as to derive the category of gas permeability using specified boundaries (in the Czech Republic it is recommended to use following ones: $k = 4.0 \cdot 10^{-12}$ m^2 between high and medium permeability and $k = 4.0 \cdot 10^{-13}$ m^2 between medium and low permeability) and/or to use measured values for calculation of a so called "radon potential" derived from any of available radon potential models.

In case the same probe is used for soil gas radon concentration measurement as well as for permeability measurement (the special type of "lost" sharp tip for gas permeability measurement must be used), it is necessary to start with the gas permeability measurement (higher underpressure during soil gas sampling could cause a destruction of an internal surface of the cavity and affect the permeability measurement).

Note. Direct measurements of gas permeability can be certainly utilized during the diagnostic measurements and assessment of the contact layers between the building and the soil (description of the transfer of radon from soils into the buildings – "transfer" point of view).

5.5. PERMEABILITY UNITS

Permeability of rocks (soils) is defined for the flow of liquid medium (water) through the rock and the subject is described in hydrological literature. Derived application for other media (as gas, namely hydrocarbons in petroleum industry) is also mentioned. This relates to radon.

The flow of water through a rock medium is described by Darcy's law (1856):

$$Q/S = K\,(h_1 - h_2)/\Delta L$$

where Q – volume of water penetrating per unit time through the area S [m$^3 \cdot$ s^{-1}]
S – area [m^2]
K – hydraulic conductivity (also coefficient of filtration) [m/s]
$(h_1 - h_2)/\Delta L$ – applied hydraulic pressure (eg. difference of height of the water levels/ difference of horizontal/vertical length L of flow)

For other media than water, the density of the media ρ, the gravitational force F = mg (mass × gravity acceleration), and viscosity μ of the media must be taken into consideration:

m – mass [kg]
g – gravity acceleration [m/s^2]
μ – dynamic viscosity [Pa . s = kg/m . s], Pa (pascal) = N(newton)/m^2 = kg . m/(s^2 . m^2)
ρ – density of the liquid (other media) [kg . m^{-3}]

For the flow of liquid (and other media, specified by ρ and μ) in percolate rock environment, the permeability k [m^2] (also coefficient of permeability) is introduced by relation

$$K = k \cdot \rho \cdot g/\mu$$

Note: k [m^2] – is the characteristics of permeability of the solid phase of the rock ("intrinsic" permeability)
K [m/s] – is dependent on characteristics (permeability) of the solid phase of the rock and on the liquid (other) medium of flow specified by its and μ.

The dimension of permeability k [m^2] is given from the above equation. The older "industrial" unit of permeability was Darcy (D), 1 D = $9.87 \cdot 10^{-12}$ m^2. Dynamic viscosity of air at 10 °C is μ = $1.75 \cdot 10^{-5}$ Pa . s.

6. Building site assessment method

In the Czech Republic, detailed radon risk assessment is used to design preventive protective measures in new buildings. This approach is obligatory, i.e. the detailed assessment and classification of radon risk (since 2004 called radon index) of the building site is an integral part of building permission. For the purposes of new buildings, since 1990 the soil characteristics are measured in-situ and protective measures are designed with respect to the measured properties of the soil and to the dwelling design. The main advantage of the method is the fact, that it is a site specific, individual approach that enables to propose an optimal preventive strategy corresponding to local conditions.

At the same time, the methods for radon risk assessment are used for mapping purposes as well. In this case, the results serve as a base for the description of radon potential of specific geological units.

6.1. ORIGINAL METHOD 1990

Already the first uniform method, that had been used for radon risk classification in the Czech Republic since 1990 (Kulajta et al. 1990), was based on the assessment of two main parameters: the soil gas radon (^{222}Rn) concentration and the permeability of soil and rock for gasses. The higher the soil gas radon concentration and the permeability of soil layers, the higher the probability of radon penetrating into the building. As can be seen in Tab. 6-1, the original method utilized the same categories of radon risk (radon index) and the same boundaries, that are used in the Czech republic for the classification up to now.

The main disadvantage was given by the fact that the method was too rough and uncertain. The main problems were connected with the permeability classification (See Chap. 5). It was based on the pedological description and permeability classification derived from the grain size analysis, the other factors influencing the permeability were not taken into consideration. Furthermore, the permeability were not classified with respect to changes in vertical profiles from surface to the level of expected foundation depth of the building.

Radon index (RI) category	Soil gas radon concentration c_A (kBq . m^{-3})		
Low	c_A **< 30**	c_A **< 20**	c_A **< 10**
Medium	**30 ≤ c_A < 100**	**20 ≤ c_A < 70**	**10 ≤ c_A < 30**
High	c_A **≥ 100**	c_A **≥ 70**	c_A **≥ 30**
	Low	*Medium*	*High*
	Permeability		

Tab. 6-1. Radon index (risk) assessment

The necessary extent of soil gas radon concentration measurements was uncertain as well. The classication of radon risk could be uselessly expensive, because it was recommended to perform two stages of radon survey in case of large areas (at the first stage in the grid 20 × 20 m, in the next one in more detailed grids 10 × 10 m or 5 × 5 m) and the final assessment with respect to spatial variability of results was not exactly specified. The statistical evaluation was based on the normal characteristics (the sum of the arithmetic mean and the standard deviation), although neither a normal nor a log-normal model is generally applicable for the description of soil gas radon concentration data (Neznal, Neznal and Šmarda 1994b).

6.2. MODIFIED METHOD 1994

The modified uniform method for assessing the radon risk of foundation soils (Barnet 1994), withdrew the main limitations of the previous one and improved the final assessment. Robust nonparametric estimates, such as the median or the third quartile, were found to be more suitable for the description of soil gas radon concentration data. The values lower than 1 kBq . m^{-3} were excluded from the data sets before evaluation due to the detection reliability of instruments and possible sampling errors.

As for permeability classification, it enabled to classify that decisive parameter in two ways (particle size analyses and/or direct in situ measurements). These data were completed with the description of changes in vertical profiles with respect to the expected foundation depth of the building. But neither the precise conditions for direct measurements, nor the minimum number of measurements and nor any statistical evaluation were specified.

The necessary extent of soil gas radon concentration measurements was defined (a minimum of 15 × 15 soil gas radon concentration measurements was required when a buiding site for a single family house was evaluated, the measurements of larger areas were made in a 10 × 10 m grid), but the final assessment in case of larger areas has not been still fixed.

A lot of questions connected with the uncertanties appeared during the commercial practice:

As the soil gas radon concentration may vary widely over a small distance, isn't it necessary to reconfirm the requirements concerning the minimal set of soil gas radon concentration values, the grid of measuring points and the statistical evaluation of data? What is the most suitable and repeatable method for determining the soil gas permeability? Could we find another – more suitable and easily determinable – parameter describing the radon potential instead of permeability?

How to proceed, when the thickness of soil cover is too low or when the soil pores are completely saturated with water? Are the integrated or continual measurements of soil gas radon concentration applicable for the classification as well? How to classify the larger areas with heterogeneous distribution of soil gas radon concentration and/or permeability? What to do, when the measured values are closed to the limits that separate the different risk categories?

6.3. RESEARCH PROJECT 2000–2002

With respect to the uncertanties and disadvantages of the modified method, the composite authors of the modified method, Matěj Neznal and Martin Neznal (RADON v.o.s.), Milan Matolín (Charles University Prague, Faculty of Science) and Ivan Barnet (Czech Geological Survey), prepared in 2000 a project dealing with this topic. The research was divided into 10 main sections and various subsections:

A – Soil gas radon concentration measurements – mainly the choice of the basic grid used for soil gas sampling; the minimal statistical set of soil gas radon concentration values required for the evaluation; the statistical evaluation of measurement results, when a building site of one family house is evaluated, and when a large area is evaluated.

B – Soil gas sampling – the relationship between the soil gas radon concentration and the changing sampling geometry; the sampling in low permeable soils and the possibility of enlargement of the active area for sampling; the sealing during the soil gas sampling.

C – Permeability determination – the permeability of soils and rocks for gasses; the new methods and equipment for direct measurements; the spatial and seasonal variability and their impact on radon risk classification; the minimal statistical set of permeability values required for the evaluation; the advantages and disadvantages of various methods used for permeability determination.

D – Radon exhalation rate from the ground – the possibility of using this method for classification of radon risk when soil gas sampling in chosen depth is impossible (bedrock without cover, extremely low permeability, high saturation – extremely high soil moisture); methods of measurements; statistical evaluation of measurement results.

E – Integral and continual measurements of soil gas radon concentration – the analysis of a possibility to use integral and/or continual measurements of soil gas radon concentration for classification of radon risk; intercomparison measurements of various equipments; testing of high and low temperatures influence on the results of measurements performed by various equipments.

F – Geological parameters and their impact on the final assessment of radon potential of soils – the choice of another geological parameter (other than permeability), more suitable for the assessment; the study of soil moisture, saturation, efective porosity, porosity, density, bulk density; new methods and equipment for direct measurements; vertical and horizontal changes, seasonal variability and their impact on radon risk classification; advantages and disadvantages of various parameters for radon risk classification.

G – Radon availability – the practical use of radon survey results for the choice of an optimal building technology; the definition of radon availability model; the comparison of various models of "radon availability"; the definition of geological index, that includes various geological factors influencing the radon behaviour; the influence of changes in vertical profiles; the influence of changing foundation depth used for the construction; the possibility of substituting geological index for permeability determination.

H – Uniform method for radon risk classification – final version of the improved version of the uniform method.

I – Radon risk mapping – practical use of the new method for radon risk mapping; quantity of measurements required for radon risk mapping in various scales; the comparison of detailed measurements and radon risk maps at the scale 1 : 50 000; the questions connected with the assessment of the radon map reliability.

J – Radon reference sites in the Czech Republic – the choice of new reference sites; detailed measurements at new established reference sites; first intercomparison measurements at reference sites; the statistical evaluation of soil gas radon concentration test measurements.

6.4. NEW METHOD FOR ASSESSING THE RADON RISK OF BUILDING SITES 2004

The new method for assessing the radon risk of building sites became obligatory in 2004. The new method as well as the results of the above mentioned research project are described in detail in Neznal et al. 2004.

As for the soil gas radon concentration measurements, there were finally no reasons to change significantly the practice. It was recommended to perform the detailed survey in a 10 × 10 m grid in the area of the assumed constructions. When a building site of one family house is evaluated, it is necessary to realise at least 15 soil gas sample measurements. The radon risk classification is based on the assessment of values of soil gas radon concentration and their distribution. When categorising areas of individual buildings or groups of buildings (small statistical sets), particularly significant statistical parameter for the evaluation of measurement results is the third quartile (i.e. the 75th percentile). The values lower than 1 kBq . m^{-3} are not included in the data set evaluated by this method. The evaluation procedures of measurement results, when large areas are assessed, were defined.

The research confirmed the hypothesis, that measured soil gas radon concentrations do not depend on changing sampling geometry if the soil layers are homogeneous even in case of low permeable environment (Neznal and Neznal 2002). When it is almost impossible to sample the soil gas under normal conditions, the new method enables to enlarge the active area by retracting the sampling probe back to the surface (a perfect sealing of all parts of the sampling equipment is required). The new method includes the rules for correct sampling in various conditions.

Due to the permeability determination and other geological parameters, it was recommended to use the detailed description of all parameters and their changes in vertical profile from surface up to the level of assumed building foundations or to the level of assumed contact building – soil. It is necessary to measure the permeability directly in situ in the required extent and/or to use so called expert evaluation of permeability. In the framework of this expert evaluation the responsible person has to describe as well as possible following parameters: permeability, grain size, soil moisture, saturation, efective porosity, porosity, density, bulk density, compactness, thickness of Quaternary cover, weathering character of the bedrock, modification of layers by various antropogeneous activities. This description should be completed by the description of a resistance during the soil gas sampling, or by grain size analysis (see Chap. 5).

The research dealing with the radon exhalation rate measurement resulted in the conclusion that the measurement of this parameter cannot be recommended to be used as a standard supplementary method for radon risk classification of foundation soils (Neznal and Neznal 2002a).

The method defined following parameters:

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 (RI). If RP < 10, then RI is low; if $10 \leq RP < 35$, then RI is medium; if $35 \leq RP$, then RI is high.

For the classification purposes, the new method enables to use the assessment based on the classification table, i.e. on direct measurements of soil gas radon concentration and the expert evaluation of permeability (Tab. 6-1), or the assessment based on the radon potential model, i.e. on direct measurements of both parameters (Fig. 6-1, Fig. 6-2).

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 – the radon index of the building

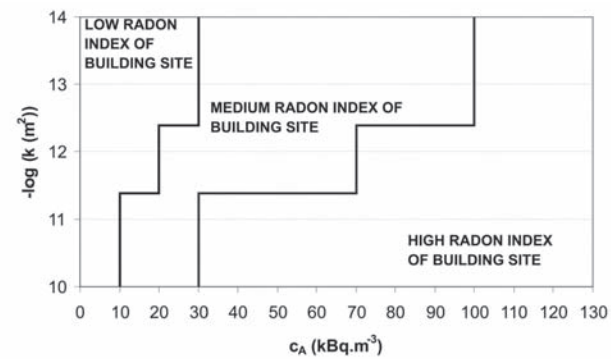


Fig. 6-1. Radon index of the building site (according to formerly used methodology).

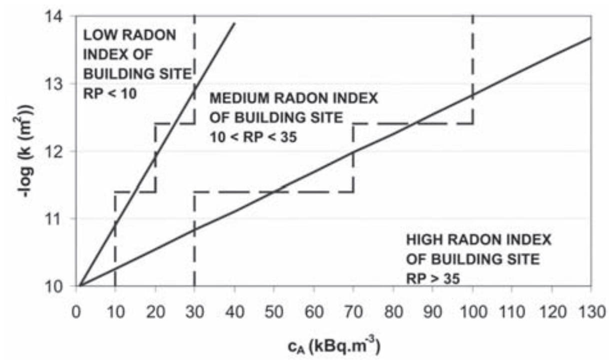


Fig. 6-2. Radon potential of the building site.

site (RI) and on their own rules for the radiation protection of buildings. Because it considers the foundation depth, especially in case of deep foundation levels various factors should be taken into account (mainly the vertical changes in permeability up to the level of the building's contact with the soil or bedrock, information about bedrock types with respect to their ^{226}Ra concentration and the potential for increased soil gas radon concentrations with depth).

6.5. VERIFICATION OF THE NEW METHOD FOR RADON INDEX ASSESSMENT

Since 2004, the usefulness of the new method has been verified continually mainly by the commercial practice. As the detailed radon survey and the classification of radon risk is obligatory for each building site area of a new building, the number of assessment realized for commercial purposes annually in Czech republic is really high. RADON v.o.s., one of about hundred private firms dealing with radon risk monitoring, performs radon measurements usually at almost one thousand areas per year (which represents about 20000 soil gas radon concentration measurements).

The reproducibility and the reliability of the method is verified by the system of intercomparison measurements at official radon reference sites and by results obtained in the framework of various researches as well. Although the assessment of radon index was not the main aim of those projects, it lay within the necessary conditions for further investigation.

Tab. 6-2. The results of radon index: classification based on radon potential model (RP; direct measurements of permeability) and on expert assessment of permeability and classification table

Site (house)	c_A	Permeability		RP	Radon index	
	Third quartile c_{A75} (kBq . m^{-3})	Expert assessment	Direct m . k_{75} (m^2)		RP	Table
Růžená No. 1	88.4	High	$2.4 \cdot 10^{-12}$	54.0	High	High
Louňovice No. 214	143.6	High	$1.4 \cdot 10^{-11}$	167.0	High	High
Jindřichov No. 126	203.7	High	$1.6 \cdot 10^{-11}$	254.7	High	High
Loučná nad Desnou No. 16	16.7	Low	$1.5 \cdot 10^{-12}$	9.2	Low	Low
Kuníček No. 11	90.3	High	$1.1 \cdot 10^{-11}$	94.2	High	High
Potůčky No. 37	70.7	High	$1.6 \cdot 10^{-11}$	87.6	High	High
Horní Slavkov No. 374	297.7	High	$7.9 \cdot 10^{-12}$	269.1	High	High
Střížov No. 44	54.6	Medium	$1.9 \cdot 10^{-12}$	31.1	Medium	Medium
Jablonná No. 82	31.8	High	$1.6 \cdot 10^{-11}$	38.7	High	High
Louňovice No. 296	122.3	High	$1.1 \cdot 10^{-11}$	126.5	High	High
Horní Slavkov No. 570	114.1	High	$5.7 \cdot 10^{-12}$	90.9	High	High
Horní Slavkov No. 519	73.1	High	$3.1 \cdot 10^{-12}$	47.8	High	High
Beztahov No. 47	234.4	Low	$2.0 \cdot 10^{-13}$	86.5	High	High
Divišovice No. 17	219.2	Medium	$1.9 \cdot 10^{-12}$	126.8	High	High
Milevsko No. 1408	319.4	High	$5.2 \cdot 10^{-12}$	248.0	High	High

c_{A75} – third quartile from the set of soil gas radon concentration values; k_{75} – third quartile from the set of direct gas permeability measurements

Tab. 6-3. The results of radon index: classification based on radon potential model (RP; direct measurements of permeability) and on expert assessment of permeability and classification table

Site (house)	c_A	Permeability		RP	Radon index	
	Third quartile c_{A75} (kBq.m^{-3})	Expert assessment	Direct m . k_{75} (m^2)		RP	Table
Jáchymov Na Slovanech 884	35.7	High	$1.6 . 10^{-11}$	43.6	High	High
Jáchymov Jiráskova 565	150.9	High	$1.6 . 10^{-11}$	188.3	High	High
Jáchymov B. Němcové 262	21.6	High	$1.6 . 10^{-11}$	25.9	Medium	Medium
Jáchymov Mathesiova 200	60.5	High	$9.0 . 10^{-12}$	56.9	High	High
Jáchymov D. Hrdinů 318	58.2	High	$1.4 . 10^{-11}$	67.0	High	High
Krásno Lesní 496	61.7	High	$1.0 . 10^{-11}$	60.7	High	High
Krásno Cínová 467	79.6	High	$1.6 . 10^{-11}$	98.8	High	High
Jáchymov Mathesiova 201	55.7	High	$1.6 . 10^{-11}$	68.7	High	High
Jáchymov ČSA 99	33.7	High	$1.6 . 10^{-11}$	41.7	High	High
Jáchymov B. Němcové	50.8	High	$1.3 . 10^{-11}$	56.2	High	High

c_{A75} – third quartile from the set of soil gas radon concentration values; k_{75} – third quartile from the set of direct gas permeability measurements

In 2004–2005, RADON v.o.s. realized a research project “Investigation of radon transport from the foundation soils to the indoor environment through the contact between the building and the subfloor layers”.

The radon index has been determined with respect to the new method as radon potential (RP model, direct measurements of permeability) as well as using the expert assessment of permeability and the classification table (Neznal and Neznal 2006). The results of radon index evaluation are summarized in Tab. 6-2, the graphical presentation of radon potential values is given in Fig. 6-3.

How can be seen from the summary, the results of radon index based on direct measurements of permeability and the radon potential model agree with the results based on expert assessment of permeability and the classification table in all cases. That conclusion is valid even in border cases, when the observed values are closed to the border between categories of radon index.

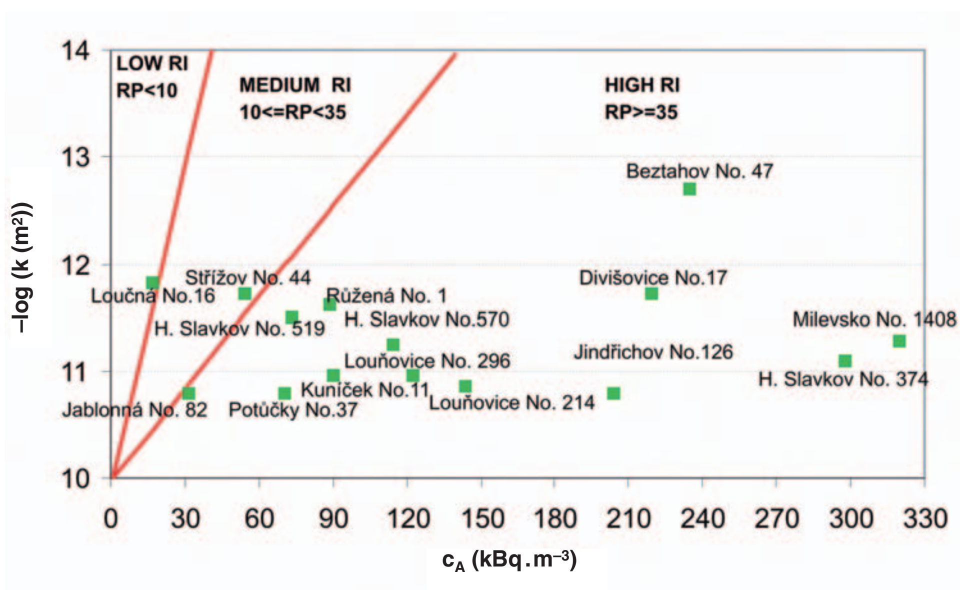
Similar results (Tab. 6-3) have been obtained during the new project “Development and experimental verification of remedial measures against radon and gamma radiation in extreme conditions due to the finished historic exploitation of silver and uranium ore” (2006–2008).

6.6. COMPARISON OF LARGE SCALE RADON RISK MAPS AND RESULTS OF DETAILED IN SITU MEASUREMENTS

Four comparisons of large scale radon risk maps and detailed classifications of radon risk based on detailed measurements were made in 1992, 1995, 2002 and 2007.

The first two comparisons (Neznal, Neznal and Barnet 1992, Neznal, Neznal and Šmarda 1993, Neznal, Neznal and Šmarda 1996) were based on the assessment of differences between regional radon risk maps at a scale

Fig. 6-3. Results of radon index based on radon potential model and direct measurements of permeability.



1 : 200 000 and results of detailed radon surveys. They concerned 630 and 968 building sites, respectively.

The comparisons showed, that the large-scale maps are generally reliable, the satisfactory reliability of radon risk maps was observed at a large number of areas (62.9 %; 56.7 % resp.). When the bedrock is formed by Cretaceous sediments or by granites or granodiorites, and/or the cover formed by loess and loess loams – a satisfactory coincidence between the results of building site characterization and the radon risk map prediction (about or more than 70 % of cases) was observed. Significant differences were found in areas with larger variability of soil environment (river terraces, or layers influenced by anthropogenic activity). In areas with the Quaternary cover formed by river terraces; or with some special rock types – chlorite-sericite phylite – detailed radon surveys did not confirmed the expected risk at more than 60 % of building sites.

Observed differences confirmed the usefulness of a direct building site characterization. The comparison found and demonstrated another disadvantage of the radon maps as well. The lowest reliability, even lower than 30 %, was found in expected high risk areas, i.e. with respect of the usefulness of maps in areas of the main interest (the search of existing houses with higher indoor values). Therefore, the Czech Geological Survey has been publishing new radon risk (index) maps at the scale 1 : 50 000 since 1999 (see Chap. 7).

The third and the fourth comparison were focused on the reliability analysis of those new radon risk maps at a scale 1 : 50 000. The reliability evaluation of maps 1 : 50 000 is more complicated, because the maps include the fourth category, called intermediate, which is not defined for detailed building site characterization and has in fact no corresponding counterpart.

In 2002, the reliability of radon risk prediction maps was analysed by comparing data from detailed radon surveys with data from the corresponding 4 radon map sheets (Neznal et al. 2004). We concentrated on the map sheets with expected all radon index categories or with predicted low and intermediate categories. The reliability was similar – about 62.2 %, when we used the rule that the intermediate category in the map corresponded to both low and medium detailed risk. But the differences between the indications from the map and the data from the survey were again substantial. The spatial distribution of radon indices was induced mainly by variations in geological conditions, which can only be characterized by a thorough geological survey. A geological map of 1 : 50 000 scale, as a basis for radon risk map, cannot register such details.

Finally, the comparison in 2007, when the whole territory of the Czech Republic had been covered by those radon maps, had to answer the question: "Is there a possibility to use the radon risk maps at a scale 1 : 50 000 for determination of radon index at a specific site and for preventive measures in new buildings without detailed in-situ investigation?". Hundreds of detailed radon index assessments (i.e. thousands of soil gas radon concentration measurements) were compared with expected radon index categories in chosen 5 map sheets.

Three ways (approaches) of testing the radon risk maps reliability have been used. The first one corresponds to the main purpose of maps, i.e. searching for existing houses with elevated radon levels, and it minimizes the influence of the intermediate category. In that case it is possible to use again the rule, that the intermediate category in the map corresponded to both low and medium detailed risk (the most important is the agreement in higher risks). The relevant reliability has varied from 63.0 to 67.1 %.

The second reliability test describes the probability, how often we can find the same category using the detailed assessment and/or reading the map. It takes into account the splitting of the intermediate category to both low and medium ones. The corresponding values have varied from 45.2 to 51.5 %.

In the third comparison, the doubtful intermediate category has been excluded. We have focused on the reliability of determination of a specific category. In areas marked as low risk areas in the maps, the reliability has been 37.3 %, i.e. in 62.7 % we have found a higher category during the detailed survey (the risk of underestimation 62.7 %). As for the medium risk, the reliability has been 52.9 %, the risk of underestimation 33.8 % and the risk of overestimation 13.3 %. As for the high risk areas, the reliability has been similar, 52.7 %, and the corresponding risk of overestimation 47.3%.

The answer of the above mentioned question was relatively easy. No, the radon risk maps cannot be recommended to be used for the determination of radon index of building sites for new buildings. On the other hand, the new maps have improved the input conditions for searching the old houses with elevated indoor radon levels.

7. Mapping of radon index

7.1. PURPOSE OF RADON RISK MAPS

The health risk coming from radon in underlying geological units can be partly regulated by monitoring of indoor radon concentrations. Due to the relatively "unfavourable" occurrence of crystalline and magmatic rocks within the territory of the Bohemian Massif, the radon hazard is very frequent compared to other European states. The areal extent of rock types having medium and high radon concentrations in bedrock is close to 50 % of the total state area. Therefore the radon and natural radionuclides exposure of citizens exceeds about 5 times the exposure coming from artificial radionuclides (Hůlka and Thomas 2007). The state financed programme of indoor radon measurements is aimed to discover the radon prone areas and to decrease the indoor radon exposure by remediation projects for particular buildings. The main task of radon risk mapping is confining the areal extent of high radon risk areas within the state territory up to detailed scales and setting the priorities of indoor radon measurements within the municipalities. The state authorities take the results of measurements in account when preparing the legislative