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ERRICCA Radon Model Intercomparison Exercise

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Abstract Numerical models based on finite-difference or finite-element methods are used by various research groups in studies of radon-222 transport through soil and building materials. Applications range from design of radon remediation systems to more fundamental studies of radon transport. To ascertain that results obtained with these models are of good quality, it is necessary that such models are tested. This document reports on a benchmark test organized by the EU project ERRICCA: European Research into Radon in Construction Concerted Action. The test comprises the following cases: (1) Steady-state diffusive radon profiles in dry and wet soils, (2) steady-state entry of soil gas and radon into a house, (3) time-dependent radon exhalation from a building-material sample. These cases cover features such as: soil heterogeneity, anisotropy, 3D-effects, time dependency, combined advective and diffusive transport of radon, flux calculations, and partitioning of radon between air and water in soil pores. Seven groups participated in the intercomparison. All groups submitted results without knowing the results of others. For these results, relatively large group-to-group discrepancies were observed. Because of this, all groups scrutinized their computations (once more) and engaged in follow-up discussions with others. During this debugging process, problems were indeed identified and eliminated. The accordingly revised results were in better agreement than those reported initially. Some discrepancies, however, still remain. All in all, it seems that the exercise has served its purpose and stimulated improvements relating to the quality of numerical modelling of radon transport. To maintain a high quality of modelling, it is recommended that additional exercises are carried out.

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Contents

1 Introduction

Numerical models are used by a number of research groups in studies of radon-222 transport through soil and building materials. Some apply models to aid in the design of mitigation systems. Others use models in conjunction with experiments to help better understand the mechanism for radon transport. Regardless of the application it seems, however, always to be important that modelling results are of good quality. To demonstrate this, it is necessary that models are tested. The present report describes a model-model intercomparison exercise organized by the modelling group of ERRICCA (*European Research into Radon in Construction Concerted Action*[1]) to help modellers identify (gross) errors in model calculations, for example, as a result of incorrect programming or incorrect model use.

In the exercise, the task is to compare modelling results for problems for which exact analytical solutions are (probably) not known. This provides an opportunity for the participating groups to test their models for relatively complex problems. Also, the test is realistic in the sense that models are normally applied to solve problems for which answers are unknown. In case of model-model discrepancies it is, however, not possible to say who is right and who is not. To resolve such problems, additional tests are needed.

The exercise includes the following cases:

Case 0: Steady-state diffusive radon profile in dry soil

Case 1: Steady-state diffusive radon profile in wet soil

Case 2: Steady-state entry of soil gas and radon into a house

Case 3: Time-dependent radon exhalation from a building-material sample

These problems cover features such as: soil heterogeneity, anisotropy, 3D-effects, time dependency, combined advective and diffusive transport of radon, and partitioning of radon between air and water in soil pores.

History

An exercise proposal was sent to 21 potential participants February 12, 1998. After some minor changes, problem definitions were fixed April 14, 1998. The initial deadline for submission of results was June 10, 1998, but that was extended to July 1, 1998. After the deadline, results were circulated among the participating groups. One group joined the exercise after the deadline, and some groups submitted revised results. The results listed in section 4 are the latest results reported. In total, seven European groups participated in the exercise.

2 Basic definitions

Soil structure

In this exercise, soil can be viewed as a porous medium consisting of grains and pores. Radon (^{222}Rn) exists in trace amounts in the pores along with water and soil gas. Beyond quantities such as porosity and bulk transport properties, there will be no detailed descriptions of the materials involved. This exercise therefore favors models that treat transport through porous media using a continuum approach.

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[1] `http://arcas.nuclear.ntua.gr/~erricca/`

A small reference element of volume δV located at the point (x, y, z) can be divided into grains of volume δV_g, air-filled pores of volume δV_a, and a water-filled pores of volume δV_w such that:

$$\delta V \;=\; \delta V_\mathrm{g} + \delta V_\mathrm{p} \;=\; \delta V_\mathrm{g} + \delta V_\mathrm{a} + \delta V_\mathrm{w} \tag{1}$$

where δV_p is the total pore volume. From this, we define porosity (ϵ), air porosity (ϵ_a), and water porosity (ϵ_w) as:

$$\epsilon \;=\; \frac{\delta V_\mathrm{p}}{\delta V} \tag{2}$$

$$\epsilon_\mathrm{a} \;=\; \frac{\delta V_\mathrm{a}}{\delta V} \tag{3}$$

$$\epsilon_\mathrm{w} \;=\; \frac{\delta V_\mathrm{w}}{\delta V} \tag{4}$$

We also define the fraction of water saturation of the pores:

$$m = \frac{\delta V_\mathrm{w}}{\delta V_\mathrm{p}} = \frac{\epsilon_\mathrm{w}}{\epsilon} \tag{5}$$

and the density of soil grain material ρ_g ($\mathrm{kg\,m^{-3}}$):

$$\rho_\mathrm{g} = \frac{\delta m_\mathrm{g}}{\delta V_\mathrm{g}} \tag{6}$$

where δm_g is the mass of grains in δV_g.

Radon concentrations

The activity of radon in δV_a is called δA_a, and we define the radon activity concentration of the air-filled pores ($\mathrm{Bq\,m^{-3}}$) as:

$$c_\mathrm{a} = \frac{\delta A_\mathrm{a}}{\delta V_\mathrm{a}} \tag{7}$$

Likewise, the activity of radon in δV_w is called δA_w, and we define the radon activity concentration of the water-filled pores ($\mathrm{Bq\,m^{-3}}$) as:

$$c_\mathrm{w} = \frac{\delta A_\mathrm{w}}{\delta V_\mathrm{w}} \tag{8}$$

Observe, that the above definitions imply that c_a gives the radon activity per geometric volume of gas-filled pore space. An alternative definition could have been to relate radon activity to the total number of gas molecules in the air-filled pores expressed as the volume those molecules occupy at some standard conditions of pressure and temperature.

Phase partitioning

In this exercise, it can be assumed that radon will not adsorb to any solid surfaces (e.g. soil grain surfaces). Furthermore, it can be assumed that the partition of radon between gas and water (locally) is instantaneous and permanently in equilibrium such that the concentration ratio in the pore space is well described by the solubility coefficient, L:

$$c_\mathrm{w} = L c_\mathrm{a} \tag{9}$$

Radon fluxes

For any point (x, y, z), we characterize the net transport of radon by the bulk flux density $\vec{j}(x, y, z)$ in units of $\mathrm{Bq\,m^{-2}\,s^{-1}}$. The term 'bulk' means that density is measured per total cross-sectional area perpendicular to $\vec{j}$. Hence, a flux J

($\mathrm{Bq\,s^{-1}}$) across some plane with geometric area A and uniform bulk flux density $\vec{j}$ gives: $J = \vec{j} \cdot A\hat{a}$, where $\hat{a}$ is a unit vector perpendicular to the plane. In this calculation, it is unimportant if A is void, or partially blocked by soil grains or water.

Radon emanation rate

Soil grains contain radium ($^{226}\mathrm{Ra}$) and radon emanates into air-filled and water-filled pores. The emanation rate, E, gives the number of atoms that emanate into the pores per unit time per kg dry mass of the soil ($\mathrm{atoms\,kg^{-1}\,s^{-1}}$). In this exercise, it is not specified what fraction that ends up in the water-filled pores and what fraction that goes into the air-filled pores.

Diffusion coefficient

Diffusion through soil will in this exercise be described by a bulk diffusion constant D ($\mathrm{m^2\,s^{-1}}$) defined by:

$$\vec{j}_\mathrm{d} = -D\nabla c_\mathrm{a} \tag{10}$$

which states that the bulk flux density of radon is proportional to the gradient of the radon concentration in the air-filled pores c_a. This definition is in common use, but it is certainly not the only possible definition. Observe, that D accounts for diffusion through both air and water filled pores such that D can account for diffusion even if the medium is fully water saturated!

Pressure field

We define the disturbance pressure field $p(x, y, z)$ (Pa) at a given location of the soil as the difference between the absolute pressure $P(x, y, z)$ (Pa) at that point and the 'aerostatic' pressure at that depth $P_\mathrm{A}(z)$ (Pa):

$$P(x, y, z) = P_\mathrm{A}(z) + p(x, y, z) \tag{11}$$

where

$$P_\mathrm{A}(z) = P_\mathrm{atm} - \rho_a g z \tag{12}$$

where the z-axis is oriented vertically (pointing upwards), P_atm is the absolute pressure at the atmospheric surface ($z = 0$), ρ_a the soil-gas density ($\mathrm{kg\,m^{-3}}$), and g the gravitational acceleration ($\mathrm{m\,s^{-2}}$).

Permeability

The transport of soil gas is assumed to be well described by Darcy's law:

$$\vec{q} = -\frac{k}{\mu}\nabla p \tag{13}$$

where $\vec{q}$ is the bulk flux density of soil gas ($\mathrm{m^3\,m^{-2}\,s^{-1}}$), k is the gas permeability of the soil ($\mathrm{m^2}$), and μ the viscosity (Pa s). If the soil is not isotropic k may be specified for each direction of interest.

3 Problem definitions

3.1 Assumptions and basic parameters

This section lists assumptions, constants etc. that are common for all cases considered in this exercise:

- All experiments are conducted at the same temperature.
- Although anisotropic gas permeabilities are considered in case 2, all other soil properties are in all cases set to be isotropic.
- Table 1 lists parameters that are common for the problem cases defined in this exercise.
- When an air chamber is said to be 'well mixed' with a certain radon concentration, it means that the chamber has a uniform radon concentration. It is ignored, that a thin stagnant layer of air may exist, for example, where the chamber meets the soil surface.
- The emanation rate E is assumed to be independent of moisture conditions and other soil parameters.
- The bulk diffusion constant D is assumed to be well described by the equation:

  $$D = \beta D'_e \tag{14}$$

  where $\beta = \epsilon_{\mathrm{a}} + L\epsilon_{\mathrm{w}} = (1 - m + Lm)\epsilon$ which can be called the partition-corrected porosity, and D'_e is set to be the effective diffusion constant found by Rogers and Nielson [Rog91A, Rog91B]:

  $$D'_e = D_0\epsilon \exp(-6m\epsilon - 6m^{14\epsilon}) \tag{15}$$

  and where D_0 is the diffusion constant of radon in free air.

Table 1. Parameter values common for all cases in this exercise. The values of solubility L and viscosity μ are characteristic for a temperature about 10 °C.

Quantity	Value	Unit	Remark
E	10	atoms $\mathrm{kg}^{-1}\,\mathrm{s}^{-1}$	Radon emanation rate
ρ_{g}	$2.65 \cdot 10^3$	$\mathrm{kg\,m}^{-3}$	Density of soil grain material
λ	$2.09838 \cdot 10^{-6}$	s^{-1}	Decay constant of ^{222}Rn
μ	$17.4 \cdot 10^{-6}$	Pa s	Air viscosity
L	0.3565	–	Radon solubility in water
D_0	$1.1 \cdot 10^{-5}$	$\mathrm{m}^2\,\mathrm{s}^{-1}$	Radon diffusivity in free air

3.2 Case 0: Profile in dry soil

Case 0 (zero) concerns radon transport in a column of dry soil. The geometry is identical to that described in case 1 (see Figure 1(A) and (B)). The column extends from $z = 0$ m to 3 m depth ($z = -3$ m). In the x and y directions, the column measures 1 m by 1 m. At $z = 0$ m, radon diffuses into a well-mixed air chamber. The system is assumed to be in steady state.

Boundary conditions

The air in the chamber is maintained at a uniform radon concentration of 1000 $\mathrm{Bq\,m}^{-3}$. Other boundaries of the soil column than that at $z = 0$ are closed off for radon transport. The disturbance pressure field $p(x, y, x)$ is zero at all places of the column.

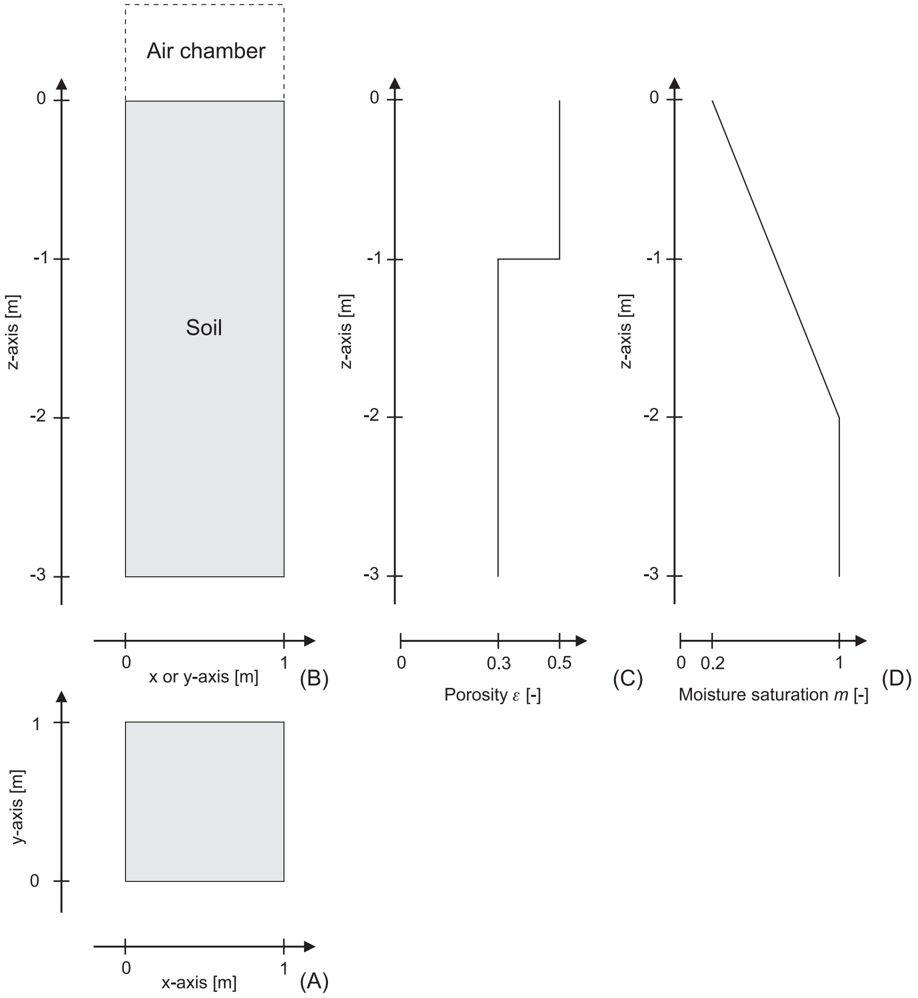

Figure 1. Case 1 geometry. (A) is the soil column viewed from the top, (B) is a side view of the column. (C) and (D) are plots of porosity (ϵ) and moisture saturation (m), respectively.

Parameters

The soil is set to be homogeneous with porosity $\epsilon(z)$=0.3 and moisture saturation $m(z)$ =0.0 (dry soil). Other parameters are given in Section 3.1

Model output to be reported

The task is to calculate the flux of radon J ($\mathrm{Bq\,s^{-1}}$) in the z-direction at $z = 0$.

3.3 Case 1: Profile in soil

Case 1 concerns radon transport in a column of soil. As shown in Figure 1, the column extends from $z = 0$ m to 3 m depth ($z = -3$ m). In the x and y directions, the column measures 1 m by 1 m. At $z = 0$ m, radon diffuses into a well-mixed air chamber. The system is assumed to be in steady state.

Boundary conditions

The air in the chamber is maintained at a uniform radon concentration of 1000 $\mathrm{Bq\,m^{-3}}$. Other boundaries of the soil column than that at $z = 0$ are closed off for radon transport. The disturbance pressure field $p(x, y, x)$ is zero at all places of the column.

Parameters

As shown in Figure 1(C), the porosity $\epsilon(z)$ is set to 0.5 above $z = -1$ m, and 0.3 below. The moisture saturation $m = m(z)$ increases linearly from $m = 0.2$ at $z = 0$ to $m = 1$ at $z = -2$ m. Below $z = -2$ m, the moisture saturation is 1. This is shown in Figure 1(D). Other parameters are given in Section 3.1

Model output to be reported

The task is to calculate the radon concentration in the air-filled pore space c_{a} ($\mathrm{Bq\,m^{-3}}$) and the flux of radon J ($\mathrm{Bq\,s^{-1}}$) in the z-direction at $z = 0$, $z = -1$ m, and $z = -2$ m.

3.4 Case 2: Entry into house

Case 2 concerns the slab-on-grade house sketched in Figure 2. Domains of importance for the problem are: slab, sub-slab layer, footer, air gap, and soil.

Radon can enter the house (only) through a smooth-walled air gap that separates the slab from the footer. The gap width is 1 mm. The thickness of slab and sub-slab layer are both equal to 10 cm. The footer reaches 1 m below the atmospheric surface and has a thickness of 30 cm. As indicated in Figure 2, the soil extends 10 m vertically, and 30 m by 30 m, horizontally. The system is assumed to be in steady state.

Flow through the gap is described by the Navier-Stokes equation. In this exercise, it can be assumed, that a flow rate Q ($\mathrm{m^3\,s^{-1}}$) through the gap causes a pressure difference Δp_{c} across the gap equal to:

$$\Delta p_{\mathrm{c}} = \frac{12\,\mu\,\Delta z}{L_{\mathrm{c}}\,w^3}\,Q \tag{16}$$

where $\Delta z = 0.1$ m is the slab thickness, $w = 0.001$ m is the gap width, and L_{c} is the total gap length. To account for diffusion of radon through the gap, the diffusion constant of radon in free air D_0 can be assumed (see Table 1).

Boundary conditions

The disturbance pressure is (1) zero at the atmospheric surface, and (2) Δp at the top of the air gap, i.e. where soil and indoor atmosphere meet (i.e. at $z = 0$). As given in Table 2, we consider Δp equal to 0 and -3 Pa. The open atmosphere is set to have a radon concentration equal to 0 $\mathrm{Bq\,m^{-3}}$. The radon concentration c_{in} at the top of the air gap (i.e. at $z = 0$) is given by the equation:

$$J = \lambda_{\mathrm{v}}\,V\,c_{\mathrm{in}} \tag{17}$$

where J ($\mathrm{Bq\,s^{-1}}$) is the entry rate of radon into the house through the air gap, λ_v is 0.5 $\mathrm{h^{-1}}$, and V is 250 $\mathrm{m^3}$. Other boundaries than those mentioned above are closed off for gas transport.

Parameters

Slab and footer are made of radium-free solid materials that are impermeable to any kind of gas transport. Soil and sub-slab gravel layer are both assumed to have porosity and moisture saturation equal to ϵ=0.40 and m=0.20, respectively. The

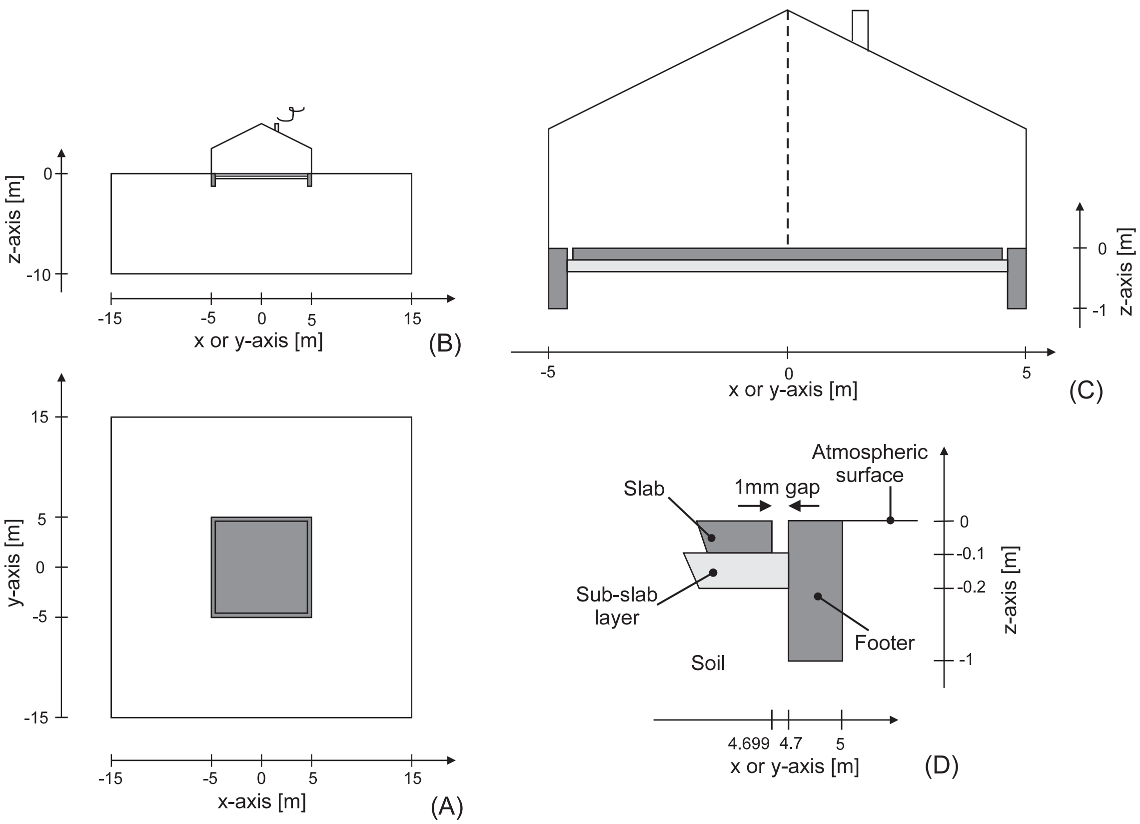

Figure 2. Case 2 geometry (not drawn to scale). (A) is the house viewed from the top, and (B) to (D) are different side views of the house.

Table 2. Parameter sets considered in case 2.

ID	Dist. pressure in house, Pa	Gas permeability, m^2		
		Sub-slab layer	Soil	
	Δp	k_{sub}	k_{h}	k_{v}
Case 2-A	0	10^{-11}	10^{-11}	10^{-11}
Case 2-B	-3	10^{-11}	10^{-11}	10^{-11}
Case 2-C	-3	10^{-9}	10^{-11}	10^{-11}
Case 2-D	-3	10^{-9}	10^{-10}	10^{-11}
Case 2-E	-3	10^{-9}	10^{-11}	10^{-10}

sub-slab layer is set to have the (isotropic) gas permeability k_{sub}. The soil is set to have the gas permeability k_{v} in the vertical direction and k_{h} in the horizontal direction. Five combinations of the parameters Δp, k_{sub}, k_{v}, and k_{h} are considered in this exercise. These are identified as case 2-A to case 2-E as shown in Table 2. Other parameters are given in Section 3.1.

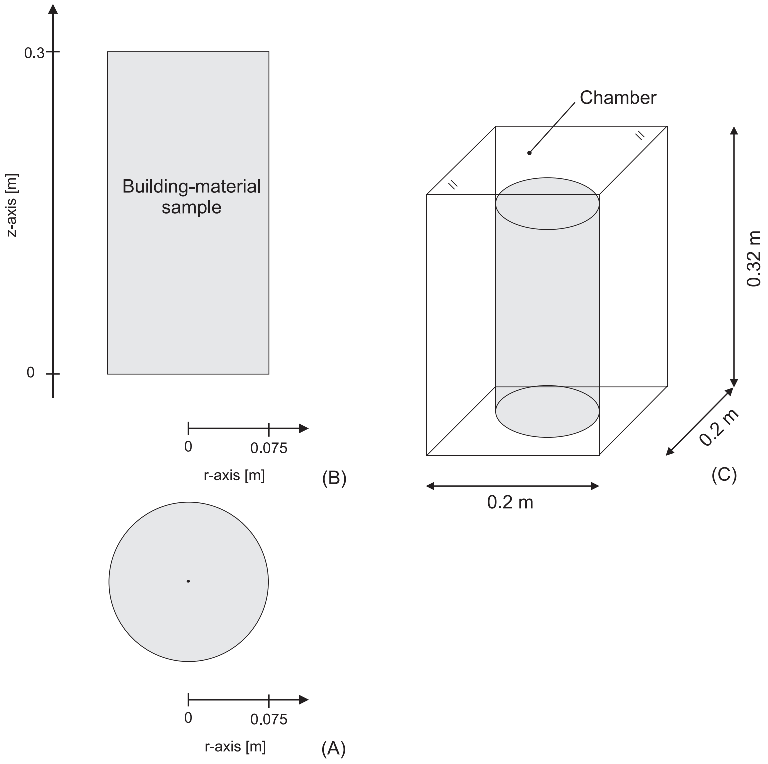

Figure 3. Case 3 geometry. (A) and (B) show the sample as viewed from top and side, respectively. (C) is sketch of the sample placed in a 12.8 L air chamber (not drawn to scale).

Model output to be reported

The task is to calculate the entry rates of soil gas Q ($\mathrm{m^3\,s^{-1}}$) and radon J ($\mathrm{Bq\,s^{-1}}$) into the house for the five parameter sets given in Table 2.

Notes

The boundary condition specified by equation 17 simulates the accumulation of radon indoors when the air-exchange rate λ_v is taken into account. This type of boundary condition can be a problem for some models. Another complication will probably be to design a sufficiently fine computational grid close to the gap.

3.5 Case 3: Building-material exhalation

Case 3 concerns a sample of building material placed in an 12.8 L air chamber as sketched in Figure 3. Radon diffuses from the sample into the chamber. The task is to calculate the exhalation rate J ($\mathrm{Bq\,s^{-1}}$) at selected times. The sample is cylindrical with the dimensions: 15 cm diameter and 30 cm height. Although Figure 3(C) shows the chamber as a box of dimensions 20 cm by 20 cm by 32 cm, the chamber is well mixed and its shape can be considered to be unimportant for the problem in question.

In this exercise, no formal distinction is made between soil and building materials. Therefore, all definitions and assumptions presented in section 2 and 3.1 also apply to the building-material sample considered in this case.

Initial and boundary conditions

For time $t = -\infty$ to 0, the chamber is maintained at a radon concentration equal to 0. At $t = 0$, the chamber is closed off and there is no transport of radon through the walls of chamber.

Parameters

The building-material sample is set to have porosity and moisture saturation equal to ϵ=0.2 and m=0.8, respectively. Other parameters are identical to the soil parameters given in section 3.1.

Model output to be reported

The task is to calculate the exhalation rate J (Bq s^{-1}) at times $t = 0$, $t = 1$ hour, $t = 12$ hours, and at $t = \infty$.

4 Results

The results reported by the seven participating groups are listed in the following. With one exception, all groups solved only part of the problems. Group 2 used two different models (A and B), and their results are therefore given as Group 2A and Group 2B, respectively.

The first part of the exercise was conducted as a blind test: All groups submitted results without knowing the results of others. Relatively large group-to-group discrepancies were observed. All groups therefore scrutinized their calculations once more. Some groups discovered misunderstandings relating to problem definitions, or found that it was necessary to repeat calculations with a finer grid size. Also programming errors were identified. A mixture of original and revised results are listed in Table 3 to 6. Each result is assigned notes as follows:

Note 1 Original results (submitted without knowing results of other groups).

Note 2 Revised results after correction for (trivial) misunderstandings relating to input parameters.

Note 3 Revised results based on a finer grid.

Note 4 Revised results after changes of the model.

The appendix (page 15) contains information on the models used by the various groups.

5 Discussion

Case 0

Case 0 can be solved analytically, and it is observed from Table 3 that all groups are consistent with the following solution based on [Co81][2]:

$$J = \sqrt{\epsilon\lambda D}\ \ (\frac{G}{\lambda} - c_0)\ \ \tanh(L_0\sqrt{\frac{\epsilon\lambda}{D}}) = 4.722824\ldots \cdot 10^{-2}\ \mathrm{Bq\,s^{-1}} \tag{18}$$

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[2] One potential problem with the use of results from [Co81] is that that publication is not based on bulk diffusivity in the same sense that this exercise is. To be useful, the results in [Co81] therefore have to be ”translated” into quantities consistent with those used here.

where $\epsilon = 0.3$, $\lambda = 2.09838 \cdot 10^{-6}\ \mathrm{s}^{-1}$, $D = \epsilon D'_e = \epsilon^2 D_0 = 9.9 \cdot 10^{-7} \mathrm{m}^2\,\mathrm{s}^{-1}$, $D_0 = 1.1 \cdot 10^{-5}\ \mathrm{m}^2\,\mathrm{s}^{-1}$, $c_0 = 1000\ \mathrm{Bq\,m}^{-3}$, $L_0 = 3$ m, and

$$G = \rho_g \frac{1-\epsilon}{\epsilon} \lambda E = 0.129749\ldots\ \mathrm{Bq\,m}^{-3}\mathrm{s}^{-1} \tag{19}$$

where $\rho_g = 2.65 \cdot 10^3\ \mathrm{kg\,m}^{-3}$ and $E = 10$ atoms $\mathrm{kg}^{-1}\ \mathrm{s}^{-1}$.

Case 1

Table 4 shows the results for case 1. For each of the six reported quantities (calculated concentrations and fluxes at three depths) there are always four or more groups in favor of a particular value. The agreement does, however, not comprise the same four (or more) groups. Only group 1, 2A, and 2B agree on all results (within about 4 %). In turn group 3, 4 or 5 constitutes the fourth or fifth "partner of agreement". For example, at $z = 0$, Group 1, 2A, and 2B found a radon flux of $2.8 \cdot 10^{-2}\ \mathrm{Bq\,s}^{-1}$. This is in agreement with group 4 and 5, but much smaller that group 3 and 6. At $z = -1$, group 1, 2A and 2B found a flux of $1.8 \cdot 10^{-2}\ \mathrm{Bq\,s}^{-1}$. Now the result is in agreement with group 3 and 4, but too low compared with group 5 and 6.

All groups agree that the radon concentration (c_a) in the air-filled pore parts should be $1000\ \mathrm{Bq\,m}^{-3}$ (i.e. the same as in the well-mixed box). This is consistent with the requirement that the radon concentration fulfills continuity phase-by-phase (see later) at media interfaces. Also, all groups agree that the radon concentration at $z = -2$ m is about $170\ \mathrm{kBq\,m}^{-3}$. As there is little transport at that depth, this probably means that there good agreement on how the source term should be calculated.

Case 2

Only group 1 and 7 attempted to solve case 2. In the pure diffusion case (case 2-A) the two models agree within 15 %. For the other cases, discrepancies between 20 to 70 % are observed. Part of the discrepancy could be that group 1 used a full 3D model for the problem whereas group 7 used a 2D model. It is observed, that Q and J increase from 2-B to 2-C. This is the effect of adding a sub-floor gravel layer to the house. The results of group 1 show that Q and J increase by a factor of 3.9. For group 7, the increase amounts to a factor of 3.0 for the flow Q and 2.4 for the radon entry J.

Table 3. Results reported for Case 0: Profile in dry soil. The meaning of the notes is given in the text.

	J at $z = 0$ $\mathrm{Bq\,s}^{-1}$	Note
Group 1	$4.72 \cdot 10^{-2}$	1
Group 2A	$4.72 \cdot 10^{-2}$	1
Group 2B	$4.72 \cdot 10^{-2}$	1
Group 3	$4.63 \cdot 10^{-2}$	1
Group 4	$4.71 \cdot 10^{-2}$	4
Group 5	$4.70 \cdot 10^{-2}$	1
Group 6	-	-
Group 7	$4.72 \cdot 10^{-2}$	2

Table 4. Results reported for Case 1: Profile in wet soil. The meaning of the notes is given in the text.

	$z = 0$		$z = -1$ m		$z = -2$ m		Note
	c_a Bq m^{-3}	J Bq s^{-1}	c_a Bq m^{-3}	J Bq s^{-1}	c_a Bq m^{-3}	J Bq s^{-1}	
Group 1	$1.000 \cdot 10^{3}$	$2.83 \cdot 10^{-2}$	$3.08 \cdot 10^{4}$	$1.08 \cdot 10^{-2}$	$1.71 \cdot 10^{5}$	$1.22 \cdot 10^{-5}$	1
Group 2A	$1.000 \cdot 10^{3}$	$2.82 \cdot 10^{-2}$	$3.07 \cdot 10^{4}$	$1.08 \cdot 10^{-2}$	$1.71 \cdot 10^{5}$	$1.27 \cdot 10^{-5}$	2,3
Group 2B	$1.000 \cdot 10^{3}$	$2.82 \cdot 10^{-2}$	$3.07 \cdot 10^{4}$	$1.07 \cdot 10^{-2}$	$1.71 \cdot 10^{5}$	$1.19 \cdot 10^{-5}$	2,3
Group 3	$1.000 \cdot 10^{3}$	$3.73 \cdot 10^{-2}$	$3.59 \cdot 10^{4}$	$1.03 \cdot 10^{-2}$	$1.68 \cdot 10^{5}$	$1.25 \cdot 10^{-5}$	1
Group 4	$1.000 \cdot 10^{3}$	$2.80 \cdot 10^{-2}$	$3.03 \cdot 10^{4}$	$1.04 \cdot 10^{-2}$	$1.70 \cdot 10^{5}$	$0.93 \cdot 10^{-5}$	4
Group 5	$1.000 \cdot 10^{3}$	$2.76 \cdot 10^{-2}$	$2.85 \cdot 10^{4}$	$1.26 \cdot 10^{-2}$	$1.71 \cdot 10^{5}$	$3.75 \cdot 10^{-5}$	4
Group 6	$1.000 \cdot 10^{3}$	$8.46 \cdot 10^{-2}$	$3.62 \cdot 10^{4}$	$1.76 \cdot 10^{-2}$	$1.73 \cdot 10^{5}$	$9.42 \cdot 10^{-5}$	1
Group 7	-	-	-	-	-	-	-

Table 5. Results reported for Case 2: Entry into house. Group 7 modelled case 3, with a 2D-model. The meaning of the notes is given in the text.

	Case 2-A		Case 2-B		Case 2-C		Note
	Q m^{3} s^{-1}	J Bq s^{-1}	Q m^{3} s^{-1}	J Bq s^{-1}	Q m^{3} s^{-1}	J Bq s^{-1}	
Group 1	0	0.111	$1.04 \cdot 10^{-5}$	0.45	$4.1 \cdot 10^{-5}$	1.74	1
Group 7	0	0.094	$1.8 \cdot 10^{-5}$	0.59	$5.4 \cdot 10^{-5}$	1.42	2

	Case 2-D		Case 2-E		Note
	Q m^{3} s^{-1}	J Bq s^{-1}	Q m^{3} s^{-1}	J Bq s^{-1}	
Group 1	$7.29 \cdot 10^{-5}$	3.00	$13.5 \cdot 10^{-5}$	5.21	1
Group 7	-	-	-	-	2

Table 6. Results reported for Case 3: Building-material exhalation. The meaning of the notes is given in the text.

	J				Note
	$t = 0$ Bq s^{-1}	$t = 1$ h Bq s^{-1}	$t = 12$ h Bq s^{-1}	$t = \infty$ Bq s^{-1}	
Group 1	$2.28 \cdot 10^{-4}$	$2.22 \cdot 10^{-4}$	$2.15 \cdot 10^{-4}$	$2.14 \cdot 10^{-4}$	1
Group 2A	-	-	-	-	-
Group 2B	$2.15 \cdot 10^{-4}$	$2.10 \cdot 10^{-4}$	$2.03 \cdot 10^{-4}$	$2.02 \cdot 10^{-4}$	3
Group 3	$2.20 \cdot 10^{-4}$	$2.15 \cdot 10^{-4}$	$2.08 \cdot 10^{-4}$	$2.07 \cdot 10^{-4}$	1
Group 4	$2.77 \cdot 10^{-4}$	$2.73 \cdot 10^{-4}$	$2.65 \cdot 10^{-4}$	$2.56 \cdot 10^{-4}$	4
Group 5	-	-	-	-	-
Group 6	-	-	-	-	-
Group 7	-	-	-	-	-

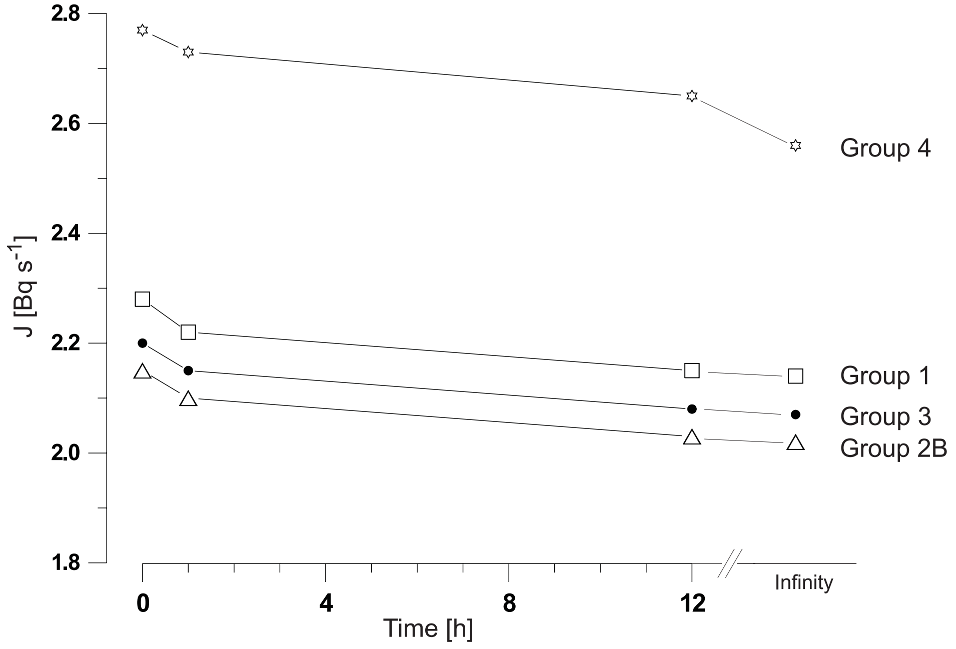

Figure 4. Plot of results reported for case 3. Group 4 used a one-dimensional approximation in their computations.

Case 3

The results of case 3 are shown graphically in Figure 4. The calculated concentrations at $t = 0$, span over a range that corresponds to about 25 % of the mean result. The four groups involved seem to agree on the (relative) time development during the first 12 hours.

The reason why group 4 finds higher values than the other three groups could well be that group 4 applied certain simplifying assumptions to simulate the three-dimensional problem (defined in the exercise) with a one-dimensional model.

Sources of discrepancies

The observed discrepancies initiated follow-up discussions, and some groups took action to change their models or to subject them to further tests. The follow-up discussions were carried at a group-to-group level. To stimulate further improvement of models, it is probably useful to highlight some of the technical issues discussed:

- Diffusivity. The terms *bulk diffusivity* and *effective diffusivity* are widely used in the radon literature, however, not always with the same meaning! Misunderstandings relating to these terms therefore is an excellent source of model discrepancies. Although some effort had been given (see the section *Basic definitions*), to define what in this exercise it meant by *bulk diffusivity*, follow-up discussion indicated that the stated diffusivities had caused some confusion.
- Interface conditions. One interesting feature of case 1 is that it includes media of different porosity and moisture content. This exercise therefore tests the treatment of radon in different phases (radon is partitioned between the air-filled parts of the pores and the water-filled parts of the pores). One aspect of all this is the question of continuity of radon concentration and radon flux at interfaces between regions of different porosities and moisture contents[3].

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[3] It is interesting to note, that Rogers and Nielson [Rog91A] discuss this problem: "Interface

In this exercise, some groups advocate the following conditions of continuity: (1) that radon concentrations phase-by-phase should be the same at the two sides of the interface (e.g. $c_a(+) = c_a(-)$ and $c_w(+) = c_w(-)$ where + and − designate locations in the two media) and (2) that the bulk flux should be the same at the two sides of the interface (e.g. $\vec{J}(+) = \vec{J}(-)$). This implies that bulk concentrations of radon as well as fluxes of radon evaluated on a pore-area basis in general will change (abruptly) across such interfaces (i.e. the concentration gradient will be undefined). This in turn has consequences for the treatment of diffusion: the diffusive flux must be related to the concentration of radon in one single phase. In the exercise the radon concentration in the air-filled parts of the pores (c_a) is used for that purpose (see equation 10).

- Computational flux "measurements". Another question of discussion was the following: "My model outputs radon concentrations at all these locations and it also gives the flow rate of soil gas, but how can I calculate the radon flux at $z = -2$ m?" It appears that the solution to this problem will vary from model to model. One easy-to-understand approach is given by Patankar [Pa80].

6 Conclusion

A model-model intercomparison exercise involving seven groups has been completed. All groups submitted results without knowing the results of others. For these results, relatively large group-to-group discrepancies were observed. Because of this, all groups scrutinized their computations (once more) and engaged in follow-up discussions with other groups. In this process, problems were indeed identified and eliminated. In some cases trivial errors had been made in the translation of input parameters from problem definitions (as stated in this document) to the framework used in the models. Others had underestimated the need for further grid refinement at critical locations. Also, some computer code errors were identified. The accordingly revised results were in better agreement than those reported initially. Some discrepancies, however, still remain. All in all, it seems that the exercise has served its purpose and stimulated improvements relating to the quality of numerical modelling of radon transport. To maintain a high quality of modelling, it is recommended that additional exercises are carried out.

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conditions for adjacent soil regions are: continuity of the pore air Rn concentration, C_0, and continuity of the pore-average flux, F/p, across the interface. It is incorrect to assume continuity of the pore-average Rn concentration across an interface. This condition generally does not occur. Continuity of pore air flux or of bulk Rn flux (F) may cause errors."

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A Addresses and models

Group 1

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All calculations were carried out with the model `RnMod3d`. This is a three-dimensional, time-dependent model based on the control-volume approach. The basis of the model is described in C.E. Andersen: *Entry of soil gas and radon into houses*, Report Risø-R-623(EN) (1992), but the model interface is not documented. The model has been programmed in Pascal and is run on a PC from the compiler/editor environment of Borland Pascal 7.0 or Delphi. The model is relatively flexible, and all exercise cases could be set up without troubles. The model has not been prepared for external use. The model is primarily used in connection with studies of radon in soil.

Group 2A & 2B

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Model 2A: `RAETRAP` is based on the code `RAETRAN` developed by Rogers and Associates Engineering Corporation, Salt Lake City, USA. KVI added a (more) user friendly interface. The model solves the one-dimensional steady-state radon transport equation (diffusion and advection) by setting up the exact simultaneous equations for a multi-layer system that approximates the real situations. These exact equations are then solved by matrix methods. The model is documented in: Stapel, C.: *Manual for* `RAETRAP`*, a 1D code for calculation of diffusion and flow of radon through porous media.* KVI. Technical Document, RT-01, 1992. Main use of the model is in the Dutch Integrated Radon Model, that consists of a interconnected series of computer models to study the influence of various parameters on exposure to radon of inhabitants of different dwelling types. Reference: Janssen, M.P.M. de Vries, L., Phaff, J.C., van der Graaf, E.R., Blaauboer, R.O., Stoop, P., Lembrechts, J.: *Modelling radon transport in Dutch dwellings*, RIVM report no. 610050005, RIVM, Bilthoven, The Netherlands, 1998.

Model 2B: `KVI-1D` and `KVI-2D` are based on the multi-phase radon transport formalism introduced by Nielson and Rogers [Rog91A] (see page 14) and are implemented by W.H. van der Spoel. Both models use the control volume approach (and thus fall under the method of finite differences) and numerically solve the time dependent radon transport equation including generation, decay, adsorption, advection and diffusion. The models are documented in: Van der Spoel, W.H., *Radon transport in sand: A laboratory study.* PhD Thesis, Eindhoven University of Technology, 1998. Main use of the models has been in studying radon transport in soil. Currently, the model is extensively used in studies on radon release from concrete and cellular concrete.

Lessons learned from the intercomparison were that one has to be extremely careful in translating parameters given in an exercise into the input parameters of a specific model. Furthermore, we observed that both 1D-models are very sensitive to the choice of degree of discretization at interfaces were rapid changes in properties take place.

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The model is named `RnFlow`. It has been programmed by István Csige. The model is a three-dimensional, time-dependent model based on the finite-difference approach. The geometry can be given in cartesian, polar or spherical coordinates. One special feature of the model is that it includes heat transport in soil. The model is not yet available on a commercial basis. The model documentation is in preparation. The model is used mainly in connection with basic research. It is planned to use the model in a procedure to determine the radon source potential of building sites.

The model was not been modified as a result of the exercise, but the exercise revealed the importance of the grid size effects on the accuracy of calculations.

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The model has been programmed at the Radiation Hygiene Dept., Institute of Public Health ”prof. dr. Leonida Georgescu”, Romania. The model is based on finite elements: first order Lagrange trial functions (a variant with higher order functions is under development). The model is one dimensional in space (constant/variable grid), and has Crank-Nicolson time stepping with variable length of the time step. All input parameter values are given from the console, and the output is in the form of an ASCII file. The transport model includes flow of water and air (the air part is in progress). The model will be available for free download from the web page of the laboratory given above. Detailed documentation is in preparation. The main use of the model is to predict migration in soil of radon and other contaminants dissolved in air or water.

As a result of the exercise (and further tests) the following problems were identified (and eliminated): certain programming errors, wrong use of given parameters, mathematical errors (illegal move of space variable parameters), treatment of the saturated-unsaturated boundary.

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The model has been programmed at the Isotopenlaboratorium in Göttingen. The model is based on one-dimensional explicit finite differences and the FTCS scheme. Model documentation is in preparation. The main use of the model is to study the influence of meteorological parameters on radon transport in soil. The model was changed as a result of the exercise (treatment of the diffusion coefficient).

Group 6

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The model is named `transrad`. It has been developed at the Grup de Fisica de les Radiacions, Universitat Autònoma de Barcelona. The model works with time and two space dimensions. The geometry consists of a vertical cut of a house, including indoor and outdoor air and soil. There is a crack around the floor of the building, simulating the floor-wall joint. Equations for pressure and radon concentration fields are solved using finite differences. There is a regular square grid with a subnested one of finer mesh size immediately under the house. This is where the largest radon concentration gradients occur. The model gives contour levels for both fields, including their time evolution, when some of their transport parameters change in time. The model is object of a Ph.D. thesis, and is not yet available in the public domain. This exercise promoted the inclusion of the effect of the water saturation in the model. Some problems were identified in case 1 at z=1 m, where the porosity (and related parameters) change abruptly.

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The name of the model is `RADON2D` *for Windows.* The program authors are M. Jiranek and Z. Svoboda. The model is based on finite elements. It is a steady-state, two-dimensional model. One special feature of the model is that it has a graphical input and output user interface. The model is not available in the public domain, but it is in use by a couple of research institutes in the Czech Republic. The model has been described in the following papers:

- Jiranek, Svoboda: *The verification of radon protective measures by means of a computer model.* In: Proc. of 5th IBPSA Conference, Building Simulation 97, Prague 1997, pp. 165–171.
- Svoboda: *The numerical solution of convective-diffusive transport*, PhD thesis, Prague 1997.
- *Manual for the program* `RADON2D`, Prague 1997.

The main use of the program relates to the verification of radon protective measures in the field of civil engineering. The model was changed as a result of the exercise. The problem was in the definition of the radon diffusion coefficient D_e, which we had defined in a different way from the other participants.

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20	6	4	5

Abstract (Max. 2000 char.)

Numerical models based on finite-difference or finite-element methods are used by various research groups in studies of radon-222 transport through soil and building materials. Applications range from design of radon remediation systems to more fundamental studies of radon transport. To ascertain that results obtained with these models are of good quality, it is necessary that such models are tested. This document reports on a benchmark test organized by the EU project ERRICCA: European Research into Radon in Construction Concerted Action. The test comprises the following cases: (1) Steady-state diffusive radon profiles in dry and wet soils, (2) steady-state entry of soil gas and radon into a house, (3) time-dependent radon exhalation from a building-material sample. These cases cover features such as: soil heterogeneity, anisotropy, 3D-effects, time dependency, combined advective and diffusive transport of radon, flux calculations, and partitioning of radon between air and water in soil pores. Seven groups participated in the intercomparison. All groups submitted results without knowing the results of others. For these results, relatively large group-to-group discrepancies were observed. Because of this, all groups scrutinized their computations (once more) and engaged in follow-up discussions with others. During this debugging process, problems were indeed identified (and eliminated). The accordingly revised results were in better agreement than those reported initially. Some discrepancies, however, still remain. All in all, it seems that the exercise has served its purpose and stimulated improvements relating to the quality of numerical modelling of radon transport. To maintain a high quality of modelling, it is recommended that additional exercises are carried out.

Descriptors INIS/EDB

ADVECTION; BENCHMARKS; BUILDING MATERIALS; DIFFUSION; ENVIRONMENTAL TRANSPORT; FINITE DIFFERENCE METHOD; FINITE ELEMENT METHOD; GAS FLOW; HOUSES; RADON 222; SOILS

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