RADON PREVENTION

RADON POTENTIAL (SOIL-GAS RADON CONCENTRATION & PERMEABILITY)

PROTECTION OF HOUSES

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November, 2018

- Introduction, history/sources of radon, RADON v.o.s.
- Building site characterization x radon maps
- Radon index determination – uniform Czech method for building site characterization
- Soil-gas radon concentration, soil-gas sampling, spatial and temporal variability as the main influencing factors
- Determination of soil permeability, direct measurements, expert evaluation, RADON-JOK
- Most common errors and failures connected with soil-gas radon concentration measurements
- Preventive measures against radon

The history of radon started on the border between the current Czech Republic and Germany:

The first reference to negative health effects of radon appeared in the 16th century: Paracelsus (1493 – 1514) described a specific "miners disease" that occurred in silver mines in Jachymov (Joachimstahl) and Schneeberg. The symptoms and the development of the disease differed from those of tuberculosis.

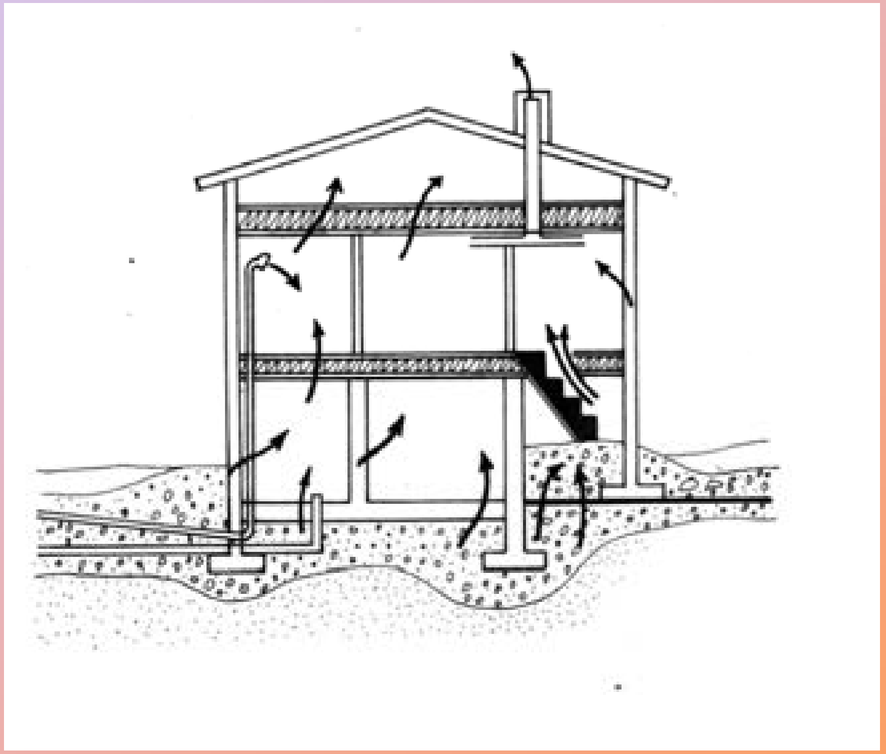
But as late as in 1952, W.F. Bale (USA) discovered the reason: inhalation of short-term radon decay products.

Radon sources:

radon penetrating into the house from foundation soils

building materials

water



In the 80´s of the last century:

Houses with elevated indoor radon levels were discovered in the Czech Republic.

Sources:

- building materials with higher content of radium (START houses);
- radon penetrating into the house from foundation soils.

In the beginning of the 90´s:

Legislation dealing with radon (radon prevention, remediation) .. the need to develop a methodology for the evaluation of foundation soils in terms of radon risk.

In 1990: RADON v.o.s. („“Neznal Brothers“) was established as the first private Czech firm dealing with radon measurements:

14th of June, 1990 – more than 10 000 days dealing with radon …

Beside commercial activities, the firm has participated in many research projects (Czech Republic, Europe) ..

& we sell equipment for radon risk monitoring (radon detectors, sampling system, equipment for in situ permeability measurements RADON – JOK).

Our database contains results of more than 360 000 soil-gas radon concentration measurements.

International cooperation

Regular International Workshop on the Geological Aspects of Radon Risk Mapping organized in Prague since the beginning of 90-ties.

„Prague workshop has indeed become the epicentre of radon research, also beyond Europe.“ Peter Bossew, BfS, Germany (during the 11th workshop in 2012)

International Intercomparison Measurements of Soil-Gas Radon Concentration

Badgastein, Austria, 1991, New York, U.S.A., 1995

Prague and/or reference areas, Czech Republic, 1996, 2002, 2010, 2012, 2014, 2018

Spain - Saelices el Chico, 2011
Brazil - Poços de Caldas, MG, 2014
Serbia - Niška Banja, 2014

International cooperation

System for soil-gas sample collection – currently the most used in the world.

In-situ measurements of gas permeability – Czech equipment is used as the unofficial standard.

Method for the determination of radon index of building sites (or its parts) has been applied for the purpose of radon risk mapping:
Canada: North American Soil Geochemical Landscape Project (contribution to Canada´s New National Radon Strategy)
EU: European Geogenic Radon Map – „Neznal Radon Potential“

Authors of the Czech method participated in the German research project (BsF) focused on the methodology of determining the radon risk of building sites.

International cooperation

Cooperation on the preparation of the ISO Standard Measurement of radioactivity in the environment - Air: radon-222 - Part 11: Test method for soil gas with sampling at depth

Topic leaders: Roselyne Améon (France), Martin Neznal (Czech Republic)

.. (Matej Neznal)

Goal: To prepare the standard suitable for a wide range of applications .... published on April 15th, 2016.

Applications dealing with radon risk management - drawing up of radon potential maps, defining radon-prone areas, characterisation of radon potential of building sites, characterisation of soil contaminated with radium-226, defining mitigation techniques to be applied in a building, verification of applied mitigation techniques, etc.

Phenomenological observation - understanding radon transport mechanisms in the soil and from the soil into the building, identification and analysis of radon entry parameters, earthquake prediction, etc.

Radon index determination - Czech method for building site characterization

EUROPE

⇨ **no regulation in some countries**

⇨ **if there is a regulation, decision making in the pre-construction phase based:**

⇨ **mainly on radon risk mapping**

the territory is divided into radon-prone and radon-nonprone areas

(.. nowadays radon priority areas ..)

⇨ **or on modelling**

BUT:

The decision whether or not a dwelling needs radon protection can be based on the assessment of radon potential at a given place - on a building site characterization.

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.

Gustav Åkerblom in Prague 1990, experiences from Nordic countries, + exchange of experiences (f.e. Switzerland - Surbeck …)

… (In the Czech Republic since 1991;

2014: last modification of the uniform method for determination of radon index of building sites)

Similar approach f.e. in Germany (Kemski et al.) …

Main advantage of the method:

It is a site-specific, individual approach that enables to propose an optimal preventive strategy corresponding to local conditions.

Disadvantages of this approach, connected for example with temporal changes of measured parameters, are not critical.

Results of the building site characterization are used for the design of protective measures.

(This approach is obligatory in accordance with the Czech Atomic Law)

If the radon index is other than low
(i.e. medium, or high),
the building must be protected against radon.

Protective measures are designed and installed in accordance with the Czech National Standard (CSN 730601 Protection of houses against radon from the soil).

WHY WE DO NOT USE THE LARGE-SCALE RADON RISK MAPS (for radon index / radon potential determination) ?

Czech Republic: occurrence of crystalline and magmatic rocks within the territory of the Bohemian Massif

⇨ radon hazard very frequent compared to other European states

Purpose of radon risk maps:

to confine the areal extent of high radon risk areas within the state territory up to detailed scales and to set priorities of indoor radon measurements within the municipalities.

SCALES OF MAPPING

First step: ***Derived radon risk maps 1 : 200 000 (1990)***

Input

former Uranium Exploration, state enterprise:

soil-gas radon measurements at first 148 test sites covering all major rock types

location of areas with an increased frequency of the uranium anomalies and location of uranium waste dumps

Geophysics, state enterprise, and Faculty of Natural Sciences, Charles University:

airborne gammaspectrometric data

Czech Geological Survey:

pedological maps

The contours of major geological and lithological units were used as a base for radon risk expressed in three categories - low, medium and high.

The maps were hand drawn and not prepared for computer processing.

BARNET I. (1990): Radon risk mapping in Czechoslovakia. In Radon investigations in Czechoslovakia, edited by I. Barnet (Czech Geological Survey, Prague), Vol. 1, pp. 19-23.

Section of the Derived radon risk map 1 : 200 000 - Central Bohemia (Pribram vicinity)

Polygons of geological units are marked by the radon index category; dashed areas = areas with an enhanced frequency of uranium anomalies; orange areas = waste dumps.

RADON DATABASE

administered by the Czech Geological Survey since 1990 (uniform method for soil-gas sampling and measurement)

close cooperation with private companies joined in the Association Radon Risk: members of the Association have supported the National Radon Programme by granting results of their measurements to the common database with the restriction of data assimilation for scientific purposes only and for developing the bedrock radon knowledge of the state territory

The position of the test sites has been digitised using base topographical maps (scale 1 : 50 000).

The rock type characterization has been derived from the geological maps of the same scale, published by C.G.S., the characterization of the soil cover has resulted from the in situ description performed by the measurement provider. The rock type and the soil cover characterization have been coded with the aim of easier data processing and generalization of mineralogically characterised lithotypes.

Following items form one record in the radon database:

- ⇨ **Localisation data**
- ⇨ **Radon data**
- ⇨ **Uranium data - content of uranium obtained by field gammaspectrometry, if available**
- ⇨ **Soil data - permeability**
- ⇨ **Geological data - bedrock, cover, anthropogenous influence, tectonics**
- ⇨ **Other data - date of measurement, source of data, method of measurement, method of soil air sampling, etc.**

Radon risk map 1 : 500 000

1990 – 1998: soil-gas radon database was filled with 7800 data enabling much more precise determination of radon risk in particular rock units

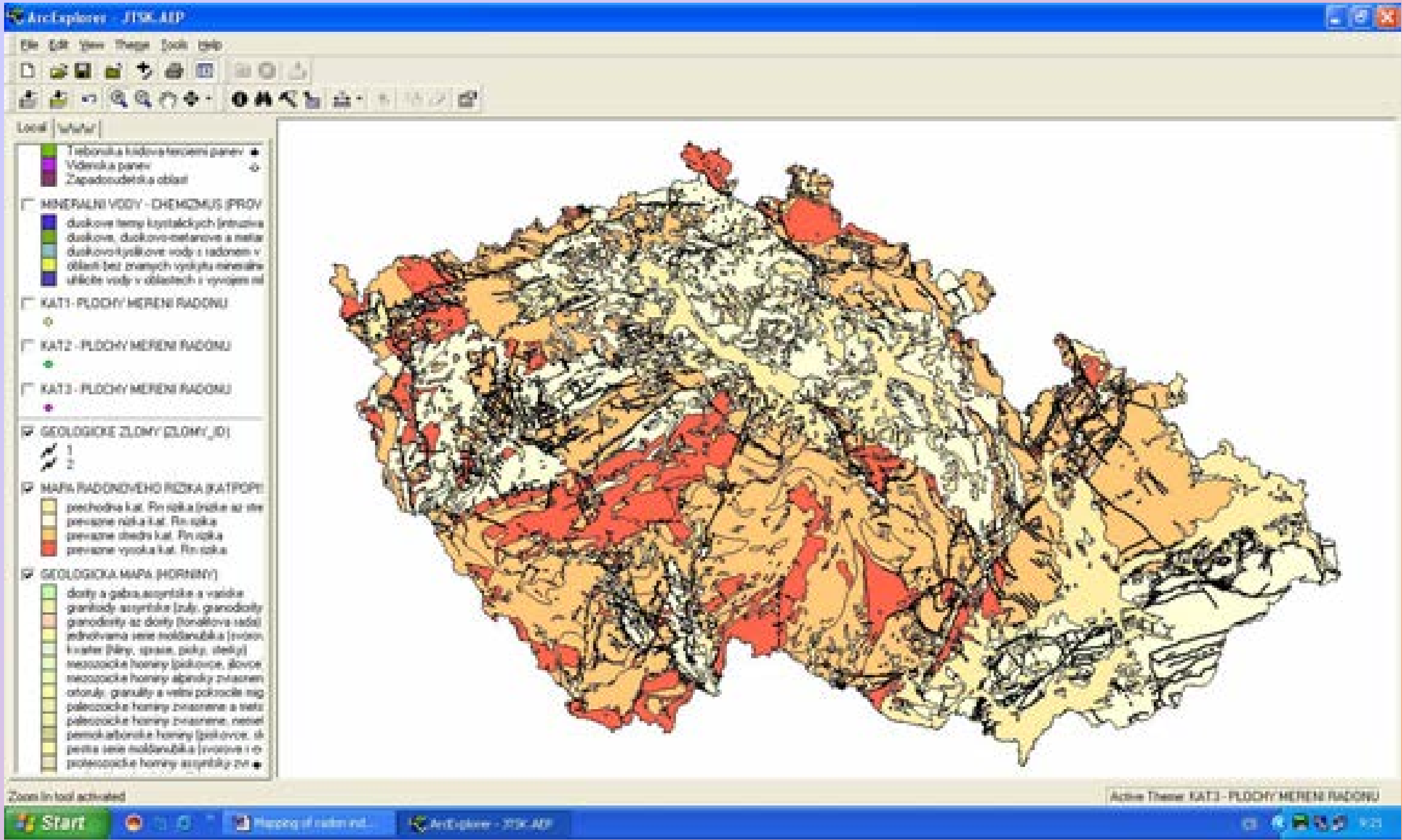
1998: atlas of geoscientific maps on a scale 1 : 500 000 (published by Czech Geological Survey)

the atlas was fully based on the vectorised geoscientific data including the polygons of major geological units

GIS processing enabled to characterize rock units from the point of view of mean soil gas radon concentrations, permeability and prevailing radon risk category

The radon risk map 1 : 500 000 is included in the Atlas of Maps of the Czech Republic – GEOCR500 together with 10 other maps with geoscientific themes, published on the CD ROM. Radon risk is characterized by three basic categories (low, medium and high) and one interstage category (typical for the radon risk from low category to medium in the inhomogeneous Quaternary sediments of allochthonous origin). The contours of geological units are filled after the prevailing radon risk in particular rock types.

Due to the ArcExplorer - freeware application, the single layers from the CD ROM can be combined from all 11 maps with the geoscientific themes and enable to construct the maps after users´ demand.



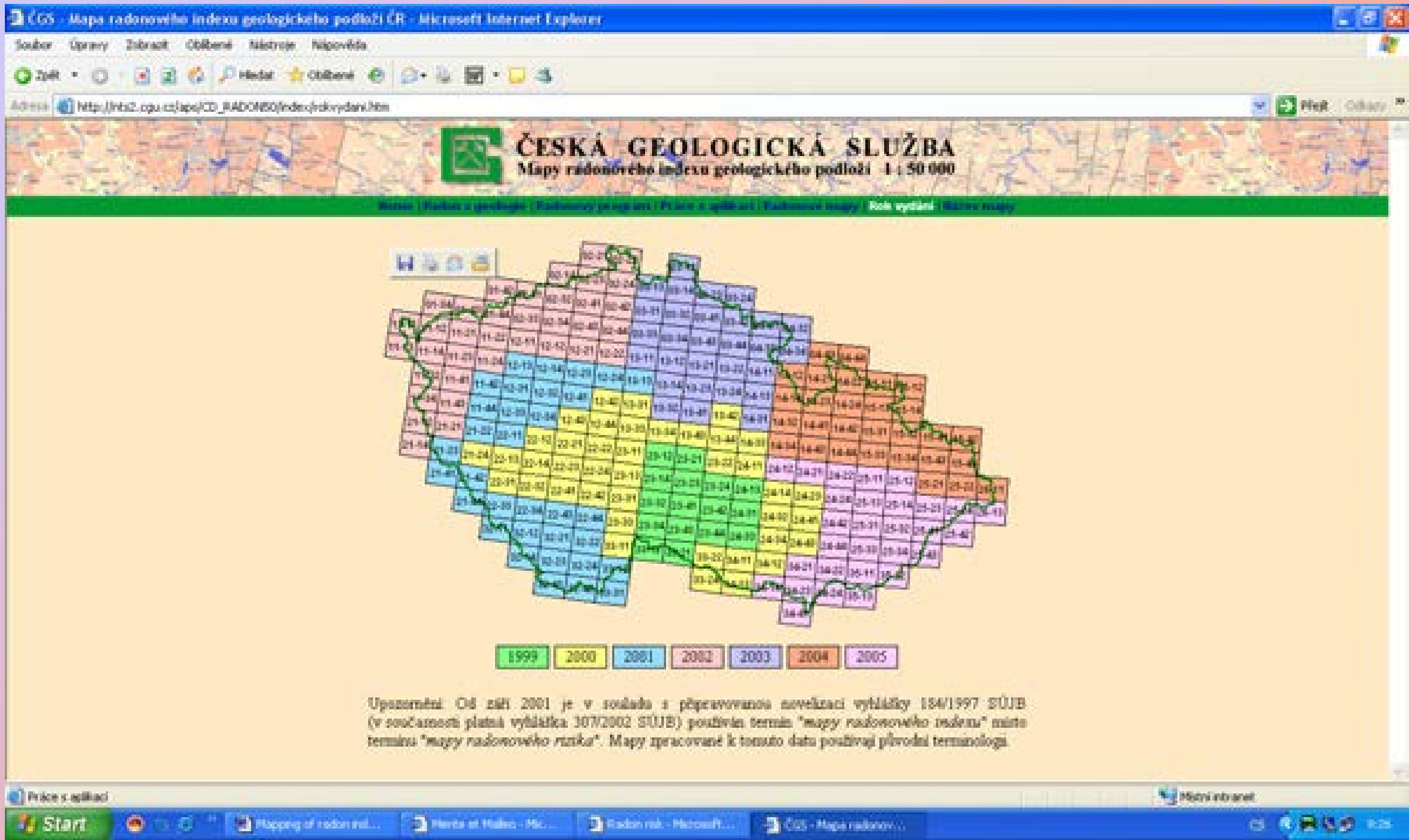
Radon risk map on a scale 1 : 500 000

(light yellow – low, beige – interstage, orange – medium, red – high radon risk categories)

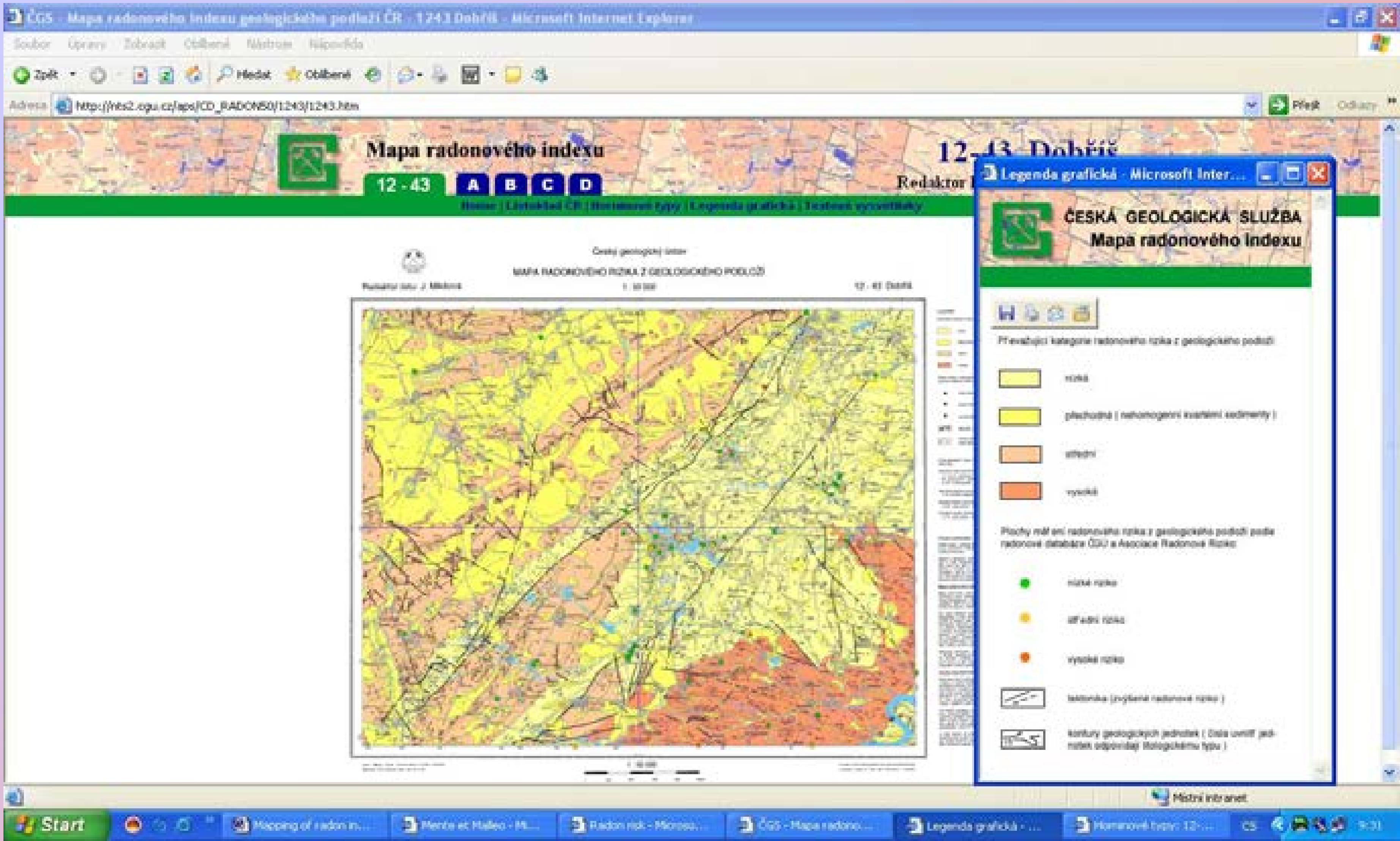
BARNET I. - MIKSOVA J. – PROCHAZKA J. (1998): Radon database and radon risk map 1 : 500 000 of the Czech Republic. In: Barnet, I.; Neznal, M., eds. Radon investigations in CR. Vol. 7. Praha: Geological Survey; RADON, corp.; pp. 1-5.

Radon risk maps 1 : 50 000

An extensive application of the vectorised data in the state administation and research institutions opened way to supporting data sources which could be used to improve the quality of radon risk maps.

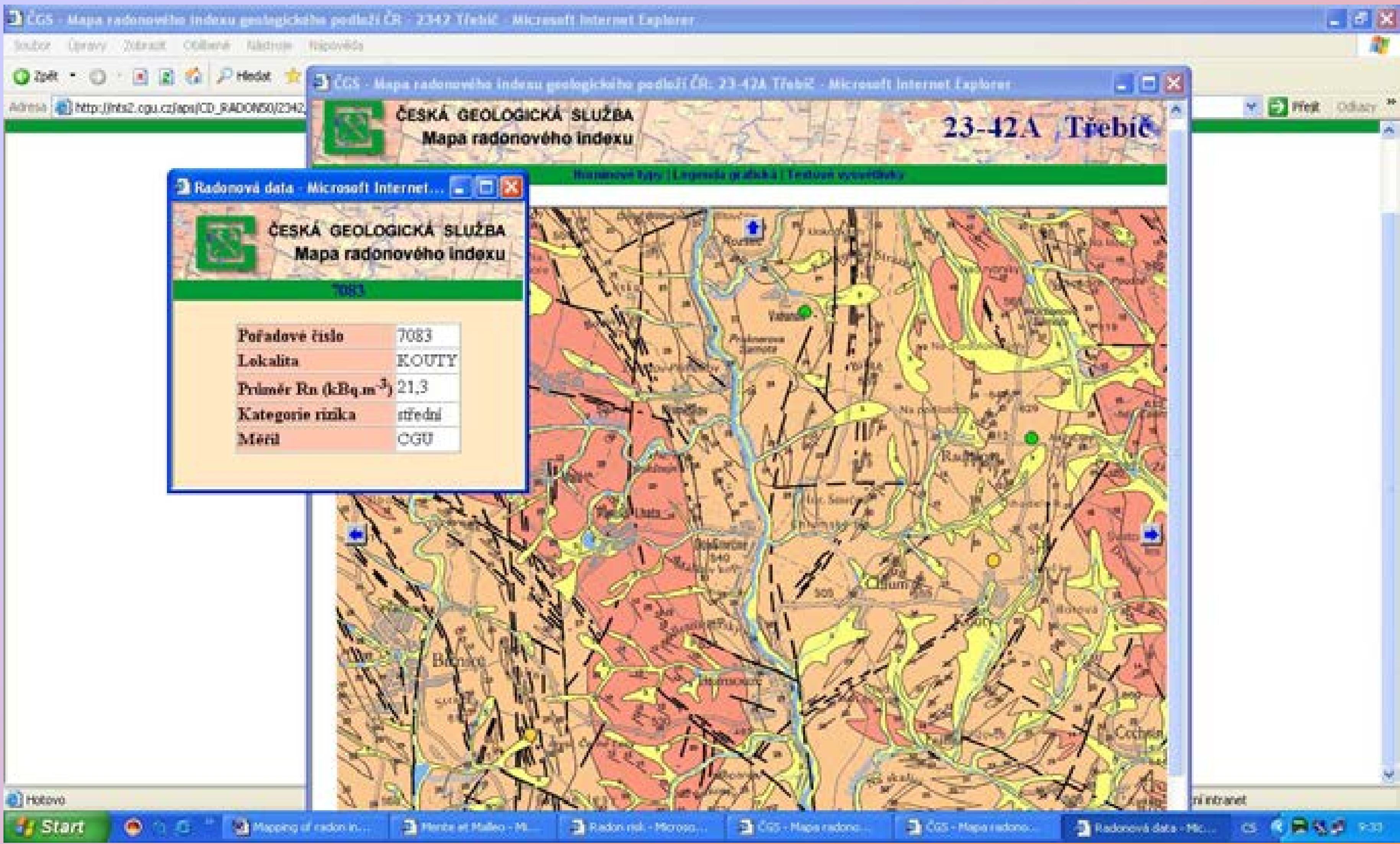


1999 – 2005: the whole state territory of 78 800 km^2 was covered by 214 map sheets on a scale 1 : 50 000



Radon index map on a scale 1 : 50 000 and opened legend window

(light yellow – low, yellow – interstage, orange – medium, red – high radon index)



Zoomed quadrant of radon index map on a scale 1 : 50 000 and information window for the particular test site (number, locality, mean soil gas radon, radon index category and provider of measurement)

BARNET I. - MIKSOVA J. - TOMAS R. - KARENOVA J. (2000): Radon risk mapping of the Czech Republic on a scale 1 : 50 000. In: Barnet, I.; Neznal, M., eds. Radon investigations in CR. Vol. 8. Praha: Geological Survey; RADON, corp.; pp. 4-15.

COMPARISON OF LARGE-SCALE RADON RISK MAPS AND RESULTS OF BUILDING SITE CHARACTERIZATIONS

Four comparisons were made in 1992, 1995, 2002 and 2007.

The first two comparisons were based on the assessment of differences between regional radon risk maps in the scale 1:200000 and results of detailed radon surveys. They concerned 630 and 968 building sites, respectively.

1992 (example):

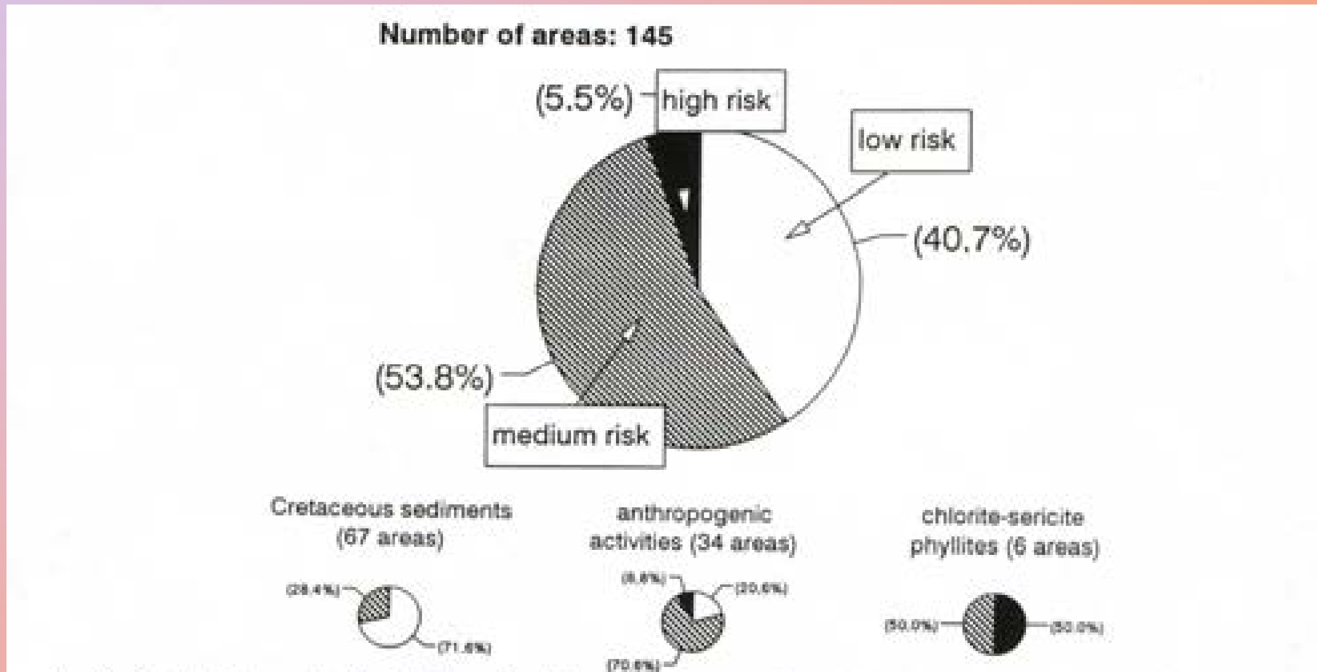


Fig. 8a. Detailed radon risk classification of building areas in expected low risk regions due to regional radon risk maps.

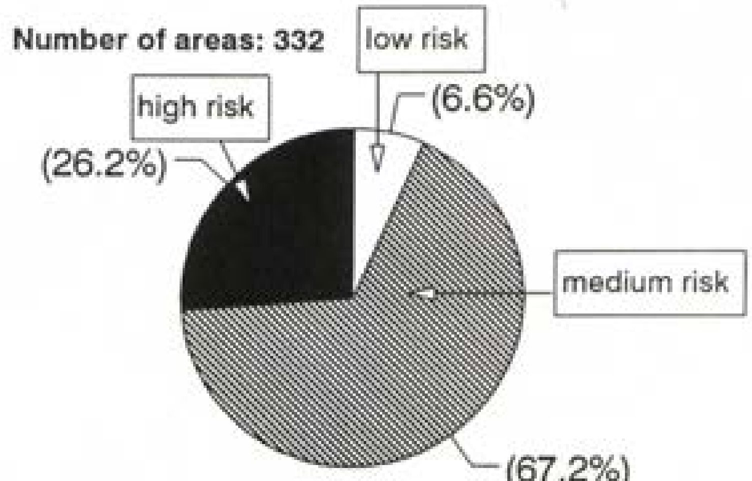


Fig. 8b. Detailed radon risk classification of building areas in expected medium risk regions due to regional radon risk maps.

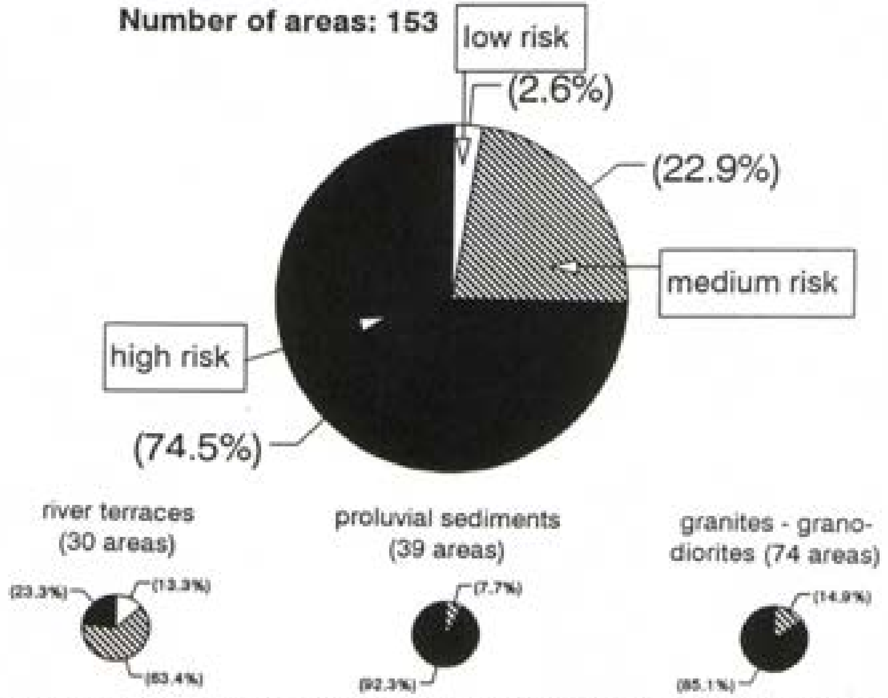


Fig. 8c. Detailed radon risk classification of building areas in expected high risk regions due to regional radon risk maps.

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1993): Testing of Radon Risk Maps Reliability. In: Barnet, I., ed. Radon Investigations in CS. Vol. 4. Praha: Geological Survey, pp. 12-17.

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1996): Assessment of Radon Potential of Soils - A Five Years Experience. Environment International 22, pp. S819-S828.

2002 and 2007:

The third and the fourth comparison were focused on the reliability analysis of new radon risk maps in the scale 1:50 000.

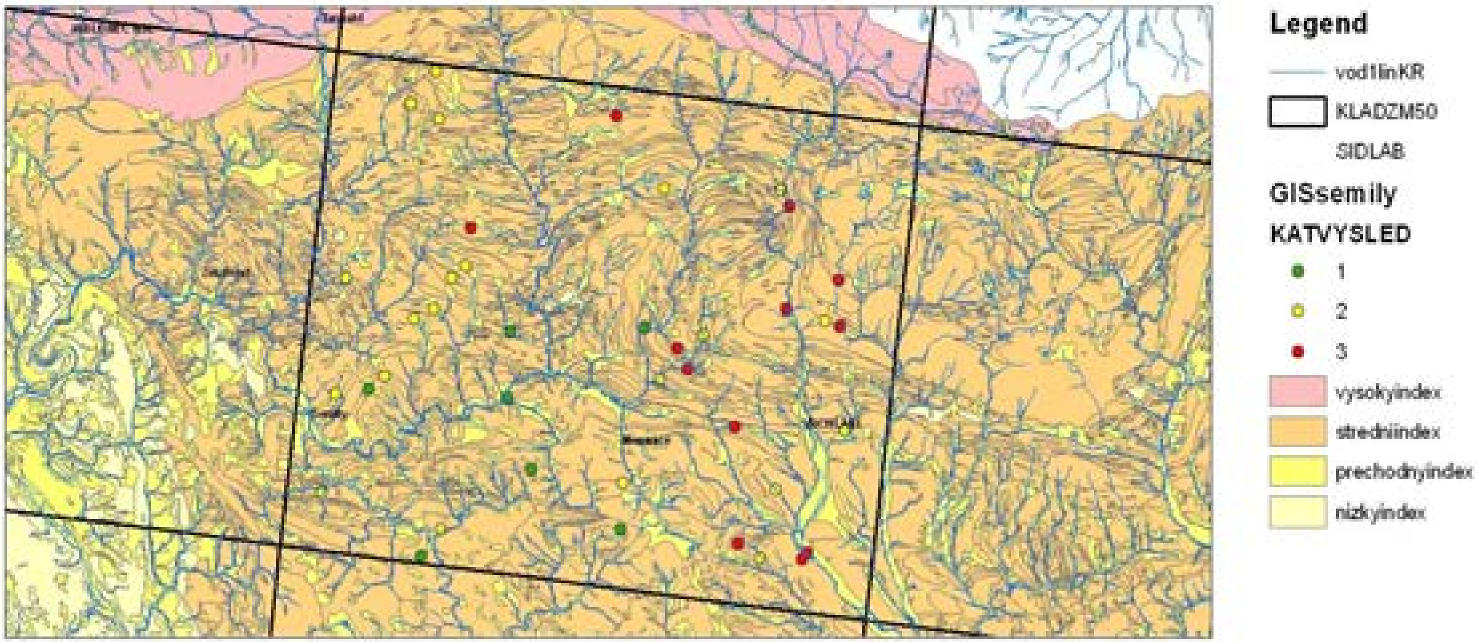
RADON v.o.s. data:

detailed measurements and classification from 599 areas

Czech Geological Survey data:

detailed measurements and classification from 240 areas

(the reliability evaluation of maps 1:50000 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).



Map sheet Semily

Reliability of maps:

low risk:

data RADON v.o.s.

R = 37,3 % (risk of underestimation 62,7%)

data CGS

R = 36,7 % (risk of underestimation 63,3%)

medium risk:

data RADON v.o.s. R = 52,9 % (33,8 % x 13,3 %)

data CGS R = 68,4 % (15,8 % x 15,8 %)

high risk:

data RADON v.o.s.

R = 52,7 % (risk of overestimation 47,3 %)

data CGS

R = 59,7 % (risk of overestimation 40,3 %)

- Geology is never homogeneous .. Quarternary cover + thickness, tectonics, bedrock (even in detail x M 1:50000)

  Area 100 x 100 m has in the map 1:50000 2mm x 2mm (very often two or even three categories of radon index/potential during the detailed survey)

  Standard building site – area of 20 x 40 m

  - in the map 0,4 mm x 0,8 mm, tj. 0,32 mm^2

CONCLUSIONS

⇨ New maps have improved the input conditions for searching the old houses with elevated indoor radon levels: As for the expected high risk areas, the reliability of maps increased to more than 50%.

⇨ On the other hand, the reliability of radon risk maps is still limited. Radon risk maps cannot be recommended to be used for the determination of radon index of building sites for new buildings.

SYSTEM OF SOIL-GAS RADON DATA STANDARDIZATION IN THE CZECH REPUBLIC

about 100 institutions (mostly private firms) dealing with the determination of radon index of building sites (= measurement of soil-gas radon concentration and classification of permeability of soil)

each subject

- ⇨ **has to pass the training course „Determination of radon index of building sites“**
- ⇨ **has to pass the intercomparison measurement of soil-gas radon concentration at three field radon reference sites**
- ⇨ **has to verify regularly all measurement devices for the determination of soil-gas radon concentration in radon chamber**
- ⇨ **has to get the authorization from the State Office for Nuclear Safety**

SYSTEM OF RADON DATA STANDARDIZATION IN THE CZECH REPUBLIC

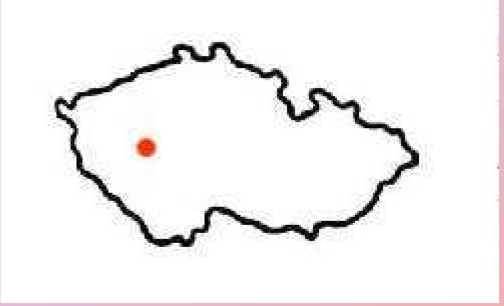
National radon chamber:
(Located in Příbram)

- **Verification of instrument, its function, sensibility and calibration,**
- **Verification of data processing.**

Radon reference sites:
(Located in the central Bohemia)

- **Test of soil gas sampling,**
- **Transfer of soil gas sample and its timing,**
- **Test of the radon instrument and its function,**
- **Elimination of thoron,**
- **Stability of field operation,**
- **Test of correct data processing.**

CHARACTERISTICS OF RADON REFERENCE SITES, CZECH REPUBLIC



Radon reference sites

Number of stations at each site: 15

Grid of stations: 5x5 m

Distance of the 3 reference sites: 12 km

Reference site	c_A ^{222}Rn (kBq/m^3)	Permeab. of soil	Basement rock	Soil	U (ppm)	Terrain	Access for cars
Cetyne	32	L,(M),H	orthogneiss	SL	2.0	meadow	+
Bohostice	52	(L),(M),H	orthogneiss	LS,CS	2.3	meadow	+
Buk	155	H	granodiorite	LS	3.6	meadow	+

UNIFORM METHOD FOR THE DETERMINATION OF RADON INDEX OF BUILDING SITES

⇨1990 first proposal

⇨1991 complete set of measurement methods

⇨1994, 2004, 2013 modifications

Neznal M., Neznal M., Matolín M., Barnet I., Mikšová J., The New Method for Assessing the Radon Risk of Building Sites, Czech Geological Survey Special Papers 16, (48 pages, English and Czech version), Published by Czech Geological Survey, Prague

available on www.radon.eu

Building site characterization:

Basic principles

⇨ simple and low-cost sampling and measuring techniques are used

⇨ radon index determination is based on

- soil-gas radon concentration measurement,
- in-situ permeability measurement, or expert evaluation of permeability (description of vertical soil profiles)

⇨ both parameters are measured in the depth of 0.8 m below the ground surface

⇨ at least 15 in-situ measurements of both parameters are required to evaluate the radon index of a building site for one family house

TERMINOLOGY

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.

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**.

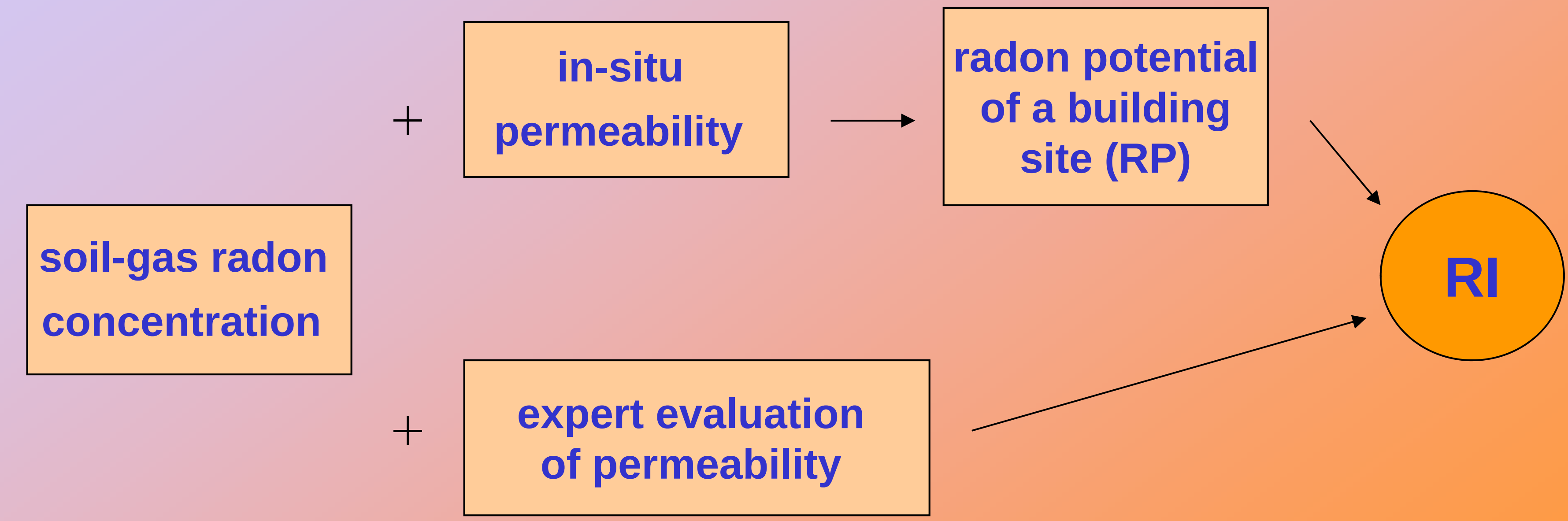
Vertical soil profile: The description of particular soil layers characterizing their structural and mechanical properties, depth, and thickness. This description is used in the expert evaluation of permeability.

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 $\mathbf{N_{75}}^{\mathbf{th}}$ value of the data set, where $\mathbf{N_{75}}$ equals **(0.75N + 0.25)** rounded-off to the nearest lower integer.

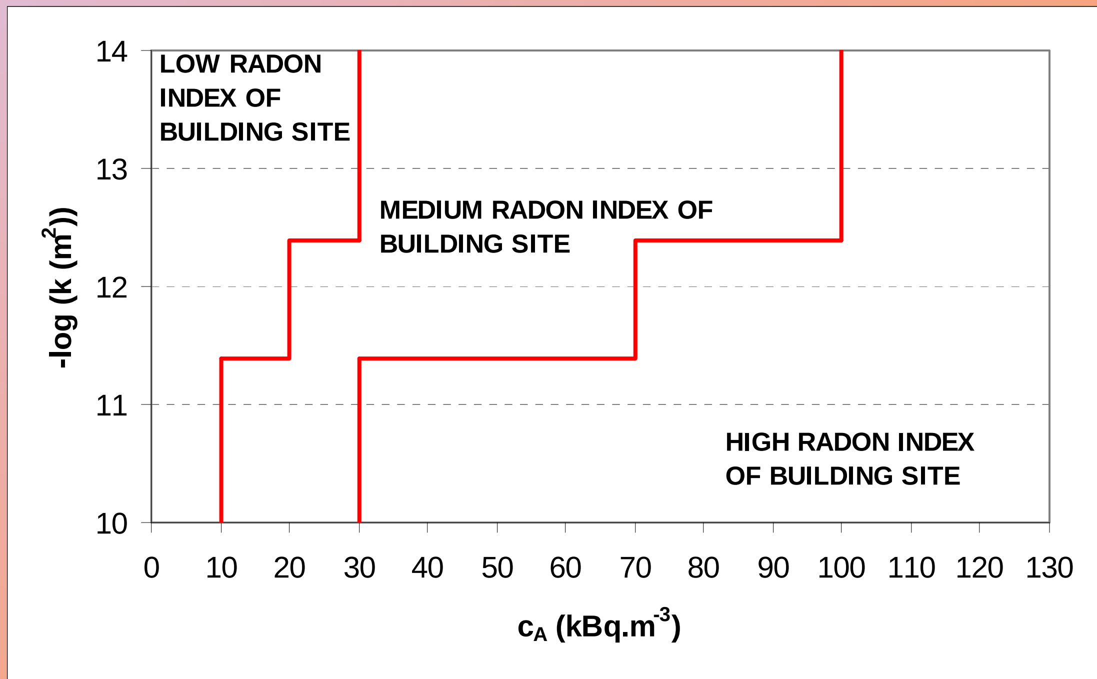
RADON INDEX OF A BUILDING SITE

Determination of the radon index of a building site (RI) is based on two factors: soil gas radon concentration and 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 assessment.

The final RI determination is derived from permeability data.



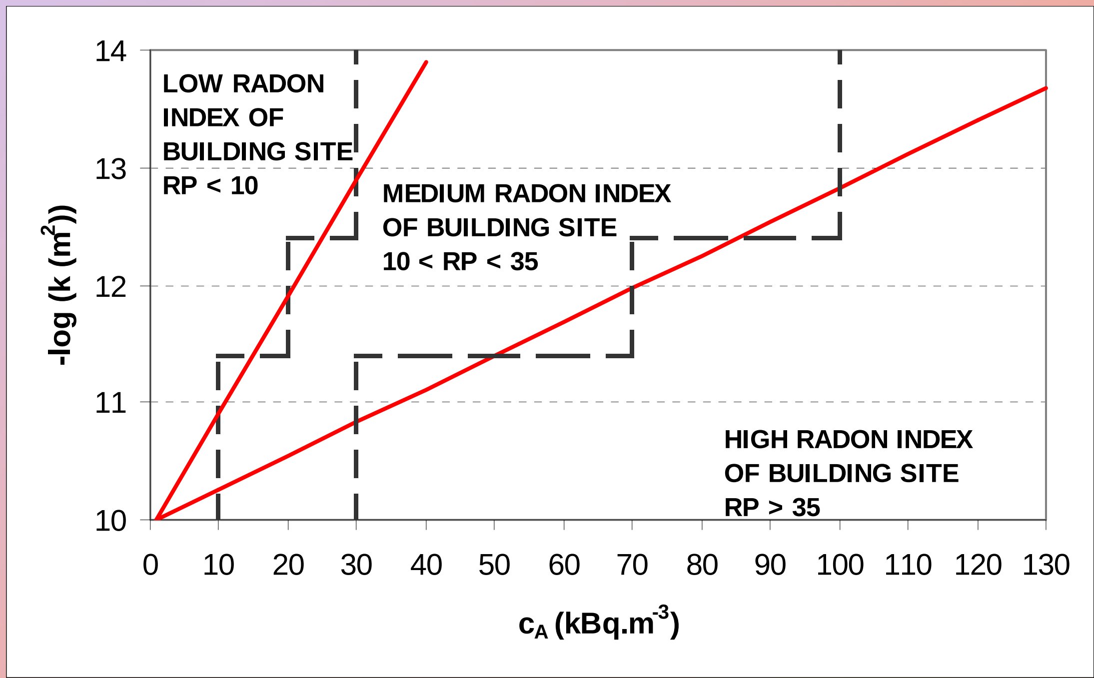
Radon index	soil-gas radon concentration ($kBq.m^{-3}$)		
	low permeable soil	medium permeable soil	high permeable soil
low	< 30	< 20	< 10
medium	30 – 100	20 – 70	10 – 30
high	> 100	> 70	> 30



RADON POTENTIAL OF A BUILDING SITE

The model for the assessment of RP is based on the former RI classification table. The amendment implements continuous lines, which substitute former fractional lines separating low, medium and high RI.

⇨ This substitution enables a more precise assessment in border cases.



$RP = (c_A - 1) / (- \log k - 10)$ „Neznal Radon Potential“

A couple of the straight lines (V - shaped), which delimit the medium radon index, can be defined generally. They are given by equations:

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

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

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

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

The value of c_{A0} must be negative or approaching zero. The value of k_0 should correspond to maximal realistically possible permeability.

To follow continuity with the formerly used methodology the equations describing the limits and the parameter RP are optimal to be defined in the following form:

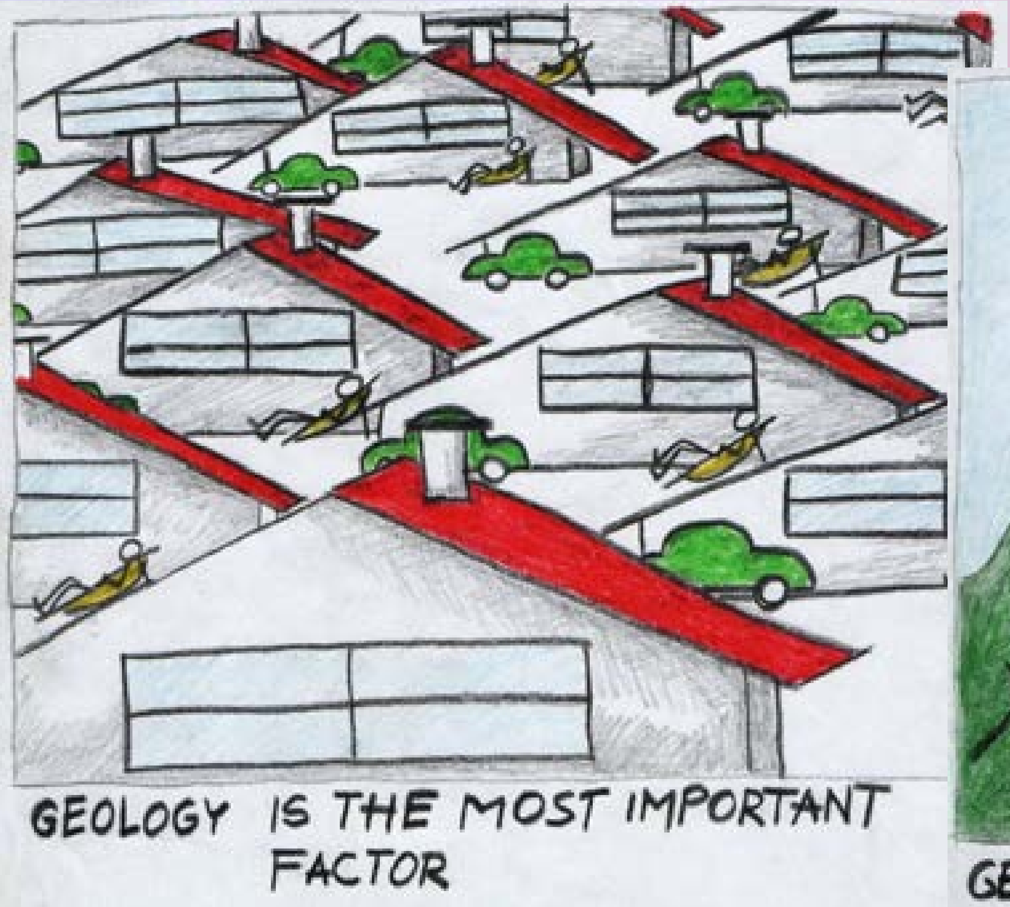
$- \log k = 1/10 \, . \, c_A - (1/10 + \log 1E\text{-}10) = 0,1 \, c_A + 9,9$

$- \log k = 1/35 \, . \, c_A - (1/35 + \log 1E\text{-}10) = 0,0286 \, c_A + 9,971$

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

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

The degree of required radiation protection of the building depends not only on geological conditions, but also on the type of the building.



RADON INDEX OF A BUILDING

The radon index of a building (RB) expresses the degree of required radiation protection the building requires against radon penetration from the ground.

> **⇨ 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.

.. procedures described in the Czech National Standard (CSN 730601 Protection of houses against radon from the soil).

Research and „frequent questions“

⇨ the foundation depth

(results from „green field“ x changes in geological conditions/settings x even various layers of basements)

⇨ detailed radon survey for the reconstruction/renovation

⇨ detailed radon survey at places strongly influenced by various anthropogenic activities (f.e. asphalt cover ..)

SOIL-GAS RADON CONCENTRATION

In general, the measurement of soil-gas radon concentration

(= volume activity of radon in the soil air)

is based on the detection of the radioactive decay effects of radon and its decay products.

Since radon and its decay products are emitting alpha and/or beta particles as well as photons in principle the whole spectrum of detectors can be used for measurement in combination with a suitable sampling technique.

⇨ ionization chambers: radon containing air is admitted to the electrical field and radiation from decaying atoms ionises the air; the charge carriers are accelerated to the electrodes of the chamber and the resulting current is detected as a measure of the quantity of decayed radon atoms

⇨ scintillation materials (ZnS (Ag)): energy of alpha particles is converted into scintillation photons, which are registered in a photomultiplier tube

⇨ solid state nuclear track detectors (track etch detectors) or thermoluminescent detectors: heavy ionizing radiation creates remaining changes in the structure of solids

(a) instantaneous measurement (grab sampling)

⇨ **instantaneous value of soil-gas radon concentration**

(b) integral measurement

⇨ **average soil-gas radon concentration related to a chosen measuring interval**

(c) continual measurement

⇨ **sequence of average (or instantaneous) values of soil-gas radon concentration**

Observed spatial variability of soil-gas radon concentration

⇨ need for a method that enables to collect a large number of soil-gas samples in a short time period

⇨ **proposal of a very simple sampling system (1991):**

a small-diameter hollow steel probe with a free, sharpened lower end (a lost tip) combined with a large-volume syringe is used

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1991): Radon infiltration risk from the ground in Chaby, Prague, in Radon investigations in Czechoslovakia, edited by I. Barnet (Czech Geological Survey, Prague), Vol. 2, pp. 34-39.

Soil-gas sampling

Research of available literature – mainly from U.S.A.

a large spectrum of methods that are available for collection of soil-gas samples have been described, starting from complicated systems such as packer-probe used by TANNER (1988)

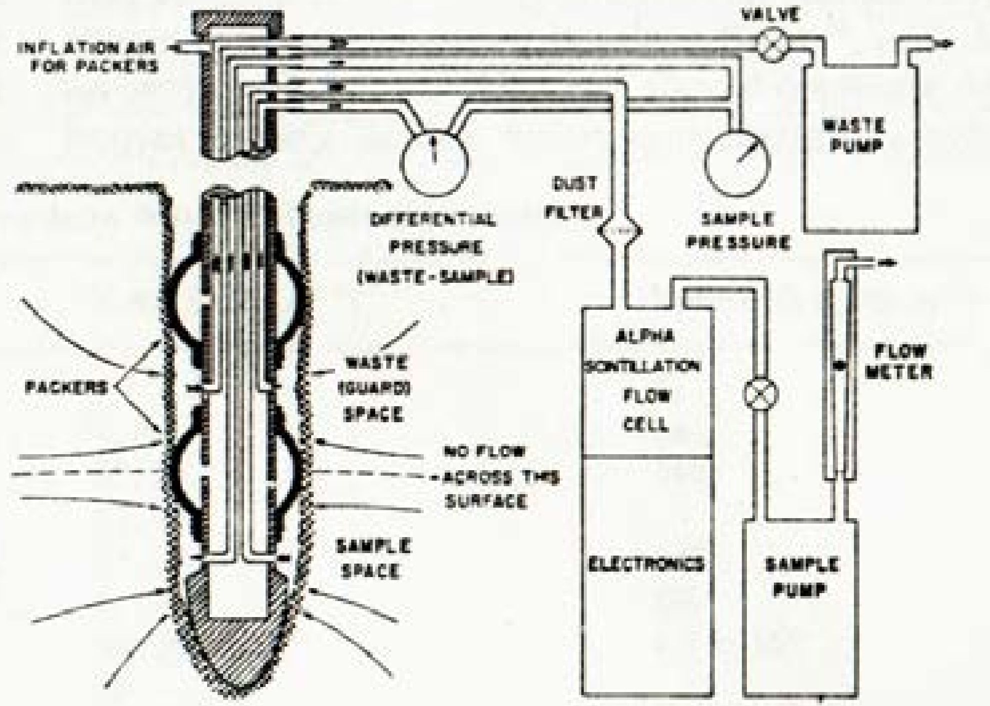


Figure 2. Schematic diagram of apparatus for extracting and measuring radon concentration of soil gas and measuring flow rate and driving pressures for permeability calculation. The hole diameter used is about 3.5 cm but is not critical.

TANNER, A. B. (1988): A Tentative protocol for measurement of radon availability from the ground, Radiation Protection Dosimetry, Vol. 24, No. 1/4, pp. 79-83.

or a small-diameter probe used by REIMER (1990)

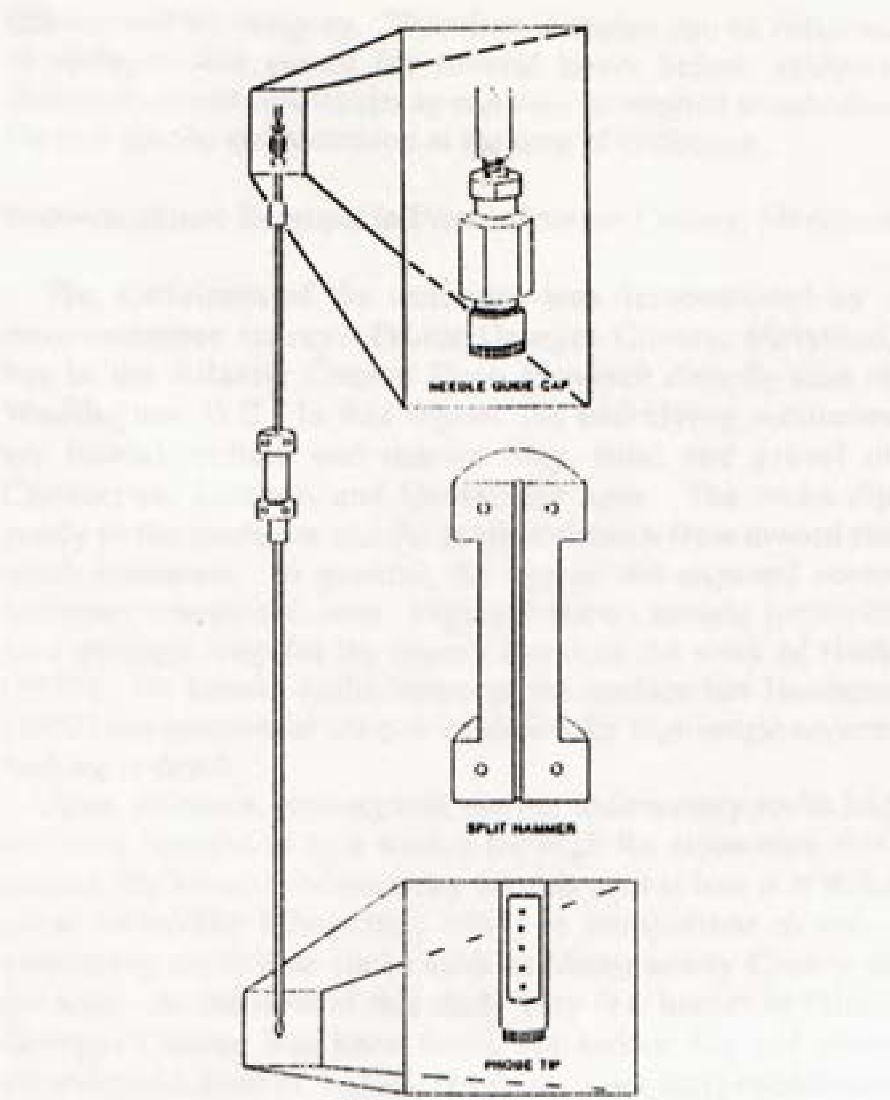


Fig. 1. Schematic drawing of the soil-gas sampling probe showing the tip, hammer, and needle guide components.

REIMER, G. M. (1990): Reconnaissance techniques for determining soil-gas radon concentrations: An example from Prince Georges County, Maryland, Geophysical Research Letters, Vol. 17, No. 6, pp. 809-812.

Soil-gas sampling

First field test

Bottle of Champagne

Collection of a soil-gas sample and introduction of the sample into a previously evacuated ionization chambre

⇨ ⇨

Step 1: Inserting the free, sharpened lower end (lost tip) into the lower end of the sampling probe.

Step 2: The probe with the tip is prepared at the sampling place.

Step 3: Preparing the drive in head.

Step 4: The probe is pounded to a chosen depth using the special hammer and the drive in head.

Step 5: Inserting of the punch wire into the probe.

Step 6: The sharp tip is moved a few centimeters lower, which makes a cavity at the lower end of the probe.

Step 7: Preparation for sampling.

Step 9: Deflation of the first sample. The rubber tube must be kept closed between the first and the second sampling.

Step 8: The soil-gas sampling. The first sample is not used for measurement, it serves to introduce the soil-gas into the probe.

Step 10: The soil-gas sampling (the second sample).

Step 11: The second soil-gas sample is introduced into previously evacuated ionization chamber.

NOTES:

⇨ The entire system must be perfectly sealed. The use of a sampling system that is not perfectly sealed, may result in an underestimated soil-gas radon concentration.

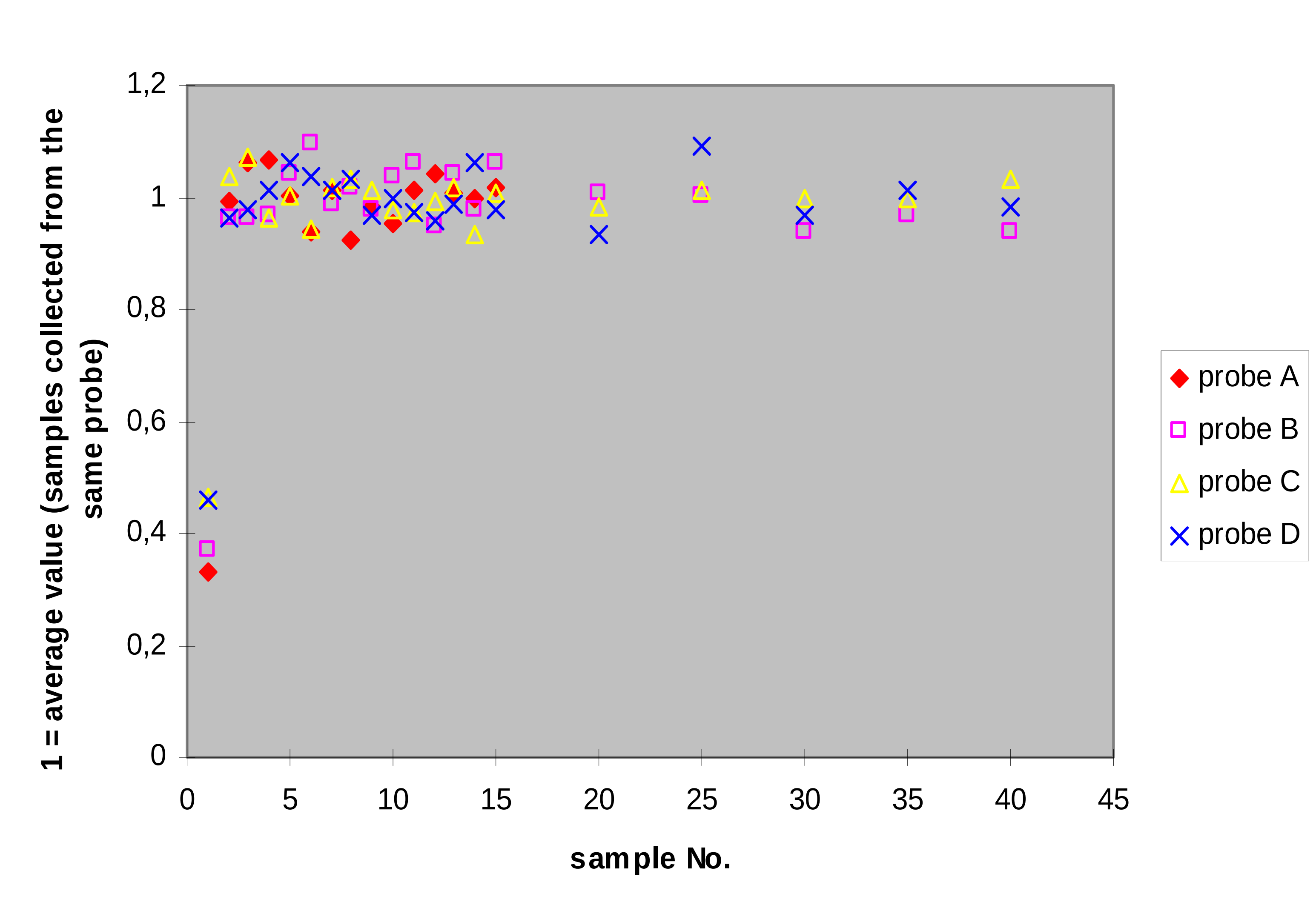
⇨ The soil-gas samples are collected from a depth of about 1.0 m below the ground surface (the depth of 0.8 m below the ground surface is used in the Czech Republic).

⇨ 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; recommended minimal internal surface of the cavity = 940 mm^2 (corresponding to a cylinder having f.e. 10 mm in diameter and 30 mm height).

⇨ If the soil permeability is very low, the cavity at the lower end of the sampling probe can be enlarged by retracting the probe several cm toward the surface.

⇨ The resistance against sampling occurred during the collection of the sample, although it is a subjective description, gives the information about permeability, as well.

The capacity of the soil as a source of radon is large enough to get a satisfactory reproducibility of measured soil-gas radon concentrations in repeatedly collected samples.



MEASUREMENT OF SOIL-GAS RADON CONCENTRATION

Lucas cells (scintillation method), or ionization chambers

⇨ alpha particles emitted during the disintegrations of radon and its short-lived decay products are used for the detection of radon

gradual decay of each atom of radon is accompanied by the emission of three alpha particles:

disintegration of ^{222}Rn: energy 5,5 MeV

disintegration of ^{218}Po: energy 6,0 MeV

disintegration of ^{214}Po: energy 7,7 MeV

When the soil-gas sample is introduced into a Lucas cell, or into a ionization chamber, the average number of registered alpha particles significantly changes in time. At first, it increases rapidly due to the growing activity of radon decay products.

The equilibrium is reached approx. 3 hours after the introduction of the soil-gas sample into the detector, after that the average number of registered alpha particles decreases slowly.

If we suppose that

(a) no short-lived radon decay products are present in the soil-gas sample in the moment the sample is introduced into the detector, and

(b) the detection efficiencies of the alpha particles with different energies are the same,

we can express the relation between the detected number of pulses (counts) and the measured soil-gas radon concentration by the following equation:

$$c = (N(t_v, t_r) - Nb(t_v)) / K \cdot R(t_v, t_r) \cdot V \ ,$$

where

c	$/Bq.m^{-3}/$	is the radon concentration in soil-gas (or in air) sample,
t_v	$/s/$	is the time of counting,
t_r	$/s/$	is the time delay between introducing the sample into the detector and the beginning of counting,
$N(t_v, t_r)$	$/s^{-1}/$	is the measured number of counts,
$N_b(t_v)$	$/s^{-1}/$	is the detector background corresponding to the time of counting,
K	$/1/$	is the average detection efficiency per one alpha particle,
$R(t_v, t_r)$	$/1/$	is the number of alpha particles, which will be emitted into the detector during the time interval from t_r to $t_r + t_v$ if the original introduced radon activity is 1 Bq,
V	$/m^3/$	is the volume of the soil-gas (or air) sample.

Note: Under typical circumstances, the assumption (a) is fulfilled. The soil and the sampling system themselves play the role of a filter, which removes the radon progeny from the collected soil-gas sample.

The parameter $R(t_v, t_r)$ can be determined using following equations:

(i) If $t_r > 180$ min then

$$R(t_v, t_r) = 3 \cdot t_v \cdot EXP(-\lambda_1 \cdot t_r),$$

where

λ_1	$/s^{-1}/$	is the ^{222}Rn decay constant.

(ii) If $t_r \leq 180$ min then

$$R(t_v, t_r) = W_1 \cdot EXP(-\lambda_1 \cdot t_r) \cdot (1 - EXP(-\lambda_1 \cdot t_v)) -$$
$$- W_2 \cdot EXP(-\lambda_2 \cdot t_r) \cdot (1 - EXP(-\lambda_2 \cdot t_v)) +$$
$$+ W_3 \cdot EXP(-\lambda_3 \cdot t_r) \cdot (1 - EXP(-\lambda_3 \cdot t_v)) -$$
$$- W_4 \cdot EXP(-\lambda_4 \cdot t_r) \cdot (1 - EXP(-\lambda_4 \cdot t_v)),$$

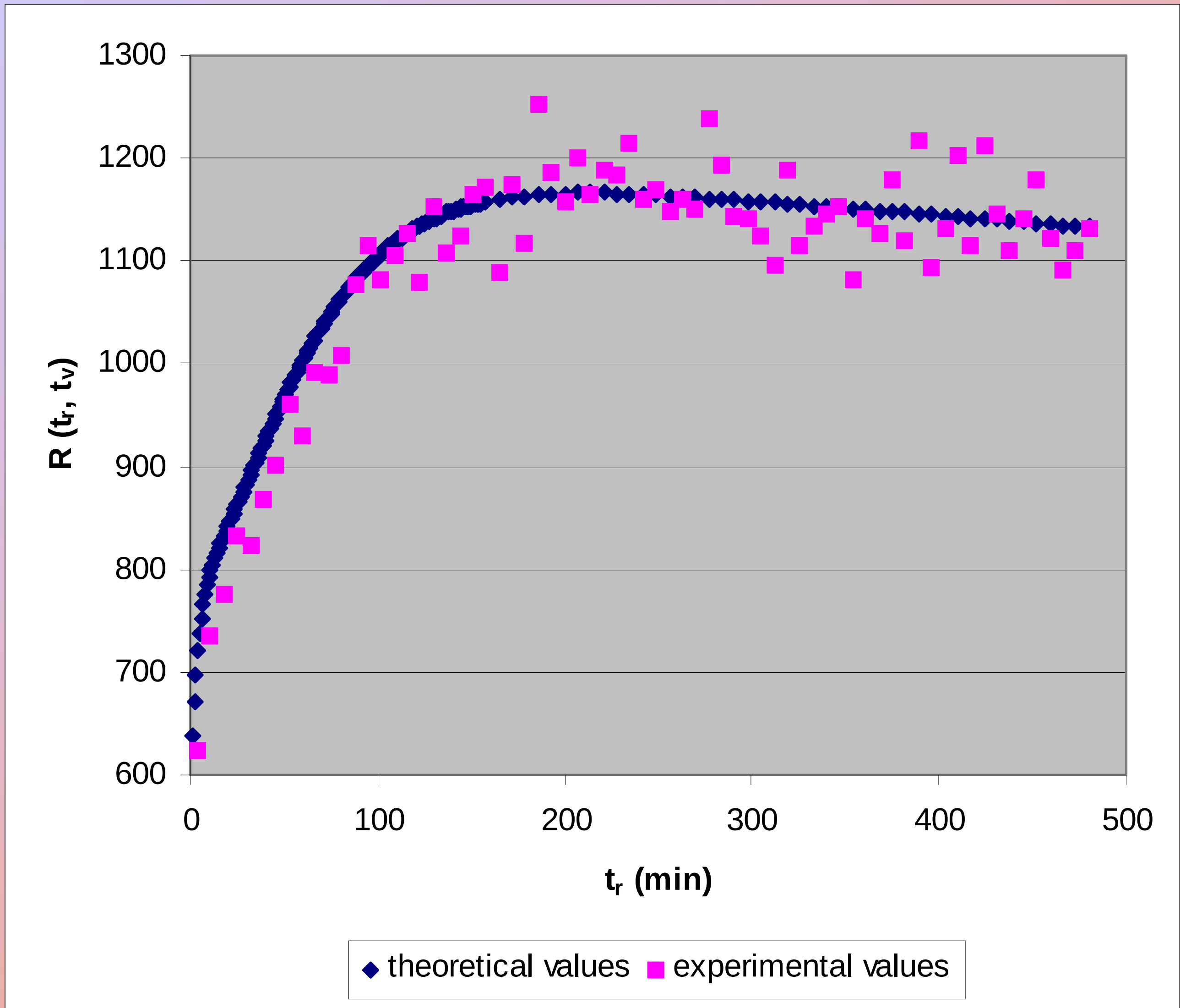
where

$$W_1 = (1/\lambda_1) + [\lambda_2/(\lambda_1 .(\lambda_2 - \lambda_1))] + [\lambda_2 \cdot \lambda_3 \cdot \lambda_4 /(\lambda_1 .(\lambda_4 - \lambda_1).(\lambda_3 - \lambda_1).(\lambda_2 - \lambda_1))],$$
$$W_2 = [1/(\lambda_2 - \lambda_1)] + [\lambda_3 \cdot \lambda_4 /((\lambda_4 - \lambda_2).(\lambda_3 - \lambda_2).(\lambda_2 - \lambda_1))],$$
$$W_3 = \lambda_2 \cdot \lambda_4 /((\lambda_4 - \lambda_3).(\lambda_3 - \lambda_2).(\lambda_3 - \lambda_1)),$$
$$W_4 = \lambda_2 \cdot \lambda_3 /((\lambda_4 - \lambda_3).(\lambda_4 - \lambda_2).(\lambda_4 - \lambda_1)),$$

and

λ_1	$/s^{-1}/$	is the ^{222}Rn decay constant,
λ_2	$/s^{-1}/$	is the ^{218}Po decay constant,
λ_3	$/s^{-1}/$	is the ^{214}Pb decay constant,
λ_4	$/s^{-1}/$	is the ^{214}Bi decay constant.

Calculated (theoretical) values of R (t_v, t_r) are in a relatively good agreement with experimental values of R (t_v, t_r), which were obtained by repeated measurements of the same soil-gas sample.



In practice, different measuring modes are used depending on the measurement purposes.

In general, it is possible to start the counting in any moment after the transfer of the sample into the detector and to use the above mentioned equations,

or it is possible to start the counting in a fixed time after the transfer of the sample and to calculate the value of the measured parameter using a calibration constant, which had been previously determined for the chosen time interval with a calibration source.

⇨ INSTRUMENTATION

The initial development of soil-gas radon concentration measurements and of radon risk mapping in the Czech republic was connected with the scintillation method.

The family of devices called LUK first appeared in 1991.

As the measured soil-gas radon concentrations are relatively high ranging from 0.1 to several hundred of kBq.m^{-3}, the sufficient volume of Lucas cells is about 100 ml.

A relatively new device based on **ionization chambers** and designed for the in situ soil-gas radon concentration measurement was developed several years ago.

The detection principle of the measuring system called **RM - 2** is based on an ionization chamber operating in a current mode.

The substantial characteristic features of the system are: very easy operating and control modes; applicability of the device under demanding weather conditions; simple decontamination of chamber inner surfaces from radon progeny deposition.

The measuring system consists of a set of cylindrical ionization chambers IK-250 with a detection volume of 250 ml and an electrometer ERM-3 (voltage reader device).

In the upper part of the chamber, there is located a inlet valve with a silicon hose, providing input of the soil-gas sample into the inner detection volume. The input hose can be equipped with a filter providing a radon decay products suppression.

The detection system operates in two measuring modes,

(i) measurement starting 15 minutes after the transfer of the sample into the chamber and

(ii) standard equilibrium measurement.

Time period needed for the measurement of one sample is 120 s.

The soil-gas is used as an operating detection gas inside the ionization chamber. The detector operates in a non-saturated mode of a volt-ampere characteristic. The operating voltage between electrodes of the chamber is 40 V.

Spatial and temporal variability of soil-gas radon concentration

In our experience, spatial variations of soil-gas radon concentrations are more important than temporal ones. The soil-gas radon concentrations may vary, often greatly, over a small distance. The occurrence of heterogenities may indicate the presence of faults or tectonic zones.

As the areas with a homogeneous geological structure and with a homogeneous soil-gas radon concentration are rare, any evaluation based on a single measurement is almost worthless.

On the other hand, the occurrence of spatial variations represents a serious reason, why protection of a buildings should be based on the results of a building site characterization, not on large scale radon risk maps.

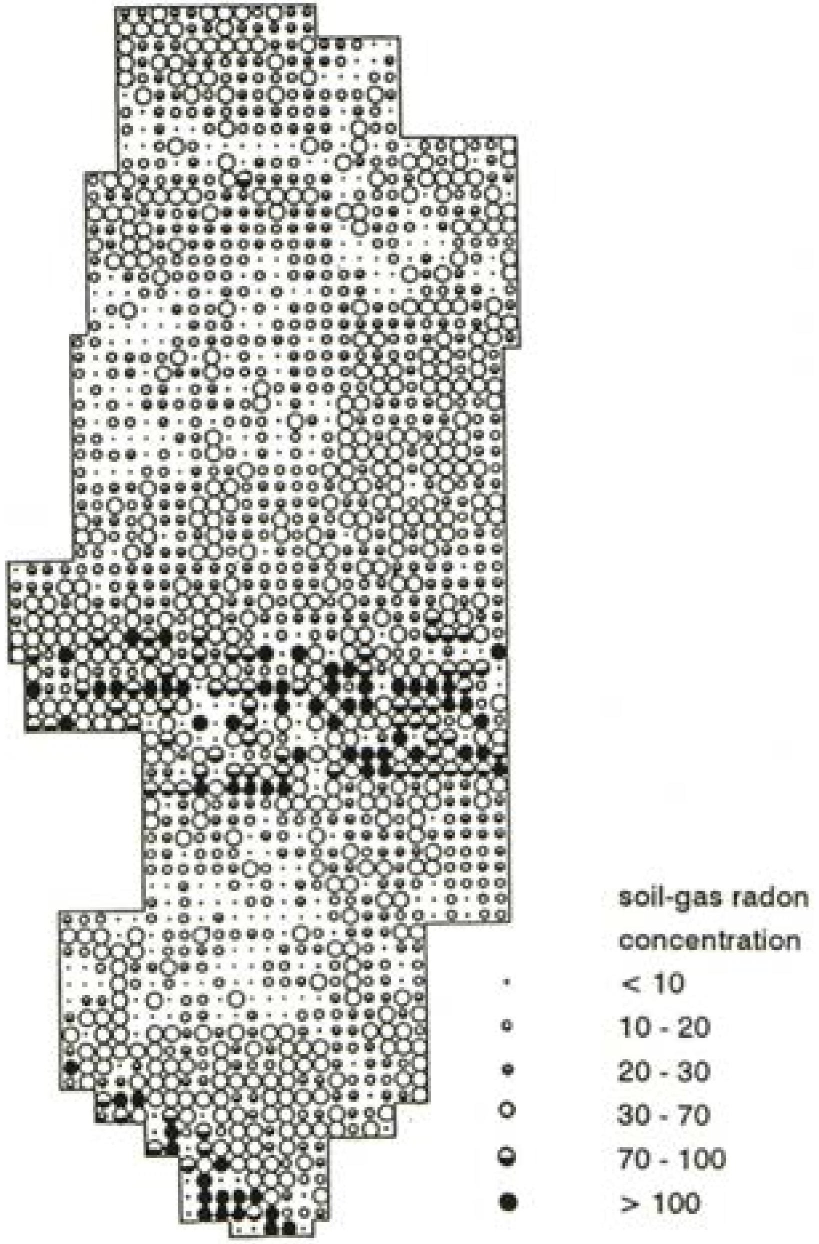


Fig. 2. Spatial variability of soil-gas radon concentration ($kBq \cdot m^{-3}$), Chaby, Prague, 1990.

EXAMPLE:

Detailed radon survey of a large area in Chaby, Praha (1990):

1689 soil-gas samples in the scale 10 x 10 m,

range from 0.4 to 248 kBq/m^3.

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1991): Radon infiltration risk from the ground in Chaby, Prague, in Radon investigations in Czechoslovakia, edited by I. Barnet (Czech Geological Survey, Prague), Vol. 2, pp. 34-39.

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1996): Assessment of Radon Potential of Soils - A Five Years Experience. Environment International 22, pp. S819-S828

STATISTICAL EVALUATION OF MEASUREMENT RESULTS

The frequency distribution of measured soil-gas radon concentrations need not be normal.

1993: almost 90 randomly chosen data sets were analysed

The distribution of a significant part of data sets was heterogeneous, i.e. neither a normal nor a log-normal models were found to give an adequate fit to the radon concentration data.

2000-2001: detailed analysis of 13 large data sets and of 30 smaller ones

When data sets with a larger variability are evaluated, a substitution of the grid 20 x 20 m for the grid 10 x 10 m causes a substantial enlargement of confidence intervals for the median and for the third quartile.

In case of small data sets (15 soil gas radon concentration values corresponding to a building area for a single family house), the correctness of the statistical evaluation is more or less disputable in the majority of cases.

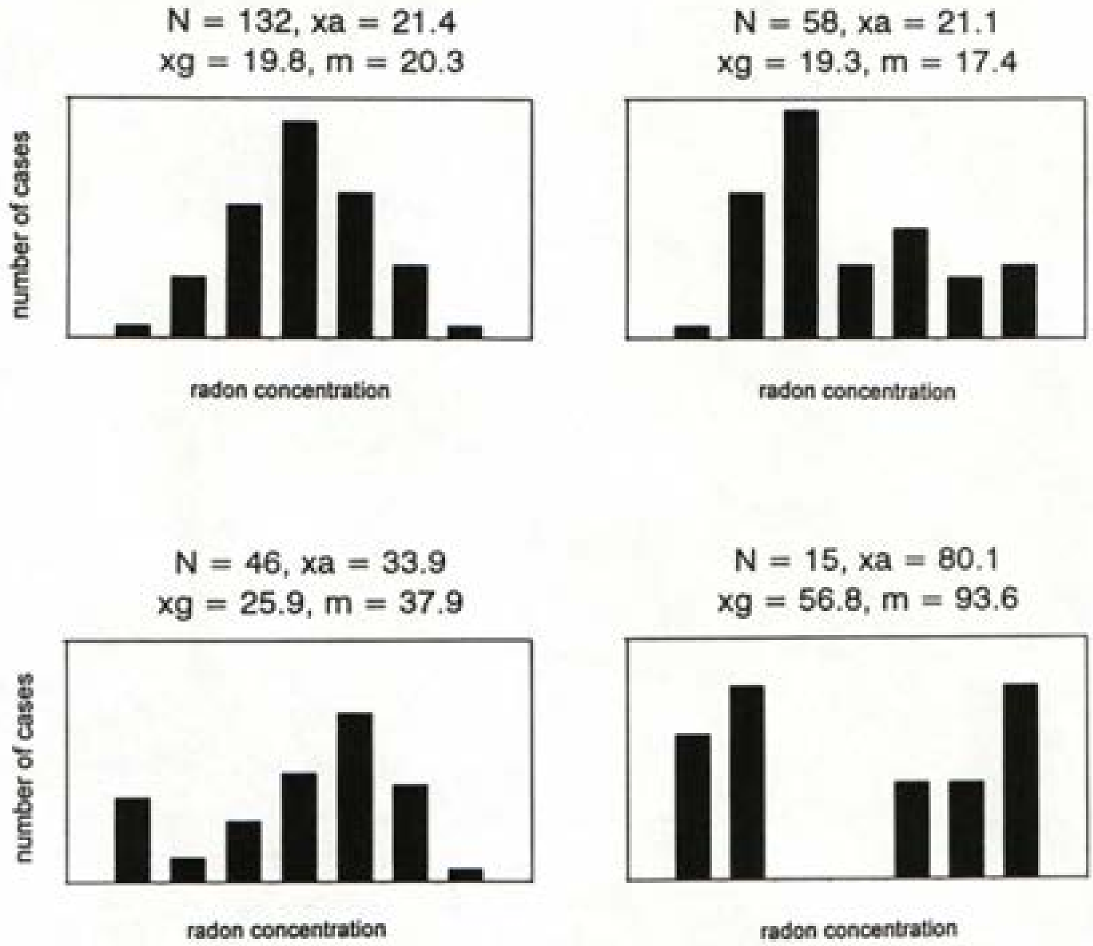


Fig. 7. Examples of observed soil-gas radon concentration ($kBq \cdot m^{-3}$) frequency distributions. N = total number of measuring points; xa = arithmetic mean; xg = geometric mean; m = median.

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1996): Assessment of Radon Potential of Soils - A Five Years Experience. Environment International 22, pp. S819-S828

⇨ **From the statistical point of view, there is no reason to decrease the minimal number of measuring points, i.e. at least 15 measurements**

(if the building area is larger than 800 m^2, measurements are made at a scale 10 x 10 m).

Robust nonparametric estimates such as median or the third quartile are supposed to be the best parameters for the description for soil-gas radon concentration data.

TEMPORAL VARIATIONS – REPRODUCIBILITY OF EVALUATION

As the protection of new buildings against radon penetration from the ground is based on in-situ measurements, possible influence of temporal variations of measured parameters on the evaluation results is very important.

Several long-term research projects dealing with this problem have been carried out.

EXAMPLE A_T:

1990 – 1992: A 14-month observation of the soil-gas radon concentration using two permanently installed probes at two test sites distanced several meters was performed.

The geological structure was almost the same at both sites: sandstone weathering residuum covered by fine-grained sand with loamy admixtures. At site 1, the soil surface had been contaminated by natural radionuclides in the past.

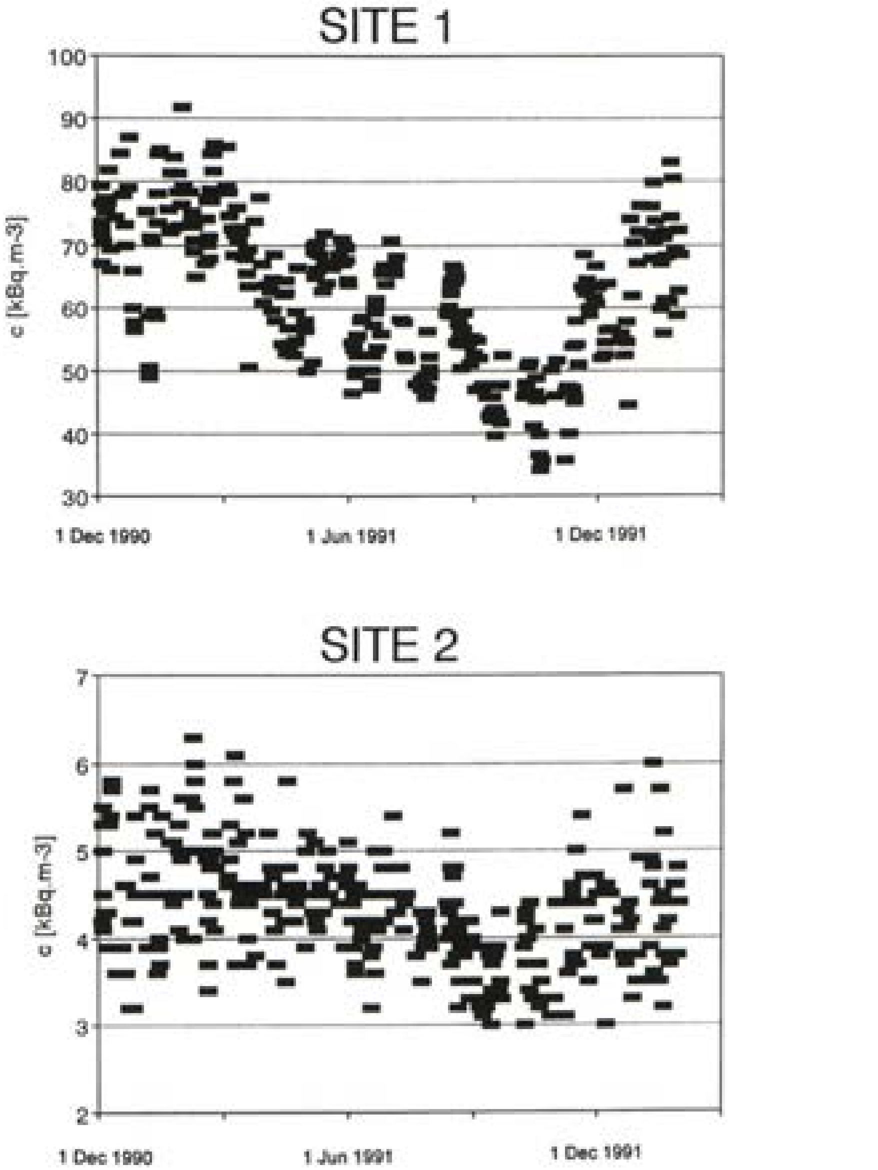


Fig. 4. Temporal variations of soil-gas radon concentration, December 1990 - January 1992.

Site 1: range from 34.1 kBq.m^{-3} to 91.8 kBq.m^{-3} (number of measurements: 270), arithmetic mean = 60.2 kBq.m^{-3}, standard deviation (SD) = 11.3 kBq.m^{-3}, SD/mean = 0.19.

Site 2: range from 3.0 kBq.m^{-3} to 6.3 kBq.m^{-3} (number of measurements: 270), arithmetic mean = 4.3 kBq.m^{-3}, SD = 0.6 kBq.m^{-3}, SD/mean = 0.15.

The general temporal pattern was represented by higher winter/spring and lower summer/autumn values, but seasonal variations were not so large.

Short-term changes of radon concentrations at site 1 and at site 2 were often different, or even opposite.

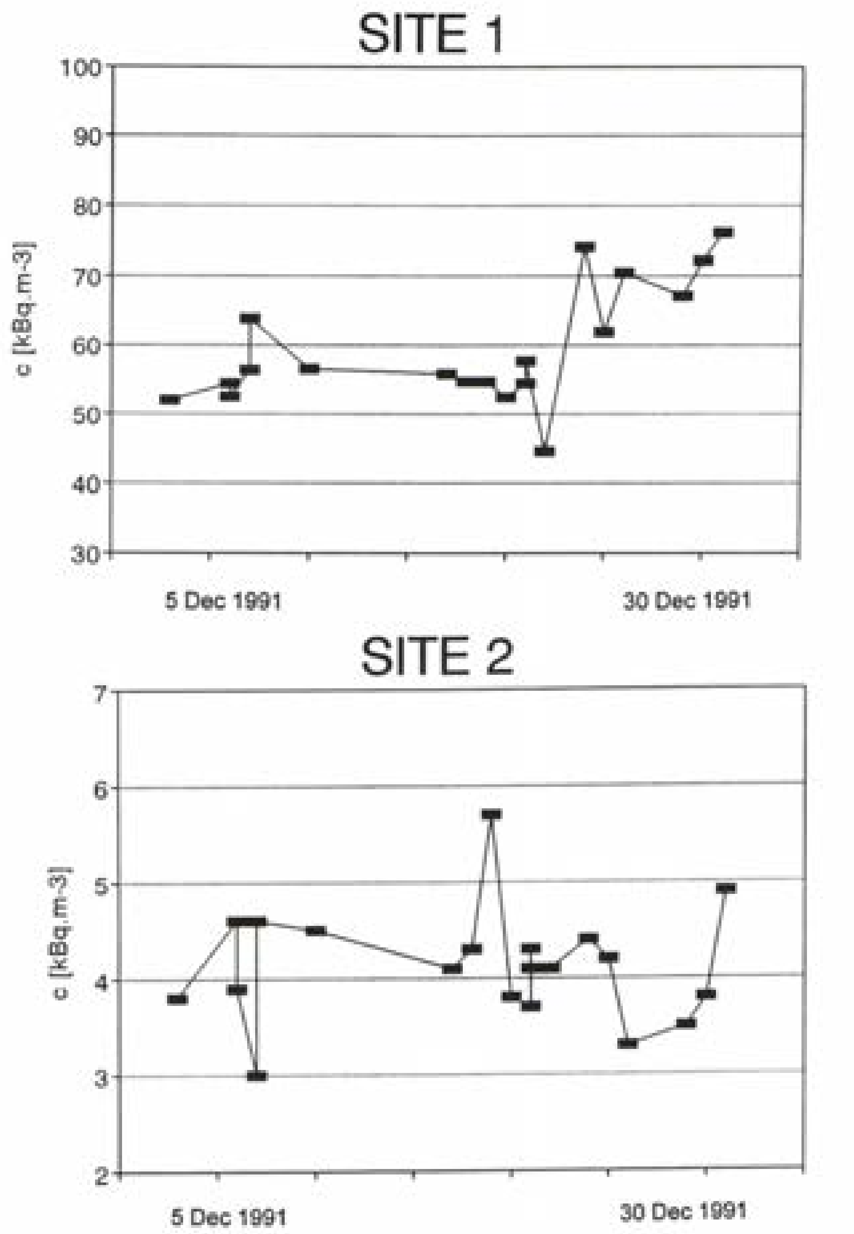


Fig. 5. Temporal variations of soil-gas radon concentration, December 1991.

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1992): Temporal Variations od Soil Gas Radon Concentration, in Radon investigations in Czechoslovakia, edited by I. Barnet (Czech Geological Survey, Prague), Vol. 3, pp. 6-12.

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1996): Assessment of Radon Potential of Soils - A Five Years Experience. Environment International 22, pp. S819-S828

EXAMPLE B_T:

1992 – 1993: **Repeated soil-gas sampling at five reference areas with different geological structure and soil permeability were performed. Two different soil-gas sampling methods were tested:**

(a) "probes", i.e. the standard sampling method using small-diameter probes (the probes were pounded into the ground anew every measuring day, i.e. the location of measuring points was not exactly constant),

(b) "chambers", i.e. the soil-gas samples were collected from cylindrical chambers permanently installed in the soil.

Measurements were repeated nine times at 25 measuring points at each reference area, using both methods. Average values of soil-gas radon were compared.

Table 2. Relation between average soil-gas radon concentration (c) and soil temperature (T) / soil moisture (M).

Area (permeability)	Sampling	Correlation coefficient c, T	Correlation coefficient c, M
Ruprechtice (high)	probes	- 0.36	0.29
	chambers	- 0.54	0.59
Rynoltice (high)	probes	- 0.68	0.86
	chambers	- 0.62	0.76
Dolní Suchá (medium)	probes	- 0.12	- 0.72
	chambers	0.56	0.36
Na Rozkoši (medium)	probes	- 0.13	0.36
	chambers	0.30	- 0.46
Ostašov (low)	probes	- 0.41	0.27
	chambers	0.16	- 0.13

Only a weak relationship between average soil-gas radon concentration and soil temperature, and between radon concentration and soil moisture has been observed.

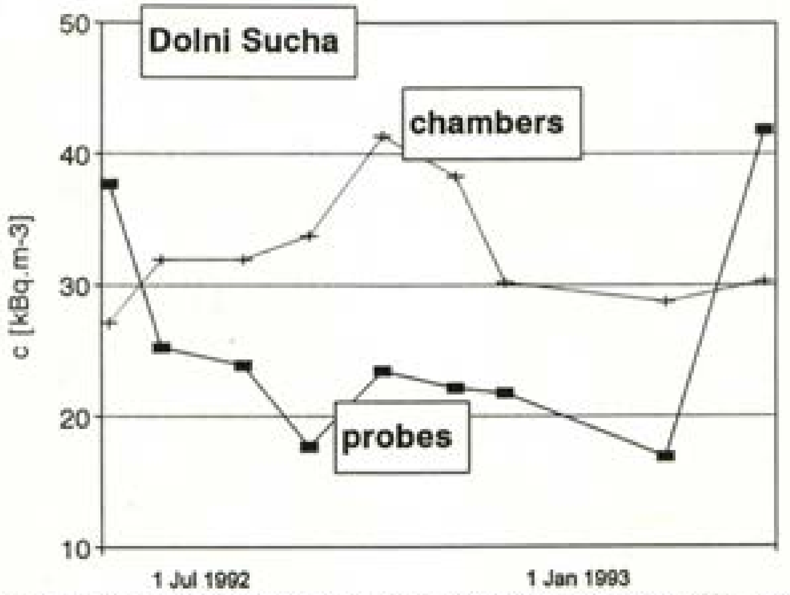


Fig. 6. Temporal variations of average soil-gas radon concentration, May 1992 - May 1993.

It seemed to be different for different sampling methods. Different correlations coefficients were obtained at areas with different geological structure.

CONCLUSIONS:

⇨ Observed temporal variations of soil gas radon concentrations often corresponded not only to real variations of the measured physical parameter, but also to fluctuations and errors connected with sampling and measuring techniques.

⇨ The influence of changing meteorological conditions might not be as important as the influence of changing sampling depth, the influence of geological heterogenities, and the influence of sampling and measuring errors.

⇨ The highest values of average soil-gas radon concentration obtained at any area during a 1-y period were about two times the lowest ones (more exactly from 1.5 to 2.5).

Reproducibility of the classification method:

Table 3. Repeated radon risk classification based on the sum of the arithmetic mean and of the standard deviation of population.

Area (permeability)	Category of risk (month)								
	5 92	6 92	7 92	9 92	10 92	11 92	12 92	3 93	5 93
Ruprechtice (high)	h	h	h	h	h	h	h	*	h
Rynoltice (high)	m	l	m	m	m	m	m	m	m
Dolní Suchá (medium)	m	m	m	m	m	m	m	m	m
Na Rozkoši (medium)	m	m	m	m	m	m	m	m	m
Ostašov (low)	h	m	h	m	m	m	*	*	m

l - low, m = medium, h = high risk area
* two areas were inaccessible in winter

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1995): Temporal Variability od Soil-Gas Radon Concentration - Some Remarks, in Gas Geochemistry, edited by C. Dubois (Northwood) Science Reviews, pp. 529-534.

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1996): Assessment of Radon Potential of Soils - A Five Years Experience. Environment International 22, pp. S819-S828

EXAMPLE C_T:

1994 – 1995: **Measurements at the test site on the surface of the uranium mill tailings confirmed previous results.**

Temporal variability of soil-gas radon concentration expressed as the ratio (SD/mean) decreased with the depth below the surface:

SD/mean was lower than 0.10 at the depths of 1.5 and 0.8 m,

while it ranged from 0.13 to 0.25 at the depths from 0.5 to 0.3 m.

NEZNAL, M. – PERNICKA, F. (1996): Temporal Changes of Soil-Gas Radon Concentration at a Test Site - Uranium Mill Tailings, in Radon investigations in the Czech Republic, edited by I. Barnet (Czech Geological Survey, Prague), Vol. 6, pp. 79-87.

EXAMPLE D_T:

2000 – 2002: Repeated measurements of soil-gas radon concentrations at several test sites were performed.

Reproducibility of the classification method (based on the radon potential of building sites)

2000-2001							
Month	07	09	11	01	03	05	07
Area Dubnice	m	m	m	m	m	m	m
Month	08	10	12	02	04	06	08
Area Žibřidice	h	h	h	h	h	h	h

l = low radon index

m = medium radon index

h = high radon index

2001-2002													
Month	03	04	05	06	07	08	09	10	11	12	01	02	03
Area Lysá n. L.	m	l	l	l	l	l	m	l	l	l	l	m	l
Month	03	04	05	06	07	08	09	10	11	12	01	02	03
Area Kocanda	m	m	m	m	m	m	m	m	m	m	m	m	m
Month	11	01	02	03	04	05	06	07	08	09	10	11	12
Area Klánovice	l	l	l	l	l	l	l	l	l	l	l	l	l

CONCLUSIONS CONCERNING THE REPRODUCIBILITY:

⇨ Temporal variations of soil-gas radon concentration and of soil permeability occur, but their influence is not critical.

⇨ The sampling depth of 0.8 m represents a relatively good compromise between the required reduction of errors caused by the radon concentration variability and the required reduction of weather effects on the one side and the practicability of the method under field conditions on the other side.

⇨ The probability that any area will be classified as a low radon index area and after several months as a high radon index one is very low.

The reproducibility of the radon index classification is satisfactory.

It is evident that the conclusions are valid for the geological and meteorological conditions that are typical for the Czech Republic, or maybe for Central Europe. The situation in other countries with a substantially different climate or geology may be different.

VARIATIONS OF SOIL-GAS RADON CONCENTRATION WITH DEPTH

EXAMPLE A_D:

1993 – 1994: **Eight reference areas with various geological settings were chosen with respect to the characteristics of the underlying bedrock, origin, permeability and stratification of soil deposits, and depth and variability of groundwater level.**

Soil-gas radon concentration as well as soil permeability were determined at depths of 0.3, 0.6, 0.9, 1.2 and 1.5 m.

Fifteen measurements were made at each depth and at each reference area - average values were evaluated.

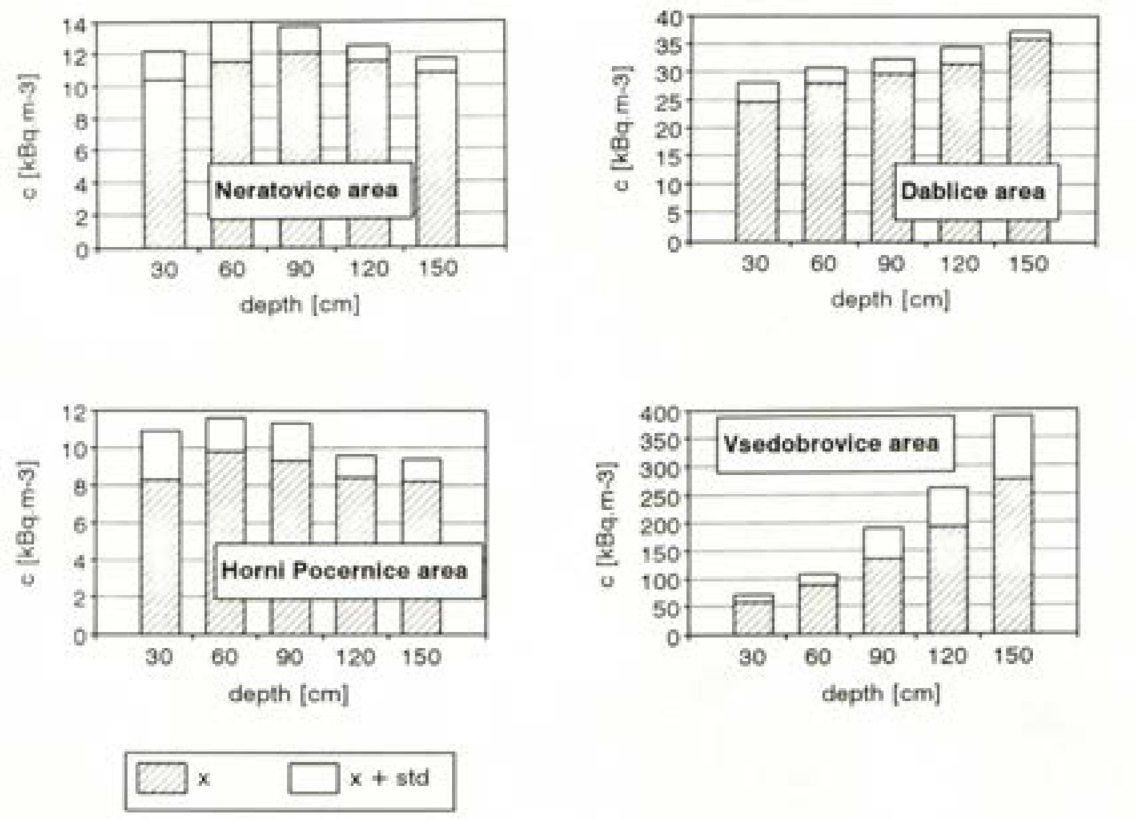


Fig. 3. Variability of soil-gas radon concentration with depth (x = arithmetic mean; std = standard deviation).

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1994): Variability of Radon with Depth in Various Soil Profiles, in Radon investigations in the Czech Republic, edited by I. Barnet (Czech Geological Survey, Prague), Vol. 5, pp. 55-61.

NEZNAL, M. – NEZNAL, M. – SMARDA, J. (1996): Assessment of Radon Potential of Soils - A Five Years Experience. Environment International 22, pp. S819-S828

Variability of radon concentration with depth was different at areas with different geological characteristics.

Almost constant soil-gas radon concentration was observed at areas with relatively homogeneous and highly permeable Quarternary fluvial sands covered by clayey loams, or in case of highly permeable eluvial deposits of Cretaceous sediments - sands covered by sandy loams.

Insignificant increase of radon concentration with depth was measured at areas with relatively homogeneous and medium permeable loess loam.

Significant increase of radon concentration with depth was observed at areas with granodiorites characterized by extensive weathering and by high radon potential.

EXAMPLE B_D:

The collection of soil-gas samples in low permeable soils is often complicated due to a high resistance that must be overcome.

An enlargement of the cavity, from which the samples are taken, is then required.

This action may affect the measurement result.

⇨ 2000: A relationship between the soil-gas radon concentration and the changing sampling geometry was studied at four reference areas characterized by low permeable soils and/or by a high soil moisture.

At each reference area: nine measuring points.

At each measuring point: soil-gas samples collected from different sampling depths using different dimensions of the active area.

Following seven cases were tested:

‚geometry 60(2)cm‘

- sampling depth 60 - 62 cm, height of the cavity 2 cm;

‚geometry 80(2)cm‘

- sampling depth 80 - 82 cm, height of the cavity 2 cm;

‚geometry 80(5)cm‘

- sampling depth 80 - 85 cm, height of the cavity 5 cm;

‚geometry 80(10)cm‘

- sampling depth 80 - 90 cm, height of the cavity 10 cm;

‚geometry 70-90cm‘

- sampling depth 70 - 90 cm, height of the cavity 20 cm, (the probe was retracted back to the surface);

‚geometry 60-90cm‘

- sampling depth 60 - 90 cm, height of the cavity 30 cm;

‚geometry 40-90cm‘

- sampling depth 40 - 90 cm, height of the cavity 50 cm.

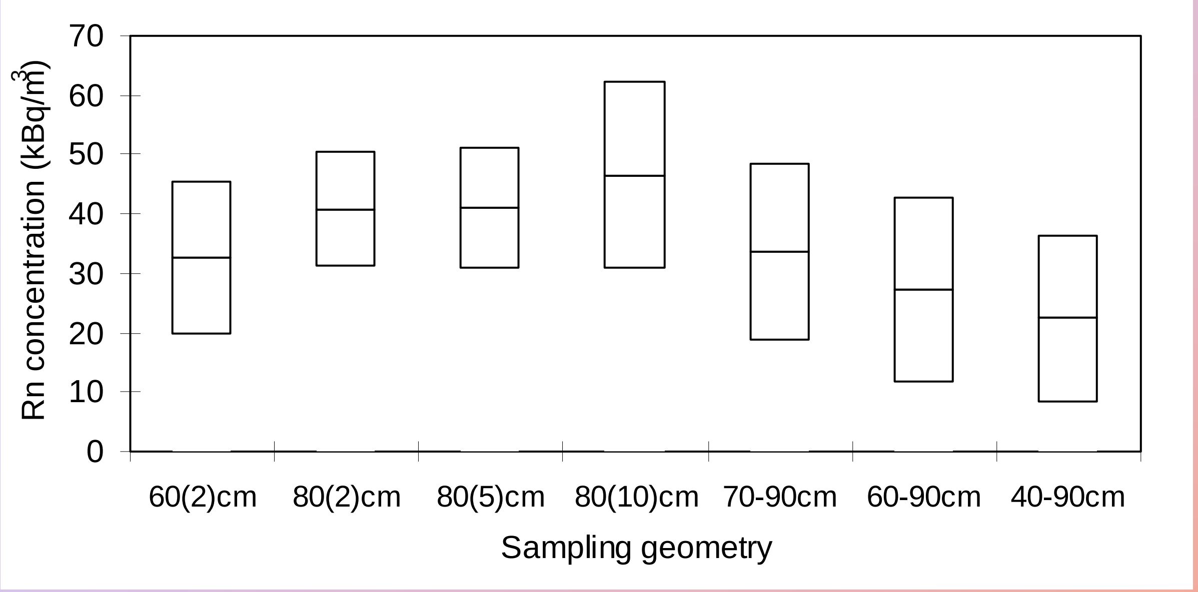


Fig. 1. Reference area Svetice: Soil-gas radon concentration (arithmetic mean ± standard deviation) vs. sampling geometry.

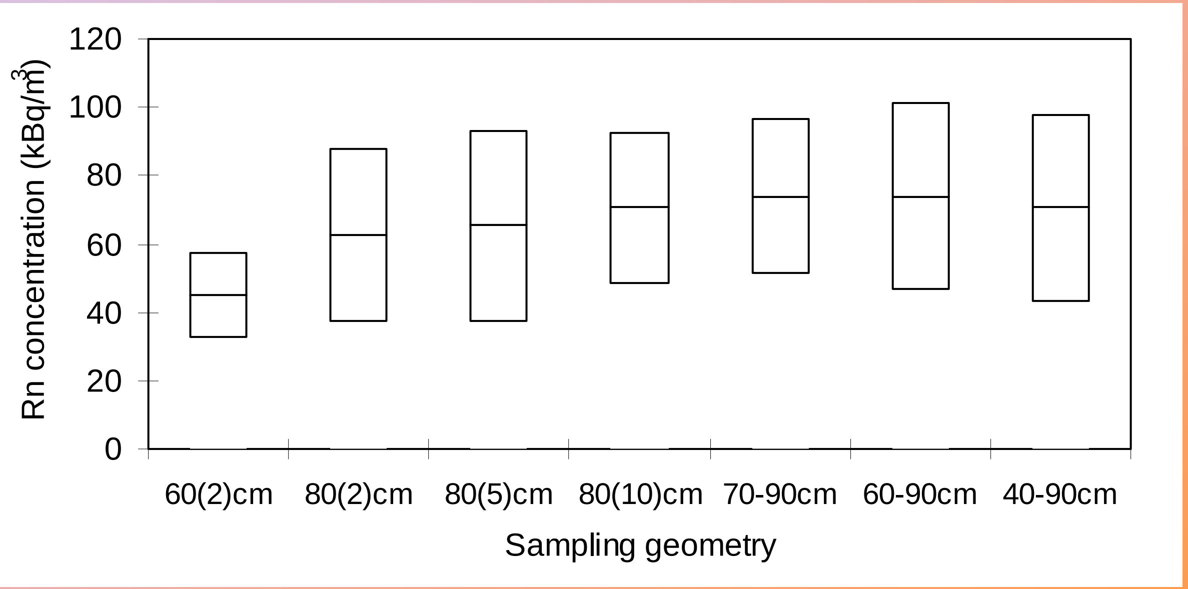


Fig. 2. Reference area Ptice: Soil-gas radon concentration (arithmetic mean ± standard deviation) vs. sampling geometry.

Relative comparison of average soil-gas radon concentrations obtained using different sampling geometry

Geometry	Reference area			
	Svetice	Dubnice	Ptice	Ruzena
60(2)cm	0.79	0.82	0.69	0.59
80(2)cm	0.99	1.01	0.96	0.90
80(5)cm	1.00	1.00	1.00	1.00
80(10)cm	1.13	1.02	1.08	0.94
70-90cm	0.82	0.93	1.13	0.95
60-90cm	0.66	0.62	1.13	0.77
40-90cm	0.55	0.39	1.08	0.67

CONCLUSIONS CONCERNING THE VARIABILITY OF SOIL-GAS RADON CONCENTRATION WITH DEPTH AND THE SAMPLING GEOMETRY:

⇨ **Measured soil-gas radon concentrations do not depend on changing sampling geometry if the soil layer is homogeneous and low permeable.**

Reference area Ptice: no decrease of soil-gas radon concentration, even when the height of the active area was increased to 50 cm („geometry 40-90cm“).

⇨ **A decrease of soil-gas radon concentration with increasing dimensions of the active area indicates that the vertical soil profile is not homogeneous and that the soil permeability is higher in shallow depths.**

The upper part of the cavity reaches the more permeable soil layers with lower radon concentration. Due to a lower resistance, the soil-gas sample is collected mostly from the upper part of the active area.

⇨ **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 (under certain condition to 0.5 m below the surface). A similar approach can be used when the sampling layer is saturated with water.**

⇨**A good knowledge of the vertical soil profile is very important for a correct interpretation of measured soil-gas radon concentrations.**

⇨ **A perfect sealing of all parts of the equipment is required when soil-gas samples are collected in low permeable soils.**
Reference area Ptice: The collection of a 100 ml soil-gas sample took very often more than 10 minutes.

NEZNAL, M. – NEZNAL, M. (2002): Determination of Soil Gas Radon Concentration in Low Permeable Soils. In: Book of Abstracts, Seventh International Symposium Natural Radiation Environment. Rhodes, pp. 319 – 320.

Determination of soil permeability: RADON-JOK

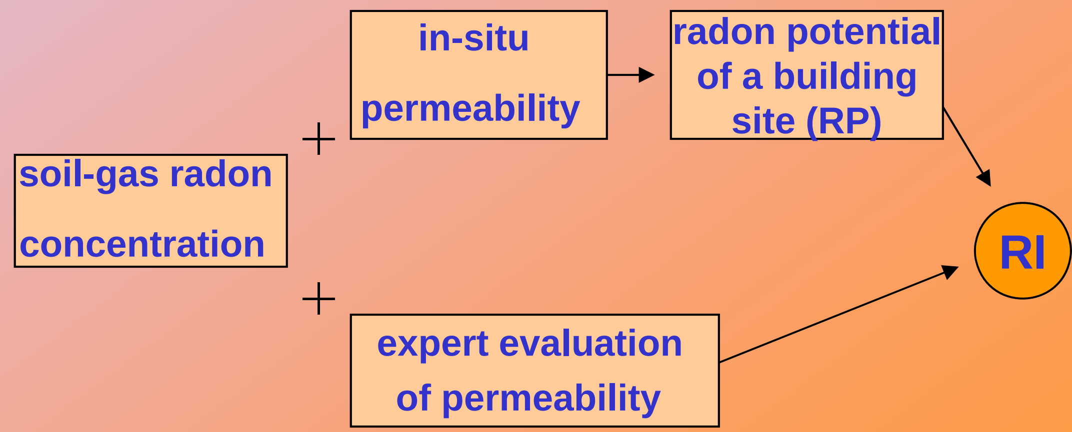
(= the second decisive factor in determining the radon index of a building site)

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.

The permeability of soils can be determined by:

⇨ **direct *in situ* permeability measurements (***the permeability is given in* m^2**),**

⇨ **expert evaluation of permeability (***leads to assigning the low – medium – high categories***).**



Original classification method (1991):

The permeability was derived from the weight percentage of fine fraction (< 0,063 mm) in a soil sample.

Permeability	**Weight percentage of fine fraction ‚f‘ (< 0,063 mm)**
high	*f < 15 %*
medium	*15 % < f < 65 %*
low	*f > 65 %*

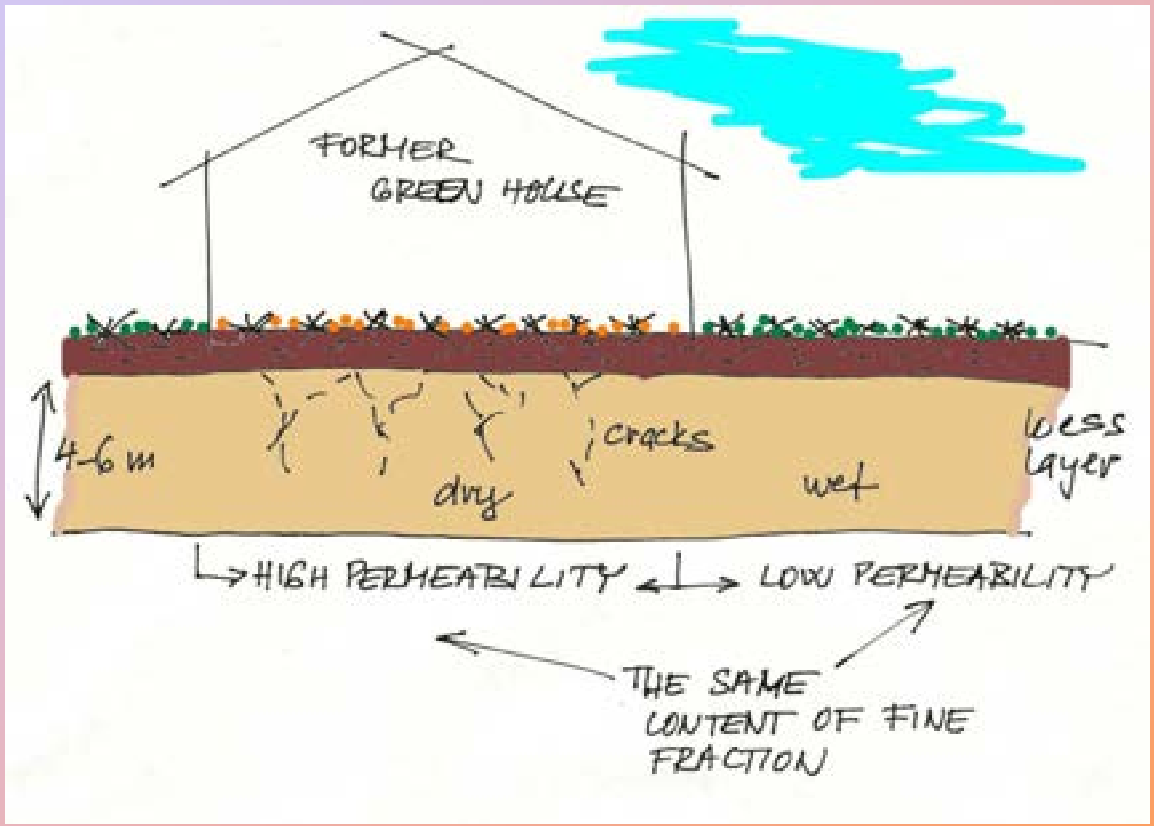
BUT:

The grain size analysis of two different samples may give similar results, although the real permeabilities are quite different.

EXAMPLE A_P:

Loess is a typical example of soil with a high amount of the fine fraction, very often higher than 70 %, which leads to its classification as a low permeable environment.

But if the soil moisture is low, e.g. due to a weak precipitation, the loess layer may become medium or even high permeable.



Note: The radon potential was similar in the whole area, because the soil-gas radon concentration values under the green-house was substantially lower than the soil-gas radon concentration outside the green-house.

EXAMPLE B_P:

Fluvial sands from river terraces are mainly high permeable due to their typical grain size.

But if the sands have high soil moisture, i.e. almost all poruses are filled with water, the efective porosity gets near zero and the permeability is low.

⇨ modifications of the original method (1994, 2004)

NOWADAYS PRACTICE:

The permeability of soils and rocks for gases can be determined by direct in situ permeability measurements or by an expert evaluation.

DIRECT IN-SITU PERMEABILITY MEASUREMENT

The methods consist 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).

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

⇨ The requirements for the number of measurements are the same as for the soil gas radon concentration measurements, i.e. at least 15 measuring points (if the building area is larger than 800 m^2, measurements are made at a scale 10 x 10 m).

⇨ The same statistical parameter, i.e. the third quartile of the data set, is used as a decisive value for the assessment.

The internal surface area of the cavity formed by pounding out the free tip must be exactly defined for each measurement system.

⇨ The same system as for the soil-gas sample collection can be used:

A distance ring and a distance screw allow to keep a constant height of the cavity at the lower end of the sampling probe.

Inserting of the distance ring.

The sharp tip is moved to the exact distance using the punch wire and the adjusted distance screw.

Inserting of the punch wire into the probe.

Screwing the distance screw till it touches the distance ring.

Various devices can be used.

Due to the lack the gas permeability standardization, the results obtained from various devices should be standardized against the RADON-JOK device, widely used in the Czech Republic.

RADON-JOK (= a portable equipment for in situ measurements of gas permeability of soils)

Principle: air withdrawal by means of negative pressure

The air is pumped out from the soil under constant pressure through a specially designed probe with a constant surface of contact between the probe head and the soil. A special rubber sack, with one or two weights, pumps the air from the soil and allows to perform measurements at very low pressures.

The gas permeability is derived from the air flow through the probe. The air flow is given by the known volume of air (= 2000 ccm) in the rubber sack - depression of the bottom of the sack between two notches - and by the pumping time measured.

Measurements are performed independently of any source of energy (electricity, compressed air).

one or two weights

rubber sack (2000 ccm)

Theoretical framework for the gas permeability measurement is based on Darcy´s equation. The soil is assumed to be homogeneous and isotropic and a standard state is considered. The air is assumed to be incompressible (pressure differences are very much smaller than the atmospheric pressure). The air flow can be expressed by the equation:

$$Q = F \,.\, (k / \mu) \,.\, \Delta p$$

where

Q	**/$m^3.s^{-1}$/**	**is the air flow through the probe,**
F	**/m/**	**is the shape factor of the probe (depending on its geometry),**
k	**/m^2/**	**is the gas permeability of the soil,**
μ	**/Pa.s/**	**is the dynamic viscosity of air (at 10°C μ = 1,75 . 10^{-5} Pa.s),**
Δp	**/Pa/**	**is the pressure difference between surface and the active area of the probe.**

KOOREVAAR, P. – MENELIK, G. – DIRKSEN, C. (1983): Elements of soil physics. Developments in Soil Science 13. Elsevier Science Publishers B.V., The Netherlands, 228 p.

Determination of the shape factor of the probe:

$$F = 2 \, . \, \pi . \, L \; / \; \ln \; \{ 2. \, L \, . \, [(4D-L)/(4D+L)]^{1/2} \; / \; d \; \}$$

where

L	**/m/**	**is the length of the active area of the probe head,**
d	**/m/**	**is the diameter of the active area,**
D	**/m/**	**is the depth below the surface**

and the approximation l >> d has been used.

DAMKJAER, A. – KORSBECH, U. (1992): A small-diameter probe for in-situ measurements of gas permeability of soils, Radiation Protection Dosimetry, Vol. 45 No. 1/4, pp. 85-89.

RADON-JOK

shape factor F = 0,149 m (L = 50 mm, d = 12 mm, D = 825 mm),

measuring range: approx. from k = 10^{-11} m^2 to k = 10^{-14} m^2

The maximum detection limit (measured time of 8 s corresponds to k = 1.4 10^{-11} m^2) is given by the resistance of the equipment.

The minimum detection limit depends on the time spent in any given measurement (measured time of 3600 s corresponds to k = 1.7 10^{-14} m^2).

It is possible to extend the range to higher values using a probe with a reduced shape factor.

Recommended permeability classification (Czech Republic):

boundary between high and medium permeability k = 4.0 10^{-12} m^2

boundary between medium and low permeability k = 4.0 10^{-13} m^2

EXPERT EVALUATION OF SOIL PERMEABILITY

The evaluation 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 (large amount 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 their permeability (low – medium – high). Estimating the proportion of the fine fraction (particle size <0.063 mm) is also necessary in this classification.

⇨ Evaluating the resistance encountered when drawing the soil gas samples for the radon concentration measurements in all sampling points, and estimating the prevailing permeability category (low – medium – high).

For the evaluation of spatial variatiability, at least two hand drill tests must be performed in case of a small building site (≤ 800 m^2). If the building area is larger than 800 m^2, at least one more drilling must be added for each additional 30 sampling points.

The following questions should be considered whenever the expert soil permeability evaluation is 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?*

Comments concerning the determination of soil permeability:

2001-2002: Detailed measurements from more than 20 areas have been used for comparing the results obtained using different methods of permeability determination.

At most areas the final classification based on the vertical profile assessment was consistent with the results of direct *in-situ* measurements, and partly with the data derived from particle size analysis.

⇨ Where the permeability derived from particle size analysis is contradictory, the underestimation of permeability is caused mainly by low soil moisture and/or by the occurrence of significant macro- and micro-fissures.

⇨ Overestimated permeability can be observed especially in fine-grained sands with relatively high soil moisture.

Statistical evaluation:

Individual permeability values are substantially affected by small-scale changes of the measured soil volume, especially in areas of medium to low permeability.

The statistical evaluation can be affected by the occurrence of high permeability outliers, and by inexact values under the lower limit in cases of extremely low permeability.

⇨ A large number of measurements should be required for evaluating *in-situ* measurements of permeability.

Most common errors and failures connected with soil-gas radon concentration measurements and causes of the failures

Measurement of soil-gas radon concentration

Large range of applications:

Applications dealing with radon risk management - drawing up of radon potential maps, defining radon-prone areas, characterisation of radon potential of building sites, characterisation of soil contaminated with radium-226, defining mitigation techniques to be applied in a building, verification of applied mitigation techniques, etc.

Phenomenological observation - understanding radon transport mechanisms in the soil and from the soil into the building, identification and analysis of radon entry parameters, earthquake prediction, etc.

Large range of methods:

spot / continuous / integrated measurement methods connected with active / passive soil-gas sampling

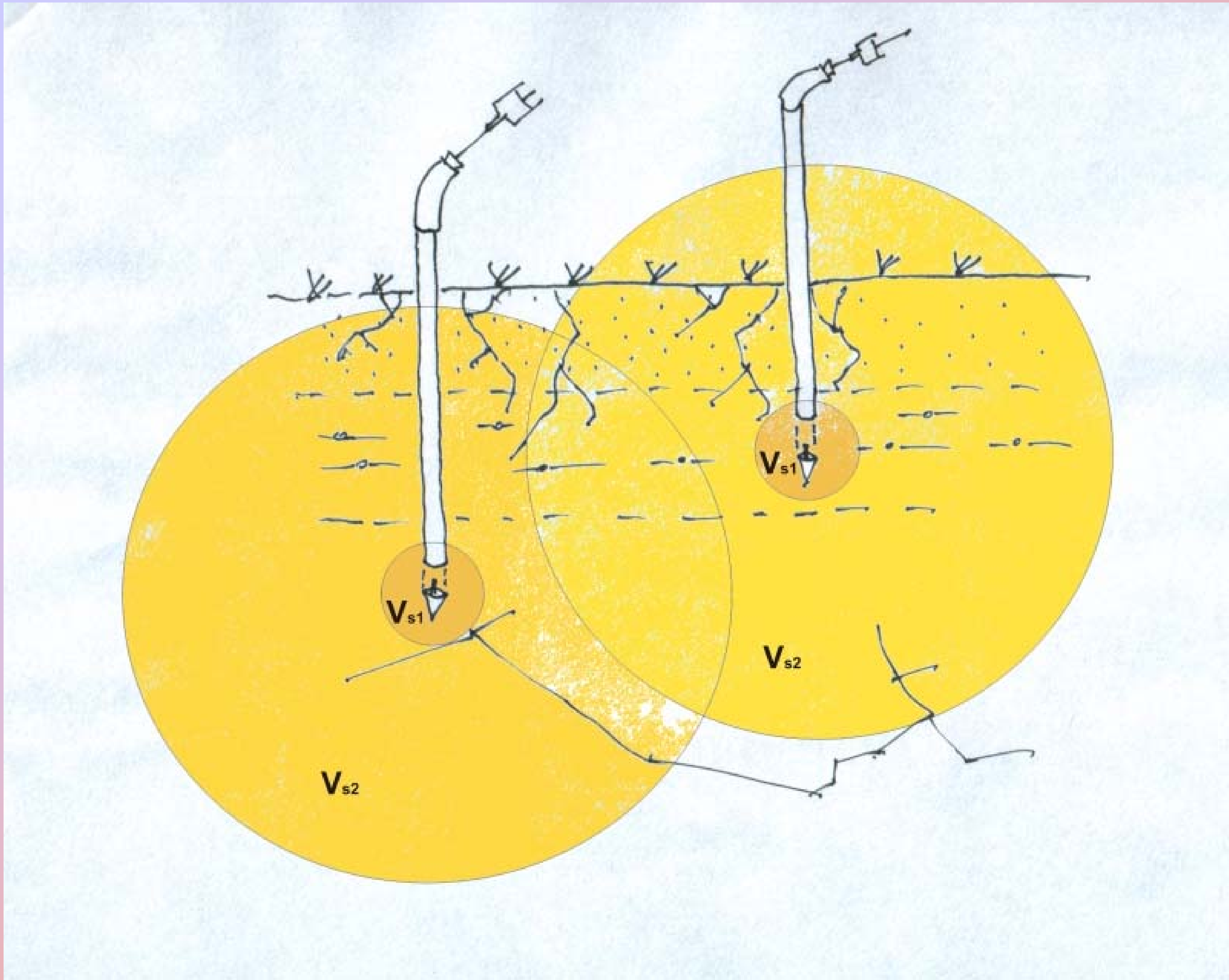
(In case of spot measurement methods, the soil-gas sampling is active only. Integrated methods are typically associated with passive soil-gas sampling.)

Minimal sampling depth

Theoretically, the radon activity concentration in the soil gas can be defined for any variable depth below the ground surface and it generally increases with depth below the surface in an ideal homogeneous soil. But there is a minimal depth below the ground surface, at which the parameter can be really measured.

The minimal depth depends on the soil properties at a given place and on the measurement method used. In particular, it depends on the volume of the soil gas sample. When the depth below the ground surface is lower than the minimal depth, the soil gas sample will be diluted with atmospheric air and the real value of radon activity concentration in the soil gas will be underestimated.

… the capacity of the soil gas is not unlimited in the soil



Vs1
Vs1
Vs2
Vs2

If a homogeneous soil environment is assumed, the minimal sampling depth can be derived using a spherical model:

$$r = ((3 . V_s) / (4 . \pi . n . (1 - s)))^{1/3} ,$$

where

$\mathbf{V_s}$ is the volume of the soil gas extracted from the soil during the soil gas sampling, in cubic metre;

$\mathbf{V_{soil}}$ is the volume of a sphere of an homogeneous soil, which contains the volume of soil gas available for extraction, in cubic metre;

r is the radius of the sphere of an homogeneous soil, V_{soil}, in metre;

s is the water saturation of soil, i. e. the part of soil pores filled with water, in percent;

n is the soil porosity, i. e. the ratio of the volume of soil pores and the volume of soil, in percent;

$\mathbf{n_{ef}}$ is the effective soil porosity, i. e. the ratio of the volume of soil pores filled with air and the volume of soil; $n_{ef} = n . (1 - s)$, in percent.

In the homogeneous soil environment, the minimal sampling depth should be larger than the radius **r**.

As the real soil environment is almost never homogeneous, the minimal sampling depth should be **at least twice larger** than the radius **r** under normal field conditions (probably **more times larger**).

Informative values:

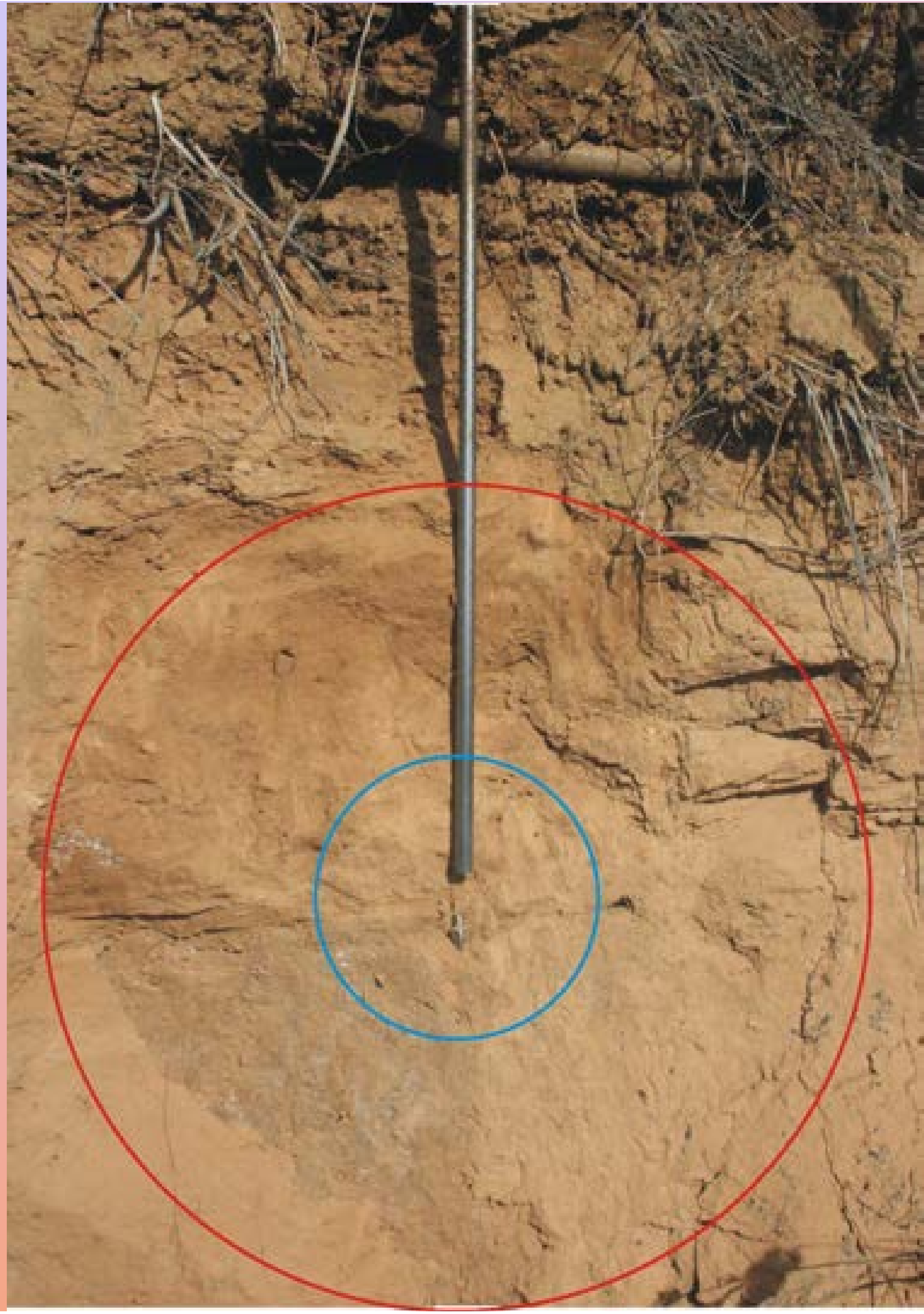
V_s m[3]	l	n	s	$1-s$	n_{eff}	r m
0,0002	**0,2**	0,25	0,45	0,55	0,1375	**0,07**
		0,25	0,9	0,1	0,025	**0,124**
		0,4	0,45	0,55	0,22	**0,06**
		0,4	0,9	0,1	0,04	**0,106**
0,001	**1**	0,25	0,45	0,55	0,1375	**0,12**
		0,25	0,9	0,1	0,025	**0,212**
		0,4	0,45	0,55	0,22	**0,103**
		0,4	0,9	0,1	0,04	**0,181**
0,005	**5**	0,25	0,45	0,55	0,1375	**0,206**
		0,25	0,9	0,1	0,025	**0,363**
		0,4	0,45	0,55	0,22	**0,176**
		0,4	0,9	0,1	0,04	**0,31**
0,025	**25**	0,25	0,45	0,55	0,1375	**0,351**
		0,25	0,9	0,1	0,025	**0,62**
		0,4	0,45	0,55	0,22	**0,3**
		0,4	0,9	0,1	0,04	**0,53**

Ideal spherical model „homogeneous soil“

sample volume:

--- 0,2 l (r = 0,106 m)

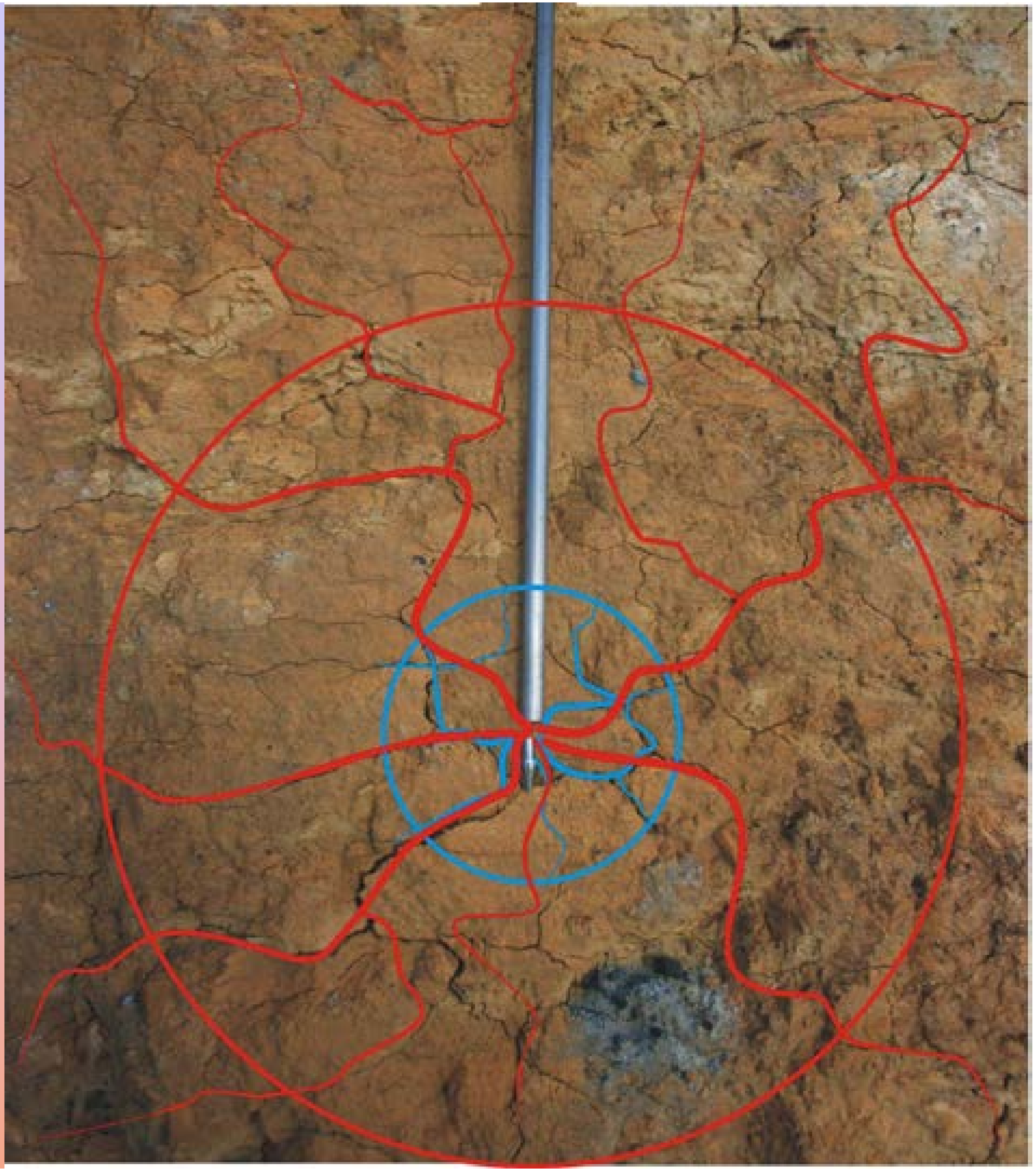
--- 5 l (r = 0,310 m)



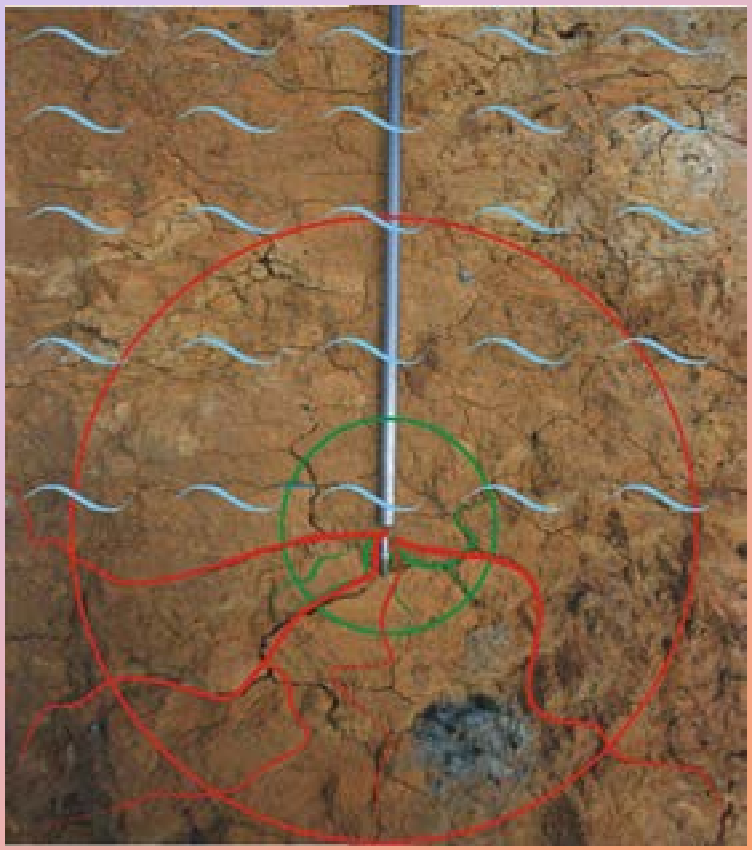
BUT
the soil is
never
(really NEVER) „homogeneous“

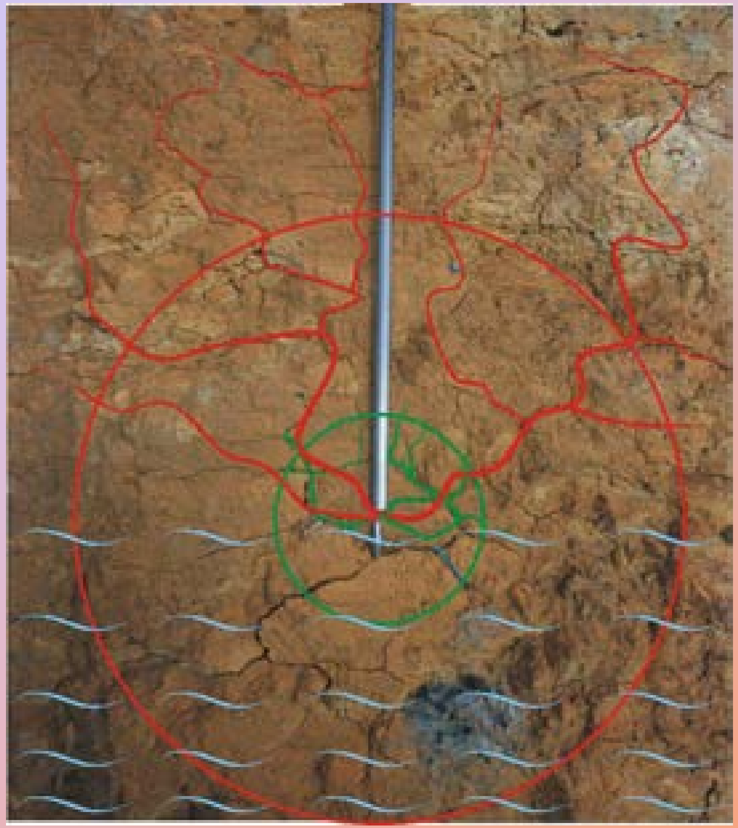
In case the volume of the soil gas sample is large, it is very difficult, almost impossible to define the sampling depth.

Temporal variability of soil gas radon concentration ???
temporal variability of the depth of real soil gas sampling



.. sometimes, when the upper layers are full of water, the large sample is taken from deeper layers ..





.. while at some other time, when the water saturations comes deeper, the large sample is sampled from the upper layers ..

Causes of failure

Real sampling depth (depth interval) is not well-defined

Reasons:

⇨ the soil is never homogeneous and properties of different soil layers (permeability, effective porosity, and others) change with time depending on changing meteorological conditions

⇨ when the real sampling depth is not well-defined, the soil-gas coming to the sampling system (active, or passive) “uses the easiest way”, i. e. at a given time, it comes preferably from layers with a higher permeability / with a higher diffusion coefficient)

⇨ soil parameters, which affect convection and diffusion of gases in the soil, change with time

Causes of failure

Dilution of the soil-gas sample by the atmospheric air

Reasons:

⇨ the sampling depth is lower than the minimal sampling depth

important note: the minimal sampling depth at a given place changes with time, because it depends on the effective soil porosity, which is not constant

⇨ the sampling system is not perfectly sealed

important note: in general, the problem may concern both active and passive sampling systems, but sealing of the measuring apparatus in the soil is difficult especially in the case of passive systems

important note: the negative influence of the dilution may also change with time

Causes of failure

Examples of inappropriate (not very suitable) sampling methods

The sampling (measuring) apparatus – for example small diameter probe for active sampling, or a passive integrated radon detector, or a passive continuous radon monitor – is inserted into a previously drilled hole with a larger diameter. When the sampling (measuring) system is sealed only on the top (close to the ground surface), the sampling depth is not well-defined.

Measured soil gas radon activity concentration cannot be then related to any sampling depth.

Moreover: The probability that soil gas sample will be diluted with atmospheric air is very high.

Causes of failure

Passive sampling:

A. B. Tanner (1991) Passive detection of radon isotopes depends on diffusion of radon atoms from the sites of their generation to the location of the detecting or collecting device. Because some radon decays en route to a passive detector in soil, the radon activity concentration measured by the detector must be less than the concentrations in those soil pores where it is undiminished by diffusion to the detector cavity.

The "true" radon activity concentration may be significantly underestimated especially in moist soils, or when large detector cavities are used.

As the soil moisture usually changes during a one-year cycle, a degree of underestimating may also change with time.

Tanner A.B. (1991) Error in measuring radon in soil by means of passive detectors. The international journal of radiation applications and instrumentation. Part E Nuclear Geophysics. Vol 5, N° 1-2, pp 25-30

Causes of failure

Other influence quantities

⇨ instrumental background noise
⇨ **influence of changes of soil characteristics (moisture and temperature) on the response of the measuring system located in the soil;** in this case, both parameters shall be measured and results of the radon activity concentration in the soil gas shall be corrected
⇨ **influence of any meteorological parameter on the response of the measuring system located on the soil surface;** in this case, such parameter shall be measured and results of the radon activity concentration in the soil gas shall be corrected
⇨ the presence of other gaseous radionuclides alpha-emitters or gamma-emitters in the detection chamber, including other radon isotopes and their decay products, **especially the presence of thoron (radon-220) and its decay products**

The most important conclusion

Anyone planning soil-gas radon concentration measurement should first examine the suitability and reproducibility of the method

having regard to the measurement target and to local conditions.

Preventive measures in new houses

… reminder … approach for new buildings:

- determination of radon potential of a building site (= detailed radon survey) is obligatory with the purpose to classify the risk of radon penetrating from the soil into the building
- proposal of optimal preventive strategy corresponds to local conditions (radon index of a building site) and to building type (radon index of a building)
- preventive measures are realized using radon-proof construction products (radon-proof membranes); test methods are available
- design and installation of preventive measures in accordance with the Czech National Standard
- efficiency of preventive measures is controlled

Basic experience:

Preventive protective measures in new houses are more effective and cheaper than remedial measures in existing buildings.

Preventive measures

Czech National Standard: CSN 730601 Protection of houses against radon from the soil; 1995, 2000, 2006

author: Martin Jiranek, Czech Technical University, Praha

- concerns not only preventive measures in new houses, but also remediation of existing buildings

⇨ principles of designing and application of various types of radon reduction techniques

⇨ requirements for radon-proof insulation (membrane)

- only material with measured radon diffusion coefficient can be used for radon-proof insulation

BASIC PRINCIPLES

protection of new houses against radon penetration from the ground is based on the use of radon-proof insulation; or radon-proof insulation in combination with passive, or active ventilation systems

advantage of radon proof insulation: it protects the building also against dampness and water

disadvantage: sensitivity to puncturing

special attention must be given to jointing and to pipe penetration

passive ventilation systems must be installed in such a way that they can be easily changed to forced (active) systems

⇨ simple airing of the drainage layer by means of pipes that run from one side of the building to another side is not a convenient solution

⇨ recommended ventilation system: several perforated pipes that are connected to one vertical exhaust pipe on which a fan can be installed in the future

Enclosure to Questionnaire D8 – Question C)

Work Package No. W4 – Protecting New Buildings

New Buildings			
Generic Solution:		N°	CZ/GSN/1
Type	**RADON-PROOF INSULATION**		
Country	Czech Republic		

Illustration

Description

This solution is designed to ensure the airtightness of floors and basement floors in contact with soil. Only materials with measured radon diffusion coefficient can be used for radon-proof insulation. The thickness of insulation is calculated according to Czech Standard CSN 730601 from the following equations:

$$d \geq l.\text{arcsinh}\frac{\alpha_1.l.\lambda.C_S}{E_{lim}} \quad \text{(m)}$$

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

where C_S is the third quartile of radon concentration in the soil gas on the building site (Bq/m^3), 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), α_1 is the safety

Enclosure to Questionnaire D8 – Question C)

Work Package No. W4 – Protecting New Buildings

…hat should eliminate the inaccuracies arising during the soil gas radon concentration measurements (for …ermeable soils α_1 = 7,0, for soils with medium permeability α_1 = 3,0 and for low permeable soils α_1 = …s the interior air volume (m^3), n is the air exchange rate (h^{-1}), A_f and A_w are the floor and the basement …eas in direct contact with the soil (m^2) and C_{dif} is a fraction of indoor concentration caused by diffusion, …s estimated to be 10% of the highest permissible radon concentration indoors (in the Czech Republic …ualled to 20 Bq/m^3 for new buildings and 40 Bq/m^3 for existing buildings).

…g materials must function effectively over their required service time. From this point of view the …ce should be given to insulating materials with longer durability and higher resistance to ageing, i.e. …materials are PVC or PE foils and membranes based on plastomeric (APP modification) or elastomeric …odification) bitumen. On the other hand membranes based on oxidised bitumen should not be applied, … their resistance to soil corrosion as well as to weathering is very low. As far as the reinforcing fabrics … only membranes with moisture resisting fabrics made of mineral, glass or synthetic fibres should be …c. Concerning application aspects, bonded sheets (fully adhered to the substrate) represent higher …f protection compared to unbonded sheets, which rely on perfect joints to a far greater extent than do …membranes, because radon can travel in the air gap beneath the unbonded membranes to the untight … the insulation. Complete insulating systems with extra components for external and internal corners, …d pipe entries should be preferred to pure and simple insulating materials.

…to use the system

…oof insulation as a single measure can be applied only when the third quartile of radon concentrations …d on the building site is less than:
…0 kBq/m^3 in highly permeable soils,
…40 kBq/m^3 in soils with a medium permeability,
…00 kBq/m^3 in soils with a low permeability.

…stallation Diagnosis

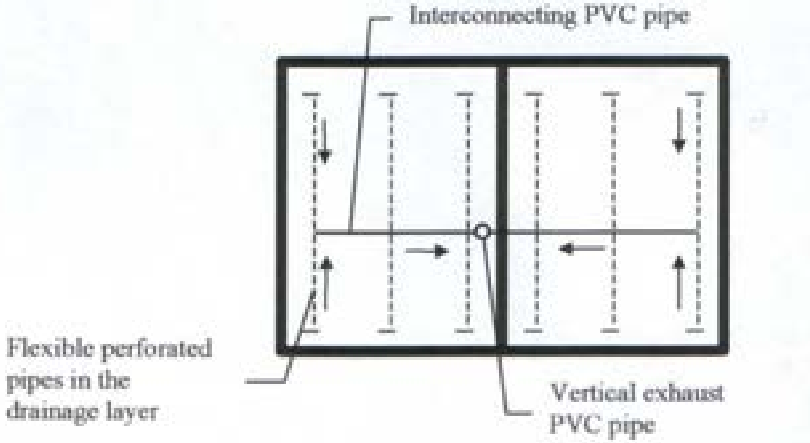
…re information for the effective design it is necessary to determine the radon index of the building site. …that these parameters must be measured:
… concentration in the soil gas in at least 15 points (the measuring depth is 0,8 m)
…ability of the soil

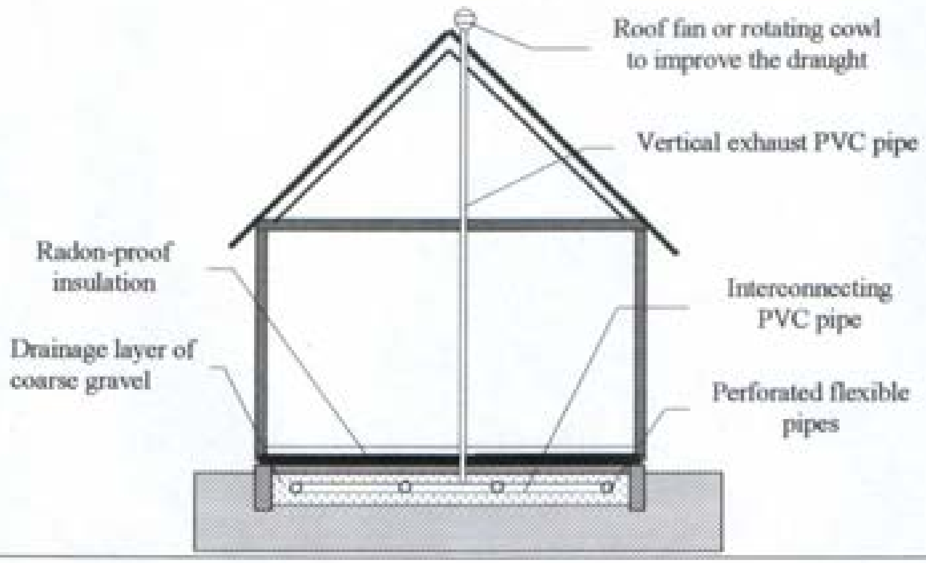
…tions

… radon index of the building site is higher than low, radon-proof insulation is a basic measure, which … applied in all new houses. On the other hand when the third quartile of radon concentrations is …n the above-mentioned limits, radon-proof insulation should be combined with other measures, such as soil ventilation or floor gaps ventilation.

Type	RADON-PROOF INSULATION IN COMBINATION WITH SOIL DEPRESSURIZATION
Country	Czech Republic

Illustration





Realization of preventive measures against radon started in the Czech Republic more than 26 years ago

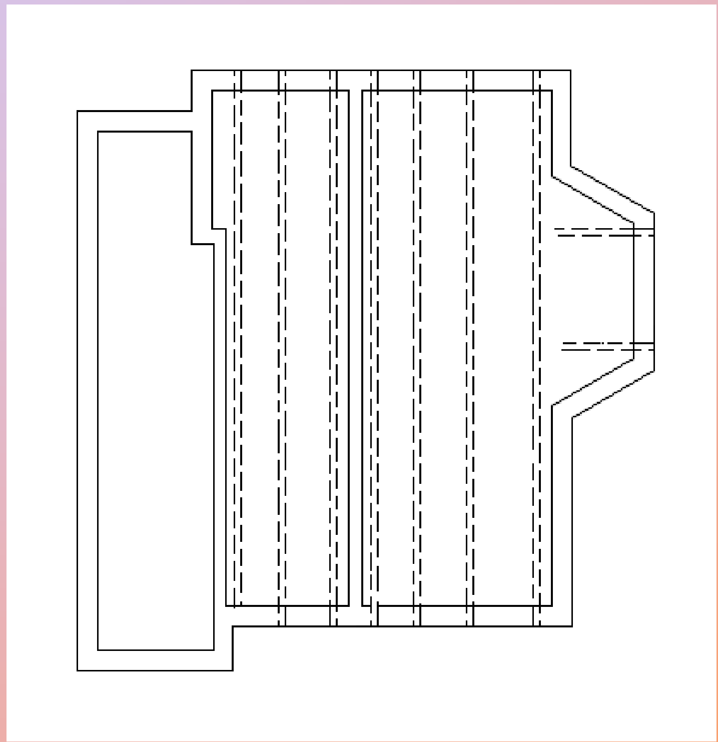
long-term measurements of indoor radon concentration

⇨ in a non-negligible number of houses, the protection has failed (greater amount of failures found in houses built before 1995, i.e. before publication of the first version of CSN 730601)

Factors responsible for failures

⇨ leakages in joints and around pipe penetration
⇨ partial application – insulation is not applied over the entire surface
⇨ perforation of insulation during construction works
⇨ use of insulating materials that were not tested on radon diffusion, or use of low quality products
⇨ passive ventilation with inlet and outlet holes in external walls only (without vertical exhaust)

Example A: single-family house built in 1999



c_{A75} = 204 kBq.m^{-3}
k_{75} = 1.6 10^{-11} m^2
RP = 255
high radon index

indoors: > 700 Bq.m^{-3}

Perforated pipes in the subslab drainage layer of gravel and a radon-proof membrane made of polypropylene were used to prevent radon entry into the house. Joints of the membrane were made of self-adhesive bitumen belts.

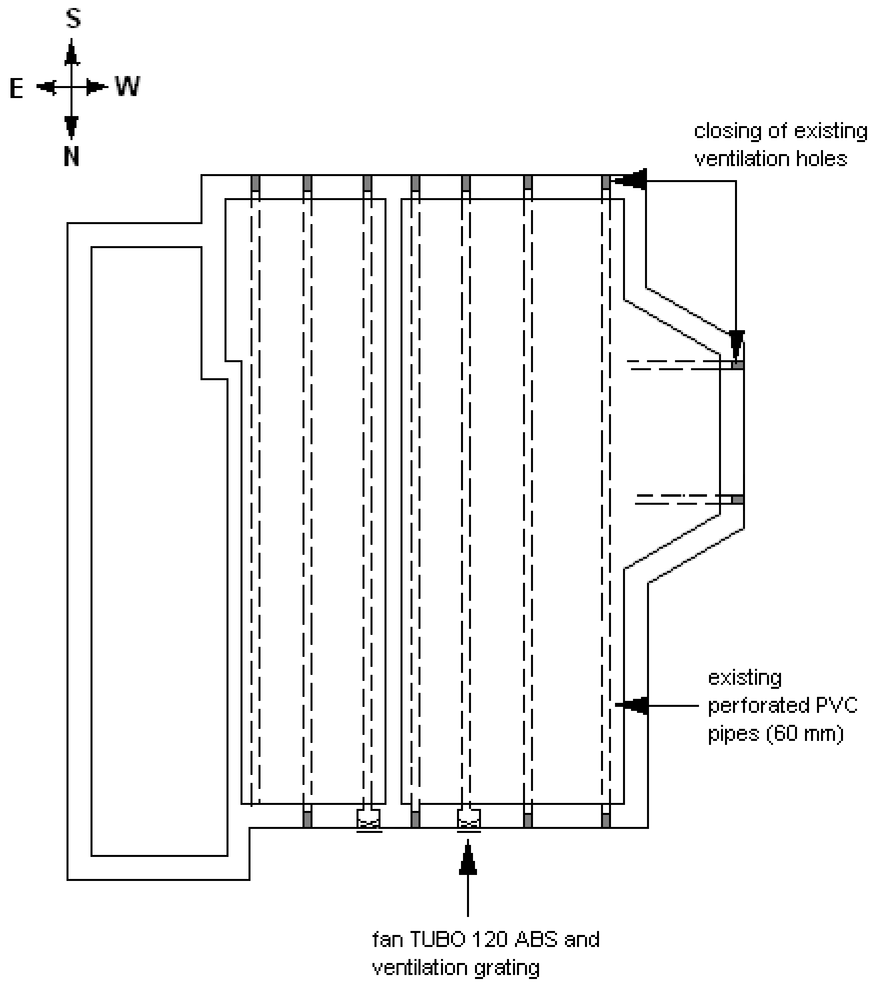
Reasons of a failure of preventive protective measures :

A radon survey of the building site before the construction of the house was not performed. The information on a real radon potential of the ground was thus not available.

Chosen preventive measures were not adequate. A passive subslab ventilation instead of a more appropriate active ventilation system was proposed.

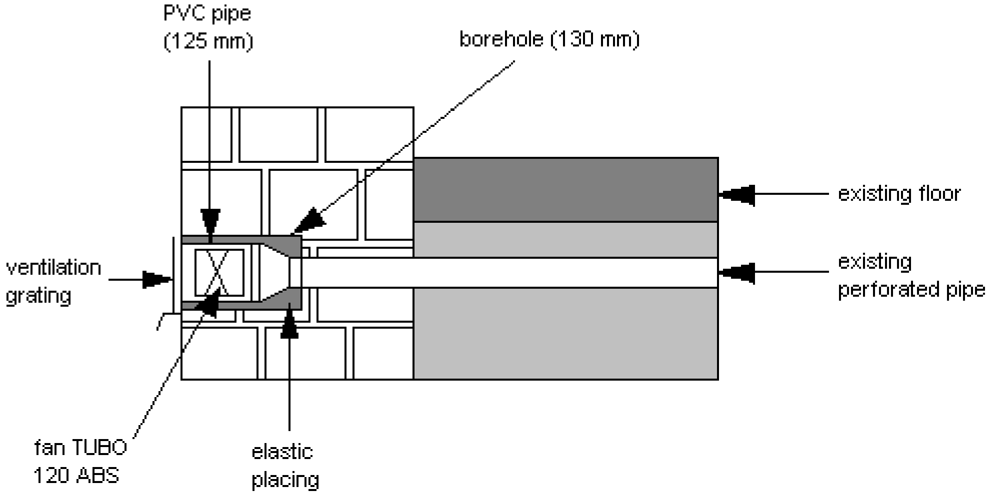
Note: *Under certain condition, the passive subslab ventilation may even cause a change for the worse. On the windward side of the house, an overpressure may originate in the drainage system. The drainage system itself then provides the air that is contamined by radon from the ground and transported through the leakages into the house.*

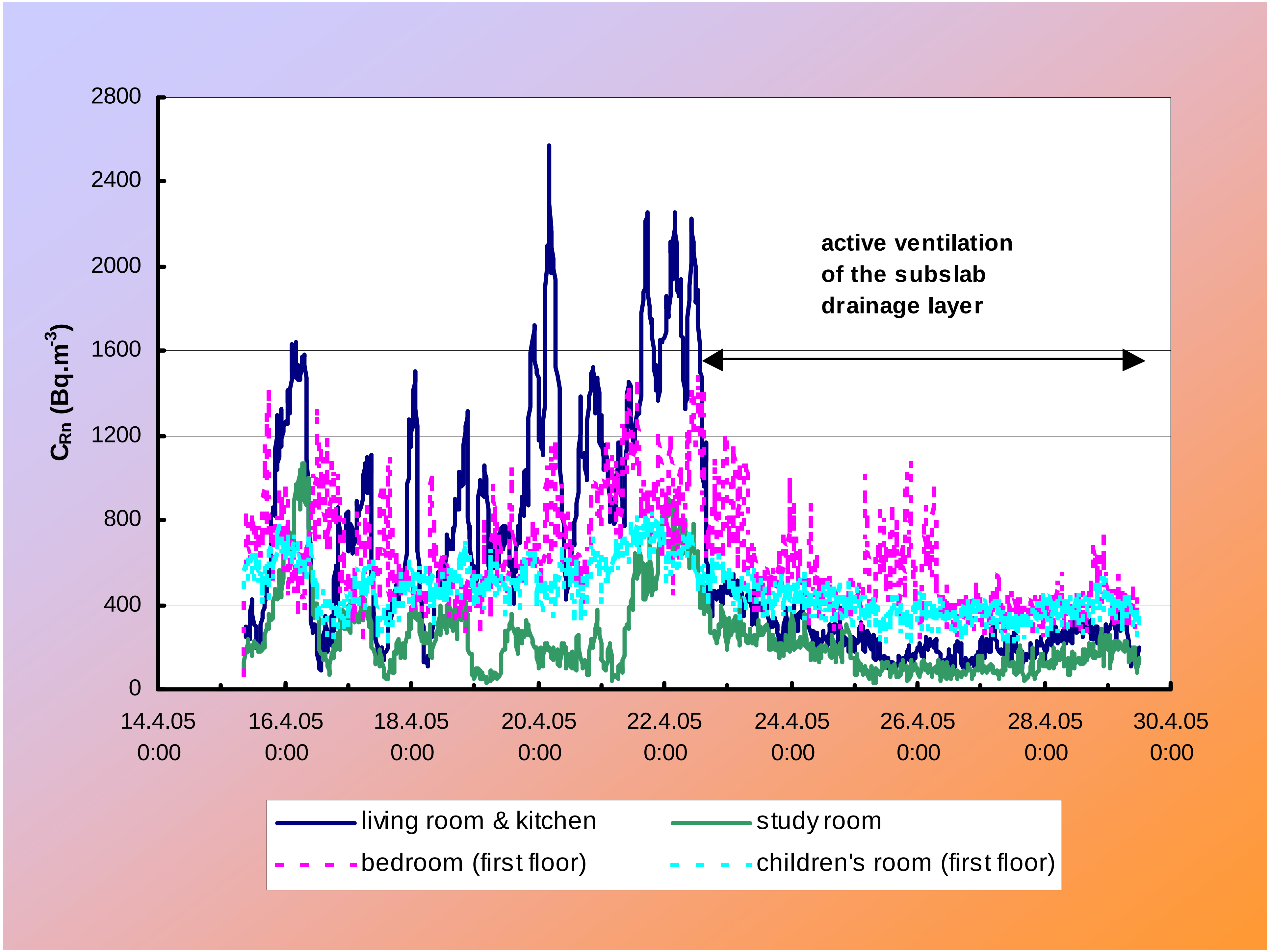
Imperfections occurred during the construction. Some joints of the polypropylene membrane were not sealed perfectly and the membrane was probably also punctured during the construction of the floor at least in one room.



At the end of 2004, a simple remedial action was performed:

Two small fans were connected to the perforated tubes changing the original passive subslab ventilation system to an active one.





2800
2400
2000
1600
1200
800
400
0
C_{Rn} (Bq.m^{-3})
14.4.05 0:00
16.4.05 0:00
18.4.05 0:00
20.4.05 0:00
22.4.05 0:00
24.4.05 0:00
26.4.05 0:00
28.4.05 0:00
30.4.05 0:00
active ventilation of the subslab drainage layer
living room & kitchen
study room
bedroom (first floor)
children's room (first floor)

Example: two new houses in one village

house A

c_{A75} = 144 kBq.m^{-3}

k_{75} = 1.4 10^{-11} m^2

RP = 167

high radon index

house B

c_{A75} = 122 kBq.m^{-3}

k_{75} = 1.1 10^{-11} m^2

RP = 127

high radon index

BUT

indoors: <100 Bq.m^{-3}

indoors: >400 Bq.m^{-3}

Reasons: Both houses were protected against radon penetration from the ground, in both houses a passive protection based on an application of radon-proof membrane was used.

BUT

house A: protective measures were effective

house B: protective measures failed

(i) a non-adequate type of the radon-proof membrane was used;

(ii) the subslab drainage layer of gravel was not ventilated;

(iii) imperfections occurred during the construction, some joints of the membrane were not sealed perfectly and the membrane was probably also punctured during the construction of the floor in some places

Thank you