and for soils with low permeability α_1 = 2,1).

On the assumption that the insulation is homogeneous, its minimal thickness can be calculated from equation (5.4), which is obtained after replacing E in equation (5.3) by E_{lim} from equation (5.2).

$$d \geq l . \operatorname{arcsinh} \frac{\alpha_1 . l . \lambda . C_s . (A_f + A_w)}{C_{dif} . n . V} \qquad (\mathrm{m}) \qquad (5.4)$$

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 probability of under-dimensioning or over-dimensioning is thus strongly reduced.

The method for dimensioning the radon-proof insulations described above has formed a part of Czech Standard ČSN 730601 “Protection of buildings against radon from the soil” [3].

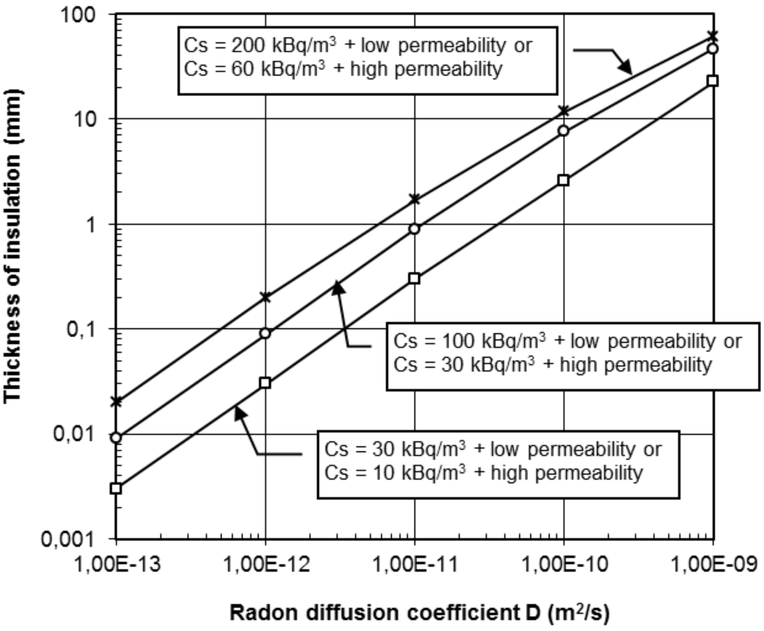

Fig. 5.1 - Thickness of the insulation calculated according to equation (5.4) for different values of D and for various combinations of soil gas radon concentration and soil permeability. The chart is valid for a new-built house with habitable rooms in the basement and a ventilation rate of 0,3 h^{-1}.

The principle for designing according to this method can be identified from Fig. 5.1, in which the thickness of the insulation is plotted as a function of the radon diffusion coefficient and various combinations of the soil gas radon concentration and the soil permeability. It is clear that the thickness of insulation with D lower than 10^{-12} m^2/s can be only several tenths of one millimetre, even in areas with high radon concentration in the soil. Such a small thickness can hardly be produced and applied due to sensitivity to puncturing, so thicker insulation must be used in practical applications. However, the applicability of insulation with D of the order of 10^{-11} m^2/s will be very strongly dependent on the characteristics of the building 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 radon diffusion coefficient lies in the interval between 5.10^{-12} and 3.10^{-11} m^2/s. This interval corresponds to the production thickness of the most frequently-used insulating materials, i.e. 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).

5.2 Dimensioning radon-proof insulations in other countries

The way that the radon diffusion coefficient is applied differs from country to country. In general, there are two different approaches to the use of the diffusion coefficient for the design of radon-proof insulations:

1. setting a maximum radon diffusion coefficient value;
2. determining the thickness of the radon-proof insulation in dependence on the radon diffusion length.

Setting a maximum radon diffusion coefficient value

According to this approach, every material that is to act as a radon barrier must have a radon diffusion coefficient D below the strict limit value. This approach is applied for example in Ireland where, according to Building Regulations 1997 [1], the maximum radon diffusion coefficient value is set at 12.10^{-12} m^2/s.

The main problem with this approach is how to choose the limit value correctly. To be safe and reliable under all circumstances (for all types of houses and for all radon concentrations in the soil), the limit value should be as low as is reasonable. However, the lower the limit is set, the more materials will be of no use. For a typical single-family house, typical soil gas radon concentration and typical thickness of the membrane, the maximum value of the radon diffusion coefficient should be around 1.10^{-11} m^2/s. Materials with higher diffusion coefficients are excluded from use as radon barriers. Fig. 4.1 shows quite clearly that there are a great number of unsuitable materials.

Another disadvantage is that this approach does not express the real radon barrier properties of the insulation, because it does not take into account its thickness. For example, insulation 0,5 mm in thickness with a radon diffusion coefficient of $D = 12.10^{-12}$ m^2/s has the same resistance against radon penetration as insulation 1,5 mm in thickness with a radon diffusion coefficient of $D = 36.10^{-12}$ m^2/s.

Determining the thickness of the insulation from the radon diffusion length

This approach usually compares the thickness of the material with the radon diffusion length, calculated as $l = (D/\lambda)^{1/2}$. For example, in Germany a material can be considered to be radon-tight if it is at least three times thicker than the radon diffusion length l [8].

Limits for the minimum thickness of insulating materials 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 should be at least three times thicker than the diffusion length leads to relatively thick barrier materials. The required thickness exceeds the production thickness if the radon diffusion coefficient is higher than 1.10^{-12} m^2/s, in the case of plastic membranes, or 4.10^{-12} m^2/s in the case of bitumen membranes (see Fig. 5.2). This simply leads to the conclusion that the requirement $d \geq 3l$ is stricter than the previously described limit for D, and will be met by a considerably smaller group of materials.

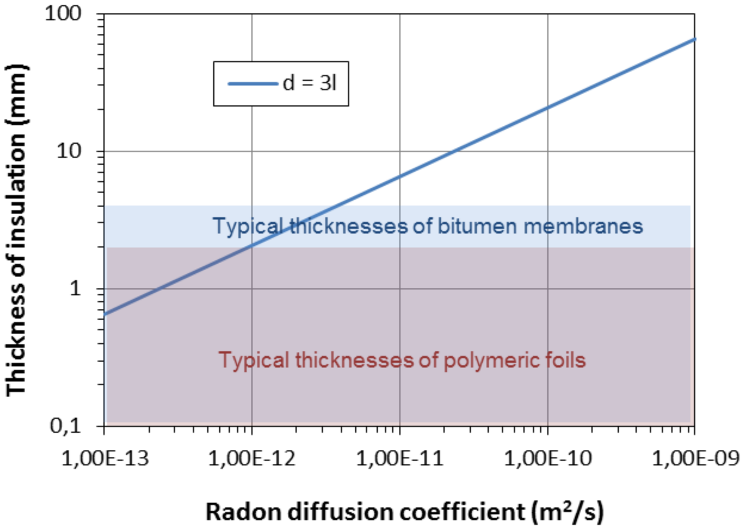

Fig. 5.2 - The thickness of radon-proof insulation calculated according to the formula d = 3l (valid for all types of houses and radon concentrations in the soil).

5.3 A proposal for a uniform approach to the dimensioning of radon-proof insulations

Different approaches for determining which material can be considered as radon-proof and for defining the minimal thickness of the insulation have some negative consequences. A product considered in one country to be suitable for application as a radon barrier can be considered unsuitable for this purpose in another country. The thickness of a radon-proof insulation determined in one country may not be considered sufficient in other countries, etc. This also complicates the position of producers in their effort to provide reliable information about the radon barrier properties of their products. Consequently, it is not easy to select a suitable radon-proof insulation of an appropriate thickness from the range of products available on the international market.

The proposed method for dimensioning radon-proof insulations benefits from the positive aspects of all the methods, and at the same time attempts to eliminate negative aspects. The method takes into account the radon risk of foundation soils, the barrier properties of the insulation expressed by the radon diffusion coefficient, and the parameters of the building (the area in contact with the soil, the ventilation rate and the existence of other radon preventive measures). At the same time, it replaces the complicated calculations typical for the Czech approach by a simple procedure based on tabulated radon resistance values.

Radon resistance R_{Rn} is a parameter that expresses the ability of the insulation to resist radon penetration. It is defined as the ratio between the thickness d of the insulation and the radon diffusion coefficient D of the insulation:

$$R_{Rn} = \frac{d}{D} \qquad [\mathrm{s/m}] \qquad (5.5)$$

The concept of radon resistance gives reliable results (radon resistance expresses the real amount of radon penetrating through the insulation), if the distribution of radon within the insulation under steady state conditions does not differ much from the linear shape. This requirement is usually met, if the thickness of the insulation satisfies the condition $d \leq 1{,}5l$ (l is the diffusion length of radon in the insulation). If the thickness is greater, the real amount of radon penetrating through the insulation is lower than the amount corresponding to its radon resistance. If in this case the radon resistance is used for dimensioning the radon-proof insulation, the calculated thickness will be greater than is necessary. In any case, radon resistance provides either reliable results, or results that are on the safe side. This means that the concept is applicable in common building practice.

The principle of the new approach to the dimensioning of radon-proof membranes is really simple – the radon resistance of the insulation applied for protecting a particular building against radon from the soil shall be higher than the minimum radon resistance prescribed for that building, in dependence on the radon risk of the foundation soils, the method for ventilating the building, and the position of the habitable rooms in the building (in the basement and on the above-ground floors only). Minimum radon resistance values $R_{Rn,min}$ are summarized in Tab. 5.1.

Tab. 5.1 - Minimum radon resistance $R_{Rn,min}$ of the radon-proof insulation applied for protecting new buildings with habitable rooms against radon from the soil

Type of the building		**Radon resistance $R_{Rn,min}$ [Ms/m] for the following radon-prone areas (radon risk categories of foundation soils):**		
		low	**medium**	**high**
1	A naturally ventilated building without a basement, with habitable rooms on the ground floor	25	75	150
2	A building on row 1, with passive subsoil or air gap ventilation	15	50	100
3	A building on row 1, with mechanical ventilation of habitable rooms, or with active subsoil or air gap ventilation	7	25	50
4	A naturally ventilated building with habitable rooms in the basement	50	150	300
5	A building on row 4, with passive subsoil or air gap ventilation	30	100	200
6	A building on row 4 with mechanical ventilation of habitable rooms, or with active subsoil or air gap ventilation	15	50	100

In practice, after finding the relevant minimum radon resistance $R_{Rn,min}$ in Tab. 5.1, the designer selects the radon-proof insulation in such a way that the ratio between its thickness and the radon diffusion coefficient (equation 5.5) gives at least the same radon resistance value or a greater radon resistance value. At the same time, the *d/l* ratio between the thickness of the insulation and the radon diffusion length in the insulation should be lower than 1,5 to avoid unnecessary oversizing of the insulation. An overview of the thicknesses of the radon-proof insulation determined according to this method can be identified from Fig. 5.3, where the thickness of the insulation is plotted as a function of the radon diffusion coefficient and various radon resistance values. The line for the thickness d = 1,5l, above which oversizing occurs, is also indicated.

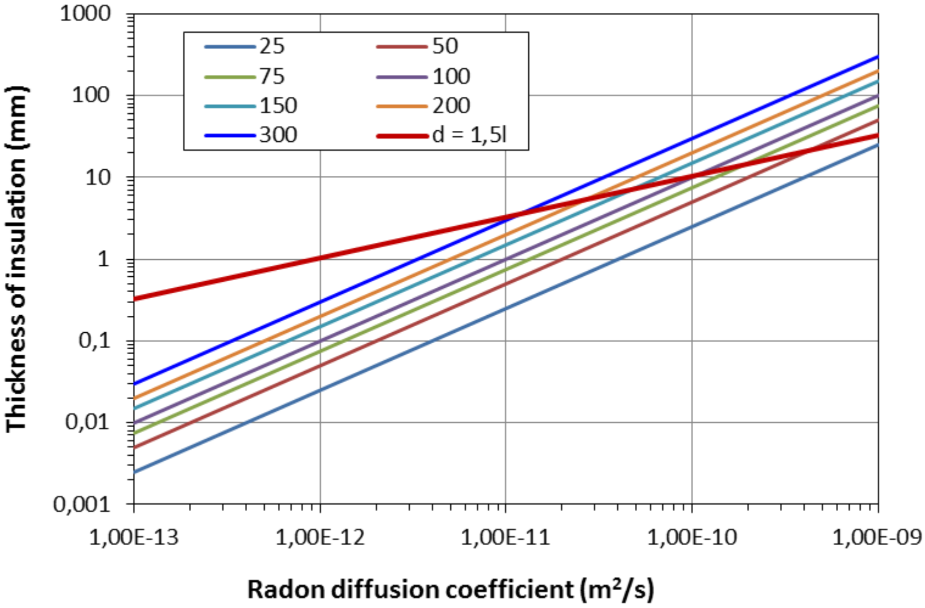

Fig. 5.3 – Thickness of the insulation for different radon diffusion coefficient values and for various radon resistance values (Ms/m)

The values presented in Tab. 5.1 were obtained by the standardized procedure used in the Czech Republic and described in paragraph 5.1. When calculating the highest permissible radon exhalation rates E_{lim} for different types of buildings according to equation (5.2), the following parameters and their values were considered: the floor-to-ceiling height of the habitable rooms was considered to be 2,6 m, A_f = 20 m^2, A_w = 23 m^2, V = 52 m^3, C_{dif} = 20 Bq/m^3, a mean ventilation rate of 0,2 h^{-1} was assumed in naturally ventilated buildings, whilst a rate of 0,6 h^{-1} was considered in buildings with mechanical ventilation. All values were selected so as to be on the safe side. As a result, the following values of E_{lim} were obtained (after rounding): 5 Bq/m^{2}h for habitable basement rooms, 10 Bq/m^{2}h for habitable rooms on the ground floor, 15 Bq/m^{2}h for mechanically ventilated habitable basement rooms, and 30 Bq/m^{2}h for mechanically ventilated habitable rooms on the ground floor.

In the next step, after inserting E_{lim} into equation (5.4), we performed repeated calculations of the insulation thickness for different values of the radon diffusion coefficient and for assumed radon concentration values in the soil (20 kBq/m^3 for low risk soils, 70 kBq/m^3 for medium risk soils, and 140 kBq/m^3 for high risk soils). From the known thicknesses and radon diffusion coefficients it was possible to determine the corresponding radon resistance values.

Identifying radon-prone areas or radon risk categories of foundation soils is a routine practice in nearly all European countries. Although different methods are used (some are based on indoor radon measurements, some use geological data or direct measurements of the radon concentration and the soil permeability on the building site, others use combined approaches, etc.), the output is always the same – three categories of risk (low, medium and high). It is obvious that only some methods provide information on the radon concentration in the soil on a particular building site. However, the categories express the radon potential of foundation soils, irrespective of the method that has been used for determining them. Each category can therefore be represented by a certain radon concentration value. When calculating the radon resistances in Tab. 5.1, we used radon concentrations corresponding to the borderlines between particular risk categories applied in the Czech Republic for soils of medium permeability. Potentially higher values that may sometimes occur are to a certain extent covered by the safety factor $\alpha_1 = 3$.

6 FUTURE ACTIVITIES

In our future activities, we will work on developing a new measuring device for determining the radon diffusion coefficient. This device will be based on innovative radon detectors assembled into each container. It will simplify the measurement process and increase its accuracy.

We want to be able to carry out research on a reference material with a known, theoretically calculated radon diffusion coefficient value. The existence of a reference material would help in identifying real measurement uncertainties and also incorrect methods.

Applying the radon diffusion coefficient as an indicator of the degree of degradation of waterproofings appears to be a very promising approach. We will therefore also focus on research in this area.

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