The new method for assessing the radon risk of building sites

1. Introduction

The present publication summarizes the results of a three-year research project assigned by the State Office for Nuclear Safety (SONS). The company RADON v.o.s. corp. has acted as the principal investigator, while the research, field work, data processing, and editing of the final text were completed with assistance from the Faculty of Natural Sciences at Charles University in Prague and the Czech Geological Survey. The text has been reviewed by the State Office for Nuclear Safety, the National Radiation Protection Institute, and the Czech National Authority for Nuclear, Biological, and Chemical Protection. The main research goal was the development of a new uniform method for assessing the risk of radon penetrating from the underlying soil or bedrock, based on determining the radon index of the building site. This method is expected to become obligatory for all radon specialists in private companies and other entities that deal with assessing the radon risk of building sites in the Czech Republic. The activities of such specialists are based on a permit issued by the State Office for Nuclear Safety (SONS). Obtaining this permit requires passing the geological and radiometric training course at the Faculty of Science of Charles University, and a quality certification at the State Office for Nuclear Safety. Thus, the subjective evaluation of geological conditions that these workers must make when carrying out the risk assessment procedures are based on professional, scientific experience and knowledge.

This publication is bilingual. Each version is comprised of two main parts. The first of these (chapter 2) contains a description of the new radon risk assessment method. The second part, which consists of the following chapters, gives concise descriptions of the particular branches of research that lead to establishing the new method. The data and results of the individual research projects are described in separate reports by SONS (in Czech), while the present publication gives only a brief summary due to its limited scope. The new method is partly based on the previous one presented by BARNET (1994). The newest results, having been gathered during the research activities of the Radon Programme of the Czech Republic and within this research project, mainly concern the statistical evaluation of soil gas radon concentration measurements, the method of soil gas sampling, the determination of soil permeability, radon exhalation rates from soil surfaces, single and continual measurements of soil gas radon concentration, the study of geological conditions influencing the assessment of radon potentials, and the comparison of different methods of radon availability models. All of these topics contributed substantially to formulating the new radon risk assessment method. The use of this method for radon index mapping on a regional scale was also tested; this research was completed by establishing radon reference sites for comparison measurements, and for tests used by private companies and institutions that deal with measuring soil gas radon concentrations.

The new radon risk method is based on a more detailed building site assessment, with increased attention given to determining the permeability of inhomogeneous geological environments. The proposed classification method is better at determining the radon index in borderline cases, and at considering the influence of variable permeability on the final assessment of the measured site.

2. Determining the radon index of a building site: the new method

2.1. INTRODUCTION

Determining the radon index of a building site is based on the assessment of radon (^{222}Rn) concentration in the soil gas and of the permeability of the underlying soils. The higher the soil gas radon concentration and the permeability of soil layers, the higher the probability of radon penetrating into the building.

The radon index of the building site (RI) generally expresses the site's radon potential. The radon index of the building (RB) expresses the degree of protection a building requires against radon penetration from the underlying bedrock or soil. The radon index of the building itself is derived from the radon index of the building site , while also considering the depth of the building's basement, the building's foundation type, and the properties of the underlying soils. At a building site having a certain radon index, the radon index of a building on that site can differ depending on whether it is founded on the surface or has underground floors.

The method presented here for determining radon index is based on the results of research conducted between 1994 and 2002. It is a modification of the method that has been valid since 1994. Section 2.6 summarizes the information that should be included in any report on the radon survey of a building site, and which should be available for building experts and radon protection workers.

The present method has been formulated in accordance with Act No. 18/1997 Coll. (the Atomic Law), with respect to changes given by Act. No. 13/2002 Coll. and the Decree of the State Office for Nuclear Safety (SONS) No. 307/2002 Coll. on Radiation Protection. All experts, companies and institutions dealing with the determination of radon index must possess the valid SONS permit for these activities.

2.2. TERMINOLOGY

The following terms appear in the description below:

Radon: the ^{222}Rn isotope of radon.

Radon activity concentration in soil gas: the number of radioactive decays of ^{222}Rn in one cubic meter of soil gas per second, also referred to as soil gas radon concentration.

Radon index of a building site (RI): index indicating the level of risk of radon release from the bedrock, surface material, and\or soil. The categories are low, medium, and high.

Radon index of a building (RB): index expressing the degree of required radiation protection a building needs against radon penetration. It is derived from the RI, the building foundation type, and the characteristics of the underlying soil or bedrock.

Radon potential of a building site (RP): the value expressing the radon index of the building site. If $RP < 10$, then RI is low; if $10 \leq RP < 35$, then RI is medium; if $35 \leq RP$, then RI is high.

Soil: includes soils, weathered rocks in the upper part of the soil profile (including organic matter), unweathered rock exposures in the upper layers influencing the evaluation of RI, and any artificial material that may be present.

Soil gas: the mixture of gases in the soil pore spaces.

Gas permeability: the parameter characterizing the potential for radon and other gases to migrate through the soil. Permeability is determined by direct measurements or by an expert evaluation of the soil. Also referred to simply as permeability.

Vertical soil profile: the description of particular soil layers characterizing their structural and mechanical properties, depth, and thickness. This description is used in the expert evaluation of permeability.

The third quartile: the 75 % percentile of a data set of N measurements. For the purposes of RI determination, the third quartile is calculated as follows: the data are arranged in an increasing order, and the third quartile is the $\mathbf{N_{75}^{th}}$ value of the data set, where $\mathbf{N_{75}}$ equals $\mathbf{(0.75N + 0.25)}$ rounded-off to the nearest lower integer.

2.3. RADON ACTIVITY CONCENTRATION IN SOIL GAS

The soil gas radon concentration is the first decisive parameter for determining the radon index of a building site. The soil gas radon concentration is determined by measuring the radioactivity of a soil gas sample taken from a depth of 0.8 m.

The basic conditions for the determination methods are:

(a) The radioactivity measurements must achieve the limit of detection of 1 kBq . m^{-3}.

(b) The devices must be calibrated for radon and radon progeny measurements by the National Metrological Centre.

(c) The sampling and measurement methods must have been field tested at radon reference sites for the comparison of measurements.

In accordance with the Czech State Norm ISO 31-9, the soil gas radon concentration is indicated as $\mathbf{c_A}$, and the values are reported in kBq . m^{-3} using one decimal position.

Instantaneous measurements of soil gas radon concentration are usually taken, though in principle integrated or continual methods can also be used in fulfilling the above mentioned requirements.

If an instantaneous measurement of the soil gas radon concentration is taken, a background control with scintillation or ionizing chambers is required before sampling. The background should not exceed 1/10 of measured signal.

Thorium present in the rocks and soils generates the alpha emitter thoron (^{220}Rn). Its soil gas concentration is usually on the same order of magnitude as radon. For soil gas radon concentration measurements completed immediately after the soil gas sampling, it is necessary to use correction procedures for the influence of thoron on the resulting concentration values.

2.3.1. Number of sampling points

Due to the inhomogeneous distribution of radon in soils and the frequent presence of outliers, the reliable determination of RI requires obtaining a set of soil gas radon concentration measurements.

When a building site smaller or equal 800 m^2 (a typical area for a single family house, a detached building, for outbuildings, or for reconstructions involving changes in the contact with the ground) is evaluated, at least 15 sampling points must be measured. These sampling points must be taken within the building's ground plan and its close vicinity.

When a building site larger than 800 m^2 (an area for more than one building, or for a larger single building) is evaluated, soil gas samples are collected in a 10 × 10 m grid. Again, the building's ground plan and its close vicinity must be covered. For cases in which other buildings or concrete\asphalt covers are present, the regularity of the sampling point grid can be adapted as necessary; i.e. the location of some sampling points can be changed, though it is necessary to measure the radon distribution over the entire building area.

In cases involving the occurrence of local radon concentration anomalies (higher than three times the third quartile: 3 . $\mathbf{c_{A75}}$) it is recommended that the number of sampling points be increased and that a 5 × 5 m grid be used.

2.3.2. Method of soil gas sampling

The soil gas samples are usually collected using small-diameter hollow steel probes with a free, sharpened lower end (a lost tip) combined with a large-volume syringe or a pump. The entire system must be perfectly sealed. The use of sampling systems that are not perfectly sealed, or that do not reach a sufficient level of vacuum to collect gas samples in soils of low permeability, may result in an underestimated soil gas radon concentration. Therefore, such systems must not be used.

The internal volume of the cavity, which is created at the lower end of the sampling probe, must be large enough to enable the sample collection. The minimum internal surface area that must enter the soil is 940 mm^2 (corresponding to a cylinder having 10 mm in diameter and 30 mm height).

The soil samples are collected from a depth of 0.8 m below the ground surface. If the soil gas samples cannot be collected due to extremely low soil permeability, high groundwater saturation, or the presence of shallow, solid rock layers, the following modifications can be used. If the soil permeability is very low, the cavity at the lower end of the sampling probe can be enlarged by retracting the probe about 10–15 cm toward the surface. Sometimes (upper soil layers with higher permeability are not reached, the probe remains fixed in the soil, as well as contamination of the soil gas by atmospheric air can be avoided) the probe can be retracted to 0.5 m below the surface, while maintaining the perfect sealing of the whole system. A similar approach is often used when the sampling layer is saturated with water. In cases involving shallow solid rock layers, the minimal sampling depth can be changed to 0.5 m below the surface. Changing the position of the sampling points within the 10 × 10 m grid can also be done in all above described cases. However, all deviations from the standard sampling depth of 0.8 m must be reported, including an explanation and an estimate of potential influence of these differences to the evaluation results.

If none of the above mentioned modifications work, the building site assessment can be postponed to the time at which the building foundation surface will be exposed. Other methods such as radon exhalation rate measurements, ^{226}Ra mass activity (Bq . kg^{-1}) measurements, and emanation power determination can be applied. These techniques have not been standardized for various reasons; and for those exceptional cases in which it is necessary to deploy them, the measurements must be performed with an understanding of the parameters influencing radon migration and the detailed field conditions.

Soil gas sampling and the soil gas radon concentration measurements must not be performed under extreme meteorological conditions.

2.3.3. Data treatment and the presentation of soil gas radon concentration results

The radon risk categorization of entire or parts of building sites is based on evaluating the measurements of the radon concentration and distribution in soil gas.

When classifying a building site for a single building (with a building site smaller or equal 800 m^2, involving at least 15 soil gas radon concentration measurements), the main value used for this classification is the third quartile of the set of soil gas radon concentration data $\mathbf{c}_{A75}$. Values smaller than 1 kBq . m^{-3} are excluded from the data set. The person performing the readings, and who is responsible for the classification, must consider all local radon concentration anomalies and variations. The final report must contain the following statistical parameters: minimum, maximum, arithmetic mean, median, and the third quartile.

The classification of larger areas (building sites larger than 800 m^2, requiring soil gas radon concentration measurements in a 10 × 10 m grid) depends on the homogeneity of the data. If the data set is homogeneous, the third quartile of the whole data set is used as the decisive value. Values smaller than 1 kBq . m^{-3} are again excluded.

If the data set is not homogeneous, the three following situations must be considered:

(a) the inhomogeneous building site is formed by several homogeneous subsites.

(b) a fault zone crosses the building site.

(c) local radon anomalies are present at the building site.

In cases (a) and (b) the building site is divided graphically into homogeneous subsites, which are considered and processed separately. The spatial variations in permeability can also be helpful for this evaluation.

If the number of measured values is large enough (more than 50 soil gas radon concentration measurements), histograms of radon distribution can be used for assessing the data homogeneity along with a visual evaluation. Another method for testing data homogeneity uses a log graph of relative rank **r** versus ascendantly ordered values: $\mathbf{ln[r/(1-r)]}$, where $\mathbf{r = i/(n+1)}$, and **i** is the rank of the value in **n** ordered data. If the shape of the curve approaches a straight line, the distribution is normal, or log-normal. If the shape of the curve resembles a fractional line, the data set is polymodal.

The third quartile of the corresponding data set is used again as a basic value for the classification. For homogeneous building sites (or subsites) the third quartile of the entire relevant data set is used. For building sites that contain several subsites with different soil gas radon concentrations, the highest of the third quartiles of the corresponding data sets are used.

In case (c), the radon specialist must weigh the significance of the local anomalies and their relation to geological and non-geological factors, and thus judge whether or not they are random occurrences. Supplementary measurements (if available) are also taken into consideration. In such cases the classification is especially dependant on the expertise of the worker. The observed anomalies may influence the final determination of the RI.

When larger building sites are evaluated, the final report must contain not only the basic statistical parameters mentioned above (minimum, maximum, arithmetic mean, median, third quartile), but must also show all measured values of soil gas radon concentration in numerical and graphical forms. The graphical presentation enables a better understanding of spatial variability of this parameter.

2.4. SOIL PERMEABILITY

The permeability of soils is the second decisive factor in determining the radon index of a building site. As higher permeability enables the increased migration of soil gas and radon from the soil into the building, a higher radon risk can be expected in more permeable soil environments.

2.4.1. Determining soil permeability

The permeability of soils can be determined by:

⇒ direct in situ permeability measurements

⇒ expert evaluation of permeability.

The permeability is designated by the symbol **k**. When direct in situ measurements are performed, the gas permeability is given in $\mathbf{m^2}$ (rounded to one decimal position, e.g. $1.7 . 10^{-12}$ m^2). Expert evaluation of permeability leads to assigning the low – medium – high categories.

2.4.1.1. Direct measurement of soil permeability

Direct in situ permeability measurements are performed at a depth of 0.8 m beneath the ground surface.

The *in situ* method consists of measuring the airflow during suction from the soil or when pumped into the soil under constant pressure. The procedures for permeability measurements are similar to those of soil gas sampling (small-diameter hollow steel probes with a free, sharpened lower end – a lost tip). The internal surface area of the cavity formed by pounding out the free tip must be exactly defined for each measurement system. Various devices designed for in situ gas permeability measurements can be used. There can be complications with determining the shape factor of the probe (which depends on its geometry and internal dimensions) and with the individual corrections for the free flow of air in specific instruments. For these reasons, and due to the lack the gas permeability standardization, the results obtained from various devices should be standardized against the RADON-JOK permeameter, widely used in the Czech Republic (www.radon-vos.cz/index_en.html).

Direct in situ permeability measurements are based on fixed measurement geometry. The size of the measuring cavity in the soil must not be enlarged. It is recommended that the auxiliary limit for low permeability $\mathbf{k = 5.2 . 10^{-14}\ m^2}$ be used. When $\mathbf{k < 5.2 . 10^{-14}\ m^2}$ (the measuring time of the RADON-JOK permeameter is higher than 1200 s), the permeability need not be exactly measured. The resulting value for the summary of results will be $\mathbf{k < 5.2 . 10^{-14}\ m^2}$, and the resulting value for statistical evaluation is substituted by $\mathbf{k = 5.2 . 10^{-14}\ m^2}$.

As for the resistance of the equipment against the free flow of air, the limit for high permeability is $\mathbf{k = 1.8 . 10^{-11}\ m^2}$. When $\mathbf{k > 1.8 . 10^{-11}\ m^2}$ (measuring time of RADON-JOK permeameter is shorter than 6 s), the value for the summary of results will be $\mathbf{k > 1.8 . 10^{-11}\ m^2}$, and the resulting value for statistical evaluation is substituted by $\mathbf{k = 1.8 . 10^{-11}\ m^2}$.

For direct *in situ* permeability measurements, the requirements for the number of measurements are the same as for the soil gas radon concentration measurements, i.e. at least 15 measurements for a single building (with a building site ≤ 800 m^2), or the taking of measurements in a 10 × 10 m grid for building sites > 800 m^2. The same statistical parameter, i.e. the third quartile of the data set (marked $\mathbf{k_{75}}$), is used as a decisive value for the assessment. The third quartile diminishes the influence of outliers and local permeability anomalies.

It is not necessary to describe the vertical soil profile when direct in situ permeability measurements are performed.

Only when the data set of direct in situ permeability measurements (**k**, in m^2) is available can the radon potential of the building site (RP) be used for determining the RI (see section 2.5.1.).

2.4.1.2. Expert evaluation of soil permeability

An expert evaluation of soil permeability is necessary when in situ permeability measurements are not performed at all sampling points of soil gas radon concentration measurements. This expert evaluation, which results in classifying the site as low, medium, or high permeable, is based on the description of the vertical soil profile to a minimum depth of 1 m (or to the lowest depth that can be reached by a hand drill, in cases involving large amounts of coarse material or unweathered rock near the surface). The evaluation must involve at least one of the following methods:

- ⇒ A macroscopic description of the fractions in samples from a depth of 0.8 m, with the classification of its permeability (low – medium – high). Estimating the proportion of the fine fraction (f, particle size < 0.063 mm) is also necessary in this classification. For f > 65 %, the permeability is low; when 15 % < f ≤ 65 %, the degree of permeability is medium; and when f ≤ 15 %, the permeability is high. The final classification is then corrected with respect to the factors that could influence the actual permeability (see questions that are presented at the end of this section).
- ⇒ Evaluating the resistance encountered when drawing the soil gas samples for the radon concentration measurements at all sampling points, and estimating the prevailing permeability category (low – medium – high).

For the better evaluation of vertical and horizontal changes in permeability, at least two hand drill tests must be performed for building sites ≤ 800 m^2. For larger building sites these two drillings must be increased by at least one for each additional 30 sampling points.

The following questions should be considered whenever such expert soil permeability evaluations are used:

- ⇒ Can high soil moisture in the sampling horizon influence its actual permeability (i.e. the degree of water saturation may decrease the effective porosity)?
- ⇒ Can low soil moisture in the sampling horizon influence its actual permeability (i.e. lower degrees of water saturation may increase the effective porosity)?
- ⇒ Can the unusually low porosity of a sampling horizon influence its actual permeability (i.e. its high density or compactness may decrease the permeability)?
- ⇒ Can the unusually high porosity of a sampling horizon influence its actual permeability (i.e. its low density and loose texture may increase the permeability)?
- ⇒ Is the occurrence of macro- and micro-fissures high enough to increase the otherwise low permeability?
- ⇒ Is the degree of inhomogeneity of the fine fraction such that it could increase the otherwise low permeability?
- ⇒ Is the content of the coarse fraction (fragments, cobbles, stony debris) so high that it could increase the actual permeability?
- ⇒ Could the character of the weathering surfaces of rocks in the sampling horizon, or the presence of faults, increase the actual permeability?

⇒ Could anthropogenic effects on the ground surface or in the upper soil layers (such as deep ploughing or the presence of paths etc.) increase the actual permeability?
⇒ Could anthropogenic effects on the ground surface or in the upper soil layers (such as the deep compactness of upper soil layers, or the presence of concrete or asphalt coverings) decrease the actual permeability?
⇒ Is the building site situated on a slope with vertical and horizontal variability of soil layers with different permeability, which could increase or decrease the resulting permeability?

Note: If the results of detailed geological or hydrogeological survey at the same building site are known, it is not necessary to perform special hand drillings during the radon survey. The available detailed results can be used for the expert evaluation of soil permeability.

When the expert evaluation of soil permeability is used, the RI is determined according to a classification table (section 2.5.2.).

2.4.2. The reporting of permeability results, classification

Building site assessment and the determination of the site's radon index (RI) involves the following permeability determination procedures.

2.4.2.1. Direct measurement of soil permeability

The third quartile of the data set (k_{75}) is an important value for the classification of a single building (at a building site ≤ 800 m^2, and with at least 15 direct *in situ* permeability measurements). The authorized person responsible for the final classification must consider any local permeability anomalies and variations and the spread of data. The final report must contain the following statistical parameters: minimum, maximum, arithmetic mean, median, and the third quartile.

The permeability classification for larger areas (building sites > 800 m^2, where permeability measurements must be made in a 10 × 10 m grid) depends on the homogeneity of the site and the data set. If the building site is geologically homogeneous, especially regarding its permeability, the third quartile of the data set (k_{75}) is used for the classification.

If a large building site is not homogeneous, three options must be considered with respect to the geology of the site:

(a) the inhomogeneous building site can be divided into several homogeneous subsites.
(b) a fault zone with distinct permeability crosses the building site.
(c) local permeability anomalies occur at the building site.

In cases (a) and (b) the official expert divides the building site into homogeneous subsites, which are considered and processed separately. The spatial variability of soil gas radon concentration can also be helpful in this assessment.

The third quartile of the corresponding data set is used again as a basic value for the classification. For homogeneous building sites the third quartile of the whole data set, for inhomogeneous sites the highest third quartile of the subsites, which are for the given building site or building decisive.

For case (c) the official expert responsible for the assessment must weight the importance of the local anomalies and their connection with geological or non-geological factors (e.g., whether or not they are random occurrences). These anomalies can influence the final classification of permeability and the determination of the RI. The final classification depends on the expert's decision.

When larger building sites are evaluated, the final report must contain the required statistical parameters (the minimum, maximum, arithmetic mean, median, and the third quartile), and all permeability values presented in numerical and graphical form for a better understanding of the spatial variability of this parameter.

2.4.2.2. Expert evaluation of soil permeability

When classifying a single building site (≤ 800 m^2 and 2 hand drillings), the evaluation of soil permeability (as low, medium, or high) is based on the description of the soil profile to a minimum depth of 1 m (or to the depth specified in section 2.4.1.2.) and on the chosen supplementary method (macroscopic description, or resistance to vacuum).

The resulting permeability is classified as low, medium, or high.

For larger building sites (> 800 m^2) the homogeneity of the soil's characteristics is determined by drilled holes. The degree of permeability (low-medium-high) at homogeneous building sites is chosen directly by the official expert.

If the large building site is not homogeneous, three options must again be considered with respect to the site's geological conditions:

(a) the inhomogeneous building site can be divided into several homogeneous subsites.
(b) a fault zone with distinct permeability crosses the building site.
(c) local permeability anomalies occur at the building site.

Inhomogeneous building sites are then divided into homogeneous subsites, which are considered separately. The expert evaluation of soil permeability is based on the description of the soil profile to a depth of 1 m, on the nature of the method used (macroscopic description or resistance to vacuum), and on the assessment of any horizontal and vertical changes of soil properties that may be present. The spatial variability of soil gas radon concentrations can also be helpful in this assessment.

The resulting permeability is classified as low, medium, or high with respect to presented rules, i.e. only a single evaluation at homogenous sites and the highest category of the separate subsites for a building covering several soil permeability subsites.

The final report must contain the resulting degree of permeability (low – medium – high), macroscopic descriptions of soil profiles from all hand drillings, and an estimation of the content of the soil's fine fraction from a depth of 0.8 m or the evaluation of vacuum resistance from all sampling points.

2.5. RADON INDEX ASSESSMENT

Determination of the radon index of a building site (RI) is based on two factors: soil gas radon concentration, and the permeability of soils. Other factors concerning the structural and geological situation (such as bedrock types, the presence of faults, the relief of the terrain, and regional geological units) are also useful for the final determination.

The final RI determination is derived from the permeability data. If numerical values of both soil gas radon concentration and permeability are available, the building site radon potential method (RP) is used (section 2.5.1.). For numerical values of soil gas radon concentration and the expert evaluation of soil permeability (given as low, medium, or high), the assessment procedure is described in section 2.5.2.

2.5.1 The radon potential of a building site

If the results of both soil gas radon concentration measurements and in situ permeability measurements are available for all measuring points, a radon potential (RP) model can be used for determining the RI.

The model for assessing the RP is based on the formerly used RI classification table. The amended version uses continuous lines instead of the fractional lines for separating the low, medium, and high RI categories (Fig. 1). This change enables the more precise assessment of borderline cases.

A couple of the straight lines (V-shaped, Fig. 2) that delimit the medium radon index can be defined by the following equations:

$$-\log k = \alpha_1 \cdot c_A - (\alpha_1 \cdot c_{A0} + \log k_0),$$

$$-\log k = \alpha_2 \cdot c_A - (\alpha_2 \cdot c_{A0} + \log k_0),$$

where α_1 and α_2 are the slopes of these limit lines and (c_{A0}; $-\log k_0$) are the coordinates of their intersection point. The RP is then defined by the equation:

$$\mathbf{RP = (c_A - c_{A0}) / (-\log k + \log k_0).} \qquad [1]$$

To follow continuity with the formerly used method (BARNET 1994) the equations describing the limits and the RP parameter are optimally defined as:

$$\mathbf{-\log k = 1/10 \cdot c_A - (1/10 + \log 1E{-}10) = 0.1\, c_A + 9{,}9}$$

$$\mathbf{-\log k = 1/35 \cdot c_A - (1/35 + \log 1E{-}10) = 0.0286\, c_A + 9.971}$$

$$\mathbf{RP = (c_A - 1) / (-\log k - 10),} \qquad [2]$$

i.e. the slopes of lines are given by the values 1/10 and 1/35, and their intersection corresponds to the values $\mathbf{c_A = 1\ kBq \cdot m^{-3}}$, and $\mathbf{-\log k_0 = 10}$ when $\mathbf{k_0 = 1E{-}10\ m^2}$.

A graphical presentation is given in Fig. 2.

The third quartile of the soil gas radon concentration data set (c_{A75}) and the third quartile of the permeability data set (k_{75}) are the input values for assessing a building site using the RP model presented in Fig. 2.

In exceptional cases, the authorized person performing the assessment can use other statistical parameters for the final determination of RI (see section 2.3.3.). However, they must give their reasons for this decision in the final report.

The RP value is derived from the building site assessment given by equation [2], and enables the determination of RI as low, medium, or high (if $RP < 10$, then RI is low; if $10 \le RP < 35$, then RI is medium; if $35 \le RP$, then RI is high).

2.5.2. Radon index assessment in other cases

If the expert evaluation of soil permeability is used (i.e. if the permeability is determined without numerical values),

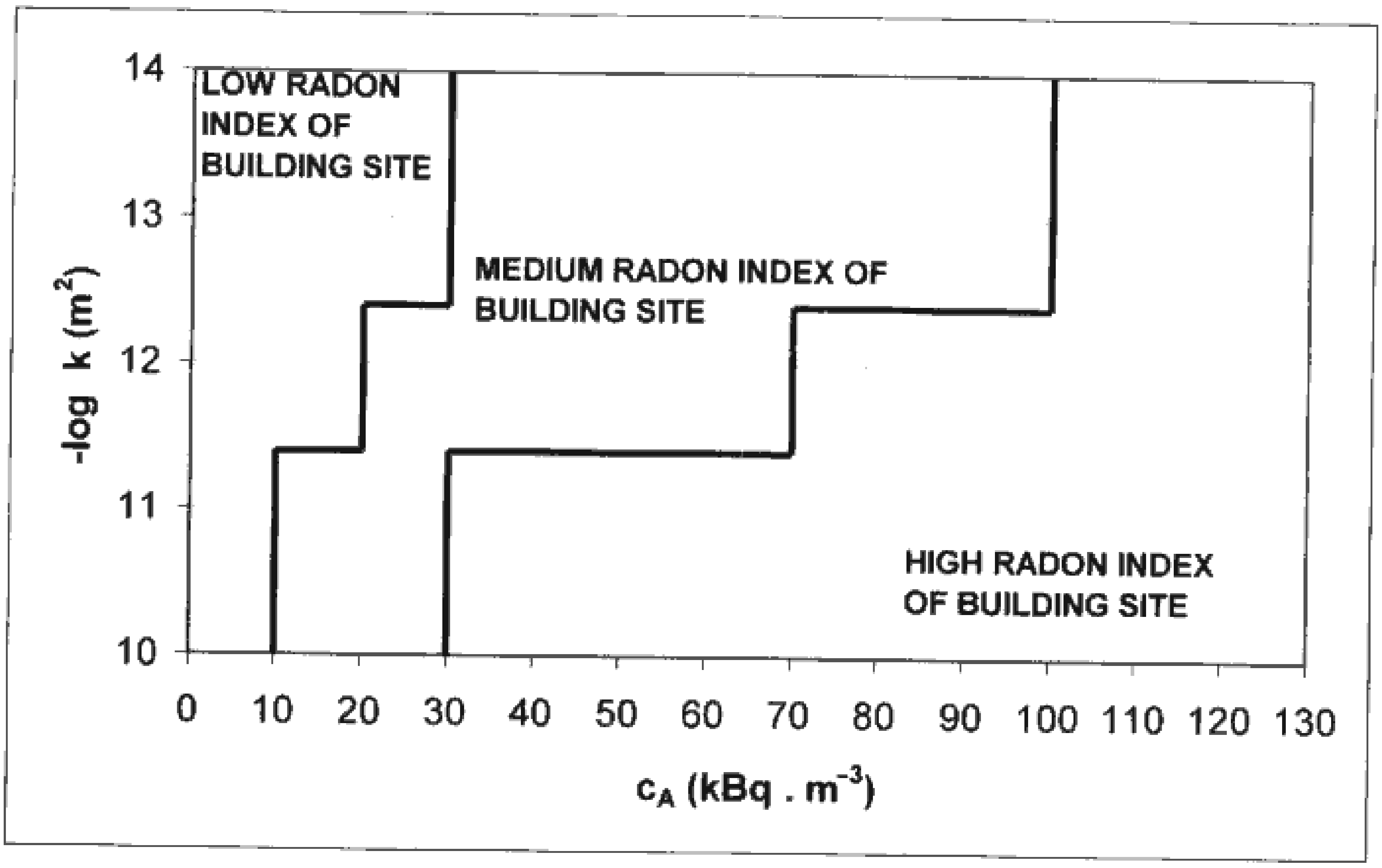

Fig. 1. Radon index of the building site according to formerly used methodology (BARNET 1994).

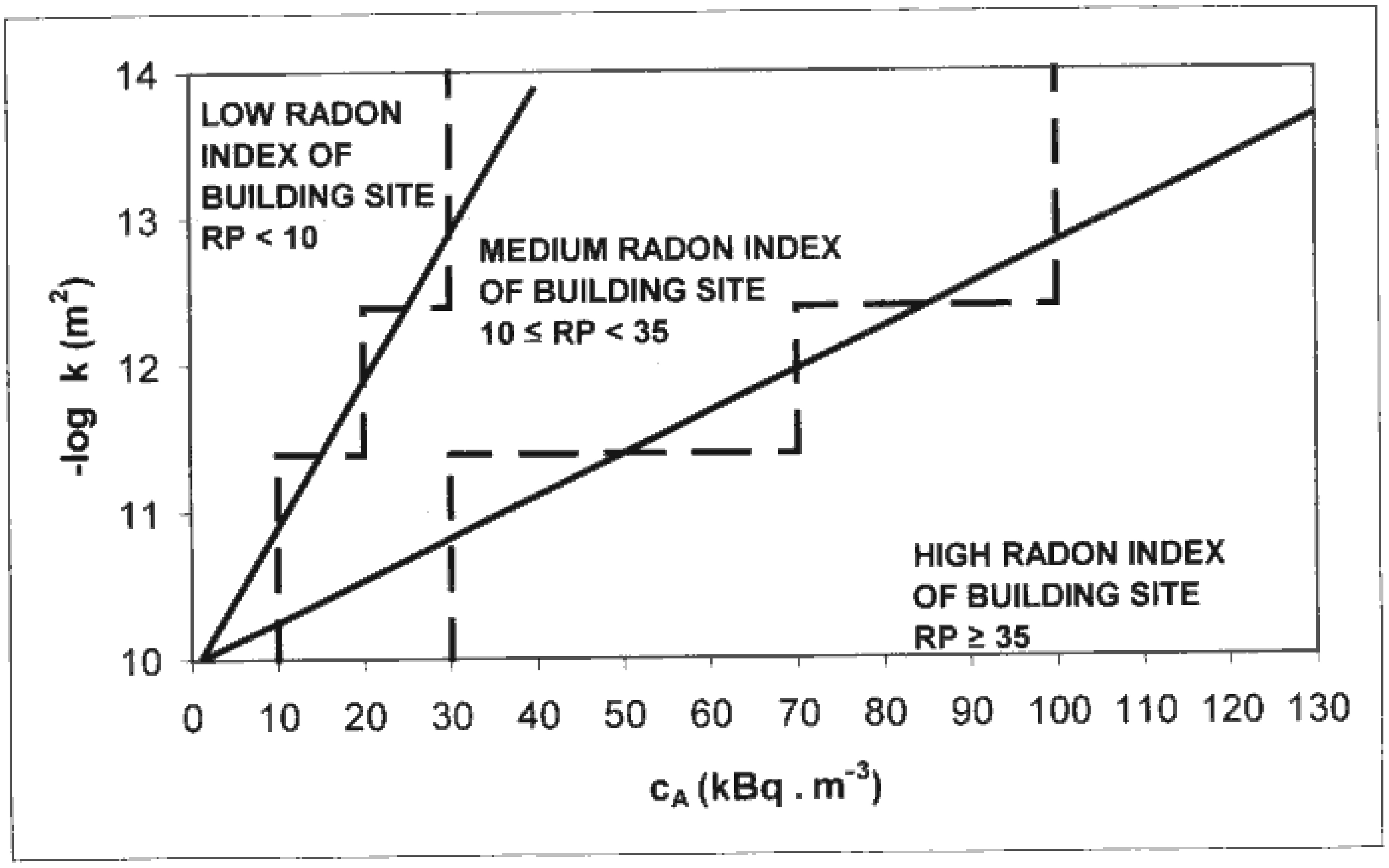

Fig. 2. Radon potential of the building site.

Table 1. Radon index assessment

Radon index (RI) category	Soil gas radon concentration (kBq . m^{-3})		
Low	$c_A < 30$	$c_A < 20$	$c_A < 10$
Medium	$30 \le c_A < 100$	$20 \le c_A < 70$	$10 \le c_A < 30$
High	$c_A \ge 100$	$c_A \ge 70$	$c_A \ge 30$
	low	*medium*	*high*
	permeability		

the radon index of the building site is assessed using the following classification table (Tab. 1):

The input parameter for RI assessment is the third quartile c_{A75} of the soil gas radon concentration data set, or the highest c_{A75} calculated for the subsites comprising an inhomogeneous building site (see section 2.3.3.).

In exceptional cases, the expert assessor can use other statistical parameters for the final determination of the RI (see section 2.3.3.). However, they must give their reasons for this decision in the final report.

The permeability is determined by expert evaluation (section 2.4.1.2. and 2.4.2.2.).

The resulting radon index of the building site (RI) is given as one of the three categories: low, medium, or high.

2.6. DETAILED RADON SURVEY

This section does not deal with the determination of the radon index of the building site (RI) itself, but summarizes the requirements of a detailed radon survey for determining the radon index of a building (RB).

For single family houses or other buildings without cellars, having a foundation depth of 0.8 m under the ground surface, or closer to surface or above the ground surface, there are no special requirements involved in conducting the detailed radon survey (i.e. the determination of the radon index of the building site (RI)).

For cases in which the foundation depth is unknown or is situated at a depth greater than 0.8 m, further data should be obtained in the course of the detailed radon survey (the foundation depth and other factors can be considered only if relevant data are available).

In these latter cases, the field work, the permeability documentation, and the final report must be accompanied by:

⇒ A description of the vertical soil profile (or profiles) to a minimum depth of 1.5 m, with the permeability determination of deeper soil layers (section 2.4.1.2 and 2.4.2.2.).

⇒ Information about bedrock types with respect to their ^{226}Ra concentration and the potential for increased soil gas radon concentrations with depth.

The radon index of a building (RB) expresses the degree of required radiation protection the building requires against radon penetration from the bedrock. It is based on the radon index of the building site (RI), and considers the foundation depth and any vertical changes in permeability up to the level of the building's contact with the soil or bedrock. The determination of the radon index of a building (RB) is performed by building experts. It is based on the results of a detailed radon survey and on their own rules for the radiation protection of buildings.

This is the end of the description of the new assessment method. The following chapters provide a concise description of related research topics and their results.