Session Title**: Radiation Protection of the Public and the Environment - Radon**

MITIGATION OF HOUSES WITH EXTREMELY HIGH INDOOR RADON CONCENTRATIONS

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INTRODUCTION

Based on the latest indoor radon survey it is estimated that in the Czech Republic more than 6000 houses has the indoor radon concentration above 1000 Bq/m^3. Among this group we can find houses, where the radon concentration in basements or cellars exceeds 100 kBq/m^3 and the ground floor radon concentration reaches several tens of kBq/m^3. Inhabitants of such houses are exposed to higher risk of lung cancer incidence and therefore mitigation of such houses should be the primary objective. Unusually high indoor radon concentrations are normally attributed to soil conditions - extremely high soil permeability and an enormous radon concentration in the soil gas. Consequently it makes sense to use one of the most straightforward remedial methods that take action in the soil, i.e. sub-slab depressurization. According to recent findings other mitigation techniques are not believed to be effective (effectiveness of additionally applied radon-proof insulation is only approximately 50 %, indoor air mechanical ventilation systems are due to high installation and operation costs not so much economically attractive, etc.).

Sub-slab depressurisation systems (SSD systems) belong among the most effective radon remedial measures [1, 2, 4, 7]. These systems are designed in order to lower the air pressure beneath the buildings and to decrease the radon concentration in the soil gas. The air pressure is lowered by means of fans, which draw air from one or several sumps, perforated pipes placed into the drainage layer or from perforated tubes drilled beneath the existing floors [5, 7]. The effectiveness of such systems varies between 70 and 98 %, which means that indoor radon concentration decreases to 30 % up to 2 % of the initial values [4]. The effectiveness is mainly influenced by the vertical profile of soil permeability and by the air tightness of the building substructure.

EXAMPLE OF MITIGATION

The applicability of sub-slab depressurization systems for mitigation of houses with unusually high indoor radon concentrations has been studied on an old single-family house that was built in the area formed by highly permeable soils with high radon content in the soil air. The ground floor of the living part contains five habitable rooms (Fig. 1). The house has a small cellar located under 1/5 of the ground floor area and accessible from the shed. Two types of floors, i.e. the timber floor (in the study room and kitchen II) and the cracked concrete slab were found in the house.

A set of diagnostic measurements [3, 6] had been performed before the remedial measures were designed and installed. As a result of extremely high radon concentrations in the sub-floor region (up to 600 kBq/m^3) and leaky structures in contact with soil (radon concentration in floor cracks in the living room varied between 20 and 380 kBq/m^3), instant radon concentrations around 100 kBq/m^3 in the cellar and up to 60 kBq/m^3 in the living rooms on the ground floor were measured prior to mitigation. The average annual radon concentration in habitable rooms on the ground floor measured with track detectors was 14 069 Bq/m^3.

Mitigation measures that were carried out in the house consist of reconstruction of timber floors and installation of active soil depressurization. Timber floors were replaced with a concrete slab fitted with a damp proof membrane, thermal insulation and floor covering (Fig. 1). The soil depressurization system was made up of two sections (Fig. 2). The first section is composed of the network of perforated pipes inserted in the drainage layer placed under the new floors and four perforated tubes drilled under the existing floors. The soil air from this section is extracted by means of a roof fan installed at the top of the vertical exhaust pipe running inside the living space and terminating above the roof. The second section was designed to withdraw by means of a small fan radon-laden air from the filling in the floor above the cellar and from perforated tubes drilled into the sub-floor region under the rooms adjacent to the cellar. It serves also for the active ventilation of the cellar.

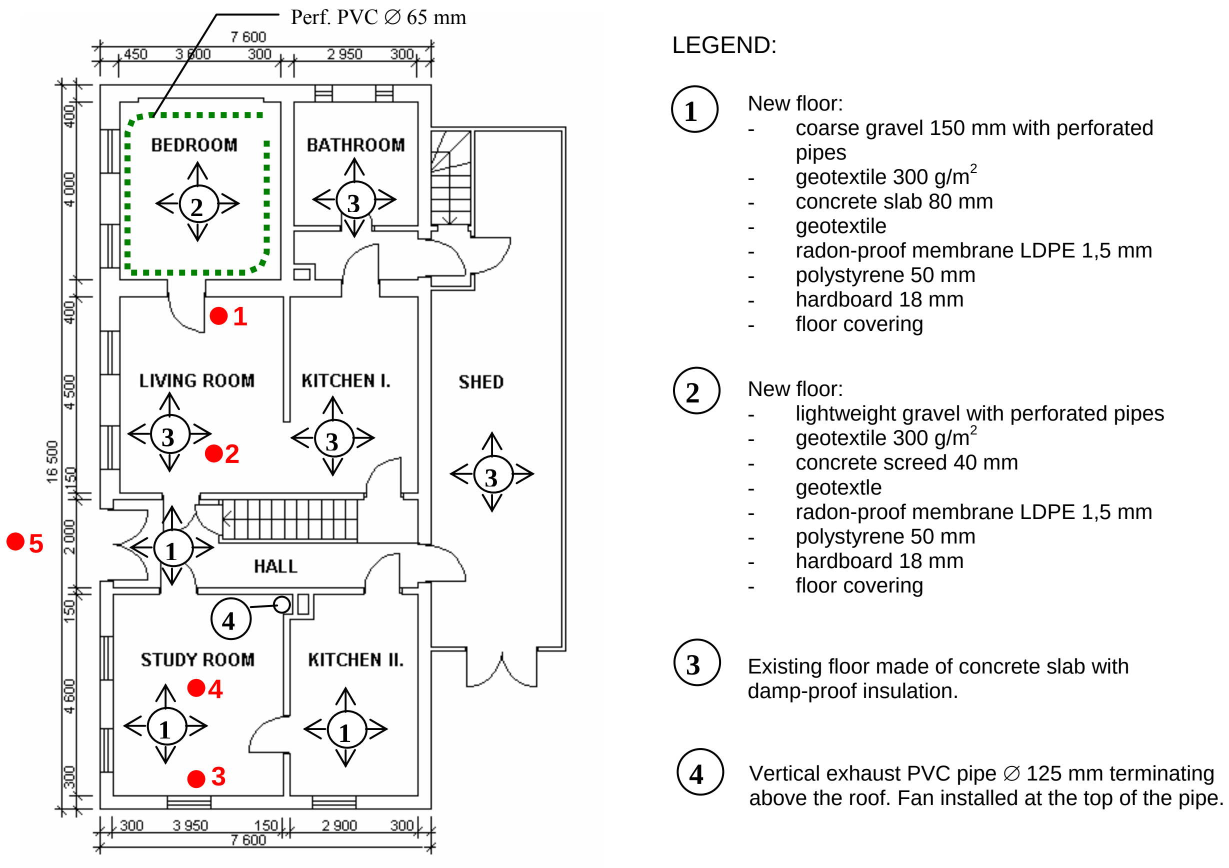

Fig. 1. Radon remedial measures and the location of measuring probes plotted in the ground floor plan of the house

A number of environmental variables were monitored using the Comet MS4+ data logger in order to determine parameters that could have effect on the radon transport from the soil into the house, performance of the soil ventilation and occurrence of negative side effects of the soil ventilation, such as the reduction of under-floor temperatures and freezing of the subsoil. Investigation of these effects is very important, because they can lead to the additional settlement of the house resulting in the appearance of micro-cracks in the house substructure. The temperature was measured by means of Pt1000TG8 sensors at four locations – outdoors, indoors, in the subslab drainage layer at the centre of the house and in the drainage layer near the perimeter wall. Pressure differentials were measured with the help of piezoresistive pressure sensors GMUD between indoors and outdoors and several points in the sub-floor region. The location of measuring probes is apparent from Fig. 1 and Tab. 1.

Tab. 1. Description of measuring probes

No.	Location	Measured quantities
1	Original soil 0,7 m under the existing floor	Air pressure, radon concentration
2	Original soil 0,1 m under the existing floor	Air pressure, radon concentration
3	Coarse gravel under the new floor	Air pressure, radon concentration
4	Coarse gravel under the new floor	Air pressure, air temperature, radon concentration
5	Original soil, in the distance of 1 m from the house and 0,7 m below the soil surface	Radon concentration

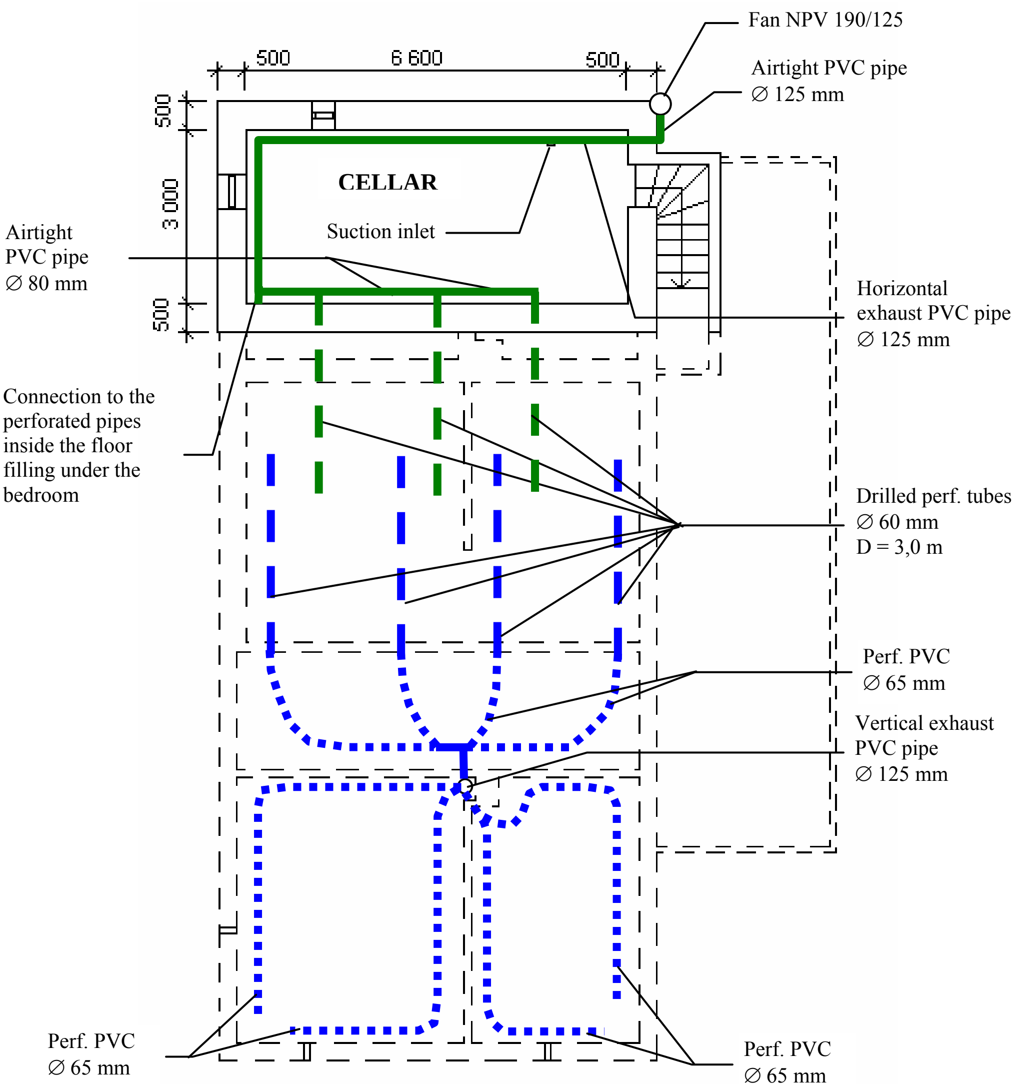

Fig. 2. Cellar and foundations plan. The first section of the soil ventilation system is plotted in blue colour, the second section in green colour.

RESULTS

After installation of radon reduction measures, various control measurements were used for the verification of the sub-slab ventilation system behaviour and effectiveness. Indoor and sub-floor radon concentrations as well as sub-floor/indoor pressure gradients were monitored in dependence on the operation mode of the ventilation system. Measurements were realized in two phases. At the beginning of the first period, which started on 4.8. and ended on 22.8. 2005, the speed of the fan in the first section was gradually increased from the first to the third speed, then fans in both sections were switched to the highest speed for one-week period and lastly the ventilation of both sections was switched off. The second control period lasted from 7.9. till 27.9.2005. In the first week the speed of the fan in the second section was gradually increased, while the fan in the section one was switched off. During the second week the fan in the section two was switched to the highest speed and at the same time the fan in the section one was gradually switched to higher speed. Finally both fans were switched off. Detailed description of operation modes during both control periods is provided in Tab. 2.

Tab. 2. Operation modes of the sub-slab ventilation system during the control periods

Period	**First control period**					**Second control period**					
Date	4.-6.8. 11:00	6.-9.8. 11:00	9.-11.8. 9:30	11.-18.8. 10:15	18.-22.8. 11:40	7.-10.9. 13:35	10.-13.9. 12:45	13.-15.9. 10:15	15.-17.9. 11:00	17.-19.9. 12:40	19.-21.9. 10:15	21.-27.9. 11:35
Section 1	1	2	3	3	OFF	OFF			1	2	3	OFF
Section 2	OFF			3	OFF	1	2	3	3	3	3	OFF

Legend: OFF – the fan is switched off, 1 – first speed (19 W), 2 – second speed (49 W), 3 – third speed (86 W)

Radon concentration in the sub-floor region during the first control period can be seen from Fig. 3. After switching on the fan in the first section, the radon concentration in all probes decreases. However, switching on the fan in the second section on 11.8. leads to increase of the radon concentration in the probes No. 1 and 2. After switching off the both fans on 18.8. the drop of the radon concentration in the probes No. 1 and 2 and at the same time the increase in the remaining probes has been observed.

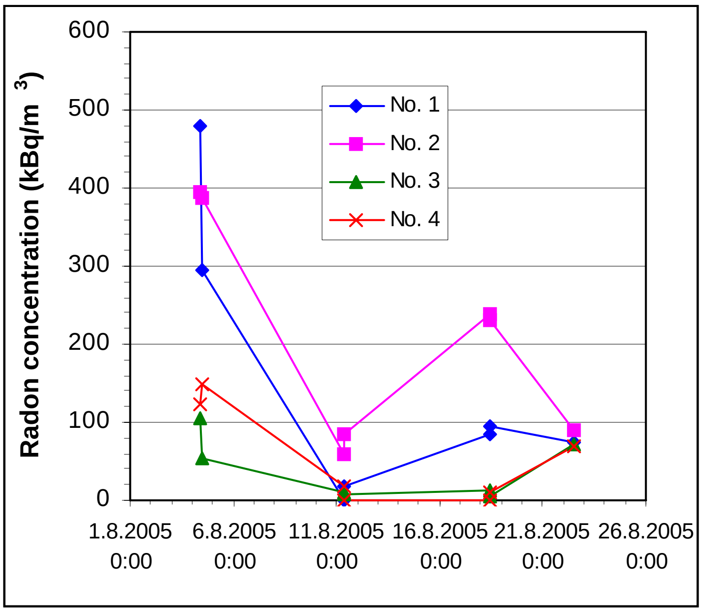

Fig. 3. Radon concentration in the sub-floor region during the first control period [6]

Similar results were obtained during the second control period (Fig. 4). Immediately after the fan in the section two had been switched on, the radon concentration in the probe No. 1 grew and in the probe No. 3 dropped. Activation of the first section on 15.9. resulted in better ventilation of sub-floor layers and decrease of the radon concentration in the probe No. 1.

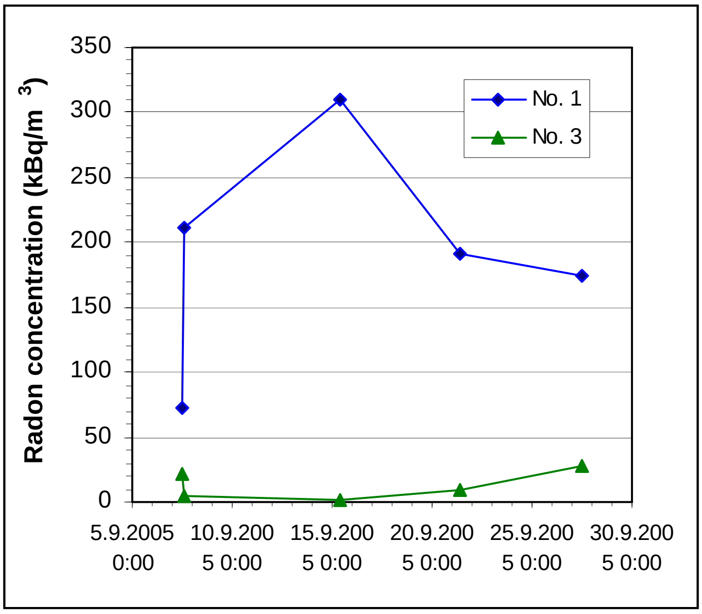

Fig. 4. Radon concentration in the sub-floor region during the second control period [6]

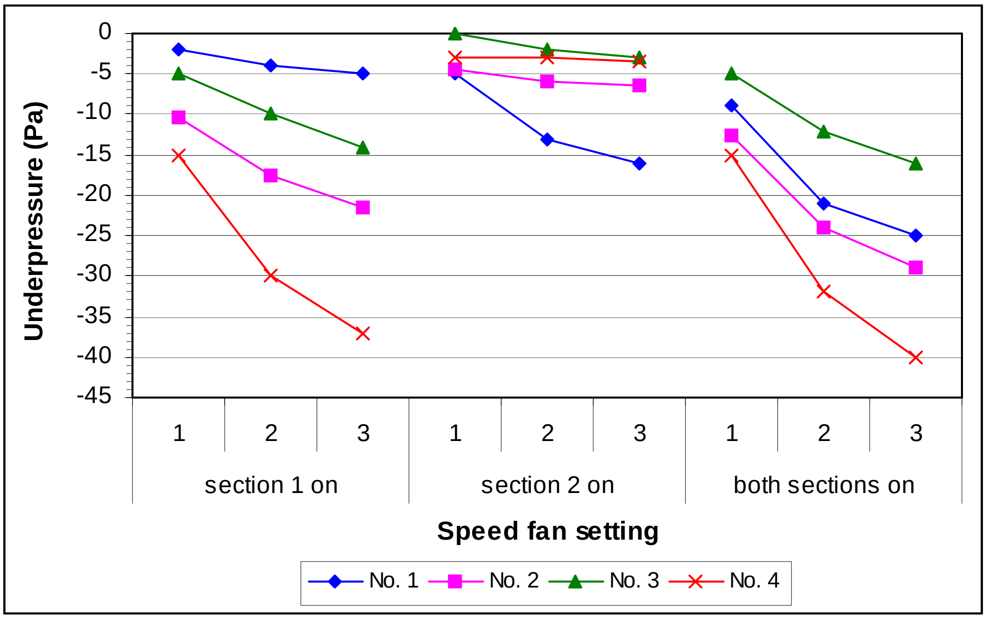

Fig. 5. Relationship between the sub-floor/indoor pressure difference at different points of the sub-floor region, fans speed and the operation mode of the soil ventilation

From these results it can be concluded that when the section one is in operation the sub-floor layer is well ventilated and thus radon concentrations are effectively reduced. On the other hand, when the section two is activated, higher radon concentrations from greater depth are moved towards the house, which results in increase of radon concentration in the sub-floor region. These observations correspond to the registered pressure field extension. Sub-floor/indoor pressure differences measured at different points of the sub-floor region are summarized in Fig. 5. If only the section one is on, underpressure in the sub-floor layers (probes No. 2, 3 and 4) is higher than in the case when only the section two is on. In the horizontal direction underpressure decreases with the increasing distance from the exhaust pipe. However, in the vertical direction (probe No. 1) the pressure field extends better for the section two in operation. If both fans are activated, the resulting underpressure equals to the summation of partial pressure differences corresponding to the sections one and two.

The influence of the pressure extension on the radon concentration in the soil is apparent from Fig. 6, where the continuous record of the soil gas radon concentration at the probe No. 5 is plotted against the sub-floor/indoor pressure difference at the probe No. 2 and outdoor/indoor underpressure. Fig. 6 demonstrates positive correlation between these parameters. Higher underpressure results in increase of the soil gas radon concentration, which is evident especially in the period when the fan in the section one was gradually switched to higher speed. Fig. 6 reveals also that even a very small pressure gradient of 2 – 3 Pa can cause significant changes in soil gas radon concentrations. All these findings confirm that the soil under the house and in its vicinity must be highly permeable.

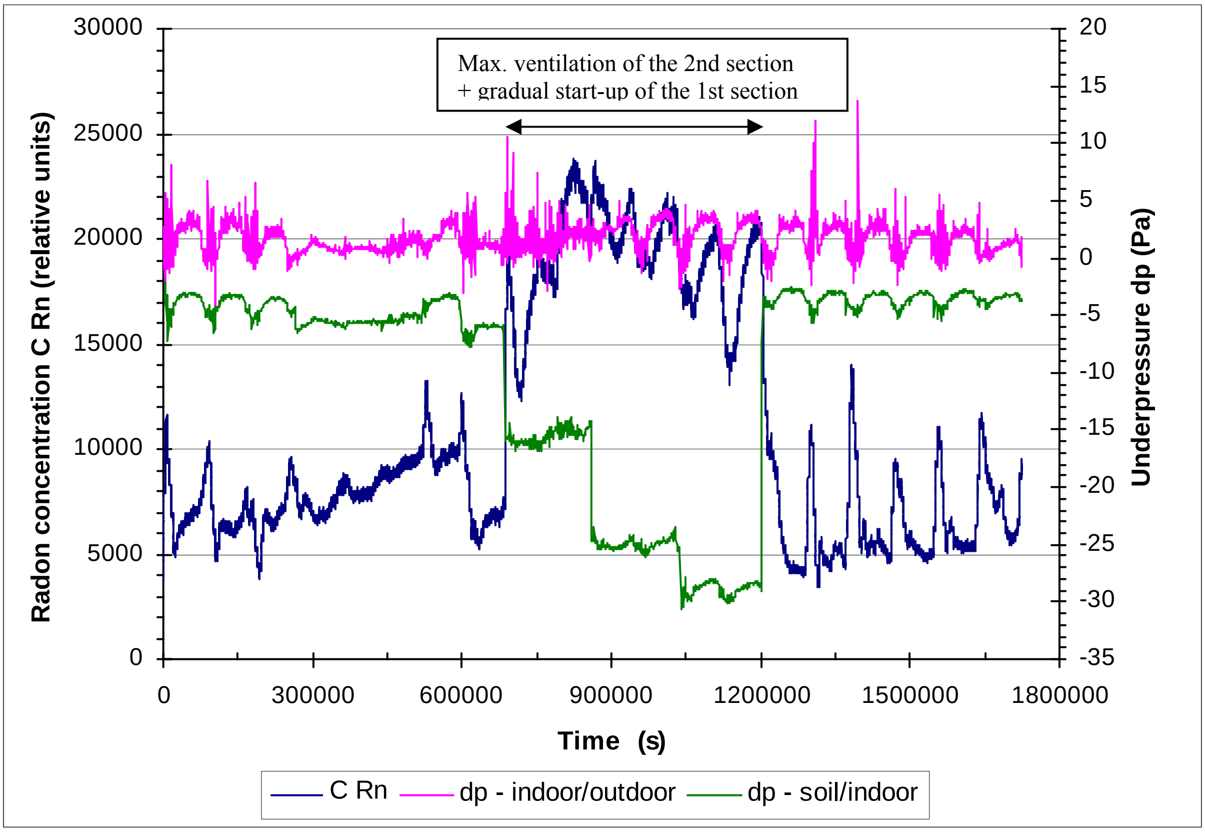

Fig. 6. Radon concentration in the soil in dependence on the indoor/outdoor and subsoil/indoor pressure gradients [3]

The effectiveness of installed measures was verified by measurements of indoor radon concentrations in all rooms during various operating modes [6]. Concentrations were registered with continuously recording monitors Radim calibrated in a national radon chamber. Continuous readings of measured concentrations, that are presented in Fig. 7-9, indicate that both sections of the soil ventilation system are nearly equally effective in decreasing of indoor concentrations. If either the first section or the second section is switched to the first speed, the reduction is significant, but not sufficient because concentrations still exceeds the action level 400 Bq/m^3. The second speed seems to be optimal as it ensures concentrations well below the action level and in addition it is not so much power consuming. Switching the fans to the third speed is not connected with further decrease of indoor radon concentrations. Immediately after the fans are switched off, concentrations in the bedroom, the living room and the kitchen I increase rapidly and within one day they reach values before mitigation. In the study room and the kitchen II the increase is not so sharp – original values are reached within two days.

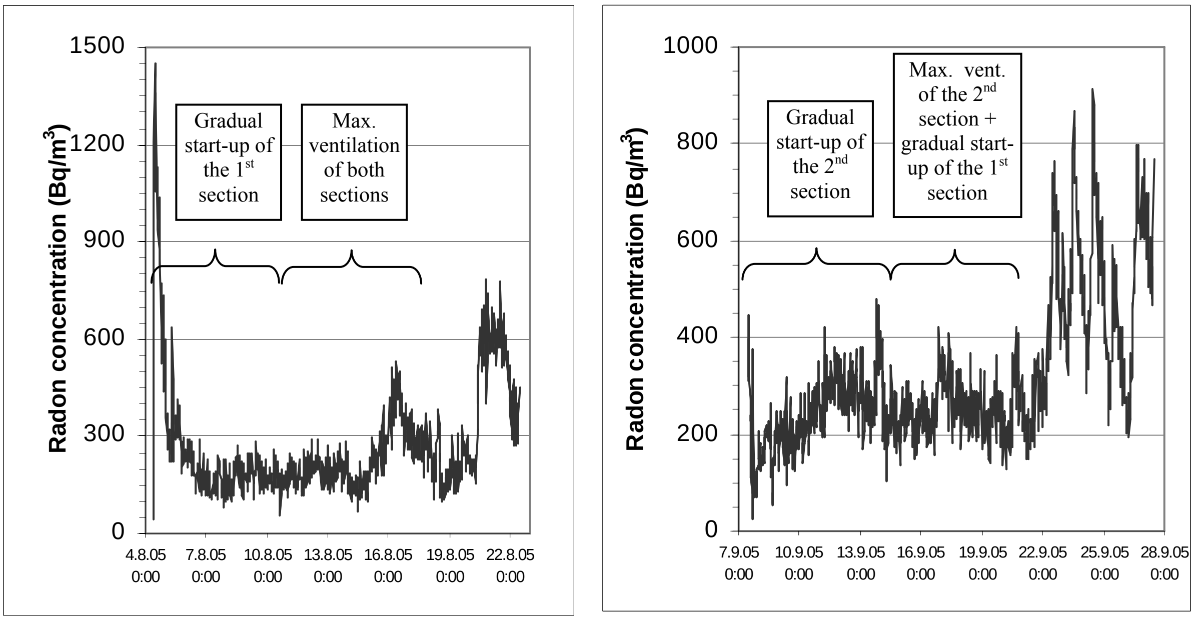

Fig. 7. Radon concentration in the kitchen II – comparison between the first and the second control periods

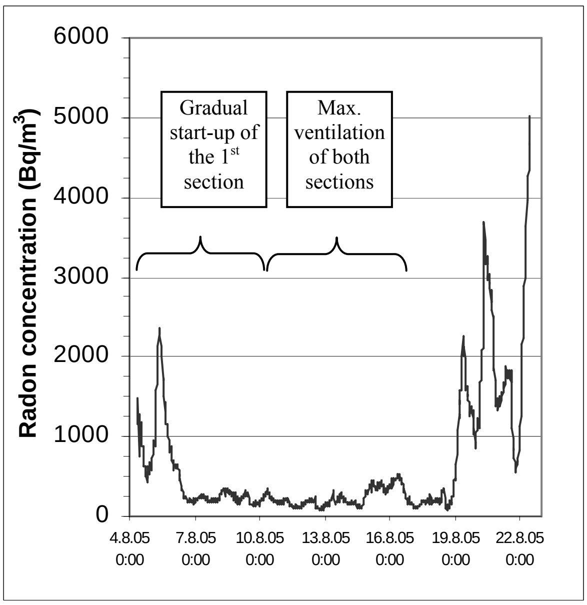

Fig. 8. Radon concentration in the living room

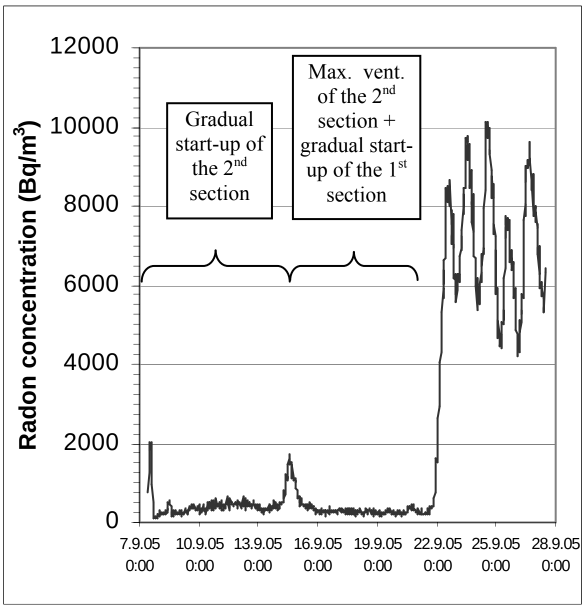

Fig. 9. Radon concentration in the bedroom

Summary of measured indoor radon concentrations together with the effectiveness analysis is presented in Tab. 3.

Tab. 3. Effectiveness of installed measures and indoor radon concentrations in dependence on various operation modes (Bq/m³)

Operation mode	**Concentration before remediation** 1)	**Gradual start-up of the 1st section, 2nd section switched off** 2)	**Gradual start-up of the 2nd section, 1st section switched off** 2)	**Maximum ventilation of both sections** 2)	**Max. vent. of the 2nd section + gradual start-up of the 1st section,** 2)	**Effectiveness (%)** 3)
Time of measurement	4/02 – 4/03	4.8. - 11.8.	7.9. - 15.9.	11.8. – 18.8.	15.9. - 21.9.	
bedroom	19 708	587	475	272	278	99
living room	18 531	455	511	229	362	99
study room	5 538	153	330	132	356	98
kitchen II.	12 500	257	241	235	251	98
ground floor - mean value	**14 069**	**271**	**290**	**198**	**243**	**98**
first floor – mean value	2 852	87	91	161	104	94

Legend: 1) the average annual radon concentration measured with track detectors, 2) the average one-week concentration obtained from electret detectors or continuous monitors, 3) calculation of the effectiveness was based on the comparison between concentrations measured before and after remediation when the ventilation of both sections was switched to maximum power.

Tab. 3 shows that the mean effectiveness of installed measures is 98 %. The mean indoor radon concentration dropped for all operation modes below the action level 400 Bq/m^3, i.e. approximately 52 times. However, if one of the sections is switched off, the radon concentration in the bedroom and the living room exceeds this level. The lowest radon concentrations in the ground floor were obtained when the ventilation of both sections had been switched to the maximum power.

Verification of the influence of soil depressurization and ventilation on sub-floor temperatures confirm our previous finding that temperatures under the house depend mainly on the indoor temperature and the presence of a thermal insulation in the floor [4]. The outdoor temperature affects the sub-floor temperature only on the house perimeter. This effect can be accelerated by continuously operating fans. In the case of our house, continuous operation of fans resulted in the decrease of the sub-floor perimeter temperature of approx. 2 °C. On the contrary, no influence on the sub-floor temperatures was observed for intermittent operation of fans.

Final adjustment of the operation mode was chosen as a result of the effectiveness analysis and with respect to minimizing of negative side effects. Fans in both sections are adjusted to the second speed (i.e. 2/3 of maximum power - 49 W) and they operate in intermittent mode. When one section is switched off, the other section is switched on.

CONCLUSION

The applied mitigation technique is characterised by very high effectiveness of 98 %. Consequently radon levels in all habitable rooms were successfully reduced below the action level for existing houses 400 Bq/m^3, i.e. 52 times.

This case study confirms that in general mitigation methods based on sub-slab depressurization and ventilation can be successfully applied even in houses with unusually high indoor radon concentrations. Obtained results demonstrate that soil depressurization systems are the most effective radon remedial measures. Thanks to their variability they can be used for remediation of nearly all types of houses.

It should be remembered that effective reduction of indoor radon is only possible, if design of soil depressurization systems takes into account specific soil and house characteristics so that the sufficient underpressure can be achieved in the soil under the whole area covered by the house. Negative side effects should be avoided by switching the fans to the intermittent mode with the frequency of operating periods depending on the rate of decrease and increase of indoor radon concentrations after switching on and off the fan.

Acknowledgement

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