Radon investigations in the Czech Republic VIII

and

the fifth international workshop on the Geological Aspects of Radon Risk Mapping

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Radon risk mapping of the Czech Republic 
on a scale 1 : 50 000

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Abstract

A new type of radon risk maps on a scale 1 : 50 000 was published in the Czech Republic. Maps are based on the vectorized countours of geological units and rock types and field soil gas radon measurements from the radon database. Radon risk is expressed in four categories. More detailed topography enables to predict the radon risk from bedrock in the intravilans of villages and towns.

Introduction and overview of research and mapping programme

The radon risk mapping programme started in the Czech Republic ten years ago. The programme is based on the close cooperation with the State Bureau of Nuclear Safety and the National Radiation Protection Institute. Both institutions deal with the distribution and evaluating of track-etch detectors in particular dwellings. As radon is generated in the bedrock, the Czech Geological Survey offered its experience in geological knowledge of the state territory to help to find out the areas where indoor radon levels could exceed the action level (200 Bq.m⁻³ equivalent equilibrium concentration - EEC).

The most important research and mapping activities performed by the Czech Geological Survey as well as the legislative acts concerning the radon programme during ten years are shortly summarized in the following overview. Most of these topics are extended in books of abstracts Radon investigations in Czechoslovakia I-IV and workshop abstracts Geological Aspects of Radon Risk Mapping V-VII. The latest legislative support to the Czech radon programme was given in 1999 by the Government Decision No.538 on the „Radon Programme of the Czech Republic“, expressing the interest of government to protect the population against the enhanced level of natural radiation.

1990 – Radon risk classification for building site assessment published
   Interministerial Radon Commission established
   Radon risk maps 1 : 200 000 published for the whole state area

1991 – Decree of Ministry of Health No. 76 „On the lowering of radiation from radon and other natural radionuclides“ issued

1992 – study of tectonic influence on radon concentration
   study of climatic variation of radon in soils
permeability influence on radon concentration
soil gas radon database established

1993 – Association Radon Risk, joining private radon companies established
seasonal radon variations
depth relationship of radon concentration
reference test sites established
study of radon in the black shales
Decree of Government No. 709 on the „Protection of Public from the Radiation Caused by Radon and other Natural Radionuclides“ issued

1996 – comparison of regional and local geology to indoor radon
study of influence of depth of sampling on the building site assessment
choice of new reference test sites in Central Bohemia
factors influencing the radon entry into houses
radon variations and Earth tidal deformations

1997 – Decree of the State Bureau of Nuclear Safety No. 184 on the „Demands on the radiation protection“ published

1998 – vectorization of geological and radiometric map 1: 500 000
study of inconsistence between geological prediction and indoor radon results
influence of tectonics on radon concentration

1999 – radon risk map 1 : 500 000 published on the CD
16 detailed radon risk maps 1 : 50 000 published
nouvellization of building site assessment published
Government Decision No.538 on the „Radon Programme of the Czech Republic“

The background for radon risk maps 1 : 50 000

GeoČR50 – GIS of digital geological maps 1: 50 000
The process of creation of geo database GeoČR50 was divided into four main steps:
1. Vectorization
2. Implementation of digital maps into GIS
3. Creation of database of unified geological legend
4. United national geodatabase GeoČR50
1) The vectorization of geological maps has been started in 1995 within the framework of the fundamental project of CGS called “Geological mapping and the creation of special purpose environmental maps at the scale 1 : 50000”. This project that covered 13 different thematic maps was started in 1985 and finished by the end of 1998. During that time more than 2000 maps (author’s manuscripts) were completed and over 1500 were published. By the end of 1997 the vectorization of all 214 geological maps that cover the whole area of the Czech Republic was finished including those maps, where the technical standards were not met. This usually happened with the first vectorized maps. Technical solution for vectorization (software platform) comprises Microstation95 (Bentley Systems), I/RasB, I/RasC and I/Geovec (Intergraph).
2) The implementation of digital maps into GIS. This process is very specific in case of geological maps because of the presence of graphical elements (for example - faults) that partly do and partly do not create boundaries of polygons of lithological formations, the presence of large complex elements (polygons with more than 10 000 vertexes) or existence of special regions (holes) inside other regions etc.

The structure of recent data model has been created in the software environment MGE v. 7.1 in connection with RDBMS Oracle 8 on the Windows NT v.4.0 platform. The data model consists of 259 features divided into four categories. The whole geodatabase consists of over 260 000 records.

3) The creation of database of unified geological index started in 1997 and was finished in 1999. This database was an essential step for the creation of a unified (without geological boundaries on the edges of map sheets) national geological database – GeoCR50. The database of geological legend consists at present of 2126 different geological units and covered four major types of information:

- Chronostratigraphical units
- Lithological description of rocks
- Lithostratigraphical units
- Regional units

Database of geological legend
1 : 50 000

![Diagram of geological legend](image)

Fig. 1 – Database of geological legend 1 : 50 000

4) In 1999 the final completion of united geodatabase GeoCR50 was started within the internal CGS project and is estimated to be finished in 2 years. Even though the national geological database is not completely finished (connecting geological bodies among map sheets) the use of
Fig. 2 - The distribution of radon risk in major rock types of the Czech Republic
such a system for environmental studies is tremendous. There are several fields where GIS of geological maps can be successfully used as for example in radon risk mapping.

Soil gas radon database

Since 1992 the Czech Geological Survey has been collecting the data coming from soil gas radon measurements for building site assessment. In details, the database contents was described in the previous book of abstracts Geological Aspects of Radon Risk Mapping VII (1998). The data coming from our measurements and private companies' measurements are obtained by uniform method based on the calibration of instruments in radon chamber and field comparison at the reference test sites. Up to now, the database contains the results from 8000 test sites (15 measurements each).

Radon risk mapping

The first radon risk maps were made in 1990, on a scale 1 : 200 000, covering the whole state area. Increasing number of data in the radon database enabled to publish the radon risk map on a scale 1 : 500 000 on the CD. More information on the mapping program is available at www.cgu.cz (info, primary projects, radon risk).

Since 1999, the Czech Geological Survey has been using the vectorized geological maps on a scale 1 : 50 000, enabling to produce more detailed radon risk maps. The principle is partly similar to generalized radon risk map on a scale 1 : 500 000, but the raster topography for the whole state territory (214 map sheets 1 : 50 000) is much more detailed. Therefore the more precise determination of radon risk from bedrock in particular villages and towns is possible. These maps (programme started in June 1999) will be used by the State Bureau of Nuclear Safety and municipal authorities for distribution of the track-etch detectors within villages and cities.

Usually at each geological map 40-90 rock types are specified. The rock types differ mostly by mineralogical composition or by stratigraphic position, the difference in primary uranium concentrations and subsequently in radon activity is not so expressive. In combination with results from the radon database the particular rock types can be grouped into prevailing categories of radon risk (see fig. 2). The rock units are divided into four categories of radon risk—low (mostly for younger sedimentary formations from Cretaceous to Neogene), interstage (inhomogeneous Quaternary sediments), medium (Palaeozoic sediments and crystalline gneisses) and high (mostly granitoids).

The coordinates of sampling sites are digitized in Didger programme and loaded into the radon database. Grouping of vectorized geological units is performed in MGE programme and transformed into Microstation programme (Bentley), where the grouped contours of rock units are filled according to the prevailing category of radon risk. The whole software procedure is illustrated in fig. 3. The test sites' positions are loaded over the vectorized radon layer and topographic raster files (intravilan plans, road network and watersheds) are attached. However, these maps do not substitute the building site assessment on the building lots.
Fig. 3 - The flowchart diagram of creation of radon risk maps on a scale 1 : 50 000
In 1999 16 radon risk maps on a scale 1 : 50 000 covered the area of Třebíč syenite body and Central Moldanubian pluton. These maps are available in digital and printed form. In 2000 the mapping area is extended to granitic bodies of Central Bohemian pluton (westward), Železné Hory pluton (northward) and Brno massif (eastward) – see fig. 4. An example of the section of radon risk map is given in fig. 5.

Testing the reliability of radon risk maps

The radon risk maps serve preferably for determining the level of potential radon release from bedrock. However, the radon entry into existing houses is strongly influenced by the building quality of the house. As the results from radon risk mapping should help to suggest the protective measures for newly built houses, the reliability of maps must be tested by comparing the radon risk categorization based on geology to real indoor radon values.

Until now, the state Bureau of Nuclear Safety has collected the indoor data in the database containing more than 100 000 measurements. From this database 464 municipalities where more than 30% of dwellings were measured, were selected. The statistical processing led to dividing the municipalities into three subsets – those where < 1%, 1 – 10% and > 10% of houses are expected to exceed the action level 200 Bq.m$^{-3}$ EEC. According to soil gas radon classification, the prevailing category of radon risk from bedrock was attached for all municipalities after the existing radon risk maps on a scale 1 : 200 000. The results of this comparison are given in fig. 6. It is obvious, that approximately in 75% cases the indoor values correspond to the predicted level of radon risk from bedrock. The remaining 25% of over- or underestimation of radon risk is caused mainly by the unconsidered building characteristics of houses or differences between regional and local geology. The data set of 464 municipalities covers various types of bedrock. The large scale comparison has proven that with a certain reliability the information obtained from regional radon risk maps can select the areas, where enhanced indoor radon values could be detected.

The detailed scale comparison was performed in the municipalities situated on the granitic and crystalline bedrock in the southern part of Central Moldanubian pluton. The bedrock in the cadastres of the villages was considered after the detailed radon risk maps on a scale 1 : 50 000. For each cadastre, the prevailing radon risk category (comprising the substantial area of intravilan) and presence of other categories in the intravilan were compared to geometric mean of indoor radon values. As seen from fig. 7, the geologically predicted high radon risk areas prevail in municipalities where more than 10% of houses are expected to exceed 200 Bq.m$^{-3}$ (which corresponds to geometric mean from indoor measurements equal to 90 Bq.m$^{-3}$ EEC).

Future aims in radon risk mapping

In 2000, 56 map sheets of radon risk maps on a scale 1 : 50 000 will be finished from the total 214 map sheets. The radon risk mapping programme should cover the rest of the state territory within next years as a basis for more sophisticated variations of radon risk maps. The plotter-printed maps are archived at the Czech Geological Survey and the State Bureau of Nuclear
Fig. 4 – The coverage of the state territory by radon risk maps 1 : 50 000.
Fig. 5 – The section of radon risk map 1:50 000 (area of granits, paragneisses, Quaternary sediments)
"LOW" municipalities
Ratio of geol. cat., 38 municipalities

- High (5.26%)
- Medium (21.05%)
- Low (73.68%)

"MEDIUM" municipalities
Ratio of geol. cat., 150 municipalities

- High (9.33%)
- Medium (79.33%)
- Low (11.33%)

"HIGH" municipalities
Ratio of geol. cat., 276 municipalities

- High (72.46%)
- Medium (26.81%)
- Low (0.72%)

Fig. 6 - The comparison of indoor radon values and geologically determined radon risk
Geometric mean EEC Bq.m$^{-3}$ in the cadastre of municipality

Category of radon risk in the intravilan
(radon risk maps from bedrock 1:50 000)

Jindřichův Hradec
Hospříz
Hadravova Rosíška
Horní Radouň
Kostelní Radouň
Horní Meziříčko
Střížovice
Kamenný Malíkov
Zahradky
Okrouhlí Radouň
Člunek
Volišov

Nová Bystřice
Blážejov
Český Rudolec
Strmilov
Staré Město p.L.
Čímař
Jaroslov n.N.
Heřmanec

prevailing radon risk category from bedrock
presence of other radon risk category from bedrock

Fig. 7 - The comparison of mean indoor radon (EEC) with radon risk from bedrock
in South-Bohemian municipalities situated on the crystalline and granitic bedrock
Safety. These maps are available for public and institutions dealing with the radon programme after order. In preparation there is a presentation of radon risk maps in the digital form on the CD, including the GIS approach to source data files.

The above mentioned radon risk maps on a scale 1 : 50 000 are based on the geological prediction of radon release from bedrock. The future trend demands for relating the data from existing indoor radon database of the State Bureau of Nuclear Safety (until now more than 100 000 houses were measured) with the geological database and the building characteristics of the houses. This connection needs to obtain the coordinates of particular houses, which will be possible after finishing the state cartographic programme of vectorized maps on a scale 1 : 10 000. Inspiring approaches in radon risk mapping from many countries are widely known among the radon geologists, therefore we do not include the references.
COMPARISON OF CALCULATED AND MEASURED SOIL-GAS RADON CONCENTRATION AND RADON EXHALATION RATE

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ABSTRACT

The computer model RADON2D for WINDOWS, that enables to estimate the radon exhalation rate from the ground surface and the distribution of soil-gas radon concentration, was tested using a large set of experimental data coming from four reference areas located in regions with different geological structure. A good agreement between calculated and experimental data was observed. In a majority of cases, a correct description of the real situation was obtained using non-modified experimental input data.

INTRODUCTION

To increase the effectiveness of preventive and remedial measures is one of the main goals of the radon program in the Czech Republic. A good knowledge of the radon entry into buildings is required, when optimal preventive or remedial actions are chosen and proposed. First, it is necessary to know the radon exhalation rate from the ground surface and the distribution of soil-gas radon concentrations in the upper soil layers. As the experimental determination of radiological and geotechnical characteristics is very often complicated, especially in case of remedial actions in existing buildings, the importance of numerical modelling is growing.

A large field research was proposed and realized to evaluate the applicability of the available numerical model.

METHODS

Numerical Modelling

The computer model RADON2D for WINDOWS (Jiránek and Svoboda 1997a, 1997b), that was used for the determination of soil-gas radon concentration and of radon exhalation rate from the ground surface, is based on the general equation for the two-dimensional steady-state radon transport in a porous medium (Nazaroff and Nero, 1988):

\[ D_e \nabla^2 C + \frac{k}{\varepsilon \mu} \vec{v} \cdot \nabla C + G - \lambda C = 0 \]  

(a)

where \( C \) is the radon concentration in the soil-gas [Bq m\(^{-3}\)], \( D_e \) is the effective radon diffusion coefficient [m\(^2\) s\(^{-1}\)], that depends on the soil-moisture, \( k \) is the permeability [m\(^2\)], \( \mu \) is the dynamic viscosity of air in soil pores [17.4 \( \cdot 10^3 \) kg m\(^{-1}\) s\(^{-1}\)], \( p \) is the pressure difference [Pa], \( \varepsilon \) is the soil porosity [-] and \( \lambda \) is the radon decay constant [2.1 \( \cdot 10^6 \) s\(^{-1}\)]. The
first term on the left side of the equation (a) represents the radon transport due to diffusion, the second one represents the radon transport due to convection. The third term expresses the increase of radon concentration caused by the radon generation in soil pores and the last term represents radon losses due to the radioactive decay.

Equation (a) is solved numerically using a finite element method. The model is based on following assumptions: each element is homogeneous, the soil-gas is incompressible, the pressure distribution is governed by Laplace equation and the flow of soil-gas is linear according to Darcy’s Law.

The model uses following input parameters: soil porosity, permeability, effective radon diffusion coefficient and radon generation rate. The soil porosity and the permeability were measured, values of the effective radon diffusion coefficient and of the radon generation rate were derived using other measured parameters.

The determination of the effective radon diffusion coefficient was based on a following equation (Rogers and Nielson, 1991):

\[ D_e = D_0 \cdot \varepsilon \cdot \exp \left(-6m\varepsilon - 6m^{14}\varepsilon\right), \]  

where \( D_0 \) is the radon diffusion coefficient in air \([m^2.s^{-1}]\), and \( m \) is the water saturation (= the percentage of pore space in soils that are filled with water [-]).

The radon generation rate \( G \) was calculated using the equation:

\[ G = \frac{1}{\varepsilon} \cdot a_{m,226Ra} \cdot \lambda \cdot f \cdot \rho_0 = \frac{1}{\varepsilon} \cdot y_m \cdot \rho_s \cdot (1 - \varepsilon), \]  

where \( a_{m,226Ra} \) is the mass activity of \(^{226}\text{Ra} \) \([Bq.m^{-3}]\), \( f \) is the radon emanation coefficient, \( y_m \) is the mass radon exhalation rate \([Bq.kg^{-1}.s^{-1}]\), \( \rho_0 \) is the bulk density of soil \([kg.m^{-3}]\) and \( \rho_s \) is the apparent density of solid particles of soil (the specific gravity of soil) \([kg.m^{-3}]\).

\[ \rho_0 = \rho_s \cdot (1 - \varepsilon). \]  

Changes of radon concentrations with depth and values of radon exhalation rate from the ground surface represent the output of the model.

Field Survey

Four reference areas with different geological structure (Dubnice, Růžená, Březiněves, Čelákovicke) were chosen for experimental testing of the model. The main goal of field measurements was to get as detailed information on geological and radiological characteristics as possible.

At each reference area (20 x 20 m, or 20 x 10 m), the survey consisted of soil-gas radon concentration and permeability measurements at nine measuring points, at each measuring point at five different depths below the ground surface (10, 30, 50, 80, and 150 cm); of the measurement of the radon exhalation rate at six measuring points; of the description of the vertical soil profile using six bores; of the collection of soil samples from different depths for the determination of the soil moisture, of the \(^{226}\text{Ra} \) activity, of the radon emanation coefficient, of the bulk density of soil, and of the apparent density of solid particles.

The survey was repeated at one reference area (Dubnice) to estimate the temporal
variability of measured parameters.


Measuring Techniques

Soil-gas samples for the determination of soil-gas radon concentrations were collected using a syringe and a small-diameter hollow steel probe and introduced into previously evacuated Lucas cells (Neznal et al., 1996a). The permeability of soil was determined by direct in-situ measurements using the equipment RADON-JOK. The method is based on the soil-gas withdrawal by means of negative pressure. The determination of the radon exhalation rate from the ground surface was based on the measurement of increasing radon concentration in a cylindrical canister placed on the ground (Neznal et al., 1996b). Similarly, the mass radon exhalation rate was derived from the measurement of radon concentration in a glass air-tight container, in which the soil sample had been closed for two weeks. The $^{226}$Ra concentration in soil samples was measured using a gamma spectrometer.

Six hand-bored drills were made at each reference area to determine the geological structure and chosen geotechnical parameters. The soil samples for the determination of soil moisture were dried at the temperature of 105-110 °C (Czech National Standard No. 721012). The apparent density of solid particles was determined using a 100 ml pycnometer (Czech National Standard No. 721011). Values of the bulk density of soil were estimated using available data obtained at areas with similar geological structure. To get all input data for numerical modelling, the soil porosity and the water saturation were calculated using the above mentioned results of laboratory analyses.

RESULTS AND DISCUSSION

Geological Structures

The four reference areas were chosen with respect to the various geological factors influencing the radon potential of soils.

At the reference site Růžená the bedrock is formed by granites (Central Bohemian Pluton). The bedrock weathering is extensive and irregular, the weathering profile is formed by clayey sands and sandy clays. The bedrock at three other areas is represented by Cretaceous sediments. In case of the area Dubnice, there were described Upper Turonian claystones and marlites. Březíněves and Čelákovice areas are formed by Lower Turonian marlites and claystones.

The Quarternary cover is represented by eluvial and deluvial deposits at the reference areas Dubnice and Růžená, by loess eolian deposits at the reference area Březíněves and by fluvial sands and sandy gravels at the area Čelákovice.

Surface conditions were different from one reference area to another one. This fact may be important when the radon exhalation rate from the ground surface is evaluated. Whilst the reference areas Dubnice and Růžená were situated in meadows, characterized by a rich vegetation, the reference areas Březíněves and Čelákovice were situated in agricultural cultivated fields after the harvest, i.e. almost without vegetation. The ground surface was
wet at the areas Dubnice, Růžená and Čelákovice, but dry at the area Březiněves.

**Soil-gas Radon Concentration**

As for the spatial variability of soil-gas radon concentration, the most heterogeneous situation was observed at the area Dubnice. The ratios SD/mean (standard deviation of the population vs. arithmetic mean) of data sets corresponding to different sampling depths ranged from 0.40 to 0.84 during the first measurements in July 1999 and from 0.42 to 0.92 during the second measurements in October 1999. More homogeneous results were obtained at other reference areas. The ratios SD/mean ranged from 0.20 to 0.50 at the area Růžená, from 0.07 to 0.33 at the area Březiněves, from 0.16 to 0.35 at the area Čelákovice.

The spatial variability of soil-gas radon concentration decreased with depth only at the areas Růžená and Březiněves. This finding corresponds with a relative homogeneity of geological conditions at these two reference areas.

Examples of observed changes of soil-gas radon concentrations with depth are given in Fig. 1 and Fig. 2. As can be seen, the changes can be significant (Březiněves area), as well as very small (Čelákovice area). This conclusion is in a good agreement with the results of a previous research (Neznal et al., 1994).

![Fig. 1: Changes of soil-gas radon concentration (cRn) with depth (arithmetic mean ± standard deviation), Březiněves area](image-url)
Radon Exhalation Rate from the Ground Surface

As expected, the highest average value of radon exhalation rate from the ground (108 mBq.m⁻².s⁻¹) was observed at the area Růžená, characterized by a high radon potential. The spatial variability expressed as the ratio SD/mean ranged from 0.16 (Čelákovice area) to 0.51 (Růžená area). The spatial variability of radon exhalation rate from the ground is thus comparable with the spatial variability of soil-gas radon concentration.

The influence of the humidity of the upper soil layer on the radon exhalation rate can be illustrated by the values of numerical ratio between the average radon exhalation rate and the average soil-gas radon concentration in the upper soil layer (depth of 10 cm). This ratio ranges from 1.3 to 2.4 at the areas Dubnice, Růžená and Čelákovice, where the ground surface was moist during measurements, while it equals 6 at the area Březiněves, where the surface was dry.

Permeability of Soil

The variability of soil permeability was high in vertical as well as in horizontal directions. The ratios SD/mean of data sets corresponding to different sampling depths ranged from 0.66 to 1.70 (July 1999) and from 0.62 to 1.57 (October 1999) at the area Dubnice, from 0.83 to 1.71 at the area Růžená, from 0.72 to 1.11 at the area Březiněves, from 0.64 to 1.08 at the area Čelákovice.

It should be noted that a typical distribution of permeability data is not normal. The use of Gaussian parameters for the evaluation of the results of permeability measurements is thus not correct. This question requires a more detailed statistical analysis.

Two examples of the relation between the soil-gas radon concentration and the permeability are given in Fig. 3 and Fig. 4.
Fig. 3: Permeability (k) vs. soil-gas radon concentration (cRn), Dubnice area (July 1999)

Fig. 4: Permeability (k) vs. soil-gas radon concentration (cRn), Březiněves area

Temporal Variability

A comparison of results of repeated measurements at the area Dubnica enables to evaluate temporal changes of measured parameters. Values of soil-gas radon concentration, of radon exhalation rate from the ground, of soil permeability and of soil moisture in July and in October 1999 were compared.
The soil-gas radon concentration was the most stable from the four above-mentioned parameters. Relative changes of the average soil-gas radon concentration were -2.3% in the depth of 10 cm, +5.1% in the depth of 30 cm, -31.2% in the depth of 50 cm, -9.0% in the depth of 80 cm, and -1.5% in the depth of 150 cm, respectively. With the exception of the depth of 50 cm, the changes were not greater than measuring errors.

The average radon exhalation rate decreased from 10.4 to 7.9 mBq.m$^{-2}$.s$^{-1}$ (-24.4%).

As for the permeability, more significant changes were observed. Relative changes of the average permeability corresponding to different sampling depths ranged from -62.6% (50 cm) to -89.3% (30 cm).

The maximal difference of the average soil moisture was observed in the depth of 50 cm - from 15.6% to 10.0%, the minimal one in the depth of 30 cm - from 14.5% to 13.1%.

Parameters Used as Input Data for Numerical Modelling

Geological situation at each reference area was represented by a sector of soil 1 m wide and 1.5 m deep. This depth was the maximal sampling and measuring depth during field measurements. The sector was divided into five or six horizontal layers to describe changes of geological characteristics.

Following boundary conditions were used. As for the radon concentration in the maximal depth of 150 cm, two different input parameters were tested. The average measured soil-gas radon concentration, or the soil-gas radon concentration calculated as a ratio of the radon generation rate and the radon decay constant using equation (c). The second estimate was thus based on the results of the determination of the mass radon exhalation rate and of the bulk density of soil. The soil surface was under a fixed depressurization of -1 Pa. The soil-gas radon concentration of 10 Bq.m$^{-3}$ on the surface, and the thickness of the surface boundary layer of 4 mm were expected (the thickness of the boundary layer is identical with the distance on which the soil-gas radon concentration becomes equal to the radon concentration in the outdoor air).

Average values of permeability corresponding to different sampling depths were used as the input data of soil permeability.

As for the other geotechnical and radiological parameters (porosity, water saturation, mass $^{226}$Ra activity, etc.), the calculations were made for several different combinations of obtained experimental values.

The results of numerical modelling of the situation at the reference area Čelákovic will be used to illustrate the applicability of the model. The modelled sector of soil is given in Fig. 5.
The characteristics of soil were obtained from the analyses of samples taken from bores V1, V2 (effective radon diffusion coefficient - $D_e$), and V4, V6 (radon generation rate - $G$), respectively. They are summarized in Table 1; $k$ is the permeability, $\varepsilon$ is the soil porosity.

**Tab. 1: Soil characteristics used as input data, Čelákovice area**

<table>
<thead>
<tr>
<th>Layer No.</th>
<th>$k$</th>
<th>$\varepsilon$ (bore V1)</th>
<th>$\varepsilon$ (bore V2)</th>
<th>$G$ (bore V4)</th>
<th>$G$ (bore V6)</th>
<th>$D_e$ (bore V1)</th>
<th>$D_e$ (bore V2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3.1E-12</td>
<td>0.44</td>
<td>0.43</td>
<td>4.8E-5</td>
<td>7.5E-5</td>
<td>8.9E-7</td>
<td>1.2E-6</td>
</tr>
<tr>
<td>4</td>
<td>9.9E-13</td>
<td>0.38</td>
<td>0.35</td>
<td>5.9E-5</td>
<td>9.9E-5</td>
<td>1.3E-6</td>
<td>1.5E-6</td>
</tr>
<tr>
<td>3</td>
<td>4.8E-13</td>
<td>0.32</td>
<td>0.32</td>
<td>2.1E-5</td>
<td>3.2E-5</td>
<td>2.4E-6</td>
<td>2.5E-6</td>
</tr>
<tr>
<td>2</td>
<td>6.4E-13</td>
<td>0.32</td>
<td>0.32</td>
<td>2.1E-5</td>
<td>3.2E-5</td>
<td>2.4E-6</td>
<td>2.4E-6</td>
</tr>
<tr>
<td>1</td>
<td>1.9E-12</td>
<td>0.29</td>
<td>0.30</td>
<td>4.8E-5</td>
<td>4.1E-5</td>
<td>2.2E-6</td>
<td>1.3E-6</td>
</tr>
</tbody>
</table>

At the reference area Čelákovice, three combinations of input parameters were tested: (A) $D_e$ and $\varepsilon$ correspond to the sample taken from bore V1 and $G$ correspond to the bore V4; (B) $D_e$ and $\varepsilon$ correspond to the bore V2 and $G$ correspond to the bore V4; (C) $D_e$ and $\varepsilon$ correspond to bore V2 and $G$ correspond to the bore V6.
Output of Numerical Modelling - Comparison of Calculated and Measured Soil-Gas Radon Concentration and Radon Exhalation Rate

The output of the model is represented by the distribution of radon concentrations in different depths and by the estimate of radon exhalation rate from the ground surface. An example is given in Table 2 and in Table 3. Calculated values corresponding to three above mentioned combinations of input parameters (A, B, C) are compared with measured values obtained at the reference area Čelákovice.

The agreement between calculated and measured data is relatively good for all tested combinations of input data. As can be seen in Table 1, larger differences of input parameters were observed in the upper soil layers (No 5 and 4). The use of a higher value of the radon generation rate (bore V6) resulted in higher radon concentrations over the whole soil profile and in a higher radon exhalation rate (C compared to A, B). The use of a lower value of the effective diffusion coefficient (bore V1) resulted in a lower radon exhalation rate and in higher soil-gas radon concentrations in the upper soil layers (A compared to B).

The analysis of results obtained at all reference areas has shown a good applicability of the numerical model. The model was sensitive especially to changes of the water saturation. Even very small changes of this parameter caused multiple changes of the diffusion coefficient and significant changes of calculated soil-gas radon concentration and radon exhalation rate. It is evident, that the sensitivity of the model to the changes of input parameters should be studied in more details.

CONCLUSIONS

The field survey was made at four reference areas situated in regions with different geological structure. It resulted in a detailed description of radiological, geological and geotechnical characteristics. Experimental data were used for testing the applicability of the computer model RADON2D for WINDOWS, that enables to estimate the radon exhalation rate from the ground surface and the distribution of soil-gas radon concentrations.

The conclusions can be summarized as follows:

Findings that concern the spatial variability of soil-gas radon concentration and the variability of soil-gas radon concentration with depth correspond to previous experience. The spatial variability of radon exhalation rate from the ground is comparable with the spatial variability of soil-gas radon concentration. The radon exhalation rate from the ground surface is strongly influenced by the humidity of the upper soil layer.

The variability of soil permeability is relatively high in vertical as well as in horizontal directions. A typical distribution of permeability data is not normal. The use of Gaussian parameters for the evaluation of the results of permeability measurements is thus not correct.

The agreement between calculated and measured data of soil-gas radon concentration and of radon exhalation rate is good. In a majority of cases, a correct description of the real situation was obtained using non-modified experimental input data. This conclusion confirm a general applicability of the numerical model. A higher sensitivity of the model to changes of water saturation was observed.
Tab. 2: Comparison of calculated and measured soil-gas radon concentration, Čelákovice area

<table>
<thead>
<tr>
<th>Depth below surface (cm)</th>
<th>calculated soil-gas radon concentration (kBq.m$^{-3}$)</th>
<th>measured soil-gas radon concentration (kBq.m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>0</td>
<td>1.1</td>
<td>1.2</td>
</tr>
<tr>
<td>5</td>
<td>2.6</td>
<td>2.4</td>
</tr>
<tr>
<td>10</td>
<td>4.0</td>
<td>3.5</td>
</tr>
<tr>
<td>15</td>
<td>5.2</td>
<td>4.5</td>
</tr>
<tr>
<td>20</td>
<td>6.4</td>
<td>5.4</td>
</tr>
<tr>
<td>24</td>
<td>6.9</td>
<td>5.9</td>
</tr>
<tr>
<td>28</td>
<td>7.4</td>
<td>6.4</td>
</tr>
<tr>
<td>30</td>
<td>7.6</td>
<td>6.7</td>
</tr>
<tr>
<td>32</td>
<td>7.8</td>
<td>6.9</td>
</tr>
<tr>
<td>35</td>
<td>8.2</td>
<td>7.3</td>
</tr>
<tr>
<td>39</td>
<td>8.5</td>
<td>7.6</td>
</tr>
<tr>
<td>42</td>
<td>8.8</td>
<td>7.9</td>
</tr>
<tr>
<td>46</td>
<td>9.0</td>
<td>8.2</td>
</tr>
<tr>
<td>50</td>
<td>9.2</td>
<td>8.4</td>
</tr>
<tr>
<td>55</td>
<td>9.4</td>
<td>8.6</td>
</tr>
<tr>
<td>60</td>
<td>9.5</td>
<td>8.8</td>
</tr>
<tr>
<td>65</td>
<td>9.6</td>
<td>8.9</td>
</tr>
<tr>
<td>70</td>
<td>9.7</td>
<td>9.1</td>
</tr>
<tr>
<td>75</td>
<td>9.9</td>
<td>9.2</td>
</tr>
<tr>
<td>80</td>
<td>10.0</td>
<td>9.4</td>
</tr>
<tr>
<td>85</td>
<td>10.1</td>
<td>9.5</td>
</tr>
<tr>
<td>90</td>
<td>10.2</td>
<td>9.7</td>
</tr>
<tr>
<td>97</td>
<td>10.4</td>
<td>9.9</td>
</tr>
<tr>
<td>105</td>
<td>10.6</td>
<td>10.1</td>
</tr>
<tr>
<td>112</td>
<td>10.8</td>
<td>10.4</td>
</tr>
<tr>
<td>120</td>
<td>11.0</td>
<td>10.6</td>
</tr>
<tr>
<td>127</td>
<td>11.2</td>
<td>11.0</td>
</tr>
<tr>
<td>135</td>
<td>11.3</td>
<td>11.2</td>
</tr>
<tr>
<td>142</td>
<td>11.4</td>
<td>11.4</td>
</tr>
<tr>
<td>150</td>
<td>11.4</td>
<td>11.4</td>
</tr>
</tbody>
</table>
Tab. 3: Comparison of calculated and measured radon exhalation rate from the ground surface, Čelákovice area

<table>
<thead>
<tr>
<th>calculated radon exhalation rate (mBq.m$^{-2}$.s$^{-1}$)</th>
<th>measured radon exhalation rate (mBq.m$^{-2}$.s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: 11.4, B: 12.5, C: 17.7</td>
<td>16.0 ± 2.6</td>
</tr>
</tbody>
</table>

A more detailed study of the model sensitivity to changes of different input parameters is recommended.

The large set of experimental data, that had been collected, could be used to another studies, or analyses, for example to propose a concept of the radon availability, i.e. a single parameter describing the radon potential of foundation soils.

REFERENCES

Czech National Standard No. 721011. Laboratory Determination of Apparent Density of Solid Particles of Soils

Czech National Standard No. 72 1012. Laboratory Determination of Moisture Content of Soils


GEOMETRY OF SOIL GAS SAMPLING, SOIL PERMEABILITY AND RADON ACTIVITY CONCENTRATION

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Introduction

Measurement of radon activity concentration in soil gas, carried out in the Czech Republic in the period 1991 - 1999, indicates the relationship of determined radon ($^{222}$Rn) activity concentration in soil gas with the depth of sampling, soil permeability, dimensions of free space for soil gas sampling and the soil sampling technique. Low permeable soils, preventing often the soil gas sampling in standard probe geometry, require the enlargement of the sampling space in the soil. Relationship between radon activity concentration in the soil gas and non-standard sampling geometry was studied.

Field experiments

In the Czech Republic, standard soil gas sampling for radon risk mapping and for detailed radon risk classification of foundation soils is performed by means of hollow iron rods from the depth 0.8 m (Barnet 1994). If soils exhibit low permeability, the sampling space at the end of the probe rod can be enlarged by pulling the rod upwards. Investigation of this intervention on determined radon activity concentration was carried out at two selected areas in 1999.

Site Jirny, 15 km east from Prague, with the bedrock formed by claystones, siltstones and sandstones of Cretaceous age, covered with deluvium silt sandstone soils, clay sandy soils and clay loams, exhibits low to medium permeability, determined by grain size analyses and direct in-situ measurements.

Site Louňovice, 15 km southeast from Prague, is formed by medium grained biotite granodiorite of the Central Bohemian pluton, weathered into sandy and loam sandy eluvium. Soil grain size analyses and direct in-situ measurements showed medium to high permeability of soils.

Relationship of radon activity concentration in soil gas with sampling depth and sampling space was studied by measurement in nine points at each site, using two diameter different types of hollow iron rods and two different types of radon detecting instruments:

- a field portable radon detector Scintrex RDA-200, with Lucas cell 170 cm$^3$, the sampling space is created by the extrusion of a free tip at the end of the rod, samples are collected by a hand pump of a volume cca 1000 cm$^3$, reported as sampling technique of small sampling
space (= cylindrical surface of about 6.8 cm$^2$ with the diameter 0.8 cm and the height 2.5 cm)

$\Rightarrow$ radon detector LUK with Lucas cells 125 cm$^3$, the sampling space is created by the extrusion of a free sharp tip at the end of the rod, samples are collected by using a hypodermic syringe of a volume cca 150 cm$^3$, reported as sampling technique of larger sampling space (= cylindrical surface of about 20.0 cm$^2$ with the diameter 1.2 cm and the height 5.0 cm).

Soil gas samples were taken from the depths 0.4 m, 0.6 m, 0.8 m in standard sampling geometry, and by pulling the rod, from depth intervals 0.75-0.8 m, 0.7-0.8 m and 0.6-0.8 m. Tables 1 and 2 introduce resulting radon activity concentration.

Table 1  Mean radon activity concentration (N = 9) at the site Jirny determined at variable soil gas sampling depth and geometry.

<table>
<thead>
<tr>
<th>Depth of sampling (cm)</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>75-80</th>
<th>70-80</th>
<th>60-80</th>
</tr>
</thead>
<tbody>
<tr>
<td>radon activity concentration (kBq/m$^3$)</td>
<td>37.4</td>
<td>48.2</td>
<td>42.7</td>
<td>43.2</td>
<td>50.9</td>
<td>48.3</td>
</tr>
<tr>
<td>stand. deviation</td>
<td>7.9</td>
<td>13.0</td>
<td>13.9</td>
<td>19.0</td>
<td>12.4</td>
<td>17.5</td>
</tr>
<tr>
<td>larger sampling space</td>
<td>32.3</td>
<td>41.2</td>
<td>46.2</td>
<td>42.4</td>
<td>40.6</td>
<td>38.7</td>
</tr>
<tr>
<td>stand. deviation</td>
<td>4.9</td>
<td>6.8</td>
<td>10.7</td>
<td>8.5</td>
<td>2.9</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Table 2  Mean radon activity concentration (N = 9) at the site Lounovice determined at variable soil gas sampling depth and geometry.

<table>
<thead>
<tr>
<th>Depth of sampling (cm)</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>75-80</th>
<th>70-80</th>
<th>60-80</th>
</tr>
</thead>
<tbody>
<tr>
<td>radon activity concentration (kBq/m$^3$)</td>
<td>87.8</td>
<td>109.9</td>
<td>137.4</td>
<td>139.2</td>
<td>121.1</td>
<td>99.2</td>
</tr>
<tr>
<td>stand. deviation</td>
<td>25.9</td>
<td>26.5</td>
<td>22.8</td>
<td>23.5</td>
<td>32.8</td>
<td>49.7</td>
</tr>
<tr>
<td>larger sampling space</td>
<td>72.6</td>
<td>104.7</td>
<td>121.1</td>
<td>122.9</td>
<td>115.7</td>
<td>100.4</td>
</tr>
<tr>
<td>stand. deviation</td>
<td>10.0</td>
<td>26.9</td>
<td>37.1</td>
<td>24.9</td>
<td>30.3</td>
<td>26.6</td>
</tr>
</tbody>
</table>

Conclusions

Radon activity concentration increases with depth of sampling: at Jirny site, of low to medium soil permeability, the increase is mild, at Lounovice site, of medium to high soil permeability, the increase is expressive. This is in agreement with the theory on the change of radon activity concentration with depth in rock environment of low and higher coefficient of diffusion and the respective escape of soil radon to the atmosphere.

Difficulty of soil gas sampling was more frequently observed at low permeable soils using the small sampling space technique.

Limited increase of soil sampling space, by pulling the rod upward (depth 75-80 cm), did not affect the observed radon activity concentration, while further extension of sampling space (70-80 cm, 60-80 cm) towards the earth surface may involve the measurement of radon
diluted soil gas from low depths below the surface. This effect is more pronounced for both small and larger sampling space at high permeable soil (site Louňovice).

Realized study indicates the necessity to apply the soil gas sampling from free soil sampling space of sufficient dimensions, and a limited possibility to enlarge the sampling space by pulling the sampling rod towards the earth surface, in both low and particularly high permeable soils. Observed changes in radon activity concentration caused by studied effects may exceed the errors of radon measurements.

References

Hypothesis: We thought that use of flux measurement allows take into account greater area (in common sense) than in case of method used officially in the Czech Republic (15 measurement of local deep radon concentration).

In 1999 seven building sites were tested by 8 measurement of radon flux. The method of evaluation was very simple: 13 l vessel is put onto soil surface and four radon concentration were estimated in regular time intervals taking the samples of the air in. The volume of samples used for measurement was negligible compared with volume of pot.

The painstakingness of used method is not far from painstakingness when 15 holes are realized. Official method one could quantified by 27-55 lis$^8$ and described method by 19-63 lis.

$^8$ lis...the sum of volume of sweat catched into special calibrated vessel [milliliter] + total number of groans
The typical dimensions of tested area for these cases were $10 \times 15 \text{ m}^2$. For graphs it was included also the another set of measurements (realised in B-sites planed as tested areas), where typical dimensions of area were $5 \times 5 \text{ m}^2$. There numbers of radon flux measurements were 7. Also numbers of radon concentration were lower ($\leq 9$ compared to 15 in case of previous set).

The method of radon concentration (official method used for risk estimation) was described many times including measurement of other quantities. We are near sure that it will be described in this Workshop again.

**Stability**

In the past the changes of radon concentration in soil were observed by thousands of Czech geologists etc. We did the same observation:

In this context it is not surprising that radon flux is changing also:
The flux and parameters of air

It is surprising that the difference of temperature of air and soil air does not influence the radon flux:

The dependence of flux to air temperature is indistinguishable (so that pressure's one!), but the dependence to soil temperature seems to be possible.
Influence of soil temperature to radon flux

The flux and concentration

In following graph the comparison of radon-describing quantities is represented. Sites of measurements are listened in part Method.

Our previous experiences were similar: as one can foresee, when radon IS underground, it can move UP. The progress we see in increasing of used pots and following accuracing of flux estimation.
But again we did not confirm our vision (hypothesis):

\[
\text{flux} \quad \uparrow \quad \text{ants cracks holes pores} \quad = \quad \text{permeability} \quad \uparrow
\]

\[
\text{radon} \quad \uparrow
\]

The ratio of flux and deep concentration after this idea may be dependent to permeability $k$.
Unfortunately the dependences is missing:

Colleagues studying the problem more precisely (modelling) claimed similar conclusion:
The permeability does not play important role (from one point of view).
Secondary results

Radon flux is derived by fitting the curve of radon-in-pot concentration increase:

\[ a_V = b_S \varphi \left( 1 - e^{-q \cdot t} \right) / q \]

where \( a_V \) is radon-in-pot concentration, \( b_S \) is radon flux and \( \varphi \) geometric factor. Theoretically \( q \) is decay constant, but really "half-time" \( q \) is many times shorter. It is caused by "leakage" of system pot + soil. At edge (contact of pot with surface of Earth) the mass is more permeable. It is partly caused by us when digging, but in most cases near-surface layer is less compact naturally. Therefore \( q \) described permeability of narrow surface layer, which could essentially differ from permeability measured in depth 0.8 m, how one can see further:

Conclusion

We still believe, that radon flux measurement is useful tool for many cases in risk estimation process.

In the case of tens mBq m\(^{-2}\) s\(^{-1}\) we believe that only strong inhomogeneity of layer between temporary and future surface could cause not-negligible radon concentration in dwelling.

In the case of hundreds mBq m\(^{-2}\) s\(^{-1}\) anti-radon measures may be applied to protect the future building against radon flow from underneath.

One could see an advance of flux measurement: When higher value of flux is estimated, pedologic (not pedofitic) evaluation is not necessary. In opposite case the profile of surface layer may be studied (but this drilling is realised in risk estimation system used temporarily in the Czech Republic in ALL cases).

Appendix

Flux 200 mBq m\(^{-2}\) s\(^{-1}\) correspond (at ventilation 0.3 h\(^{-1}\)) radon concentration (in cellar) 800 Bq m\(^{-3}\) . There any barrier between nature and building was not reasoned about, but in not-precise concrete floor case this concentration could be reached by flow of air (advection) also.
RADIOLOGICAL CHARACTERIZATION OF TWO SPANISH URANIUM MINE FACILITIES

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C/ Cardenal Herrera Oría s/n 39011, Santander, SPAIN
* ENUSA, Spanish Uranium Facilities, SA

ABSTRACT

During the last decade our Department of Applied and Medical Physics has been involved in the development of a Radiation Protection Programme to monitorize and control the environmental radiation conditions existing in the only two Spanish uranium mill facilities located at La Haba (Badajoz) and Saelices (Salamanca). Both mines are located in the west of the country, geographical area with high natural radiation levels.

In the framework of this Programme, measurements of radon, radon progeny and external gamma radiation indoors and outdoors, as well as of radon exhalation rate and natural radionuclide concentrations in tailings and soils, have been systematically carried out. In particular, two ore body areas in these uranium mill sites have been specially studied to determine the natural radiation background to be used as a reference value to design reliable criteria for the closure of both facilities, which is planning for the next year.

This paper summarizes the main results obtained from the measurements of external gamma radiation, radon concentrations, radon exhalation rate and natural radionuclide activity concentrations made in the above mentioned facilities with special emphasis in the results achieved from the ore body areas. Correlations between experimental results and a short description of the devices and methods used in the measurements are also shown.
INTRODUCTION

The La Haba and Saelices uranium milling plants are located in the province of Badajoz and Salamanca, respectively. The location of these sites is given in Figure 1. The plants were designed for processing low grade uranium ore (0.2-0.5 % of U$_3$O$_8$) and produced 80% concentrate of U$_3$O$_8$ in the form of sodium and ammonium uranate at a rate of 60 to 80 tons per year. Solid wastes were stored in the tailings piles and liquid wastes were treated before disposal to the Tajo and Agueda rivers, respectively. The plants became operational in the beginnings of the 1960’s. The first was closed and a remedial action plan for the last five years has been applied, and the second, while is now in operation, will be under an specific remedial plan for restoration at the end of this year. The main difference between the two mine facilities from a radiological point of view is related to their location, because for La Haba the nearest town is about 15 km far, while in the Saelices case is 3 km. This is one of the reasons to include also in this paper data concerning the radiological characterization of these vicinities in order to compare and derive conclusions about the goodness of a remedial action plan.

MATERIALS AND METHODS

A total of over 1000 measurements have been carried out to radiologically characterize the two aforementioned uranium mill facilities existing in Spain. Time integrating measurements of radon concentrations in air were made with soid state nuclear track detectors from Terradex, Tech/Ops Landauer, USA, using exposure periods of one to six months (Quindos et al, 1993). External gamma dose rates were measured by means of a Mini Instruments Environmental Monitor type 6-80 provided with an energy compensated Geiger Muller tube MC-70 (Burgess et al, 1980). All the external dose rates given in this
paper are referred to external exposure for dose rates from terrestrial gamma rays 1 m above the ground and exclude the dose contribution from cosmic radiation which was theoretically calculated for the latitude and altitude of each location (UNSCEAR, 1993).

Natural radionuclide activity concentrations in soil were determined by gamma spectrometry with a high purity Ge coaxial detector surrounded with appropriate shielding material to reduce the background counting rate. At each sampling site, five cores of topsoil were taken to a depth of 15 cm over an area of, approximately, 100 m$^2$. In order to obtain a representative sample the soil cores collected at each site were thoroughly mixed together in the laboratory and, then, a sample of 2 l was weighed, air dried for several days and placed in an oven at 100 °C for 24 h. The sample was subsequently reweighed to evaluate its water content, sieved to remove stones and pebbles, crushed to pass through a 2 mm mesh sieve and, at last, packed in a 250 ml PVC can and left for at least 4 weeks before measuring in
order to ensure that radioactive equilibrium was reached between $^{226}$Ra, $^{222}$Rn and its progeny (Quindos et al, 1994).

Finally, radon exhalation rate measurements were carried out with activated charcoal canisters of about 40 g and 2.5 cm height. Using exposure times of 24 h, the technique was previously calibrated in our laboratory to determine the radon adsorption efficiency as a function of the moisture content absorbed in the activated charcoal.

**RESULTS AND CONCLUSIONS**

The main results achieved are shown in Tables I, II, III and IV. The first compiles average data about natural radionuclide concentrations in tailings and soils as well as for external gamma radiation for the two facilities and towns close to them. As planned, significant differences in $^{226}$Ra concentration and external gamma dose rate were found being the values obtained in the vicinities of the two mill facilities approximately twice those for the rest of the country (Quindos et al, 1992). For both areas, the external gamma radiation doses indoors were on average, 1.4 times higher than the outdoor values referred in Table I, and from the experimental results obtained both could be considered as radon affected (Miles et al, 1992).

<table>
<thead>
<tr>
<th>MINING FACILITIES</th>
<th>Ac. $^{226}$Ra (Bq.Kg$^{-1}$)</th>
<th>Ac. $^{222}$Th (Bq.Kg$^{-1}$)</th>
<th>Ac. $^{40}$K (Bq.Kg$^{-1}$)</th>
<th>External gamma dose (nGy.h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A.M.</td>
<td>Range</td>
<td>A.M.</td>
<td>Range</td>
<td>A.M.</td>
</tr>
<tr>
<td>431.0</td>
<td>100-17000</td>
<td>38.0</td>
<td>15.0-65.5</td>
<td>1010.0</td>
</tr>
<tr>
<td>VICINITY (TOWNS)</td>
<td>82.0</td>
<td>40-3000</td>
<td>40.0</td>
<td>14.0-74.0</td>
</tr>
</tbody>
</table>

Table I
While the Program has been covering a big number of places for measurement, in Tables II and III appears only significant data about radon concentrations, expressed in Bq/m$^3$ corresponding to a selected number of neighbouring towns and workplaces for the two facilities. Annual average values were derived from the two measurements carried out by using track detectors for a six month period each.

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sageras</td>
<td>92.5</td>
<td>88.8</td>
<td>125.8</td>
<td>96.2</td>
<td>100.2</td>
<td>97.1</td>
<td>89.2</td>
</tr>
<tr>
<td>Majuelos</td>
<td>77.7</td>
<td>88.2</td>
<td>107.3</td>
<td>111.0</td>
<td>96.2</td>
<td>110.2</td>
<td>111.6</td>
</tr>
<tr>
<td>Villar Arga an</td>
<td>140.4</td>
<td>160.2</td>
<td>125.3</td>
<td>130.2</td>
<td>139.0</td>
<td>125.4</td>
<td>132.4</td>
</tr>
<tr>
<td>Villar Yegua</td>
<td>1607.0</td>
<td>1590.0</td>
<td>1210.0</td>
<td>1800.0</td>
<td>1550.2</td>
<td>1620.3</td>
<td>1750.1</td>
</tr>
<tr>
<td>Workplace 1 (laboratory)</td>
<td>122.1</td>
<td>111.0</td>
<td>136.9</td>
<td>155.4</td>
<td>131.4</td>
<td>160.2</td>
<td>151.2</td>
</tr>
<tr>
<td>Workplace 2 (extraction)</td>
<td>236.8</td>
<td>240.5</td>
<td>210.2</td>
<td>237.1</td>
<td>250.1</td>
<td>237.3</td>
<td>241.0</td>
</tr>
<tr>
<td>Workplace 3 (crushing)</td>
<td>410.7</td>
<td>477.3</td>
<td>414.4</td>
<td>584.6</td>
<td>472.3</td>
<td>438.7</td>
<td>462.5</td>
</tr>
<tr>
<td>Workplace 4 (offices)</td>
<td>60.0</td>
<td>65.0</td>
<td>62.1</td>
<td>71.0</td>
<td>62.7</td>
<td>59.2</td>
<td>62.1</td>
</tr>
</tbody>
</table>

Table II

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
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<th></th>
<th></th>
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<td>La Haba</td>
<td>65.2</td>
<td>56.2</td>
<td>69.0</td>
<td>65.2</td>
<td>60.1</td>
<td>51.3</td>
<td>62.5</td>
</tr>
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<td>D. Benito</td>
<td>56.2</td>
<td>45.3</td>
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<td>41.3</td>
<td>55.6</td>
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<td>Rena</td>
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<td>86.2</td>
<td>68.3</td>
<td>77.6</td>
<td>74.2</td>
<td>78.5</td>
<td>70.4</td>
</tr>
<tr>
<td>Quintana</td>
<td>61.8</td>
<td>65.3</td>
<td>56.3</td>
<td>58.9</td>
<td>65.3</td>
<td>60.9</td>
<td>64.5</td>
</tr>
<tr>
<td>Workplace 1 (laboratory)</td>
<td>102.2</td>
<td>101.7</td>
<td>106.3</td>
<td>95.3</td>
<td>101.5</td>
<td>105.3</td>
<td>96.5</td>
</tr>
<tr>
<td>Workplace 2 (extraction)</td>
<td>386.8</td>
<td>395.7</td>
<td>115.6</td>
<td>98.2</td>
<td>90.5</td>
<td>85.7</td>
<td>88.6</td>
</tr>
<tr>
<td>Workplace 3 (crushing)</td>
<td>415.3</td>
<td>430.5</td>
<td>104.7</td>
<td>96.7</td>
<td>92.4</td>
<td>96.7</td>
<td>86.7</td>
</tr>
<tr>
<td>Workplace 4 (offices)</td>
<td>65.0</td>
<td>68.5</td>
<td>72.1</td>
<td>51.0</td>
<td>72.2</td>
<td>99.2</td>
<td>66.3</td>
</tr>
</tbody>
</table>

Table III

40
As it can be seen, radon concentrations corresponding to workplaces in both facilities are very similar while they were under operation, decreasing for La Haba from 1995 date of closure and start of the remedial action plan in this mine. Nevertheless, radon concentration in houses in neighbouring towns are very different reaching in the case of Saelices, for Villar Yegua, values higher than those found in the mine. This is of course related with the presence of high $^{226}\text{Ra}$ concentrations in soil which could became similar to those existing inside the mine. Tabla IV compiles data referred to the radon exhalation rate measurements. Also in this case big differences were found between both uranium mining areas with higher values for the Saelices area not only inside the mine but also in the towns surrounding. Special interest have the radon exhalation rate data corresponding to two non exploiting ore body areas, named “natural” areas, located inside both uranium facilities which were taken as reference to design reliable criteria for planning the restoration of the mines, because while for La Haba this value is significantly higher than all the corresponding to the close towns, in the case of Saelices it is similar to that existing in some of them.

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>Exhalation rate (Bq.m$^{-2}$.h$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>A.M.</td>
</tr>
<tr>
<td>Saelices</td>
<td>4520</td>
</tr>
<tr>
<td>Vicinity of Saelices</td>
<td>752</td>
</tr>
<tr>
<td>(Towns)</td>
<td></td>
</tr>
<tr>
<td>La Haba</td>
<td>1830</td>
</tr>
<tr>
<td>Vicinity of La Haba</td>
<td>100</td>
</tr>
<tr>
<td>(Towns)</td>
<td></td>
</tr>
<tr>
<td>Saelices (Natural)</td>
<td>324°F</td>
</tr>
<tr>
<td>La Haba (Natural)</td>
<td>2140</td>
</tr>
</tbody>
</table>

Table IV

41
As suggested by other authors (IAEA, 1990), it can be appreciated from Figure 2 that no significant correlation between the external gamma dose rate and the radon exhalation rate has been found showing that individual results for any one of these two variables can not be used, therefore, as good predictors of the individual values for the another. Finally, a multilinear regression analysis has been carried out showing a significant positive correlation ($r=0.98$) between external gamma dose rates absorbed in air and natural radionuclide activity concentrations experimentally measured in soils. Dose rate conversion factors obtained for $^{226}\text{Ra}$ and $^{40}\text{K}$, 0.44 and 0.042 nGy.h$^{-1}$/Bq.kg$^{-1}$, agree very well with those recommended by ICRU Report 53, 1994, whilst that for $^{232}\text{Th}$, 0.46 nGy.h$^{-1}$/Bq.kg$^{-1}$, underestimates about 30% the corresponding ICRU factor. This discrepancy could be explained assuming a possible loss of efficiency in the radiation monitor response to gamma energies above 2 MeV such as those from $^{208}\text{Tl}$ (2.61 MeV) in the $^{232}\text{Th}$ decay series.

As resume, taking into account all data referred above it can be concluded that the annual effective doses coming from natural sources of radiation for workers of the two uranium mining facilities are similar to those received by the population living in their vicinities. This fact could be considered as an important input data in the preparation of a remedial action plan for the closure of this specific facilities.

![Diagram](image_url)

1 mR/h = 8700 nGy.h$^{-1}$ in air

Figure 2
BIBLIOGRAPHY


The migration of gaseous radon through the soil is depending on the geology of the region and may vary locally because of occurrence of fractures in impermeable layers and existence of fractures and faults. To identify areas with elevated radon concentration in soil gas, it is very helpful to know the geological structure of the area under study and how the high permeability soils are situated in the overburden. Topography of the surface in the Kraków area is determined by exhumed structure of late Alpine foreland is dismembered into systems of several normal fault-bounded carbonate horsts, erosional monadocks and grabens, and partially filled with marine Miocene clays of Carpathian foredeep basin. Radon geofluid, generated partially in sub-Jurassic, U-rich crystalline basement, migrates vertically to surface through permeable, jointed, faulted and karstified Jurassic limestone. Under the cover the radon fluxes is channelled by adjacent listric faults and clay/limestone interfaces around Jurassic carbonate “chimneys” and “windows”, connecting with land surface.

Basing on the geological maps of Kraków three regions in Kraków three areas, which are: i) slopes around limestone horst of Sowiniec/Saint Bronisława Hill (westward of City center), (ii) N slope of Kapelanka horst (southward of City centre) and (iii) small erosional limestone “window” in Miocene cover (northward of centre), were investigated for the elevated radon concentration in the soil gas. In situ radon concentration measurements and
radium concentration measurements in ground samples have been performed. The mean radon concentration in the soil gas obtained by CR-39 method and ionisation chamber AlphaGUARD measurements was found in the range of 30 kBq m\(^3\) which is approximately 2.5 times higher, than the average radon concentration obtained in measurements with randomly chosen 194 points (13 kBq m\(^3\)). In these measurements points only 7% of results showed values above 30 kBq m\(^3\). It is concluded that knowledge of the geological structure if the area of interest might be important to identify high radon risk area.
Comparison of the large-scale radon risk map for southern Belgium with results of high resolution surveys

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Andre.Poffijn@Health.fgov.be

Abstract

A large-scale radon survey consisting of long-term measurements in about 5,200 single-family houses in the southern part of Belgium was carried from 1995 to 1999. A radon risk map for the region was produced using geostatistical and GIS approaches. Some communes or villages situated within high risk areas were chosen for detailed surveys. A high resolution radon survey with about 330 measurements was performed in half part of the commune of Burg-Reuland. Comparison of radon maps on quite different scales shows that the general Rn risk map has similar pattern as the radon map for the detailed study area. Another detailed radon survey in the village of Hatrival, situated in a high radon area, found very high proportion of houses with elevated radon concentrations. The results of this detailed survey are comparable to the expectation for high risk areas on the large-scale radon risk map. The good correspondence between the findings of the general risk map and the analysis of the limited detailed surveys, suggests that the large-scale radon risk map is likely reliable.

1. Introduction

A large-scale national radon survey consisting of long-term measurements (3 mo) in about 5,200 single-family houses in the southern part of Belgium was performed from 1995 to 1999. An indoor radon risk map was produced using geostatistical and GIS approaches. After the large-scale survey, more detailed radon surveys were carried out in some selected high-radon areas, two of which will be presented in this article. The objective of this note is to compare the large-scale radon risk map with detailed radon maps for local areas.

2. The large-scale indoor radon risk map

As mentioned above, a data set of about 5,200 long-term indoor radon measurements was collected in southern Belgium. Track-etch detectors exposed on the first floor for a period of 3 months. Radon concentrations are lognormally distributed. Spatial variations of indoor radon concentrations are modelled by logarithmic variograms which are used to produce a Rn contour
map using the log-normal kriging technique. To define radon risk zones, we used GIS spatial overlay capabilities to perform a point-in-polygon operation to analyse the spatial relationship between high-radon houses and kriged contour map. Integrating all measured houses on kriged contour map of Rn concentrations, we defined a contour level as limit of a category of risk zones, in order that most high radon houses, say, more than 90% of houses with Rn concentrations over a given reference level fall within polygons (called anomaly zones) which are formed by the contour lines. We have three categories of Rn risk zones: high risk areas, medium risk areas and low risk areas (Table 1, Fig. 1). More details on the approaches of risk mapping can be found in our other article (Zhu et al., 1999).

![Fig. 1. Large-scale radon risk map for southern Belgium.](image)

3. Detailed indoor radon surveys

*Case of the commune of Burg-Reuland*

The Commune of Burg-Reuland situated in high risk areas (Fig. 1) was chosen for a detailed radon survey. Long-term measurements (3 mo) were performed in about 330 homes in half part of the commune. The conditions of measurements are similar to those of the previous large-scale survey. Table 2 shows statistics of the measurements.

To evaluate the large-scale Rn risk map, we will try to compare the risk map to the high-resolution Rn data. Based on the large-scale radon data set and its risk map, we calculated probability of homes with radon values over a given level which fall within a category of risk areas. For instance, 46.1% of homes with radon concentrations above 200 Bq/m³ are expected to fall within high risk areas, 35.39% of homes within medium risk areas (second column of Table 3). Data points of the detailed survey in Burg-Reuland are integrated to the large-scale risk
Table 1. Statistics for different categories of risk areas on the large-scale radon risk map.

<table>
<thead>
<tr>
<th>Risk areas</th>
<th>Total samples within areas</th>
<th>/ 800 Bq/m³</th>
<th>/ 400 Bq/m³</th>
<th>/ 200 Bq/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Measurements</td>
<td>calc.</td>
<td>Measurements</td>
</tr>
<tr>
<td>High</td>
<td>346</td>
<td>64</td>
<td>18.50%</td>
<td>187</td>
</tr>
<tr>
<td>Medium</td>
<td>522</td>
<td>2</td>
<td>0.38%</td>
<td>23</td>
</tr>
<tr>
<td>Low</td>
<td>821</td>
<td>1</td>
<td>0.12%</td>
<td>5</td>
</tr>
<tr>
<td>Normal</td>
<td>3485</td>
<td>1</td>
<td>0.03%</td>
<td>4</td>
</tr>
<tr>
<td>All</td>
<td>5174</td>
<td>68</td>
<td></td>
<td>219</td>
</tr>
</tbody>
</table>

Nb: number of homes; calc.: calculated from lognormal functions.

Table 2. Statistics for two detailed radon surveys.

<table>
<thead>
<tr>
<th></th>
<th>Nb. of homes</th>
<th>GM Bq/m³</th>
<th>Percentage of homes with radon concentrations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;100(Bq/m³)</td>
</tr>
<tr>
<td>Burg-Reuland</td>
<td>330</td>
<td>119</td>
<td>51.5%</td>
</tr>
<tr>
<td>Hatrival</td>
<td>149</td>
<td>230</td>
<td>24.2%</td>
</tr>
</tbody>
</table>

map drawn before the detailed survey. Table 3 shows the probability of homes in Burg-Reuland which have radon values over 200 Bq/m³ and fall within a given category of risk areas. Similar statistics were performed for homes with radon concentrations over 400 and 800 Bq/m³ (Table 4 and 5).

Comparison of the statistical results of the two surveys (Table 3-5) indicates that the results of the detailed survey in Burg-Reuland are close to the regional expectation for different categories of risk areas. It is also noted that only about 14% to 16.7% (last columns of Table 4 and 5) of homes with Rn concentrations over 400 Bq/m³ (or 1.8% homes with elevated values among a total of 330 measured houses) fall in "wrong places" - low risk or normal areas which is drawn on the basis of the large-scale survey data.

On the other hand, a high-resolution radon risk map produced from data set of the detailed survey shows a similar pattern as the large-scale risk map (Fig. 2 and 3) although it has more details as expected.
Table 3. Distribution of homes with radon concentrations over 200 Bq/m$^3$ in different categories of risk areas.

<table>
<thead>
<tr>
<th>Risk areas</th>
<th>National Rn risk map</th>
<th>% homes expected</th>
<th>Burg-Reuland detailed survey</th>
<th>% homes measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>46.10</td>
<td></td>
<td>60.98</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>35.39</td>
<td></td>
<td>19.51</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>15.23</td>
<td></td>
<td>18.29</td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>3.28</td>
<td></td>
<td>1.22</td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Distribution of homes with radon concentrations over 400 Bq/m$^3$ in different categories of risk areas.

<table>
<thead>
<tr>
<th>Risk areas</th>
<th>National Rn risk map</th>
<th>% homes expected</th>
<th>Burg-Reuland detailed survey</th>
<th>% homes measured</th>
</tr>
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<tbody>
<tr>
<td>High</td>
<td>79.86</td>
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<td>69.44</td>
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<tr>
<td>Medium</td>
<td>18.70</td>
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<td>13.89</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>1.33</td>
<td></td>
<td>13.89</td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>0.01</td>
<td></td>
<td>2.78</td>
<td></td>
</tr>
</tbody>
</table>

Table 5. Distribution of homes with radon concentrations over 800 Bq/m$^3$ in different categories of risk areas.

<table>
<thead>
<tr>
<th>Risk zones</th>
<th>National Rn risk map</th>
<th>% homes expected</th>
<th>Burg-Reuland detailed survey</th>
<th>% homes measured</th>
</tr>
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<tbody>
<tr>
<td>High</td>
<td>96.66</td>
<td></td>
<td>71.43</td>
<td></td>
</tr>
<tr>
<td>Medium</td>
<td>3.34</td>
<td></td>
<td>14.29</td>
<td></td>
</tr>
<tr>
<td>Low</td>
<td>-</td>
<td></td>
<td>14.29</td>
<td></td>
</tr>
<tr>
<td>Normal</td>
<td>-</td>
<td></td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 2. Radon risk map of Burg-Reuland extracted from the large-scale risk map.

Fig. 3. High-resolution radon risk map for Burg-Reuland.
**Case of the village of Hatrival**

The village of Hatrival is situated in a high risk area on the national radon risk map (Fig. 1). In a further detailed survey, we have 149 houses measured in this small village compared to 5 readings in the previous large-scale survey. As expected, high proportion of elevated radon houses are found (Table 2), about 16% of homes having radon concentrations over 800 Bq/m$^3$ and about 28% of homes with values over 400 Bq/m$^3$. The results are close to those expected for high risk areas calculated in large scale survey (Table 1).

4. Conclusions

The results of the two case studies are consistent with the statistical outcome for radon risk areas drawn in large-scale radon survey. The large-scale radon risk map is likely reliable. For statistical evidence, however, the reliability of the risk map needs to be validated by the analysis of more high-resolution surveys.

**References**

Soil gas measurements at high permeabilities and below foundation depth

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Introduction

Based on the new Swiss Ordinance on Radiological Protection, a project to assess indoor radon exposure and to define radon prone areas has been started in 1994. Radon risk mapping from geological information is very difficult, as the geology of Switzerland is very complex. However indoor radon measurements in a sufficiently large number of houses per community is an economical prediction method. Statistical analysis of measurement campaigns where all houses of a community have been measured, showed that measuring 20 houses leads to a good radon risk estimation with a low misidentification rate [2].

There is an increasing demand for construction site evaluation and for more reliable soil data to define mitigation schemes, e.g. to dimension radon wells. This is only possible with a good understanding of soil gas transport. We therefore started a project to make more reliable soil gas measurements. As the foundation of houses often lies deeper than 0.5 to 1 m, the depth where soil gas measurements are often made, a first approach was to apply the method developed by Surbeck [1] to deeper soil layers. A radon availability index (RAI) was empirically defined and proved to be a reliable indicator for radon problems in nearby houses.

Extreme values of permeability, non-Darcy flow and scale dependence of permeability initiated the development of a multiprobe method. A hydrological model was applied to model soil gas transport.

Methods

A core drilling machine and an electrical power generator are mounted onto a small caterpillar. Hydraulic energy is used to ease the repetitive operations of extracting cores every 10 to 20 cm. Drillings of 6 to 10 cm in diameter can be brought down to several meters depth. The drilling is interrupted every 50 cm to take a soil gas sample and to measure permeability. Hard metal or diamond drills are used without water rinsing to avoid clogging of the soil. Except for regions with rocks containing high levels of quartz or limestone, the drilling was in most cases brought down to below foundation depth.

Permeability is measured in the lowest ten centimetres of the advancing drilling by means of a probe with an inflatable packer. To avoid pressure losses due to high flow rates in the connecting tubing, a separate tube connects the probe volume to a manometer. A fixed volume of air is pumped under constant pressure into the surrounding soil. The time it takes is a measure for the permeability. The pressures applied vary from 100 mbar down to a few Pascal, allowing to measure permeabilities up to $10^{-8} \text{ m}^2$. Assuming spherical symmetry, the permeability is given by formula 1 [1].

$$ k = \frac{\eta V}{4\pi r^2 p T} \quad [\text{m}^2] \quad (1) $$

with $k =$ permeability, $\eta =$ dynamic viscosity, $V =$ volume of the pump, $r =$ radius of the drilling, $p =$ pressure applied and $T =$ duration.

In some cases permeabilities were so high ($> 10^{-8} \text{ m}^2$) that no more reliably measurable pressure signal could be achieved, thus a multiprobe method was tested. It consists of a strong extraction fan, that creates a constant flow out of the previously drilled hole. Multiple hollow steel probes hit at different distances from the borehole are used to measure the pressure propagation in the soil. Clogging of the steel probes was avoided by putting a rod in the tubes and extracting it after lowering the probe to the desired depth. At high permeabilities the underpressure in the soil can be followed over tens of meters. The hydrological model of Hantush and Jacob for a leaky aquifer (2) [3] was used to fit the permeabilities of the permeable and the top layer.

$$ p(r) = \frac{Q \eta}{(4\pi kh)} \ast W(r/B) \quad [\text{Pa}] \quad (2) $$

52
with \( r \) = distance from the drilling, \( p(r) \) = pressure as a function of distance, \( Q \) = flow, \( \eta \) = dynamic viscosity, \( k \) = permeability of the permeable layer, \( h \) = thickness of the permeable layer. \( W(r/B) \) is the well formula of Hantush and Jacob with the so-called leakage parameter \( B \).

\[
B = \sqrt{h_{\text{top}} k_{\text{top}} / k_{\text{top}}}
\]  

(3)

With \( h_{\text{top}} \) and \( k_{\text{top}} \) the thickness respectively permeability of the top layer. For high values of \( B \) the cover layer has a high resistivity, for low values a strong leakage occurs. The values for \( W(r/B) \) can be found tabulated in literature \([3]\). The following assumptions are made in Hantush's model: Vertical flow in the top layer, horizontal flow in the permeable layer, leakage varies as a function of pressure.

### Depth profiles

Already the very first drilling, close to a house with high radon levels, in the kanton of Ticino, showed an increase of permeability below 1 m by more than two orders of magnitude (Fig. 1). The house is located on a fluvioglacial alluvion with a thickness of several tens of meters. The underlying bedrock consists of granitic gneiss. The increase of permeability with depth can be explained by a cover of fine material lying on permeable soils like sand or gravel. This cover layer was most probably produced by wind deposition after the last glacial period, by weathering and by biological activity. The thickness varies between half a meter and several meters. This low permeability top layer also explains why radon levels in neighboring houses can be very different. Higher levels are to be expected if the foundation depth lies below the top layer.

Fig. 1. Depth profile of permeability. An increase in permeability over more than two orders of magnitude below one meter is visible.

Fig. 2. Depth profile of radon concentration. After an increase to 62 kBq/m³ at 0.5 m the radon concentration drops again below 10 kBq/m³ at 1 m.

A permeable layer covered by a clearly less permeable cover layer was very often found, if the indoor radon value exceeded 1000 Bq/m³, (measured during three months in winter, in inhabited rooms.) An other interesting result show depth-profiles of the radon concentration close to some houses with high radon levels. After an initial increase the concentration often drops again, indicating a horizontal transport of soil gas in the permeable layer and a supply of atmospheric air through the cover layer (Fig. 2). This hypothesis is supported by CO₂ and O₂ measurements. CO₂ is produced in the top layer and it's concentration behaves similar as the radon concentration. O₂ is used up by biological activity but often increases again after an initial decrease. As the first few depth profiles showed interesting results it was decided to apply this method to a bigger number of houses.

### The Radon Availability Index (RAI)

To achieve a classification of the soils, the soil gas measurements were made close to houses with indoor radon concentrations known from the federal campaign \([2]\). The indoor concentration was measured during three months in winter in inhabited rooms. The houses were selected in a way to cover different geological aspects, a big range of permeabilities, soil gas and indoor radon concentrations. About forty drillings were made.
dispersed over the hole Swiss alpine region and about ten in the Mittelland, the plain region between the alps and the Jura mountains, on tertiary and quaternary sediments.

It appeared that the best classification could be achieved taking the highest value of the radon availability index (defined below) of each profile. It separates the houses in two groups, one with radon concentrations below 200 Bq/m³ and one above 200 Bq/m³. Figure 3 shows radon concentration vs. permeability. Full points correspond to houses with a radon concentration above 200 Bq/m³ empty points to such below 200 Bq/m³. The slope of the line, separating the two classes, corresponds to the square root of the permeability. As a consequence a radon availability index is defined as:

\[ RAI = C(Rn) \times \sqrt{k} \quad [\text{Bq/m}^3] \quad (4) \]

With \( C(Rn) \) the Radon concentration in the soil and \( k \) the permeability.

![Fig. 3. Radon concentration in soil vs. permeability. Full dots: Houses with indoor levels above 200 Bq/m³, empty Dots: houses with indoor levels below 200 Bq/m³. The line corresponds to a RAI of 0.2.](image)

![Fig. 4. Indoor Radon availability index (RAI).](image)

The full point below the line in Figure 3 corresponds to a house which is in contact to fractured rock. In this case the transport of soil gas is not governed by the soil permeability. This point is thus omitted in the following graphs. The empty points above the line are due to houses with a tight construction.

The reason why the points are separated into two classes above and below 200 Bq/m³ is illustrated in Figure 4. Below a RAI of 0.2 there is a “background” not exceeding 200 Bq/m³. Above, the values increase with the RAI. As Swiss building materials are estimated to account only for 30 Bq/m³, the difference between the “background” is probably due to diffusion from the soil. Figure 4 also justifies the classification of a region as radon prone area if the mean indoor radon concentration is above 200 Bq/m³, dotted line [2]. Soil gas measurements lead to a more stringent classification if a RAI of 0.2 is taken as a limit, solid line.

Test of multiprobe steady state measurements

The first test of multiprobe steady state pressure measurements was made close to a house with high radon levels indoors but only moderate radon concentrations in the soil. The drilling showed a cover layer of 1.6 m thickness and below a highly permeable layer of clean gravel with a thickness of 50 cm. The extraction rate was 135 m³/h at a pressure of -150 Pa. The sharp pressure drop from the borehole to the first probe suggests turbulent flow around the drilling. The pressure could be followed in the soil over a distance of 18 m. Figure 5 shows the results of this first test.
Fig. 5. Pressure vs distance. Points: measured values, line: fit of Hantush’s model.

The permeabilities resulting from the fit are \((6\pm1)\times10^{-8}\) m² for the permeable layer and \((6\pm3)\times10^{-11}\) m² for the top layer. The corresponding point measurements in the borehole resulted in \((2\pm2)\times10^{-8}\) m² for the permeable layer and \((1\pm2)\times10^{-11}\) m² for the top layer. This is a fairly good agreement, taking into account that in the permeable layer the pressure point measurement was difficult \((p = 3\) Pa, \(t = 1\) s) and that the top layer is often inhomogeneous and compressed around the drilling. By increasing the extraction flow rate, this method could give reliable results up to permeabilities of \(1\times10^{-6}\) m².

Discussion

Our method is not applicable if the foundation is in contact with the bedrock. Eventual fractures, which govern the soil gas transport, are most probably not found.

The high permeability layers often have a thickness of 10 cm to 50 cm, whereas flow simulations showed that the method can be sensitive to a distance of several meters. Thus it is not clear if a cylindrical or spherical model gives better results for the point measurements.

Another characteristic of soils is scale-dependence [4,5,6], i.e. the effective permeability, measured over bigger distances, can give values more than one order of magnitude higher than found in a point measurement. In the case of soil gas measurements scale dependence could be an artifact of an underlying high permeability layer.

The multi probe method should be suitable to overcome the problems of non-Darcy flow and scale dependence.

Conclusions

Soil gas measurements below foundation depth show a great wealth of new information. A good classification of soil properties could be achieved. If soil gas measurements are to be made, the low permeability layer has to be traversed. A minimum depth of 1.5 m is suggested, best are profiles to below foundation depth. There are also implications for mitigation works. A subslab suction system should reach the permeable layer to function well. The same holds for radon wells. If a house is standing on a slope, a subslab suction system is easiest installed on the hillside, as the foundation reaches deepest there.

Further work will be towards a smaller and more economic equipment. Multiprobe measurements under static and dynamic pumping conditions should elucidate questions about scale dependence and soil inhomogeneity.

Acknowledgements

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References


Natural radionuclides in soils-relation between soil properties and the activities

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Abstract

Vertical profiles of natural radionuclides (K-40 and Ra-226) have been investigated in a soil core with 8 m in depth to elucidate its relation to the bed rock activity and to several soil properties. Pattern of the Ra-226 activity with soil depth suggests inhomogeneity of this nuclide during the accumulating process. Radiometric sorption experiments with Pb-210 as a tracer gave the result that almost all Pb(II) in the soil solution disappeared to be sorbed to the soil components.

Introduction

Much concern has been focused on monitoring of natural radioactivities in various geological fields including urban districts in Japan, partly because of the nuclear accident happened at a fuel processing company at Tokaimura in September 1999. The real problem is not just the accident itself, but many people become scared without any idea of what's radiation (and radioactivity) is. They do not even know natural radiation by which they are inevitably irradiated in everyday life.

On the aspect of potential risk by radon emanation from the ground, there are several experts in our country who have measured indoor radon in many parts of the islands for many years (1). They reported that indoor radon concentration of most of the Japanese houses being 20.8 and 18.8 Bq/m$^3$ in mean and its standard deviation, respectively would not be in dangerous situation compared with those obtained in other countries all over the world (2).

Radon emanation occurs locally rather than globally depending on various environmental factors such as meteorological, geological, geographical and construction conditions (1,3,4). It is true that before reaching a top of the soil surfaces, radon and its progenies had traveled long way from the bed rock.

The present study is focussed on the behavior of natural radionuclides contained in
soils and their relation to the bed rock radioactivities. Main source of indoor radon is
the ground beneath a building. The soil above the bedrock and bedrock itself always
contain a certain amount of U-238 and Ra-226 from which Rn-222 is to be produced.
Radon gas produced at large depth may be transported in different ways up to the
ground surface by other means than pure diffusion, which is especially the case in faults
in the bedrock(5). Water level in the ground is another factor controlling mobility of
Rn-222 with a half life of 3.8d. If Rn-222 released from the bedrock retains within a
soil layer for a while, there would be little chance for the nuclide to be out to the
atmosphere, and Pb-210, a daughter product of Rn-222, is to interact with soil
components because of its long half life.

The purpose of the present study is i) to investigate vertical distribution of natural
radionuclides(K-40 and Ra-226) of a soil core with 8 m in length, and ii) to elucidate its
relation to the bed rock activities. Sorptive properties of Pb(II) whose source in the
soil environment is not only natural but also anthropogenic has also been investigated in
the laboratory experiment using Pb-210 as a tracer.

Experimental

Instruments

Germanium gamma ray spectrometer with a high purity germanium
detector(GEM-25185-P, Seiko EG&G. Japan, 57.7mm in diameter, 28.4% relative
efficiency and a resolution of 1.67 keV at 1.33 MeV), Radiation monitor(Pylon AB-5
Canada), Nal(Tl) Scintillation counter(Aloka ARC301B, Japan), X-ray
diffraactometer(Mac Science MXP, USA), Centrifuge (Hitachi Japan), Mechanical
Shaker (Kokusan Partner, Japan)

Materials and methods

Soil samples-Cored soil sample(down to about 8 m from the surface) was collected
from Tono district in Gifu Prefecture(Japan) in July 1999.
Reference material for the activity measurement-Two soil samples with known activities
were purchased from IAEA(IAEA-Soil-6 and IAEA-312), and used as reference
materials for the measurement of Ra-226 in our soil samples.
Radioisotopes-Manganese-54, Zinc-65 and Pb-210 obtained from the Japan
Radioisotope Association in the form of chlorides in 0.5M hydrochloric acid. The
nominal specific activities of these nuclides were 240.190 GBq/mgMn, 93.232
MBq/mgZn and 159.82 kBq/mgPb, respectively.

Activity from Ra-226 and K-40 was determined by γ-ray spectrometry. The samples
were placed in sealed containers and left for at least three weeks before counting to ensure Rn-222/Ra-226 equilibration.

Chemical properties of the soil solutions were investigated on pH, Eh and conductivity.

Sorption experiments were carried out according to the procedure described previously by using Mn-54, Zn-65 and Pb-210 as radiotracers (6). On evaluating sorbed amounts of these nuclides, several standards of known activities were used.

Results and discussion

Soil samples used in this study were collected from Tono district in Gifu Prefecture (Japan) where granitic rocks and rhyolites (Nohi rhyolite) lie as the major base rock, and porcelain clay is abundant to be famous for the production of porcelain wares for a long time. There exists an old uranium mine, too.

The present authors had an opportunity to get a cored soil down to about 8 m in depth. The core was cut every 50 cm except for the uppermost portion, and each of them was homogenized, dried and stored at room temperature for the analyses.

In order to get information on chemical properties of the soils, measurements were carried out on pH, Eh and conductivity of the soil solutions. Figure 1 shows the vertical profiles of pH, Eh and conductivity in the soil solutions. It is quite different in appearance between shallow and deep parts of the cored soil. In any case, a boundary was about 350 cm in depth. All data on pH, Eh and conductivity gave values decreasing drastically from the surface down to this depth. After that, the values remained rather constant independent of the soil depth, where a reduced condition would be maintained. Redox condition of the soil environment also controls mineral composition, and thus pH values of the soil solution. Among various minerals constructing soil inorganic fraction, carbonates may be one of the predominant components determining soil pH (>8) in shallow part, whereas some type of aluminosilicates may control soil pH (about pH 5-6) in deep part of the soil. It should be noted that there appears a high conductivity region at around 700 m in depth reflecting different minerals controlling the soil pH. Such a speculation may be partly supported by x-ray diffraction analyses of the samples.

Gamma ray spectrometric analyses were then carried out on about 80 samples of the soil core. Radioactivity of Ra-226 was evaluated by using two reference materials purchased from IAEA (Soil-6 and Soil-312), while K-40 activity was obtained from a
Figure 1 Plots of pH(a), Eh(b) and conductivity(c) in soil solutions versus soil depth.
Figure 2  Vertical profiles of K-40(a) and Ra-226(b) activities in the soil samples.

Figure 3  Plots of Ra-226 activity against K-40 activity in the rock samples.
calibration curve with reagent grade KCl as a standard with known activity. Vertical profile of K-40 activity shows that all values fell in the range from 100 to 170 Bq/Kg of dried soil (Fig. 2a). High values of K-40 activity were observed at several points of the core in which aluminosilicates containing potassium would be predominant. Anyway, the values obtained in this study are within the range of 110 to 740 Bq/Kg quoted by the United Nations Scientific Committee on the Effects of Atomic Radiation (7). In contrast to the K-40 profile, Ra-226 activities were varied to a high degree with depth (Fig. 2b). The highest Ra-226 activity was found to be 82 Bq/Kg at 445m in depth where weathered products of granite were abundant in the soil components. There appear many other peaks in the figure which would reflect pertinent minerals contained in the soil. Mean Ra-226 activity was about 50 Bq/Kg, which is in line with a world average specific activity, in soil, of 40 Bq/Kg (7). It was verified that the activities of both Pb-214 and Bi-214, the progenies of Rn-222 correlate each other at all the depth investigated. On the activities of U-238 daughter nuclides, Mora and Salazar (8) reported the values after Ra-226 in the decay chain of U-238 were significantly lower than that of Ra-226, which was due to escaping Rn-222 from porous materials such as soil or volcanic material.

Activities of K-40 and Ra-226 were also measured for several rock samples collected at the same point as the soil core. Figure 3 shows plots of Ra-226 activity against K-40 activity in these rocks, which indicates that at least three types of rocks would be included in these samples; granite, sand stone and tuff. Possible minerals having high K-40 activity is of feldspars, whereas high Ra-226 content comes from biotite contained in granitic rocks.

Comparing K-40 and Ra-226 activities of both soil and rock samples suggests that the origin of those nuclides would be different, and the distribution of Ra-226 in soils would be far from homogeneous.

Behavior of radon released from the bed rock into the soil environment is influenced by many factors. Considering a situation that Rn-222 could not be out to the atmosphere within its life span, a disintegrated product of Rn-222, Pb-210 with a half life of 22.3y, would come on a stage to investigate, since lead is toxic for most of the terrestrial organisms, and origin of lead isotopes is of another importance in the environmental point of view (9).

The authors investigated sorption of Pb(II) to the uppermost portion of the core by using Pb-210 as a tracer. Table 1 lists the results of sorption isotherm of Pb(II) as well as those of Mn(II) and Zn(II). As shown in the table, the amount of Pb(II) at the maximum sorption, \( A_m(\text{Pb}) \) was more than ten times higher than corresponding values.
Table 1 Comparative lists of data on maximum sorption ($A_m$) and sorption equilibrium constant of Pb(II), Mn(II) and Zn(II) in the uppermost soil sample. Possible error of each value is estimated to be ±2%.

<table>
<thead>
<tr>
<th>Metal(M)</th>
<th>Maximum sorption $A_m$(M)/mmol/100g</th>
<th>Sorption equilibrium constant $/10^2$ cm$^3$/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pb(II)</td>
<td>5.01</td>
<td>187</td>
</tr>
<tr>
<td>Mn(II)</td>
<td>0.408</td>
<td>8.63</td>
</tr>
<tr>
<td>Zn(II)</td>
<td>0.233</td>
<td>11.6</td>
</tr>
</tbody>
</table>

for both Mn(II) and Zn(II), which indicates that if Rn-222 is retained within a soil layer for a while, a daughter product, Pb-210, would be strongly sorbed to certain soil components.

Factors influencing Pb(II) sorption to soils is to be investigated.

**Literatures**

8. UNSCEAR (United Nations Scientific Committee on the Effects of Atomic

DIFFUSIVE AND CONVECTIVE TRANSPORT OF RADON THROUGH CRACKS IN THE BUILDING UNDERSTRUCTURE

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1. INTRODUCTION

Under normal operating conditions air containing radon gas from the ground enters a building through cracks, holes and joints in the building understructure. Both diffusion and forced flow contribute to the influx of radon gas into the buildings. However, the radon community cannot agree on an opinion on relative importance of diffusive and convective components. US EPA manual from 1992 [1] on radon mitigation states that only 4% of indoor radon concentration is due to diffusion. On the other hand, Kendrick and Langner (1991) [2] showed that more than 50% of the total radon infiltration came from diffusion.

The objective of this paper is to present a theoretical evaluation of soil and house related factors that may affect the transport of radon from the soil into houses. A two-dimensional mathematical model was used to simulate the diffusive and convective transport of radon into the house through idealized openings in the understructure. With the help of model predictions, we try to find out whether diffusion or convection predominates and under which circumstances.

2. MATHEMATICAL MODEL

The mathematical model describing the generation and transport of radon is based on the partial differential equation for the two-dimensional steady state radon transport in a porous medium. This equation can be expressed as [4]:

\[ D_e \nabla^2 C + \frac{k}{\varepsilon \mu} \nabla p \nabla C + G - \lambda C = 0 \]  

where \( D_e \) is the effective diffusion coefficient \([\text{m}^2/\text{s}]\), \( C \) is the radon concentration \([\text{Bq/m}^3]\), \( k \) is the soil permeability \([\text{m}^2]\), \( \varepsilon \) is the soil porosity \([-]\), \( \mu \) is the soil gas dynamic viscosity \([\text{Pa.s}]\), \( p \) is the relative pressure of the soil gas phase \([\text{Pa}]\), \( \lambda \) is the radon decay constant \([\text{s}^{-1}]\) and \( G \) is the radon generation rate \([\text{Bq/m}^3\text{s}]\). The first term on the left-hand side of the equation (1) represents the radon transport due to diffusion, the second term represents the radon transport due to convection, the third term expresses the radon generation rate and the last term represents the drop in radon concentration due to radioactive decay.

The major assumptions adopted in the model are as follows:

- each element is homogeneous (i.e., permeability, porosity, and radon diffusion coefficient are constant within each element),
- soil gas is incompressible, i.e., \( \nabla \tilde{v} = 0 \)  

where \( \tilde{v} \) is the soil gas velocity \([\text{m/s}]\), \( \tilde{v} = \frac{k}{\mu} \nabla p \)  

- flow of soil gas is linear according to Darcy's law
- pressure distribution is governed by Laplace equation \( \nabla^2 p = 0 \).

The finite element method was used for the solution of the equation (1). The general finite element formulation of the governing equation (1) was derived by means of the Petrov-Galerkin method [7]. This approach, which is also known as streamline balancing diffusion or
streamline Petrov-Galerkin process, is based on the special selection of the weighting functions different from the interpolation functions. A detailed description of the model is presented in [6].

The computer model Radon2D calculates the pressure field within the porous medium, the air flow velocity field, the radon concentration field and from specified boundaries the radon flux density due to diffusion $E_d$ and due to convection $E_k$:

$$E_d = -\kappa \cdot \nabla C$$

$$E_k = -\frac{k}{\mu} \nabla p C = \bar{v} C$$

The velocity $v$ of air flow through cracks is computed according to Darcy’s law in which the crack permeability is defined from the crack width $w$ as $k = w^2/12$ (Baker et al. 1987). The air velocity is then expressed as:

$$v = \frac{w^2 \cdot \Delta p}{12 \mu \cdot d} \text{ [m/s]}$$

where $d$ is the thickness of the slab [m]. And finally, a flow rate $Q$ [m$^3$/s] through the crack can be found from the Navier-Stokes equation [3]:

$$Q = \frac{w^3 L \cdot \Delta p}{12 \mu \cdot d} \text{ [m$^3$/s]}$$

where $L$ is the total length of the crack [m].

3. PHYSICAL MODEL

The flow of soil gas through cracks and the resulting radon flux density have been studied on a theoretical model that represents the understructure of a typical single-family house. The cross section of the model is shown in Fig. 1 (due to symmetry only left-hand side of the house was considered). The concrete slab, which is placed between the footers, is 100 mm or 50 mm thick and rests directly on the soil. The soil block around the understructure of the house is considered to have a uniform radon generation rate $G = 0,12$ Bq/m$^3$s. Radon concentration in the deep soil gas is assumed to be under the constant value 57,2 kBq/m$^3$ (G/λ) and in the house interior of 60 Bq/m$^3$. Radon concentration in the outdoor air is set to 5 Bq/m$^3$. The interior surface of the slab was under a depressurisation of -3 Pa or - 6 Pa.

The first crack is assumed to exist at the junction between the slab and the footer behind the perimeter wall (let’s call this crack as “perimeter crack”). The second crack (called as “central crack”) is located in the middle of the slab – in the distance of 3 m from the perimeter wall. These cracks are the only openings in the house understructure. Radon diffusion through the concrete of the slab is assumed to be negligible.

![Fig. 1. Cross section of the theoretical model](image-url)
The computer model was used to find out how the radon transport through cracks and the radon flux density are influenced by variations in the soil permeability, position of cracks and width of cracks.

4. RESULTS

The velocity of air flow at the crack-indoor interface is plotted as a function of soil permeability and crack width in Fig. 2. As can be seen the velocity is proportional to the soil permeability and inversely proportional to the crack width. The ratio between air flow velocities through perimeter and central cracks is 0.75. This difference could be explained by the geometric configuration. While the soil air can flow freely from the whole sub-slab space towards the central crack, in case of perimeter crack the air flow is influenced and possibly reduced by the presence of continuous footers beneath perimeter walls (see Fig. 3).

Fig. 2. Air flow velocities through cracks in the slab 100 mm thick in dependence on the soil permeability, \( \text{dpi} = -3 \ Pa \).

Fig. 4. Pressure difference across the crack in dependence on the soil permeability. Calculated for the central crack.

Fig. 3. Air flow through the subsoil towards cracks

\[ Q = v \cdot L \cdot w \]

The same rate \( Q \) should be obtained in accordance with the Navier-Stokes equation (8). The pressure difference across the crack that is required by this equation can be found from Fig. 4, where the pressure difference is plotted against the soil permeability and for different values of the crack width \( w \), slab...
thickness $d$ and indoor underpressure $dpi$. Fig. 4 is the result of the numerical simulation by Radon2D model. It can be seen that the pressure difference across the crack is proportional to the slab thickness and indoor-outdoor underpressure and inversely proportional to the third power of the crack width.

Let's now consider the model predictions concerning the diffusive and convective components of the radon flux density from the perimeter crack with the thickness of 1 mm and length of 1 m. Correlation between these two components is presented in dependence on the soil permeability in Fig. 5. Although the values of the radon flux density on the vertical axis correspond to the previously described geometric configuration, it is possible to derive from this figure a lot of general principles.

If there is now pressure difference across the crack, the diffusive flux slowly increases according to curve $E_{d0}$ with increasing radon diffusion coefficient $D_e$ ($D_e$ increases from $5 \times 10^{-7} \text{ m}^2/\text{s}$ for $k = 1 \times 10^{-14} \text{ m}^2$ to $6 \times 10^{-6} \text{ m}^2/\text{s}$ for $k = 1 \times 10^{-9} \text{ m}^2$).

The existence of the pressure difference across the crack gives rise to the convective component $E_k$ that increases rapidly and almost linearly with the soil permeability. The variation is not truly linear due to changes in radon concentration within the crack caused by dilution effects (radon concentration at the crack-soil interface varies only slightly from 40 kBq/m$^3$ for $k = 1 \times 10^{-14} \text{ m}^2$ over 55 kBq/m$^3$ for $k = 1 \times 10^{-11} \text{ m}^2$ up to 53.8 kBq/m$^3$ for $k = 1 \times 10^{-9} \text{ m}^2$). While $E_k$ is not so much affected by changes in radon concentration, these changes alter the diffusive component quite fundamentally. Under the condition that there is a pressure difference across the crack the radon diffusion varies according to curve $E_d$, which differs from $E_{d0}$. For $k$ below $1 \times 10^{-13} \text{ m}^2$ the curves $E_d$ and $E_{d0}$ are identical then the influence of air flow through cracks on changes in radon concentration gradually increases and for $k$ below $1 \times 10^{-12} \text{ m}^2$ leads this effect to the dilution of radon concentration within the crack. This results in a temporary decrease of the diffusive transport.

For the soil permeability above $1 \times 10^{-12} \text{ m}^2$ the flow of soil gas towards the crack is strong enough to move higher radon concentration from the deep soil closer to the crack. Consequently radon concentration within the crack increases and thus the diffusive
component increases too. As can be seen in Fig. 5 for \( k \) between \( 1.10^{12} \) m\(^2\) and \( 1.10^{11} \) m\(^2\) the diffusive and convective components are of the same importance.

The maximum radon concentration within the crack was reached for \( k = 1.10^{11} \) m\(^2\) and then the concentration starts to decrease. The explanation for this behaviour seems to lie in the ratio between the soil ventilation caused by the flow of soil gas through cracks and the radon generation rate \( G \). As \( k \) increases above \( 1.10^{11} \) m\(^2\) the soil ventilation becomes greater than the radon generation rate and thus both the radon concentration within the crack and the diffusive flux decreases.

The decrease of the radon concentration at the soil-crack interface is higher at the perimeter areas of the house, where the air ventilated through cracks is partly replaced by radon-poor soil gas from the soil near the surface (Fig. 3 and Fig. 7). Therefore the radon flux density from the perimeter crack is lower than that from the central crack, where the ventilated air is replaced by radon-rich soil gas from greater depth. However for the presented geometric configuration the difference between both fluxes is not so significant - the ratio between fluxes from perimeter and central cracks is in average 0.75 (Fig. 6).

Finally the prediction of indoor radon concentration caused by the radon flux density presented in Fig. 5 is plotted in Fig. 8. The concentration curves were computed for the house with dimensions 10 x 10 m, interior air volume 250 m\(^3\) and air exchange rate 0.3 h\(^{-1}\) and for the total length of the 1 mm thick crack 60 m or 180 m. It can be seen that indoor radon concentration is influenced mainly by the soil permeability and by the total length of cracks. Another parameter that affects indoor radon concentration considerably is the radon concentration below the slab (Fig. 8 was plotted for the soil gas radon concentration within the interval 50 – 55 kBq/m\(^3\)). Fig. 8 confirms our finding presented above that for \( k \)
between $1.10^{12}$ m$^2$ and $1.10^{11}$ m$^2$ diffusion and convection through cracks contribute to the indoor radon concentration nearly equally.

5. CONCLUSIONS

Radon transport through cracks in the house understructure is influenced mainly by the soil permeability, radon concentration at the soil-crack interface, the total area of cracks and by the pressure difference across cracks. Because of its large range of variability, the soil permeability appears to have the greatest effect on the radon transport through cracks. For permeabilities below $1.10^{12}$ m$^2$ predominates diffusive transport, which is almost invariable with the soil permeability. For permeabilities between $1.10^{12}$ m$^2$ and $1.10^{11}$ m$^2$ diffusion equals convection and above $1.10^{11}$ m$^2$ predominates convective transport that is directly dependent on the soil permeability.

The radon flux from perimeter cracks will be probably in all cases lower than that from central cracks. The difference between these fluxes will be influenced by the foundation type (slab or continuous footers) as well as by the house type (with or without basement) and by the location of the cracks in the house understructure. Generally, minimal difference will be observed in houses with basements and founded on continuous footers.

Our findings could have several practical applications. The most important one concerns our former hypothesis by which a drainage layer beneath the slab could contribute to the dilution of soil gas radon concentration and thus to the reduction of radon entrance into the house. From recent point of view placing houses on highly permeable drainage layers, which are not ventilated, should not be in future recommended because such layers create suitable conditions for significant convective transport.

The simulated predictions have shown that our 2D model performs consistently with the 3D model presented by Loureiro (1990) [5].

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REFERENCES

Introduction

The accurate delineation of those areas in which radon exceeds reference levels in buildings is crucially important to the radon policies of many governments. Accurate mapping of radon-prone areas will help to ensure that the health of occupants of new and existing dwellings and workplaces is adequately protected. Radon potential maps have important applications, particularly in the control of radon through planning, building control and environmental health legislation (Appleton & Ball, 1995; in press). Radon potential maps are used (i) to assess whether radon protective measures may be required in new buildings; (ii) for the cost-effective targeting of radon monitoring in existing dwellings and workplaces; and (iii) to provide a radon assessment for homeowners and sellers. It is important, however, to realise that radon levels often vary widely between adjacent buildings due to differences in the radon potential of the underlying ground as well as differences in construction style and use. Whereas a radon potential map can indicate the relative radon risk for a building in a particular locality, it can not predict the radon risk for an individual building.

Identification of development sites where radon protection required in new dwellings

Potential options for targeting radon protective measures in new dwellings through the Building Control (BC) system include:

BC-1: Universal application of radon protective measures.
BC-2: Mapping defines need for protective measures.
BC-3: Mapping defines need for protective measures. Site investigation may be used to permit relaxation of regulation if the developer wishes to use this option.
BC-4: Universal site investigation defines the need for protective measures.

Whereas it might be considered that Option BC-1 would involve unnecessary expenditure in much of England and Wales, blanket installation of a radon barrier would actually involve minimal additional cost to new dwellings (about 50-100) and would result in benefits to the development other than radon protection. Universal application of radon protective measures would assist in securing the health of people in new buildings and at the same time reduce the risk of blight and undue personal anxiety. It should be noted, however, that although cost is a consideration in the assessment of regulatory proposals, it is not the deciding factor.

Options BC-2 and BC-3 both require maps that can be readily used by Building control bodies, developers and others concerned with radon protective measures. In the UK, practical options currently available for identifying areas or sites where new development requires protection include (a) National Radiological Protection Board (NRPB) grid square radon potential maps (Lomas et al., 1996), (b) geological radon potential maps, (c) a combination of NRPB grid square and geological radon potential maps and (d) site investigation.
In Option BC-3, which applied to the 1996 interim guidance for new dwellings in England and Wales, the developer had the option of applying for relaxation of the requirement for measures based on the results of a geological site investigation (incorporating desk studies, ground investigations and soil gas radon measurements). The site investigation and report would have needed to be executed by a suitably qualified geologist. Technical protocols for soil gas radon measurements and assessment of results were not clearly defined in the interim guidance. Indeed, the reliability of radon site investigations was uncertain at that time. In most cases it is impractical to assess the severity of a radon problem on a particular site accurately until the building has been constructed and occupied, therefore precautions should be taken in areas where high radon levels have been predicted by the mapping programme. In the UK, radon site investigation techniques are not yet reliable enough to be incorporated into guidance (BGS, 2000a). In the interim guidance, it was also noted that the use of the site investigation option to obtain relaxation of requirement for measures is unlikely to be a cost-effective option unless the development is for more than 10-20 dwellings.

In the UK it has been concluded that a requirement for a radon site investigation to be carried out on all new development sites (Option BC-4), as is currently required in Sweden, for example, would lead to unnecessary expenditure for both developers and Building Control authorities (BGS, 2000a,b).

Mapping radon potential on the basis of house radon and geology.

In the UK radon potential maps generally indicate the probability that new or existing houses will exceed a radon reference level, which in the UK is termed the radon Action Level (200 Bq m\(^{-3}\)). In other countries, geological radon potential maps predict the average indoor radon (e.g. Gundersen et al. 1992) or give a more qualitative indication of radon risk (e.g. Kemski et al. 1996). However, since the purpose of radon potential maps in the UK is to indicate radon levels in buildings, maps based on actual measurements of radon in buildings are preferable to those based on radiometric, geochemical or pedological data. It is also relatively inexpensive to map by this method as passive radon detectors can be distributed by post (Miles 1994). Radon potential maps based on indoor radon data grouped by geological unit have the capacity to accurately estimate the percentage of dwellings affected together with the spatial detail and precision conferred by the geological map data (Miles & Ball 1996; BGS, 2000a).

A detailed evaluation was carried out of the relative advantages and disadvantages of using grid square radon potential mapping and geological radon potential mapping to designate areas where radon protective measures are required (BGS, 2000a). Recommendations for the production of a radon potential maps for use by building control and planning systems in England and Wales have evolved from an evaluation of mapping options in areas with many house radon measurements (Derbyshire and Northamptonshire) and also in selected areas with relatively few house radon measurements (BGS, 2000a). This research demonstrated that the maps in Radon: guidance for radon protective measures in new dwellings (BR211, BRE 1991 as revised 1992) have limitations that could result in radon protection not being installed where required and vice versa. It was concluded that geological radon potential mapping in general provides the best spatial detail and accuracy as this method relates radon risk to geology - identified as the most important overall control on the concentration of radon in dwellings (Appleton and Ball, 1995). A geological radon potential mapping exercise for England and Wales was carried out using the new BGS 1:250,000 scale lithostratigraphic
In the UK, the BGS and the NRPB have devised a procedure to correlate radon levels in dwellings with geology without prejudicing the confidentiality undertakings given to householders and the DETR. Lognormal modelling of the indoor radon data (Miles 1998) produces estimates of the percentage of the housing stock above the UK Action Level for each combination of bedrock (solid geology) and drift (unconsolidated deposits, such as glacial sand and gravel, till, etc.) within a map sheet, grid square or administrative district. The influence of artificial features, such as worked out areas and landslips, may also be assessed in some areas.

The following methodology was used to produce 1:250,000 scale geological radon potential maps covering the whole of England and Wales and twenty 1:50,000 scale geological radon potential maps of some of the most radon prone areas of England.

- Using Bentley Geographics running as an addition to Bentley Microstation 95, a point topology was built using the dwelling geographical co-ordinates. Area topologies were built using BGS solid and drift geological polygons. The point-in-polygon overlay process was used to add solid and drift geological codes to each dwelling location point and the co-ordinates, geological codes and map sheet numbers were loaded back to an Access database.

- The National Radiological Protection Board (NRPB) added house radon data and removed location co-ordinates from the file to preserve confidentiality. Lognormal modelling (Miles, 1998; Miles and Ball, 1996) was then carried out by BGS on the house radon data using dBase and Excel macros. This process produced an estimate of the percentage of homes with radon exceeding the Action Level for each combination of solid, drift and artificial codes within a map sheet and 5-km grid square. In general, the accuracy of these estimates is proportional to the number of radon measurements.

- Solid, drift and artificial topologies were built together using Bentley Microstation 95 and attributed with radon potential values grouped using the following class limits: 3-5%, 5-10%, 10-30% and >30% probability of being above the Action Level.

Radon Protective Measures GIS

The BGS Radon Protective Measures Geographical Information System (RPM GIS) has been developed to provide Geological Assessments (RPM site reports) as part of the revised guidance for dealing with radon in new dwellings (BRE, 1999). The RPM GIS currently comprises 1:250,000 scale geological radon potential data with more detailed information for twenty 1:50,000 scale geological map sheets covering the most radon-prone parts of England and Wales (Figure 1). The GIS runs under Arcview and is being upgraded to 1:50,000 scale as new digital maps become available through the BGS DIGIMAP programme.
Radon site reports

A new service to provide advisory reports on the requirement for radon protective measures in new dwellings and extensions has been launched by the British Geological Survey (http://www.bgs.ac.uk/radon). These reports fulfil the requirements of the Stage 2 Geological Assessment outlined in revised guidance on the protection of new dwellings from radon gas (BRE, 1999). The revised guidance brings together the best practice for protecting new homes against radon. It updates previously published guidance, details measures that must be incorporated in new dwellings and defines the geographical areas in England and Wales where radon protection is necessary. In addition to Cornwall and Devon and parts of Somerset, Northamptonshire and Derbyshire - which were covered in previous guidance - the guidance identifies new areas where radon protection will be needed. These are parts of the Yorkshire Dales; parts of Wales and the Welsh Border; North Oxfordshire; parts of the Midlands adjacent to the currently delineated areas in Derbyshire; Northamptonshire; parts of Gloucestershire, the Lake District and Northumberland. There are also a few scattered areas in south-east England where these measures need to be applied.

There is a flow chart in BR 211 (BRE, 1999) that sets out a two-stage procedure to help determine the level of radon protection required in new dwellings. In Stage 1, the 5 km grid square radon potential maps produced by the National Radiological Protection Board (NRPB) are used to make the primary determination of the level of radon protection needed. In Stage 2, a second series of maps produced by the BGS is used to decide whether it is necessary to consider upgrading the requirement for protection indicated by Stage 1. This has the objective of avoiding cases of underprotection that might occur had the guidance depended solely on the average radon level in the 5 km grid square indicated by the NRPB maps. The BGS maps show those 5 km grid that are underlain, completely or in part, by geological units that require either basic or full protection to be installed in new dwellings.

A geological assessment may need to be carried out where the site falls within a shaded grid square on the BGS map (Figure 1). The GIS generates automatically a radon site report after the site location details (based on National Grid co-ordinates) have been entered. The GIS checks whether a site is on or close to a geological unit which potentially exceeds the action levels for either basic or full radon protection. The search area (circle or rectangle) for a site is increased by a buffer zone of 50 m in areas with 1:50,000 scale data and 500m in areas with 1:250,000 scale data. This is to allow for potential inaccuracies in the position of the geological boundaries. The advisory report indicates the highest level of protection required within the buffered search area. An abstract from a BGS Radon Protective Measures Site Report is given in the Appendix to this paper.

Consideration must be given to installing basic or full radon protection if the geological assessment shows that this is indicated. If a site falls within one of the shaded squares (Figure 1), it does not necessarily mean that it must have radon protection. This is because some of the grid squares contain bed rocks and unconsolidated (drift) deposits with lower radon potential than the maximum levels shown on the map. In many cases the geological radon potential varies considerably within a grid square. In other cases, only a very small area (sometimes only a few hundred square metres) with a radon potential exceeding the thresholds for basic or full protection occurs within the shaded grid square. The level of protection that might be required is thus site specific, and can be determined by reference to the relevant radon potential map in BR211 (BRE, 1999) followed by a geological assessment of the site.
Follow-up radon protective measures site reports

For most parts of the UK, a higher resolution assessment of radon protective measures requirements can be provided by the BGS. This comprises:

i. Assessment by a qualified geologist of the relevant 10,000, 1:10,560 or 1:50,000 scale geological map(s) covering the total search area from BGS archives.

ii. Precise identification of the level of radon protective measures indicated for all geological units encountered within the site and the immediately surrounding area.

iii. A map extract displaying the required radon protective measures in relation to the original site area and buffer, and any site plan provided by the client.

References


Acknowledgements

Some of the information in this paper is derived from the results of a number of research projects carried out for the UK Department of the Environment, Transport and the Regions (DETR) by the BGS in collaboration with Chris Scivyer (Building Research Establishment.
Figure 1 Areas where a geological assessment may need to be carried out to determine whether radon protective measures are required in new dwellings (adapted from Map 2, Annex B, BR211 (BRE, 1999); basic radon protection may be required if site is in a pale shaded square; full or basic radon protection may be required if site is in a dark shaded square). Also shown are the twenty map sheets for which 1:50,000 scale geological radon potential data is currently incorporated in the GIS. County boundaries reproduced with permission from the Ordnance Survey (Licence No. GD27219/1999).
APPENDIX: Abstract of Radon Protective Measures Site Report

SECTION 1: LOCATION AND EXTENT OF REPORT AREA

Area centred at: 485000, 265400
Radius of site area: 200 metres

Topography based on the latest 1:50,000 scale Ordnance Survey Maps with the permission of The Controller of Her majesty’s Stationery Office, Crown Copyright. Ordnance Survey licence number GD272191/2000. Display scale may vary.

KEY:

INNER RECTANGLE or CIRCLE defines site area (details provided by client).

OUTER LINE shows extent of TOTAL SEARCH AREA comprising the site area and automatically generated buffer zone. The requirement for radon protective measures indicated in Section 2 is based on a geological assessment of the Total Search Area.

Section 4 explains how the search is carried out
Section 2: Requirement for radon protective measures

The RPM GIS has determined that:

**FULL RADIUM PROTECTIVE MEASURES ARE REQUIRED FOR THE REPORT AREA.**

This assessment was derived from 1:50,000 scale data. In some cases a developer, property owner or their agent may consider that a more detailed geological assessment of the requirement for radon protective measures will be of value (see Section 5 for details). Where protective measures are indicated, guidance can be found in BR211(1999) *Radon: guidance on protective measures for new dwellings.*

Section 4 explains how the assessment is carried out

Section 3: Geological units within the search area

Below is a listing, if available, of the possible combinations of Solid Geology units and overlying Drift (Superficial) Geology units within the total search area.

These have been derived (as indicated) from searches of either:

a) Combined 1:250,000 Solid and 1:625,000 Drift geology maps
b) 1:50,000 Solid, Drift and Artificial geology maps

1:50,000 data
1. Northampton Sand Formation; No drift; Not disturbed
2. Whitby Mudstone Formation; No drift; Not disturbed
Radon in Austria

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Abstract
Several projects in Austria deal with the problem of enhanced radon exposure to the public. The Austrian Radon Project is the largest project within this task, with the aim of investigating the radon concentrations in Austrian homes. Another project concerns mitigation methods. According to the EU directive EURATOM 96/29 it is also necessary to check working places for possibly enhanced radon concentrations. These projects are and will be funded by the government. The federal government of Upper Austria sponsored a project to test the indoor air quality in kindergartens including radon measurements. Within an EU-research-project the radon concentrations in Austrian springs and groundwater were systematically listed and analyzed. Additional investigations will focus on methods to improve the radon potential maps from the Austrian Radon Project by including geological and other information.

1. Introduction
The exposure to high radon (progeny) concentrations means increases the risk for lung cancer. Therefore the governmental authorities in Austria are interested in the actual radon exposure of the population. Countermeasures to reduce the radon exposure can be started only when it is known where and why enhanced radon concentrations exist and who is exposed to such concentrations. The investigations started in the beginnings of the nineties cumulating in the Austrian Radon Project (ÖNRAP – Österreichisches Nationales Radon Projekt). Within this project approximately 10 000 homes were randomly selected and the radon (gas) concentration was measured in the two mostly used rooms. From the results of these measurements a map of the radon potential in Austria was made by use of a geographical information system (GIS). To improve the knowledge about radon mitigation methods the SARAH (SANierung RADonbelasteter Häuser) project was started. During this project several house-types were systematically investigated and different types of mitigations were tested. To improve the predictions of the radon potential from the Austrian Radon Project, a new project, called ELORA (Ermittlung des LOkalen RADonpotentials) was created. This project is now in a stage of testing different methods using the data of the Mühltal area (Upper Austria). Another project deals with the exposure to naturally occurring radiation or to technically enhanced naturally occurring radiation on workplaces. This project is called NATEXA (NATürliche EXposition am Arbeitsplatz) and is a consequence of the directive EURATOM 96/29. This project will start with the end of this year and shall give an overview on affected branches and industries. Of course a great part of this project will deal with radon. The above-mentioned projects are either fully or partly funded by the Austrian government.

The federal government of Upper Austria funded (besides a substantial part of the SARAH project) the “Kindergarten Projekt”. Within this project several properties of the buildings in which kindergartens are located were investigated for their influence on the health of the children and their teachers. One of these parameters was the radon concentration.
Finally a EU project (TENAWA) was the frame for a project to investigate the radon concentration in Austrian springs and ground water. The aim of this project was to estimate the probability of high radon concentrations in drinking water resources.

There are also some smaller projects concerning different special problems in relation with radon and radon progenies. These projects are mainly bond to universities and deal either with special sites or special mathematical treatment of radon data.

2. ÖNRAP

Within the Austrian Radon Project (ÖNRAP) the radon (gas) concentration in Austrian homes was systematically investigated. In rural areas approximately one in 200 homes was examined, in larger towns the measurement density was smaller. The homes were selected from the telephone register with a fixed step width. It could be shown that this type of selection is representative for the Austrian population. The measurements were performed by track-etch dosimeters and electret dosimeters (3 months exposure time) and charcoal detectors with LSC measurement (3 days exposure). Although short-term measurements cannot give good information on the mean radon concentration in a home it could be proved that several measurements in an area give a representative mean for this area. By using a mean winter-to-summer ratio of the radon concentration (2.0 in rural areas, 1.4 in cities), an extrapolation from the measured data to the annual mean was made. The two most often used rooms were examined in every selected home and the mean of all extrapolated annual means from the measurements in a municipality was taken as the mean radon concentration for this municipality. These data are the basis for future radon mitigation measures, i.e. these data should indicate where to look for houses with extremely high indoor radon concentration.

Because of different building types and different life-style the mean radon concentration in a municipality is not in all cases a measure for the radon risk from the ground. Therefore the radon potential was introduced. In Austria we defined the radon potential as the radon concentration in a standard situation. The standard situation is a commonly used living room at the ground floor in a house without a basement or only with a partial basement, tight windows, with two adults and less than 2 children living in and some other minor important parameters. The extrapolation from the measurement data to this standard situation was made by the ratio of the medians from the different situations, using the data of the whole area. The radon potential for a municipality is the mean of the radon potentials of the investigated homes. In this way the municipalities were grouped into 3 classes (radon potential <200 Bq/m³, 200-400 Bq/m³ and >400 Bq/m³). This classification should be used for radon precaution measures during the erection of new buildings in the future.

The classification was made on basis of municipalities, but it is clear, that generally the actual radon-risks will not change at the borders of the municipalities. Furthermore the measurements were not distributed equally dense but concentrate in the areas with a higher population. Therefore the radon potential for a municipality represents only the radon potential of the more populated area. From the governmental point of view, however, it is now the only way to administer the radon problem. A map of the radon potential can be seen in Fig. 1.

Radon Potential

Fig. 1: The radon potential in Austria
3. ELORA

The aim of ELORA is to improve the radon potential maps by using additional information. The radon potential computed during ÖNRAP has rather large uncertainties due to the limited numbers of investigated houses and the uncertainties in the necessary extrapolations. In a first attempt, a systematic correlation analysis with different parameters is under investigation in Upper Austria. These parameters concern geology, soil, hydrology and chemistry. In a multiplicative (logarithmic additive) model the main influence parameters should be revealed and should be used to improve the results from the measurements. In a second way of data treatment these main parameters should be used as a-priori information in a Bayes approach. Finally there is also the possibility to use the measured radon data as a-priori information and modify the results of the parameter-based prediction of the radon potential. All these possibilities are now under investigation and first results will be available next year.

4. SARAH

This project served to develop and test several methods of radon mitigation. A major problem in radon mitigation is the verification of its success. For that purpose the ratio of the radon concentration before and after the mitigation must be measured under well-defined conditions. Within this project the “Blower Door Method” was developed: The radon concentration is measured in the room or a part of a house while reducing the pressure by a vent with defined volume flow. Also the radon concentration in the outflow can be measured. From these data a virtual maximum radon inflow from the ground can be deduced. Doing such measurements before and after mitigation gives good information about the effectiveness of mitigation measures. Different types of mitigation were tested, starting from very cheap passive methods (just drilling holes at certain points through the walls of the basements) up to relative expensive methods like active sub-floor ventilation. Generally the cheap methods give small reduction, while expensive methods can reduce the indoor radon concentration substantially. So mean reduction costs were computed per square-meter living area and

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reduced Bq/m\(^3\). From a first investigation by the “Blower Door Method” the most adequate method can be selected and the costs for the radon mitigation can roughly be estimated.

5. NATEXA

The EURATOM 96/29 directive demands from all members of the EU a survey on the exposure to natural radioactivity on workplaces. In that connection radon may be one of the most troublesome problems. It is well known that radon can be a problem in waterworks, in underground workplaces (mining), in several types of (chemical) industries, however we do not know how many other branches may be affected and how many people are really exposed to substantially enhanced natural radioactivity. There are a lot of workplaces with possible radon problems, starting from small shops, restaurants, wine cellars in basements to warehouse workers (fertilizer), waste deposits (ashes), building material industry and the oil and gas industry. Within the first stage of NATEXA several companies (small and large) will be investigated on possible exposure problems, just to get a rough overview to which of the different types of companies we should have a closer look. A nation-wide survey on industries and companies will be started in the moment when it is clear where and in which branches enhanced exposures can be expected.

6. Kindergarten

This project was carried out by the government of Upper Austria with the aim of testing the indoor air quality and some other facts, which may influence the health of the children. A major point of interest was the radon concentration in kindergartens. In approximately 700 kindergartens the radon concentration was measured and in about 5% of them enhanced concentrations could be found, but only in very few (1%) radon concentrations above 1000 Bq/m\(^3\) were detected. Mitigation measures will start more or less immediately, partly funded by the government of Upper Austria.

It is planned to extend such radon measurements also to schools.

7. Radon in water

The EU-project TENAWA dealt with the removal of (natural) radioactivity from drinking water. During this project we investigated the probability for high radon concentration in Austria. There exists a lot of data on radon in water, however most of these data are not from randomly selected but from springs used for some special purpose. The data consists of a wide variety of water sources, from artesian wells to deep drillings, from surface water to highly mineralized water of spas, from cold to hot springs and often the documentation is not really informative. There are also multiple entries in the data bank\(^7\), because of repeated measurements in time and it is very difficult to identify all such replicas because of name changes etc.

All together approximately 6500 measurement results were used, reported from P. Kindl et al.\(^8\), M. Ditto et al.\(^9\), F. Schönhofer et al\(^10\) and H. Friedmann\(^7\). The main input to the data set

\(^8\) P. Kindl, K. Fink: personal communication, 1998.
\(^10\) F. Schönhofer, C. Kralk, K. Pock: personal communication, 1998
results from a research project of the Federal Ministry of Agriculture and Forestry\(^9\) (approx. 4300 data) within which a systematic investigation on the radon content of ground water was performed. Approx. 1600 data were measured before 1950. By comparing old data with new measurement results it could be shown for a lot of the old data that these are really reliable.

A very crude classification system was introduced which only can show its merit a posteriori. The classification into 3 classes was made according to the following criteria:

**Class 1:** Areas with all data below 100 Bq/l and less than 30% of all data above 50 Bq/l.

**Class 2:** Areas with all data below 300 Bq/l and less than 30% of all data above 150 Bq/l but not fulfilling the requirements of class 1.

**Class 3:** All other areas.

Combining the information of the radon in water data, the indoor radon concentration of dwellings and the geological situation, an attempt was made to extrapolate the radon classes for areas without radon in water data. It was assumed that mainly aquifers near to the surface are used for drinking water. Therefore, the availability of radon in the soil, causing high indoor radon concentrations, should be an indicator of enhanced radon concentrations in ground water. In the first step of the extrapolation, areas (clusters of municipalities) with high(er) indoor radon concentrations were marked as class 2 areas. In case of adjacent class 3 areas (from the original radon in water classification) and uniform geological background, the extrapolation was changed to class 3. Generally areas of granite and gneiss were classified as class 2 or class 3, depending on actually measured radon in water data. Generally, isolated data, i.e. municipalities with radon data quite different from the bulk of neighboring municipalities, were assumed to be less important for the estimation of the radon class as far as it was not possible to find an explanation for it. The result of this extrapolation can be found in Fig. 2.

With the definitions of the different classes and an assumed log-normal distribution of the radon in water data we can expect the following probabilities: Class 1 means for usual ground water (no deeply drilled wells) a probability of 70% having a radon concentration of less than 50 Bq/l and approximately 15% for a radon concentration above 100 Bq/l. Class 2 means a probability of 70% for usual ground water having a radon concentration of less than 150 Bq/l. With an estimated median of 80 Bq/l the probability for finding water with a radon concentration above 300 Bq/l is roughly 15%. Finally in class 3 at least more than 15% of all water sources will have radon concentrations above 300 Bq/l.
Fig. 2: The extrapolated classification of municipalities according to radon in water.
In Table 1 the main sources of indoor radon are listed.

<table>
<thead>
<tr>
<th>Radon source</th>
<th>Radon concentration in dwellings in Bq/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Typical range</td>
</tr>
<tr>
<td>Building ground</td>
<td>up to 2 000</td>
</tr>
<tr>
<td>• geogenic source</td>
<td></td>
</tr>
<tr>
<td>• affected by human activity (i.e. mining)</td>
<td></td>
</tr>
<tr>
<td>Building materials</td>
<td>&lt; 10 – 100</td>
</tr>
<tr>
<td>Outside air</td>
<td>&lt; 10 – 80</td>
</tr>
<tr>
<td>Water</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

* In radon spa > 1 000 Bq/m³ and waterworks > 10 000 Bq/m³

Table 1: Contribution to the radon concentration in dwellings in Germany from different radon sources

Within the scope of radon mapping the following sources are investigated in Germany and classified according to regions:

• the building ground
• mining activities and mining residues
• radon in water
• radon concentration in the atmosphere near the surface.

The most important building materials show no regional dependency and will not be mapped. The other causes of indoor radon levels differ in their regional significance and in the number of buildings showing a relevant level of influence.

A decisive influence on the radon concentrations in buildings results from their constructional type which develops continuously throughout Germany, regionally, however, to differing degrees. The changes which have to be expected above all in eastern Germany becomes clear in Table 2, where the differing ages of housing stock are presented on the basis of the results of the 1995 census of living areas and buildings [1].
Following the reunification, a building boom occurred particularly in the former East German states and new regulations had to be observed. The building of new houses and the reconstruction of existing buildings, caused radon-relevant change in housing stock over a relatively short time. This process is still going on. Some developments, like energy saving construction, can affect the radon concentration in buildings. Especially the insulation of older houses without reconstruction of the soil touching area of these buildings and the installation of new heating systems could increase the radon concentration.

Measurements of radon concentration in recently constructed houses, which were built without additional protective measures against radon turned out that the continuing improvement in the insulation of buildings against soil water dominantes the decreasing air exchange rate inside. As a result both, the mean value and the variation range of the radon concentration indoors are decreasing.

### Status of the Investigations

**Radon concentrations in houses**

In Germany, measurements of radon concentrations in houses in the former West German states began in 1978, with the aim of gaining a first overview of the frequency distribution, the most important radon sources, and the factors influencing radon concentrations. For the purposes of validating the frequency distribution of radon concentrations in dwellings, a complementary study was performed in the federal states in eastern Germany, in the years 1991 to 1993. Certain individual projects served of the investigation of the health effects of radon exposure in houses and of the evaluation of special focuses of public interest, i.e. radon due to mining activities.

Measurements of radon concentrations were performed in a total of over 50 000 houses (approx. 0.3 % of the housing stock in Germany).

<table>
<thead>
<tr>
<th>Federal state</th>
<th>Year of construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Berlin East</td>
<td>13.1</td>
</tr>
<tr>
<td>Brandenburg</td>
<td>19.4</td>
</tr>
<tr>
<td>Meck.-West Pomera.</td>
<td>24.6</td>
</tr>
<tr>
<td>Saxony</td>
<td>32.1</td>
</tr>
<tr>
<td>Saxony-Anhalt</td>
<td>31.9</td>
</tr>
<tr>
<td>Thuringia</td>
<td>33.6</td>
</tr>
<tr>
<td>New Federal States</td>
<td>28.4</td>
</tr>
<tr>
<td>Old Federal States</td>
<td>10.6</td>
</tr>
</tbody>
</table>

**Table 2:** Percentage of residential buildings in different East German states ordered according to the year of construction [1]
Due to the differing aims of the measuring programmes, measurements were carried out using different methods, under differing measuring conditions and with differing durations, also with extreme differences in the distribution density of measuring locations. While the duration of, and conditions for the measuring programmes were determined in accordance with the defined aims, the distribution density for the measuring locations depends significantly on the interests of the population and the district administration in the investigations.

Table 3: Measurements of radon performed in houses in Germany with public funding
Measurements in 3420 communities

Figure 1: Number of dwellings per community in which measurements of radon concentrations were performed for periods ranging from several months to one year.

The problem posed by the number of measurements per community is illustrated below in an example. Where, within a community with 200 houses, 10 houses (5%) prove to have a radon concentration of over 200 Bq/m$^3$, the likelihood of detecting such a value through the performance of, respectively, 2 measurements is lower than 10%, 10 measurements lower than 34%, and 20 measurements lower than 66%. Because of the log-normal distribution which characterises the radon concentration in houses it is very unlikely that one will detect the real maximum values of the municipalities within a sample with an order of 1 - 5 houses. One must rather presume that the small number of measurement values available here will fall within the range of concentrations which are most frequently found (the range around the modal value).

Geogenic radon potential

With the aim to locate the most important regions concerning radon in houses,
investigations of the geogenic radon potential began in Germany in 1989. Since this time, measurements have been carried out at over 2,000 measuring locations.

These investigations were prefered to indoor radon measurements in the whole country for the following reasons:

- The radon potential is temporal invariable and is the basis parameter for the estimation of indoor radon with help of transfer functions.
- In contrast to this an estimated time scale of at least 10 years is required for the performance of fully extensive measurements in buildings. Over this period the structural state of buildings tends to undergo serious changes, and for this reason it would be not possible to arrive at a consistent evaluation of the entire area covered by Germany.
- Radon should not be presented as being a problem in areas where it is not relevant according to the aims of radiation protection.
- Areas on which there are at present no buildings, but which represent potential building sites, should be included in the evaluation.
- The motivation of the population to participate in indoor measurements to get a statistically sufficient number of results is very difficult.

**Mining areas**

In a research project which is to be completed in the present year, the mining areas in Germany are being identified which are potentially of significance relating to the radon concentrations in houses.

These are areas where:

- The mining of raw materials has occurred in geological horizons with increased concentrations of radium 226 are present.
- Mining activities have been carried out close to the surface and subsidences occur as a result of mining.

An overview of areas relevant in terms of radon in houses is depicted in Figure 2.

**Further action**

From the radiation protection point of view, the tasks to be carried out with priority are the identification of communities in which:

- Additional measures for protection against radon in new buildings are to be recommended, because the standard measures for the building protection against moisture from the ground are not sufficient against the ingress of radon.
- Radon concentrations over the European reference value for existing houses occur with an increased frequency.
- Radon concentrations > 400 Bq/m³ in buildings are only to be found with a very low level of probability and radon concentrations of greater than 1000 Bq/m³ do not occur.
The priority of different regions with respect to further radon indoor measurements is shown in Figure 3 very roughly. In priority 0 regions no further measurements will planed and the priority 4 means the highest urgency for measurements. This map takes into account the soil radon potential and measured indoor radon concentrations. As a result of a discussion with the geologists of the Federal states administrations it is very probably, that the area of highest priority will be half as small.

Complementary measurements of radon in houses serve the purpose of validating geological indications, and are concentrated on older houses. Basing on the map of priority measurements must be carried out in around 100 000 – 200 000 buildings.

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Mapping of the Geogenic Radon Potential in Germany -- the State of Matters

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Radon production in the subsurface and radon transfer from building ground into houses are the essential agents controlling indoor radon concentrations (APTE ET AL. 1999; BARNET ET AL. 1998; KEMSKI ET AL. 1998, 1999; KIES ET AL. 1994; KREIENBROCK, SIEHL 1996; ). A geogenic radon potential can be derived from the mapped distribution of geological units and accompanying measurements of in situ permeability and radon concentration in soil gas to serve as a regionalised geology-based prediction tool for radon concentration in houses. For planning purposes, a series of maps of the geogenic radon potential in Germany have been produced by a distance-weighted interpolation of radon activity concentration in soil gas using approx. 2000 measuring sites and taking into account geological boundaries (Fig. 1). To validate this source-based areal prediction using GIS techniques, the soil-gas database was correlated with a set of about 33000 long-term indoor radon measurements between several month and one year in living rooms of 3237 municipalities (Fig. 2).

The indoor radon concentrations in living rooms were averaged for the respective municipalities as the smallest administrative unit, because exact geographic positions of each indoor data were not available. The centre of each municipality is coded with the generalised geological characteristics of the specific area, giving correct assignments in regions with homogeneous geology, but is critical in municipalities with a highly varying geology. Distance-weighted interpolation on a 3 km raster basis within the boundaries of similar geological units yield comparable data sets of radon concentration in soil gas and indoor air (Fig. 1,4). The results demonstrate a fairly good correspondence of regions of increased geogenic radon and increased indoor values. The interpolated raster data of both groups are a log-normally distributed with values ranging between 6 and 2106 Bq/m³ for the indoor data and between 2 and 1003 kBq/m³ for the soil gas data (Fig 3). Using the median values of both distributions, a average transfer function \( tf \) can be calculated:

\[
\frac{\text{soil (median)}}{\text{indoor (median)}} = 571
\]
Fig. 1: General map of the radon concentration in soil gas in Germany.
Fig. 2: Location of soil gas measuring sites and indoor radon data.
To standardise both distributions for comparison, a hypothetical maximum of soil gas concentration can be derived by:

$$h_{\text{max (soil)}} = \max(\text{indoor}) \cdot tf = 1202 \text{ [kBq/m}^3]\text{ ]}$$

The hypothetical soil gas maximum is near the maximum of the interpolated soil gas activity concentration of 1003 kBq/m$^3$ and is thus a realistic value. The distributions of the indoor and soil gas data can now be standardised to equal range of (0; 1) by division of each raster value by the respective maximum. A ratio $q$ between the indoor and soil gas raster data is then calculated using:

$$q = \frac{\text{indoor} \text{(soil)}}{\text{soil} \text{(ind)}}; \text{ where } q = 1 \text{ corresponds to } tf = 571$$

The calculated ratio indicates the factor of over- and underestimation of indoor radon by the geogenic prognosis. Values above 1 denote an underestimation of the geogenic radon potential in its influence on indoor radon, values below 1 stand for overestimation. Figure 5 depicts the regional distribution of $q$. This map is useful for identifications of regions where further investigations are necessary. The uncertainty of the geogenic prognosis $q$ between 0.33 and 3 is an acceptable range, it corresponds to transfer functions between approx. 190 and 1700. This range matches the results.
of a case study on the ratio between soil gas radon and indoor radon in the Fichtelgebirge (LEHMANN ET AL 1998). Main drawbacks of this general approach to validate the geogenic prognosis are:

- lack of sufficient precision of the geographic position of the indoor values, critical especially in regions with high variability of the distribution of the geological units,
- information concerning mining areas and other technical human activities are not included,
- age and specific properties of the dwellings are not taken into account.

To improve the outlined method of prediction, the Federal Office of Radiation Protection has launched a research project to elaborate empirical transfer functions for the estimation of radon contamination of houses in the Federal Republic of Germany. In six testing areas with different geogenic radon potential (fig. 4,5) detailed investigations are done in cooperation between the Institute of Geology of Bonn University and the consulting company Kemske & Partner. For statistical evaluations of the correlation between soil gas radon measurements near houses and corresponding long-time indoor measurements in a spot-to-spot assignment, approx. 1200 soil gas measuring sites were selected to sample the relevant geological units. In 1400 exactly located dwellings one-year-measurements of indoor radon were performed and comprehensive specifications to the properties of the houses were made by the occupants. The main topic of this work is to obtain specific transfer functions for different geological environments and to specify the radon relevant properties of houses e. g. constructing type, age, foundation and other site and building specifications. The results will be presented during the workshop.
average indoor radon in living rooms [Bq/m$^3$]

- > 400
- 100 to 400
- 0 to 100

geological boundaries

- testing area for validation
- testing area for detailed mapping

Fig. 4: General map of the average indoor radon in living rooms in Germany.
Fig. 5: Comparing standardised average indoor radon with soil gas radon for validation of geogenic prognosis
References


The Use of GIS for Assessing Rn Risk Potential

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ABSTRACT

This paper describes the use of geostatistical analysis and GIS techniques to assess gas emanation hazards. The Mt. Vulsini volcanic district was selected for this study because of the wide range of locally present natural phenomena which affect gas migration in the near surface. In addition the large number of soil gas samples that were collected in this area should allow for a calibration between the generated risk/hazard models and the measured distribution of toxic gas species at surface. The approach used during this study consisted of three general stages. First data was digitally organised into geognostic layers, then software functions in the GIS program „ArcView“ were used to compare and correlate these various layers (or „themes“), and then finally the produced risk (hazard) map was compared with soil gas data in order to validate the model.

INTRODUCTION

A Geographic Information System (GIS) can be thought of as "an organised collection of computer hardware, software and geographic data, designed to efficiently capture, store, update, manipulate, analyse, and display all forms of geographically referenced information." In this work a number of geological factors were studied which relate to the production, migration and accumulation of hazardous gases in the near-surface environment. The GIS program "ArcView" was then used to combine these factors, and their spatial relationships, to produce a gas emission risk map of the studied Latera plain (Vulsini Volcanic District, Latium, central Italy).

The methodological approach used in this study consisted of the following distinct activities: i) selection of the geological variables (layers) related to the investigated phenomenon (hazardous gas emanation); ii) conversion of these variables into a suitable digital format, by collecting, organising and digitising geo-referenced map data at different scales (1:100,000 and 1:25,000) into the layers. This data may occur as either points, lines or polygons; iii) simplification of the data by subdividing each layer into a small number of „classes“ (numerical values); iv) assignment of numerical scores to each class on the basis its correlation with the investigated phenomenon; v) application of geostatistical techniques to calculate a weighting factor for each layer-grid which assesses the importance of its contribution to hazardous gas emanation; vi) overlaying the grid-layers to obtain an algebraic sum of the weighted cell scores; and vii) comparison and validation of the obtained RRM (Radon Risk Map) model with the geochemical information provided by soil gas surveys.

GEOLOGY OF THE STUDY AREA

The Latera geothermal field (Latium, central Italy) is located in the western part of the Quaternary potassium-alkaline Monti Volsini volcanic area, which was activated during the tensional phase related to the opening of the Thyrrenian basin about 0.9 million years ago (Fig. 1).
In the study area geological, geophysical and geochemical studies were performed in the past for geothermal exploration (Bertram et al., 1984). This area was considered promising in this respect due to the extensive Quaternary volcanic activity, large travertine deposits, the presence of thermal springs with a major CO₂ gas component, and an anomalous heat flux produced by a high geothermal gradient (Gianelli & Scandiffio, 1989). Subsequent drilling confirmed that the Latera area hosts an important water-dominated geothermal field in Mesozoic carbonate formations, with temperatures ranging from 210°C to 230°C. Both shallow and deep surveys in the Latera plain show the presence of a NNE-SSW-oriented structural high bordered by normal faults.

The risk model for noxious gas emission in the Latera area has been developed considering a wide spectrum of geological information, such as geology (Ra content) (Orlando et al., 1998), faults, geothermal gradient, depth to carbonate substratum, spring locations, Rn emanation from soil.

**Issues Relating to Indoor Radon**

Radon can migrate from underlying soil and rock through foundations and accumulate inside buildings. The reduced atmospheric pressure in the houses relative to the soil, and various entry points (e.g. cracks in building foundations, sump holes, slab-to-foundations wall joints) are the main causes for radon entering a building from the soil. The lowest levels (i.e. the basement and main floor) generally pose the greatest risk for radon accumulation and, thus, human exposure (Kendal et al., 1994; Slunga, 1988).

The health effects of radon are the subject of much debate. Recent reports indicate that a portion of the population may be exposed to potentially harmful levels of radiation from radon progenies (²¹⁸Po and ²¹⁴Po). When these elements are inhaled, they lodge in the lung and can cause damage by alpha radiation as it decades. A number of reports summarise the available epidemiological data relating exposure to radon progeny (UNSCEAR, 1993; USEPA, 1992, National Research Council, 1991; Bowie & Bowie, 1991; Cross, 1987; Hopke, 1987; Harley, 1984; Wicke, 1984; Arche et al., 1976). The correlation between health hazards and regional distribution of radon-generating rocks has been recently questioned because of the lack of data on the concentrations and the exhalation rates of Rn from the soil. It is difficult to establish a link between cancer and radon without the knowledge of the spatial variation of this gas, although the emission is known to be affected by geology and environment. Ball et al. (1992) suggested that the concentration of radon in buildings is likely closely related to that in the soil, although there is no well established method of estimating radon levels in individual dwellings based on soil radon data. The relation is unlikely to be straightforward because the radon values in houses are dependent on the many building variables listed above, as well as the habits of the inhabitants. In order to avoid these complications the local geology and structural setting were considered as a fundamental starting point.

**GIS Approach**

Initially a grid had to be established over the entire study area which could be combined with themes, using the „intersect“ function in Arcview. This creates spatially-equivalent, geo-referenced cells in each theme which allows for the comparison and merging of these various data sets. This grid consists of cells with 200 x 200 m sides based on a compromise between resolution and computational speed. The various themes represent data of three different forms, point data, lines and polygons. The transformation processes are described below,
followed by the method used to merge all geognostic layers using the Arcview „intersect“ function, in order to assign unique class scores to each individual cell.

The fault data had to be represented as polygons due to the fact that the influence of a fault (i.e. Rn mobility due to secondary permeability) is not restricted to a thin finite line but rather has a maximum along a central zone that diminishes perpendicular away from the fault trace. The program Arcview has a „buffering“ function which allows the user to define various concentric zones around a feature (point, line or polygon), with each zone being assigned a score based on its distance from the core. In the present work a quadratic formula was used to define this distance. As for all polygonal data sets, this distribution was subsequently divided on the basis of individual cells, as described below.

As mentioned above the Arcview „intersect“ function must be used in order to merge the polygonal source themes (Ra content, faults or Rn emanation) with the grid. Using the radium concentrations in different geological units as an example, this function creates a mosaic theme whereby a multitude of small polygons are defined based on the contact between the geological units and the boundaries of each grid cell. Each polygon is assigned a score value corresponding to the class of radium content (or lithotype). In order to assign a unique score value to each cell of a given theme, the score values for all polygons within a given cell are weighted based on their respective areas and summed to obtain the total cell score. For example if one particular cell is 50% covered by a polygon with score 1 and 50% covered by one with score 2, the resultant unique value for that cell is 1.5, according to the formula:

\[
S_T = \left( \frac{\sum \text{area}_S \times S_i}{\text{area } T} \right)\]  

(1)

where \(S_T\) is the total cell score, \(\text{area}_S\) is the area of the polygon with score \(S_i\), \(S_i\) is the score value, and \(\text{area } T\) is the total area of the cell. The total cell score is normalised to obtain the cell Index (I) using:

\[
I = \left( \frac{S_T}{S_{\text{max}}} \right) \times 100
\]

(2)

Where \(I\) is the cell index, \(S_T\) is the total cell score and \(S_{\text{max}}\) is the maximum score of the theme. The result is a map in which cells with the highest scores identify the highest radon potential risk areas for that particular theme. The merging of these themes, and the approach developed to try and minimise the subjectivity of assigning various weighting factors to each theme is discussed below.

The elaboration of multiple maps or themes using GIS requires the merging of disparate data sets and the calculation of a final risk probability. This probability is obtained first by weighting each theme based on either a statistical analysis of the importance of that theme’s contribution to the studied final parameter (in this case indoor radon) or by relying on the subjective judgement of experts. In the present work a weighting parameter was produced for each theme by using a more objective approach based on a covariance analysis of the various data sets. The RRI was then calculated for each cell of the grid model based on a covariance matrix between the variables (as well as between the variables and the radon risk). This matrix was defined \textit{a priori} according to the opinion of the operator by assessing correlation using a high, medium or low criteria (which was necessary to estimate the weights using the kriging technique).

These three levels were then assigned numerical values (out of a maximum of 1) which were inserted in the subsequent step:
By constraining the weights to sum to one ($W_1 + W_2 + W_3 + \ldots + W_n = 1$) the estimation is statistically unbiased. The calculated weights are 0.21 for faults, 0.11 for springs, 0.17 for geothermal gradient, 0.21 for $R_n$ emanation, 0.16 for depth to substratum, and 0.14 for elevation. Finally the values for each theme are summed resulting in the Radon Risk Index (RRI) as follows:

\[
Cov(X,Y) = \begin{cases} 
\text{High} = 0.80 \\
\text{Medium} = 0.50 \\
\text{Low} = 0.30 
\end{cases}
\]  

where $"X_i"$ is the map layer and "$w_i$" is the weight estimated by kriging (with the constraint of non-negativity, i.e. $w_i \geq 0$). The combination of all the RRI values for the various cells results in the final Radon Risk Map (Fig.2).

**DISCUSSION**

Considering the high number of considered variables, the construction of a credible model requires the following steps:

1. A preliminary elaboration of the risk model using all considered variables;
2. Considerations about redundant variables;
3. Elaboration of a risk model using fewer, more critical variables

In the first step, all variables were considered during the elaboration of the risk model. As the kriging method allows a weight to be assigned depending on the correlation of each layer with the studied phenomenon, the low weight calculated for the radium content variable, highlight the redundancy of this variable. For this reason a covariance matrix using only six variables was elaborated.

Equation (4) allows for the calculation of the RI, which was defined using a probability graph, which allows for a more objective approach to threshold estimation (SINCLAIR, 1991). This procedure entails approximating by straight line segments (or identifying inflection points) of a probability curve, and then picking threshold values at abscissa levels. In the simplest case a single threshold will define two populations (background and anomalous values); if, however, the two populations are not clearly separated, they may overlap in an interval defined by two bounding threshold values. This approach has highlighted 4 classes, each referring to a unique hazard level:

- Class 1 = no risk (0-17)
- Class 2 = low risk (17-28)
- Class 3 = medium risk (28-35)
- Class 4 = high risk (>35)

The distribution of risk classes in the Latera Plain is reported in the map given in figure 2, where each class indicates the potential for hazardous-gas emission in an area.
CONCLUSIONS

This work provides a method for the integration of geological factors responsible of hazardous gas emission phenomena using GIS and geostatistical techniques. This methodology allows for the objective identification of potential risk areas, removing the subjectivity generally involved in environmental and geological risk assessment.

The risk model elaborated for the Latera plain (Latium, central Italy) has made it possible to quantify the danger due to Rn in the investigated area using a risk index. The proposed method permits the elaboration of risk models based only on existing geological data, without the need for survey data. Yet in this case the obtained results may be useful only to delineate a rapid and general picture of the hazard of the investigated area, and to define the best strategies for subsequent geochemical surveys. Instead, in order truly calculate an area’s risk, the model needs to be validated using field geochemical data.

Refinements of the RI estimate can be achieved by including soil characteristics, such as permeability and moisture, as well as measurements of uranium or radium using gamma radiation intensity. At present we are in the process of comparing these results with a regional Rn soil gas survey, which will help to validate the results of the model. In the future we hope to conduct more detailed soil-gas surveys in order to better investigate areas which the model / regional survey show a high risk.

REFERENCES


RADON RISK MAP OF THE CITY BRNO

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Abstract

Data of radon risk mapping of the city Brno area from 1992 to 1999 were collected from databases of six private companies measuring radon risk there. The data sets are completed now. The first results are presented in this paper. In the city Brno area only low (385 measured sites) and medium (300) radon risk categories were found. The largest number of measured areas were situated in places with loess and loess loam (total quantity 344 sites, with medium radon risk category 158 sites), recent fluvial sediments (64, 32) and anthropogeneous deposits (61, 23). High values of radon volume activity in soil gas were found predominantly in Quaternary sediments and in granodiorite, type Veverská Bitýška, low values in leucotonalite and metabasalt.

Introduction

"Radon map of the city Brno" is the name of the author's thesis prepared now at the Charles University, Faculty of Science, Prague. To this purpose the data of radon risk mapping from the area of interest in the time interval 1992 – 1999 were yielded by six private companies voluntarily and out of charge. All these companies have their instruments calibrated, they use the uniform method and they have the certification for measurements. The radon risk data from several tens measured sites could not be used (missing important information, errors). A newly created database contains now for each of 685 measured places X,Y coordinates (obtained from the company Geodezie Brno), number of samples of soil gas sucked on the locality, minimum, maximum, arithmetic average, standard deviation and the third quartile of measured values of radon volume activity, nivel of radon risk, nivel of permeability of soil, symbol for the geological unit (taken from the Geological Map of Brno Surroundings, 1: 50 000) and other. Some data are missing. All information is written to the table in EXCEL 97. The first steps in the radon data processing and the first results are described in this paper.

Geological overview


Brno is situated in the south-eastern part of the Czech Republic. In the area of Brno agglomeration are found these stratigraphic and regional geological units:
- Proterozoic – the Brno Massif,
- Palaeozoic – Devonian, Carboniferous,
- Mesozoic – Jurassic,
- Tertiary and Quaternary.
The Brno Massif is a predominantly magmatic body composed of the Cadomian East and West granodiorite areas tectonically separated by the Metabasite Zone of an unknown age. The East granodiorite area is formed by granodiorites and tonalites (the U content is 0.87 ± 0.05 ppm, Hrouda et al. 1983 in Hanžl, Melichar 1997) and is situated in the northern and eastern part of Brno. The West granodiorite area is composed of granites, granodiorites, tonalites (the U content is 1.72 ± 0.12 ppm, Hrouda et al. 1983 in Hanžl, Melichar 1997) and diorites (the U content is from 0.02 to 0.66 ppm, Štecl, Weis 1986) in the diorite belt along the eastern margin, near the Metabasite Zone. The primary intrusive contacts between diorites and granodiorites are usually tectonically modified. The West area is found in the western and north-western part of the city. The Metabasite Zone consists of basalts, tuffitic rocks and rhyolites (the U content is similar to diorites). The rocks are metamorphosed in the greenschist facies conditions. The Metabasite Zone is located from the centre of the city to the north.

Devonian-Carboniferous limestones and black shales and lower Carboniferous greywackes, shales, conglomerates and sandstones are situated near the centre and in the eastern part of Brno.

Jurassic biomicrite limestones are found in the east of the city.

Tertiary sediments, calcareous clays, clays, sands and gravels, are located in the south and east of Brno.

Quaternary sediments in the area of interest include fluvial sandy gravels and sandy loams, colluvio-fluvial sandy loams, colluvial loams (mainly along the rivers and streams), loess and loess loams (in the biggest part of the Brno area). Anthropogeneous deposits are predominantly situated in the middle of the city.

Main dislocations in the Precambrian fundamental complex are oriented in the N-S (the Babi lom zone) and in the NNE-SSW directions (the Boskovice furrow linea). Younger faults are in the NW-SE direction.

Data processing, first results

Information about geology, radiometric prospection and about properties of the soils and rocks from the Brno area will be used for data processing by suitable statistical methods. In contradiction to radon risk mapping in other cities (Havránek, Veselý 1992, Barnet, Neznal 1994, Hricko 1997) the radon risk data from the Brno area were measured by six private companies. Some differences in the radon risk classification (based on the soil gas radon concentration and on the category of soil permeability) can occur. It is seen from the following overview.
In the Brno area radon risk data from 685 localities were collected. Only low (385 sites) and medium (300 sites) radon risk places were found (fig. 1). In the following summary the numbers of the measured places (more than 4 and with radon risk classification) with the location in the geological units are written.

<table>
<thead>
<tr>
<th>Geological unit</th>
<th>total</th>
<th>low risk</th>
<th>medium risk</th>
<th>medium risk sites/ total sites [%]</th>
<th>type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rocks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>THE BRNO MASSIF</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>metabasalt</td>
<td>11</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>(Vev Bityška)</td>
</tr>
<tr>
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<td>5</td>
<td>0</td>
<td>5</td>
<td>100</td>
<td>(Jundrov)</td>
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<tr>
<td>leucotonalite</td>
<td>9</td>
<td>8</td>
<td>1</td>
<td>11</td>
<td>(Král. Pole)</td>
</tr>
<tr>
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<td>52</td>
<td>33</td>
<td>19</td>
<td>37</td>
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<tr>
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<td>13</td>
<td>7</td>
<td>6</td>
<td>46</td>
<td></td>
</tr>
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<td></td>
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<td></td>
</tr>
<tr>
<td>calcareous clay (Karpatian)</td>
<td>10</td>
<td>3</td>
<td>7</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>calcareous clay (Moravian)</td>
<td>31</td>
<td>18</td>
<td>13</td>
<td>42</td>
<td></td>
</tr>
<tr>
<td><strong>QUATERNARY</strong></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>fluvial sandy gravel (Gunz-Mindel)</td>
<td>25</td>
<td>14</td>
<td>11</td>
<td>44</td>
<td></td>
</tr>
<tr>
<td>fluvial sandy gravel (Riss)</td>
<td>9</td>
<td>4</td>
<td>5</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>loess, loess loam</td>
<td>344</td>
<td>186</td>
<td>158</td>
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<tr>
<td>colluvial sediment</td>
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<td>5</td>
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<tr>
<td>coll. - fluv. sandy loam</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>fluvial sandy loam</td>
<td>64</td>
<td>32</td>
<td>32</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>anthropogeneos sed.</td>
<td>61</td>
<td>38</td>
<td>23</td>
<td>38</td>
<td></td>
</tr>
</tbody>
</table>

108
The low radon risk category site is possible to find with stronger probability in the area with metabasalt and leucotonalite and medium radon risk category site in the area with granodiorite, the Veverská Bitýška type, and calcareous clay (Karpotian).

The radon volume activity values from all data sets are in the wide intervals. In the Brno area the values of the third quartile change from 2.4 to 76.7 kBq/m³, arithmetic mean from 2.5 to 70.7 kBq/m³, maximum from 3.8 to 175 kBq/m³. The three highest values of the third quartile of the radon volume activity sets were obtained in calcareous clay (76.7 kBq/m³) and fluvial sediments (75.1 and 69.0 kBq/m³). The highest values of radon volume activity were measured in loess (175 kBq/m³), granodiorite, the Veverská Bitýška type (123 kBq/m³) and fluvial sediments (112 kBq/m³).

Majority of the measured sites were situated in Quaternary deposits, loess and loess loams. Values of the third quartile of the radon volume activity sets change in the interval 11.3 to 69.0 kBq/m³, maximums in the interval 15.0 to 175 kBq/m³. Detailed investigation will follow.

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References


Fig. 1 - Radon risk map of the Brno area

- Low risk  - Medium risk
I. Barnet - M. Neznal (Eds.)

Radon investigations
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