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Radon charcoal cleaner

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Name of project

Radon charcoal cleaner

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Summary

Radon is the second biggest cause of lung cancer after smoking and scientific evidence suggests that 3-14 % of lung cancers are caused by exposure to indoor radon. There are three different sources which can cause high radon levels in a house; soil and rock under and around the house, the construction material and household water. There are several mitigation methods for radon suppression, which are described in this report, that are being used today. Choice of mitigation method is depending on source of radon and other circumstances in different houses.

This research project was undertaken NRPI Czech Republic, IEAP CTU in Prague, MidDec Scandinavia AB, Sweden and Bjerking AB, Sweden. The aim of the project is to develop and verify a new technology for radon mitigation in buildings with elevated concentrations of radon, in order to obtain another tool for radon mitigation.

There are several ways of remediating radon, especially when radon from the ground is the source. Reducing radon concentration in houses where the construction material is the source can be more difficult and costly. Therefore it is suggested to concentrate on the charcoal trap for houses with radon mainly from the construction material as an alternative to installing a mechanical ventilation system.

The aim of initial experiments performed in NRPI was to propose and verify an appropriate model describing indoor air radon behaviour under active charcoal filter operation which should allow us to develop a proper prototype of charcoal air cleaner commercially applicable both in homes and in offices, schools, hospitals, etc.

To fulfil the main goal the experiments were divided into three types in order to study i) efficiency of two different types of charcoal (K48 and 207B 1,5KI), ii) influence of radon trap on the radon activity in a small volume (142 litres) with zero ventilation (simplified approach); iii) influence of radon trap and the realistic values of indoor - outdoor ventilation ranging up to approx. 0,5/h on the radon activity in large volume (45 m^3). Results from the experiments were compared with theoretical models and it showed good comparison.

The experiments showed that the charcoal type K48 adsorbed radon better compared to charcoal type 207B 1,5 K. It also showed that the radon suppression factor was strongly depending on the ventilation and the charcoal trap was less efficient when the ventilation was higher.

Important technical parameters of future prototype are mass of charcoal, temperature, air flux and ventilation. Concerning radiation protection needs data from the experiments indicate that the risk of radiation is not a limiting factor but it needs to be further studied. The most crucial parameter seems to be energy consumption when cooling the charcoal to obtain high efficiency in radon reduction with a reasonable mass of charcoal that can be put in a family house.

In continuing experiments the ability for activated charcoal to adsorb not only radon but also pollutants in the indoor air can be tested. If this proves successful it would give the charcoal trap an advantage compared to other radon suppressing methods.

A future plan is also to integrate the charcoal bed system with a device for radon measurement, which could automatically detect radon concentrations and control the charcoal cleaning system.

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1 Background

Radon is a naturally occurring radioactive gas produced from the radioactive decay of uranium, which is found in rocks and soil. Radon escapes easily from the ground into the air, where it disintegrates through short-lived decay products called radon progeny. As we breathe, radon progeny are deposited on the cells lining the airways where the alpha particles can potentially cause lung cancer.

Scientific evidence suggests that 3-14% of lung cancers are caused by exposure to indoor radon. Radon is the second biggest cause of lung cancer after smoking. As many people are exposed to low and moderate radon concentrations, the majority of lung cancers related to radon are caused by these exposure levels rather than by higher concentrations. The WHO Handbook recommends as reference level 100 Bq/m^3. If this level cannot be reached due to country-specific conditions, the chosen level should not exceed 300 Bq/m^3 according to recommendations of WHO. WHO is now preparing a new handbook “Handbook for radon communication with building professionals”, which means they are now entering the field of radon mitigation.

International Atomic Energy Agency (IAEA) addresses radon as one of the main sources of radiation exposure. IAEA require that the government shall provide information on indoor levels and associated risks and, if appropriate, shall establish and implement an action plan for controlling public exposure to indoor radon.

According to the European Basic Standards Directive (draft February 2010) each member state in the EU shall establish an action plan to manage long term risk from radon exposure in dwellings, buildings with public access and workplaces for any source of radon ingress, whether from soil, building materials or water.

There are three different sources which can cause high radon levels in a house; soil and rock under and around the house, the construction material and household water. The radon concentration in the indoor air is depending on different parameters such as uranium concentrations in the soil and/or construction material, leakage of air into the ground and ventilation system. There are several mitigation methods for radon suppression, which are described in this report, that are being used today. Choice of mitigation method is depending on source of radon and other circumstances in different houses.

This research project was undertaken by National Radiation Protection Institute (NRPI) Czech Republic, Institute of Experimental & Applied Physics, Czech Technical University, IEAP CTU in Prague, MidDec Scandinavia AB, Sweden and Bjerking AB, Sweden.

NRPI is a governmental institution established by the State Office for Nuclear Safety. Its main role is to provide measurements and expertise, intercomparison, radiation monitoring network data acquisition and processing, preparation of methodologies, guidance and recommendations.

IEAP CTU is a university research institute concentrated mainly on basic research such as detector techniques, subatomic physics, particle physics and astro physics and its applications (low background measurements, special pixel detectors, radon research and development programme – diffusion, emanation, measurement of radon activities).

MidDec is working on radon regulating in another Vinnova project and is also collaborating with CTU.

Bjerking AB is a consultant company which covers consultant services in the whole building process, from architects and construction engineers to building management installation services, civil engineering, geotechnical and environmental investigations. Bjerking AB has a very long experience with radon mitigation in different type of buildings. Bjerking took part in the first radon investigations made in single family houses in 1978 and has conducted numerous radon investigations, including suggesting suitable mitigation methods, in different types of buildings throughout the years. Several research projects have been carried out in the radon field and Bjerking is involved in educational programmes given by Swedish Radiation safety Authority (SSM).

2 Introduction

The aim of the project is to develop and verify a new technology for radon mitigation in buildings with elevated content of radon. The project was concentrated on the feasibility study of the suppression of radon concentration in houses in Sweden and other countries, in which the level of radon concentration is above acceptable levels.

Suppression of radon concentration could be a combination of different, e.g. shielding foils on the ground, ventilation under the house or using radon trap in the ventilation loop based on charcoal filtration.

The original proposal included the following items:

- simple model (different scenarios) of radon suppression inside building based on radon capturing on charcoal;
- definition of technical parameters of prototype (mass of charcoal, needed temperature) to decide needed size of the hole installation.
- compilation of existing mitigation methods of radon suppression;
- proposal of test of future prototype
- estimation of radiation protection (radioactivity inside charcoal container, access to the container, waste handling);
- study of roles of aerosols in air and their influence on radon behaviour.

Radon trapping which is subject of the feasibility study is based on technology used in low background experiments located in underground laboratories (Super-Kamiokande – neutrino oscillations, NEMO 3 – double beta decay). The complicated task of achieving reduced levels of radon in the Super-Kamiokande experiment is well documented (Super-Kamiokande Collaboration, Physics Letters B 452 (1999) 418. In Modane underground laboratory the Radon Trapping Facility (RTF) was introduced in October 2004 by a team of French-Swiss-Czech scientists. The RTF takes air from the lab which is typical active at the level 10-25 Bq/m^3, purifies it to the level of 1 - 5 mBq/m^3 providing a flow of air at 150 m^3/h. The RTF is based on the same principle as that used in the Super-Kamiokande experiment modified by using cooling system. Activated charcoal is used to slow the motion of radon relative to the other components of air (nitrogen, oxygen, argon). This process is often referred to as trapping.

This report is divided into nine chapters starting with background and introduction in the first and second chapter. The third chapter includes compilation of methods used in practice today to suppress radon in houses. The fourth chapter provides detailed description of the experimental setups used for the benchmark tests. The fifth chapter describes the theoretical approach developed for the purpose of the project, processing of the experimental data as well as extrapolation of the theory towards the future prototype of radon trap facility for radon suppression. The sixth chapter defines the parameters of the first prototype proposed to be built. In the seventh chapter predicted operational conditions for requested radon mitigation efficacy is described. The eighth chapter describes briefly the needs of the project towards the protection against radioactivity captured in the charcoal during long-term running. The ninth and last chapter concludes the activities provided by the project team and proposal of future project (prototype of radon trap facility for radon suppression).

3 Compilation of methods to suppress radon activity in buildings

3.1 Background

The main source of indoor radon in most buildings is the subjacent soil gas while the building materials in most cases make only a smaller contribution. In houses with radon problem the ground stands for 80-95 % of the problem. The level of radon in a building is, however, to a large extent influenced by the properties of the building itself and its usage. Critical building parameters are, for example, coupling to the ground, leakage distribution of the building envelope, type of heating/ventilation systems and occupant living comfort preferences.

3.2 Radon from building materials

All stone-based building materials contain uranium. The quantity of uranium in the building material is normally low and is of no practical significance. However, in several countries some building materials that contain uranium in higher level were used for construction of buildings in the past. This was usually the case of light-weight concrete made from uranium-rich alum shale, fly ash, clinker, slag or waste materials from uranium ore processing.

3.2.1 Replacement of radioactive materials

This is normally a very expensive method and therefore it is recommended in exceptional cases only. However it can be used when a greater renovation of a building is planned. Materials that can be replaced are:

- Non-structural partitions. For example, non-structural walls.
- Thermal insulation in floor structures made of crushed alum shale-based lightweight concrete, waste materials from uranium ore processing, slag, fly ash, etc.
- Internal plasters made of pulverized waste materials from uranium ore processing.

3.2.2 Sealing of wall surfaces

Walls that are made of uranium rich materials can be covered with a sealing that prevents the radon formed in the wall material from being exhaled from the wall surface to the room air. The technique is most efficient on outer walls since the radon can exhale on the outside of the wall. Wall coverings can be made of different materials, such as epoxy or polyurethane paints or vinyl wallpapers usually made of two paper foils with three layers of plastic foil between. Aluminium foils are today banned due to the risk of spreading dangerous electrical currents.

In general, this method is not so much efficient. The problem with the technique is to get a good coverage of the entire wall including connections at windows and electrical sockets. Another weakness of this method is a high sensitivity of the surface coating to puncturing. If the surface coating is applied on inner surface of the external wall with low thermal resistance, it may result in surface condensation.

3.2.3 Increased ventilation

Radon exhalation from building materials with higher content of uranium is constant over time. If the air exchange is increased the radon concentration indoors will decrease proportionally. This is one of the most used and most efficient mitigation techniques convenient for such situations.

3.3 Radon from the ground

Subsoil is the most important and commonest source of radon. Common levels of radon in the soil air are 10 000 – 50 000 Bq/m^3 but on uranium rich soil the level can be up to 200 000 Bq/m^3 or even more. Radon is actively sucked from the subsoil through leakages in the substructure of the building. This is due to the under-pressure in the lower parts of buildings generated by the stack effect and wind forces. Radon can easily penetrate through a concrete structure with waterproofing – it is transported through cracks, through leakages around service pipe entries, and through imperfectly sealed inspection chambers.

3.3.1 Sealing entry routes

Sealing entry routes is commonly used remediation method and it is often used as an additional method in combination with other methods. It is always advisable to seal as many leaking points as possible in parts of the building that have contact with the ground. Common points of leaking are:

- Cracks in the structure
- Gaps between the basement wall and slabs
- Service hatches over waste pipes
- Dried out floor drains
- Incoming electric power and telecommunication cable entries
- Water and sewage pipe entries.

A variety of materials can conceivably be used for caulking, such as jointing compound, bitumen, concrete with expansive agent, epoxy based compounds, etc. The caulking can also be completed with a surface sealant.

3.3.2 Radon-proof membranes

3.3.2.1 Continuous membrane over the whole building substructure

Radon-proof membranes above or below the floor slab and over the perimeter basement walls are commonly used in EU countries as the basic protection against radon from the soil. Membranes must be applied continuously, i.e. over the entire surface of the building substructure that is in contact with the soil. All joints between membranes and all pipe penetrations must be carefully sealed. Radon-proof membranes must withstand permissible movements of the building substructure and their durability must correspond to the expected lifetime of the building. They can be selected from common waterproofing materials available on the building market. As the selection tool radon diffusion coefficient of the membrane can be used. Examples of suitable materials are: bitumen membranes, polymeric membranes such as PVC, LDPE, HDPE, PP, TPO and EVA. Materials that are highly permeable to radon and thus cannot serve as radon barriers are: cement coatings, polymer-cement coatings, bentonite and rubber membranes. In some countries bitumen membranes with Al foil are prohibited for application as a radon-proof membrane due to their very low tear resistance. Other material that is banned for radon barriers are plastic membranes with dimples, because it is almost impossible to form airtight joints with this material.

3.3.2.2 Non-continuous membrane

In some countries the radon-proof membranes are not applied continuously, i.e. over the entire surface of the building substructure in contact with the soil, but instead over the wall-floor joint or over the perimeter basement walls only. The aim of this measure is to reduce radon transport through permeable materials, joints between wall elements and cracks in basement walls.

3.3.3 Sub-slab depressurization and ventilation systems

The sub-slab depressurization (SSD) systems are the most efficient and used methods to reduce the radon concentration in the indoor air. Numerous variations of these systems are known, but the principle of their behaviour is always the same. Radon-laden air from the soil under the house is extracted to the outdoor air. As a result of the soil ventilation radon concentration under the house decreases due to dilution and a slight underpressure is generated under the house. The air pressure must be lowered under the whole building to get a good reduction of radon levels. These two effects reduce radon transport from the soil into the house. If a fan is used to draw air from the sub-slab soil, the system is called active SSD. Nevertheless, SSD system can also be passive. In passive SSD, the vent pipe is led to the open air on the roof without a fan. It should be noted that the efficiency of the passive SSD is lower than that of the active SSD.

3.3.3.1 Radon sump

Radon sump is a basic type of SSD systems. Radon sump is essentially a hole excavated under the slab through the slab or through the perimeter foundation. The soil air from the sump is drawn out to the outside air by a plastic pipe on which a fan can be installed. Radon sump is used as a remedial as well as a preventive measure.

3.3.3.2 Drilled tubes

In this case the soil air is extracted by means of perforated tubes drilled into the sub-floor region through the basement wall from the cellar, through the perimeter foundation from the trench excavated in the ground outside the house or from the internal floor pit. The length of the perforated tubes can be up to 6 m and thus they ensure better pressure distribution within the sub-slab soil than sumps, because their effective suction area is greater. This system is a Czech invention and was primarily designed for the remediation of existing buildings, however its application in new buildings becomes more and more common.

3.3.3.3 Network of perforated pipes

The system consists of the network of perforated (usually flexible) pipes that are inserted into the layer of coarse gravel placed under the slab. This method is suitable as a preventive measure for new buildings, however it can be applied also as a remedial measure in existing buildings, if reconstruction of floors is planned.

Systems according to 3.3.1, 3.3.2 and 3.3.3 can be installed in new buildings as a preparatory form. Preparatory form means that a radon sump, tubes or pipes are installed beneath the floor slab during the construction of the house. They can be later taken into use and activated if the indoor radon concentration in a completed house exceeds the reference level. The exhaust duct of these systems can be sealed inside or outside the house or it can be led through the house onto the roof to open air.

3.3.4 Soil ventilation through existing drainage piping

In this method the soil air is drawn from the ground through existing drainage piping that is located outside the footings of the house and has the form of a partial or continuous loop around the house. In proper conditions, negative pressure field and soil ventilation is obtained in large area covering also the area beneath the house. Best results are obtained when the drainage piping is located below the lowest level of the footings. This method is used rarely and only for remediation of existing buildings.

3.3.5 Air cushion method

As suggested by its name, the method is based on pumping air from the building to the sub-floor region in order to increase the air pressure in the ground under the house. This pushes away some of the radon containing air beneath the slab. Radon concentration under the house decreases due to dilution. This method is used rarely and only for remediation of existing buildings.

3.3.6 Radon well

The radon well is a Swedish invention and is intended for use in thick layers of soil with high air permeability, such as gravel and coarse sand, primary eskers. A radon well lowers the air pressure in large volume of soil, and the entire system can therefore be located outside the building. The radon well can be made in different sizes and can serve developments ranging from a one family house to a group of houses. The effect of the well extends up to 50-60 m and in some cases even longer, from the well.

The radon well is located entirely underground and can be covered with gravel or a lawn, if required. On cultural buildings such as churches and castles with radon problems, the radon well often is a usable solution, since there is no need for interference inside the buildings.

3.4 Air gap ventilation

3.4.1 Ventilation of continuous air gaps

A continuous air gap can be a part of floor structures resting on the soil or perimeter basement walls. Plastic membranes with dimples can form the air gap. The height of the gap is usually 10-20 mm. The air gap is connected usually by a vertical exhaust pipe to a roof fan or rotating cowl that draws air from the gap. Since the vertical exhaust pipe runs through the heated part of the house, it can be also used as a passive system creating a slight under-pressure in the gap without a fan. This system is used as a remedial as well as a preventive measure.

3.4.2 Ventilation of perimeter basement walls made of hollow blocks

This system is intended for use in houses with perimeter basement walls made of hollow concrete blocks through which radon penetrates from the soil into the indoor environment. Radon can be drawn from the air spaces within the basement walls before it can enter the house (‘wall suction’) or the indoor air can be blown into the walls so that radon is prevented from entering the walls (‘wall pressurization’). Application of this method is not common.

3.5 Building ventilation

3.5.1 Improving ventilation in living spaces

Improving ventilation in living spaces may include various measures. Sometimes only opening or adding the fresh air vents is adequate for lowering the radon levels by increasing the ventilation rate. In general, the energy consumption is proportional to the ventilation rate. Hence, by increasing the air exchange the energy consumption is also increased. However, if the initial air exchange rate is low, which is often the condition for the efficiency of the method, the ventilation rate should be increased to ensure the quality of the indoor air. The ventilation rate of 0.5 air exchange per hour (ACH) is a typical recommendation in many countries.

Installation of a new mechanical supply and exhaust ventilation with heat recovery system decreases the energy consumption compared to other ventilation schemes. A heat recovery system uses heat in the exhaust air to warm the incoming air. In an air-conditioned house, in warm weather, the process is reversed: the exhaust air is used to cool the incoming air. This saves between 50 and 80% of the warmth/coolness that would be lost in an equivalent ventilation system without a heat exchanger.

3.5.2 House pressurization

The principle of this remediation method is to create a slight overpressure within the dwelling compared to the sub-slab soil using a ventilation unit with a fan. The overpressure eliminates the indoor underpressure, which decreases the radon supply rate from the soil into the house. At the same time, the air exchange rate increases and thus radon concentration decreases also by dilution. To ensure efficiency of this system, the building must be relatively airtight.

In some countries house pressurization is not allowed or not recommended due to risk of moisture problems. This kind of problems may arise in cold climates when warm indoor air encounters cold structures in the house envelope that may result in condensation of water.

3.5.3 Improving ventilation in cellar or crawl space

Improving ventilation in cellar or in crawl space are commonly used remediation methods. The ventilation may be improved either with or without a fan. The simplest way to increase ventilation in the cellar or crawl space is to provide more air valves in the perimeter basement or foundation walls. In other cases it is necessary to improve the ventilation by using a fan. The efficiencies of both methods are about 50 %.

3.6 Measures for crawl spaces

Buildings on foundations with crawl space can be dealt with in the same manner as buildings with basement or buildings built on concrete foundation slabs. But the crawl space also allows other remedial techniques to be used provided that the height is big enough to allow access.

3.6.1 Sealing the ground surface

In modern buildings the ground in the crawl space normally is covered with a plastic film which serves as a barrier against the diffusion of moisture from the ground. The film is usually covered with a sand layer to hold it in place. If the film is in good condition and covers the entire ground surface it will provide a good protection against radon from the ground.

In older houses there is no plastic film and there it is possible to cover the ground surface with a plastic film. In this case it is important to get a good connection between the plastic film and the foundation wall to prevent radon from leaking up at the connection. Other possible solution is to perform a concrete slab as a gas seal. Sometimes it is also necessary to seal the foundation wall to stop radon from leaking up to the living space thru cracks or structures in the wall.

3.6.2 Reduction of air pressure under the plastic film

If the accessibility of the crawl space is such that more extensive work can be carried out it is possible to prevent soil air to enter the crawl space. The work is carried out by placing perforated drain pipes on the ground in the crawl space. The pipes are connected with a fan and covered with a plastic film. The fan evacuates soil air beneath the plastic film and lowers the air pressure and prevents radon to enter the crawl space.

3.7 Radon from water

The potential concern with radon in water is the release of radon to the air when the water is used. The amount of radon emanated depends on the initial radon concentration in the water and will increase with increasing water temperature and surface area exposed to air. The highest concentrations of radon in water occur when water is obtained from wells or springs very close to the house. Radon in water can be removed by spraying it into a confined air space, introducing air bubbles or storing the water in a tank until the radon has decayed. An alternative method uses granular activated carbon (GAC) to remove radon from the water. The GAC method has been more widely tested and is more commonly used in individual homes. Water that is treated and distributed from a central location is normally low in radon concentration because the radon has had time to decay or escape into the air.

3.8 Other methods decreasing indoor radon concentration

3.8.1 Fluid based radon mitigation system

A special radon absorption unit is principally based on a fluid absorption process that effectively removes radon gas from the atmosphere at room temperature and subsequently releases during a degassing process at slightly elevated temperature (50 - 60°C). Basic operation and technical parameters of radon absorption tower, including radon removal efficiency, are summarized in the Tab 1.

Tab. 1. Radon absorption in a laboratory-scale tower

Conditions: 3-in. I. D. Plexiglas® tower
35 ft depth of 174-in. Raschig Rings
Inlet radon concentration in air 10 725 Bq.m^{-3}
Inlet radon concentration in corn oil: 0 Bq.m^{-3}

Test No.	Rn in Air Out, Bq.m^{-3}	Air Flow, l/min	Oil Flow, l/min	Transfer Unit Number	Transfer Unit Height * ft	Radon Removal, %
38	2431	1.0	0.259	1.84	1.90	77.3
39	1993	1.0	0.259	2.13	1,65	81.4
40	1485	1.0	0.442	2.28	1.54	86.2
41	1970	1.0	0.442	1.93	1.82	81.8
42	1165	0.5	0.442	2.38	1.47	89.1
43	608	0.5	0.442	3.11	1.13	94.3
44	137	0.5	0.259	5.14	0.68	98.7
45	327	0.5	0.259	4.07	0.86	97.0
46	4341	2.0	0.259	1.27	2.76	59.5
48	4324	2.0	0.259	1.28	2.74	59.7

*Based on gas phase controlling.

3.9 Radon mitigation system based on charcoal beds

The performance of radon mitigation system (commercially available) based on adsorption of radon onto charcoal beds combined with an electronic air cleaner (EAC) was tested in a single-family house in USA. Measurements were made of the radon gas concentration, also potential alpha energy concentration and radon decay product activity-weighted size distribution with and without additional operating aerosol sources were measured. During the tests without the mitigation system in operation, the conditions in the basement of the house were as follow: the radon concentrations were in the range of 600 to 800 Bq/m^3, the Potential Alpha Energy Concentration (PAEC) was 600 to 700 nJ/m^3, the particle concentration was below 1000/cm^3, and the fraction of PAEC and 218 Po in the smallest size range, 0,5-1,6 nm were approximately 0,6 and 0,9, respectively. The tests were designed to study the influence on the measured parameters of the combined mitigation system as well as each of the separate components: fan, charcoal bed, and EAC. When all the components of the mitigation system were operating, the radon concentration was below 150 Bq/m^3 and the PAEC was below 104 nJ/m^3 with the smallest sized fraction of PAEC (0,5-1,6 nm) of about 0,4.

The tests showed that under certain conditions, the charcoal bed/EAC mitigation systems can be a potentially valuable technique for reducing a health risk due to indoor radon.

3.10 Radon reduction systems summary (RADPAR project)

3.10.1 Summary of preventive and remedial measures actually applied

Summary of radon reduction techniques that are applied in reality in different European countries is presented in Tab. 2 and Tab. 3. Preventive measures actually used are summarized in Tab. 2 and Tab. 3 gives actual remedial measures. These tables were worked out on the basis of the questionnaire prepared for the RADPAR (Radon Prevention and Remediation) project. RADPAR project is funded by the Executive Agency for Health and Consumers (EAHC) and it will run up to 2012. This project has partners from health and radiation protection institutions in 15 European countries. Responsible authorities of all countries participating in the RADPAR project were asked to complete the questionnaire investigating the experience of countries with radon prevention and remediation. Evaluation of completed questionnaires was based on responses from 13 states (A, B, CH, CZ, D, E, F, FIN, GB, GR, IRL, N, P). Countries that have no experience with radon reduction methods were not included in the following tables.

Tab.2. Summary of preventive measures actually applied in European countries

Method	Fin	IRL	N	Gr	B	CZ	A	D	P	GB	CH
Passive sub-slab depressurization (SSD)	●	●	●		●		●	●	●	●	●
Active SSD	●		●		●		●	●	●	●	●
Radon proof insulation, membrane below floor slab		●		●	●		●	●		●	●
Radon proof insulation, membrane above floor slab				●	●	●	●	●	●	●	●
Sealing the joint of floor slab and foundation wall using membranes	●		●	●			●	●		●	●
Sealing the lead-through in structures with soil contact	●		●		●		●	●			●
Use of water proof concrete instead of normal concrete				●			●	●			
Crawl space									●	●	
Combinations of methods above		●									●
Passive SSD & sealing the joint of floor slab and foundation wall using bitumen felt	●										
Arrangement for sub-slab or crawl space ventilation with exhaust air from house			●								
Radon proof membrane above floor slab + active or passive sub-slab ventilation						●					
Radon proof membrane above floor slab + active or passive floor air gap ventilation						●					

From both tables it is evident that some measures are applied in almost all countries (from the category of preventive measures the examples are passive or active sub-slab depressurization and radon-proof membrane and from the category of remedial measures this refers to sub-slab depressurization, improving natural or mechanical ventilation in the living spaces or in cellars and sealing of entry routes). On the other hand there is a great number of methods that are used in one or two countries only. The different applicability of measures arises from different construction methods, habits and materials and from differences in foundation types and house substructure types.

Tab. 3. Summary of remedial measures actually applied in European countries

Method	Fin	F	IRL	N	GR	B	CZ	A	D	P	GB	CH
Sub-slab depressurization (SSD)	●	●	●	●	●	●	●	●	●		●	●
Improving natural ventilation in living spaces	●	●	●	●	●		●			●	●	●
Improving mechanical ventilation in living spaces	●	●	●	●	●	●				●	●	●
Replacing the existing natural room air ventilation by a mechanical exhaust ventilation	●				●				●	●		●
Installation of a new mechanical supply and exhaust ventilation with heat recovery system	●		●	●			●	●				●
House pressurization							●	●	●		●	●
Improving ventilation in cellar	●	●		●	●	●	●	●			●	●
Decreasing under-pressure in the house		●	●	●				●			●	●
Sealing entry routes	●	●	●	●	●	●	●	●	●	●	●	●
Improving crawl space ventilation	●	●		●		●	●	●		●	●	●
Radon well (soil ventilation)	●											●
Soil ventilation through existing drainage piping outside the footings	●											●
Quit using water from drilled well	●											
New floors with radon-proof membrane							●			●		
Active floor air gap ventilation							●					
Mechanical ventilation of underfloor space											●	
Combination of several methods	●		●					●				●
New floors with radon-proof membrane + SSD							●					
New floors with radon-proof membrane + floor air gap depressurization							●					

Method	Fin	F	IRL	N	GR	B	CZ	A	D	P	GB	CH
Sealing +building ventilation		●		●								
Sealing +basement ventilation		●										
Building and basement ventilation		●										
Sealing + SSD								●				

Tab. 4. Effectiveness (%) of remedial measures based on the experience from different European countries

Method	Fin	F	N	B	CZ	A	P	GB	CH
Sub-slab depressurization (SSD)	65-95 99	89 98	50-95 99	90 99	85-95 99	80 90		89 99	90 100
Improving natural ventilation in living spaces	15-55 78	49 88	10-50 90		< 30			33	
Improving mechanical ventilation in living spaces	5-55 78	61 95	10-20 50						
Replacing the existing natural room air ventilation by a mechanical exhaust ventilation	15-45 66		10-20 50						
Installation of a new mechanical supply and exhaust ventilation with heat recovery system	30-65 77		10-80 90		30-60 70	60 80			
House pressurization						80 90			
Improving ventilation in cellar	20-55 72	47 71	10-50 90			50 50			75 100
Decreasing under-pressure in the house		81 96	10-50 90			50 70		60	25 50
Sealing entry routes	10-55 93	55 92	10-60 95		10-40 60	10 50		41	25 50
Improving crawl space ventilation	40-65 79	47 71	10-80 95			50 70	60-80 90	47	75 100
Radon well (soil ventilation)	80-90 95								90 100
Soil ventilation through existing drainage piping outside the footings									50 75
Quit using water from drilled well	25-55 89								
New floors with radon-proof membrane					35-45 50		60-70 100		
Active floor air gap ventilation					70-85 90				
Mechanical ventilation of underfloor space								64	
Combination of several methods	35-75 99,9					80 90			

Method	Fin	F	N	B	CZ	A	P	GB	CH
New floors with radon-proof membrane + SSD					85-95 99				
New floors with radon-proof membrane + floor air gap depressurization					80-90 95				
Sealing +building ventilation		72 97	20-80 95						
Sealing +basement ventilation		68 87							
Building and basement ventilation		67 87							
Sealing + SSD						80 90			

Note: the range of average effectiveness is plotted on the upper line, the highest effectiveness on the lower line

How effective the particular measures are in different countries can be seen from Tab. 4 that is again based on the responses to the RADPAR questionnaire. While most techniques using sub-slab depressurization and radon-proof membranes should work in principle, the results presently available have shown the considerable variability in their effectiveness. Bad installation and poor adherence to the relevant building code guidelines are major contributors to this problem in some countries. The effectiveness is also highly uncertain in case of all sealing techniques and measures based on natural ventilation.

3.10.2 Installation costs of remedial and preventive measures

Installation costs of remedial and preventive measures may differ from country to country. In general, they depend on the type of chosen measure, the technical state of the building (type and air-tightness of floors resting on the ground, presence of internal foundations, permeability of sub-floor layers, built area, layout of the house, air exchange rate etc.) and on the applicability of a particular measure in a particular building. Installation costs compiled from several studies are for the most commonly used measures summarized in Tab. 5, which distinguishes between remedial measures installed after construction and preventive measures installed during construction of new houses. From the table it is evident that preventive measures are always cheaper than remedial measures.

Tab. 5. Installation costs of remedial and preventive methods

Method	**Installation costs (EUR)**
Remedial methods	
Passive soil ventilation	500 - 3000
Active soil depressurization (sumps)	700 - 2500
Active soil depressurization (drilled tubes)	2000 - 4800
Active soil depressurization + new floors in part of the house	4800 - 8600
New floors with radon-proof membrane in the whole house + active soil depressurization	8400 - 13200
Improved natural ventilation	400 - 600
Preventive methods	
Active soil depressurization	1000 - 1800
Radon-proof membrane	400 - 1000

Note: The costs are typical values from several studies [3, 4, 5, 6]

3.10.3 Operation and maintenance costs

In case of fan-assisted measures (active sub-slab depressurization, mechanical supply and exhaust ventilation) the operation and maintenance costs cannot be neglected. In the long run they may become significant. For active soil depressurization systems fans with power consumption from 40 to 70 watts are used. Running costs of these fans, if a full time operation is considered, will therefore be 40 up to 75 EUR per annum. However, in real conditions savings in running costs can be expected, because fans are usually switched to an intermittent mode, with the frequency of the operating periods depending on radon supply rate. The fan itself is assumed to require replacing every 10 years on average at a cost of 150 up to 600 EUR. This means that over the 30-years operation of less expensive types of active soil depressurization (sumps or drilled tubes) the operation and maintenance costs will be in balance with the installation costs.

HVAC systems improving the air exchange rate between indoors and outdoors require two fans (one for supply and one for exhaust air). Since the power consumption is similar to fans used for soil depressurization, the running cost of the HVAC systems will be two times higher compared to active SSD systems. If we further consider the same intervals for fans replacement, the maintenance costs of the HVAC systems will be again twice expensive than SSD systems. In addition the costs for heating the incoming air that replaces the warm air exhausted by ventilation from the house should be included in the operation costs. The costs for additional heating will in a particular case depend on the required air exchange rate and efficiency of heat recovery. If the efficiency of 70 % is considered, these costs may vary quite considerably from 3000 EUR up to 30 000 EUR per 30-years operation.

3.11 Standardisation of radon countermeasures

From the RADPAR questionnaire responses it is evident that at this moment there is not any international standard specifying requirements for materials or components that are used in radon reduction systems or introducing methods for testing of radon specific properties of these products.

Responses to the question “What materials and components that are part of radon reduction systems should be tested to judge their performance in the system?” are summarized in Tab. 6. The first priority was given to the testing of radon-proof membranes (10 countries). High priority was also given to the testing of sealants (8 countries). On the other hand testing of ducts and air filters seem to be not so important. This may indicate that air filters are not believed to be efficient in dose reduction and pipes are not believed to be the source of indoor radon.

Tab. 6. What materials and components should be tested?

Material	Intended use	1st priority	2nd priority	3rd priority
Radon-proof membranes	Barrier against radon transport from the soil	10 A, B, CZ, D, E, F, FIN, GR, IRL, N	2 CH, P	0
Sealants	Sealing of cracks and pipe penetrations	8 A, B, D, E, F, FIN, GR, N	2 CH, CZ	1 P
Fans	Extraction of radon-laden air	5 B, CH, F, GR, P	5 A, D, E, FIN, N	1 CZ
Ducts, piping	Ground-air heat exchangers	1 D	7 A, B, CH, E, F, FIN, GR	2 CZ, N
Air filters (cleaners)	Removing of dust particles from indoor air	1 GR	2 B, E	6 A, CH, CZ, D, F, N

Note: Number of votes for the particular parameter and voting countries are presented

Quite interesting answers were obtained to the question “Which parameters verify the ability of air filters to reduce the dose caused by radon and its decay products?” Responses are presented in Tab. 7.

Tab. 7. Which parameters verify the ability of air filters to reduce the dose caused by radon and its decay products?

Parameter	**1st priority**	**2nd priority**	**3rd priority**
Power consumption	1 GR	4 CH, D, E, P	3 A, CZ, N
Filter type	0	6 A, CH, CZ, D, E, GR	2 N, P
Filtration efficiency	4 E, F, GR, P	5 A, CH, CZ, D, N	0
Dose reduction	5 A, CH, CZ, D, GR	1 E	1 N
Effect on attached and unattached fractions	4 CH, CZ, D, P	2 A, GR	2 E, N

Note: Number of votes for the particular parameter and voting countries are presented

Almost equal importance was given to dose reduction, filtration efficiency and effect on attached and unattached fractions. The second priority was given to the type of filters and power consumption.

4 Basic theory and description of experimental setups

A simplified description for the radon trapping in charcoal incorporates the absorption constant k in the equation:

$$T = k\frac{m}{f}.$$

where T is the retention time (hours), m the mass of charcoal (kg) and f the volume flow rate in m^3/hr, so constant k has units of m^3/kg and depends strongly on charcoal type, temperature and pressure. First experiment was carried out to measure the ability of two types of charcoal to capture radon activity and to find the values of k factor for both charcoals used for testing.
Since retention time T is strongly affected by column geometry, temperature, amount of charcoal and air flow rate passing through the column, the experimental setup allowed the changes and monitoring of all mentioned parameters.

The aim of initial experiments performed in NRPI was to propose and verify an appropriate model describing indoor air radon behaviour under active charcoal filter operation which should allow us to develop a proper prototype of charcoal air cleaner commercially applicable both in homes and in offices, schools, hospitals, etc.

To fulfil the main goal the experiments were divided into three types and focused stepwise on i) confrontation of the ability different types of charcoal used in routine both in NRPI (type 207B 1,5 KI used to capture iodine) and in ITEP (K48 used in RTF at LSM) to capture radon and selection of the most proper type of charcoal for future testing according to estimated value of the adsorption coefficient k; ii) studying of the influence of radon trap on the radon activity in small volume (142 litres) with zero ventilation (simplified approach); iii) studying of the influence of radon trap and the realistic values of indoor - outdoor ventilation ranging up to approx. 0,5h^{-1} on the radon activity in large volume (45 m^3).

4.1 Type I experiment

To estimate desired charcoal adsorption coefficient k according to Eq.1 mass of charcoal, air flow pass through the charcoal column and retention time can be known. The schematic view of used experimental set up is given in Fig. 1 and pictures of setup are illustrated in Fig. 2. The tests were done for the both mentioned types of charcoal and for two different masses of charcoal (0,7 kg and 2,1 kg). The air flow rate passing through the PET bottles with charcoal was provided by precise Alpha-pump (Saphymo, Germany) which allows us setup defined and stable flow rates ranging from 0.5 l/min to 1 l/min. The flow rate alone was continuously monitored by mass-flow meter Ω-omega (Omega- Engineering, UK) traceabled to precise bubble absolute flow-meter calibrator AMETEK (Mansfeld-Green, U.S.A.)

Retention time T for radon in the charcoal column was calculated from the known time variation of ratio between input and output radon concentration passing through the charcoal column continually measured by means of pair flow past through ion. chambers. Input column radon concentration a_{vin} was defined and kept on stable via stable and known mentioned flow rate F and known and stable radon source production P as a_{vin} = P/F. In order to provide stable and known radon source production P we used radium emanation source type Pylon 2000. Measured input radon concentration ranged from 2,6 kBq/m^3 to 10 kBq/m^3. To estimate theoretically expected temperature dependence of the adsorption coefficient during all measurements were both ambient air temperature and also its relative humidity monitored by means of precise continuous monitor Alphaguard (Saphymo, Germany). Monitor Alphaguard alone was also used for measurement of background radon gas concentration. The measurements were performed both in the Lab (Fig.2) and in the air conditioned NRPI radon chamber (Fig. 3).

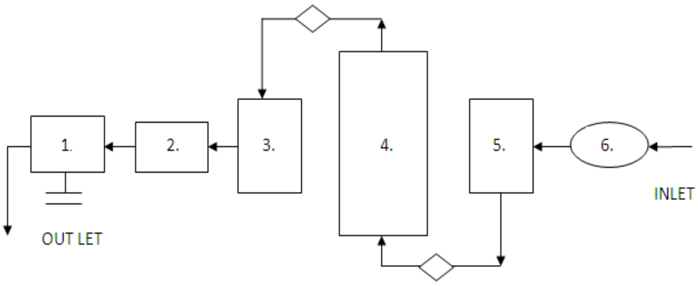


Figure 1. *Schematic view of experimental setup type I (1 = pump; 2 = flowmeter; 3 and 5 = ionization chambers; 4 = PET bottle with active charcoal; 6 = ^{226}Ra/^{222}Rn source).*

Figure 2. *Pictures of experimental setup type I used for measurement of charcoal ability to capture radon. The charcoal was given into three PET bottles. The radon activities in the input and output were monitored by two ionization chambers. The activity of radon in the air of laboratory was continuously detected by monitor Alphaguard (providing also temperature, relative humidity). As the emanation source Pylon A-2000 was used (^{226} Ra/^{222}Rn emanation source).*

Figure 3. *Type I experiment was performed also in the NRPI radon chamber.*

4.2 Type II experiment

As a next step, the experiments with stainless steel vessel of small volume (142 l) with the source of radon inside and small radon trap (inside or outside of vessel, see Figs. 4 and 5, respectively) were performed. The purpose of these tests was to obtain experimental data for theoretical description of radon trapping under the conditions with zero air ventilation in small volume. The solid emanation source of ^{226} Ra/^{222} Rn was located inside the steel vessel. Radon gas concentration inside the steel vessel was monitored by continuous monitor type Radim 3 during the tests (for three air flows through radon trap: 0 l/min; 0,5 l/min and 1 l/min). The temperature inside and outside of the steel vessel was monitored as well. Pictures of the setup are illustrated in the Fig. 6.

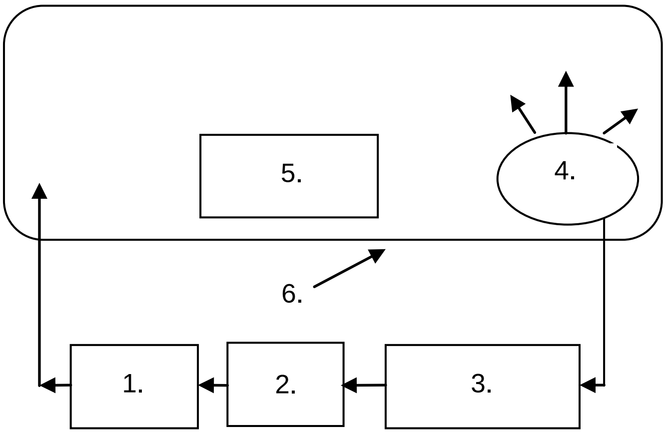


Figure 4. *Schematic view of experimental setup with stainless steel vessel. The charcoal container (PET bottle) is located outside of the vessel. (1 = pump; 2 = flow-meter; 3 = PET bottle with active charcoal; 4 =* ^{226}*Ra/*^{222}*Rn source; 5 = continuous radon monitor; 6 = stainless steel vessel).*

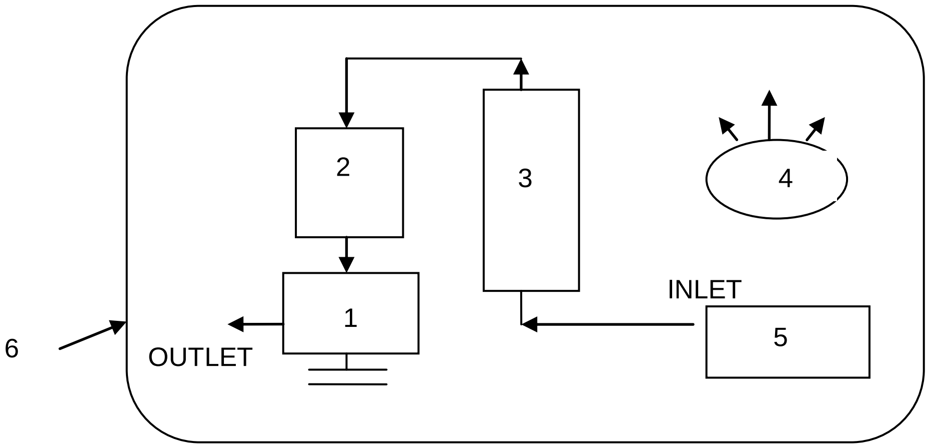


Figure 5. *Schematic view of experimental setup with stainless steel vessel. The charcoal container (PET bottle) is located inside of the vessel. (1 = pump; 2 = flow-meter; 3 = PET bottle with active charcoal; 4 =* ^{226}*Ra/*^{222}*Rn source; 5 = continuous radon monitor; 6 = stainless steel vessel).*

Figure 6. *Pictures of experimental setup type II used for measurement of radon suppression by charcoal trap for small volume without any air ventilation. As charcoal container the PET bottle was used. The measurements were performed with charcoal placed inside and outside of the steel vessel, respectively.*

4.3 Type III experiment

The key long-term measurement campaigns were conducted in the NRPI radon chamber under the conditions more close to ones in real buildings. The chamber with inner volume 45 m^3 allows to adjust and kept stable indoor ambient conditions from temperature, humidity, radon concentration, ventilation, aerosol concentration and its spectra point of view similar to dwellings. The schematic view of NRPI radon chamber and its accessory is seen in the Fig. 7.

Any time during all performed measurements in the chamber was radon concentration well-known via adjustable, constant and measured both air exchange rate radon entry rate. The well-known and constant radon entry rate into the chamber was realized via used certificated flow passing through ^{226}Ra/^{222}Rn source and constant and known air exchange rate by means of an artificial chamber ventilation system. The air exchange rate was continuously measured during all measurements with the NRPI tracer gas monitor of nitrous and radon concentration with well-known and precise continuous monitor Alphaguard traceabled to NRPI reference standards and calibrated against well-known PTB Braunschweig (Germany) reference primary atmosphere, as well.

4.4 Comment on experiments

On principle, our experiments were focused on experimental verification our developed model describing theoretical efficiency of the charcoal filter to reduce radon gas under influence of the crucial parameter of air exchange rate. Filtration efficiency we define as ratio of steady state indoor radon gas concentration corresponding to powered filter to the initial steady state radon concentration corresponding to switched off filter.

During our experiments we investigated the filter efficiency observed both during calculated retention time period applied immediately after turning-on the filter and after this period when a new steady state radon gas concentration was reached. Initial radon concentrations for switched off filter ranged from 500Bq/m^3 to 5000 Bq/m^3.

Generally, during our experiments we tested both mentioned types of charcoal placed always in the same plastic (PE) container in typical amount of approximately 70kg. The plastic (PE) container had dimensions 70 cm x 50 cm x 40 cm with two air input and output holes (8 cm in diameter) on opposite sides (see Fig. 8). As air pump fan of Sierra Misco company (U.S.A.) was used with the air flux adjusted to constant value 360 l/min. During the tests (taking more than one month) all affecting parameters such as air exchange rate, air flux passing the filter, ambient, temperature and relative humidity were recorded.

Ambient conditions during filter operation were adjust to agree with realistic indoor conditions i.e. air exchange rate ranging from 0.05/h to approximately 0.5/h, temperature around 23°C and relative humidity ranged from 40 % up to 60 %.

The data obtained were used also to estimate radiation protection needs related to the radon gas activity accumulated in the charcoal during filtration (see chapter 6).

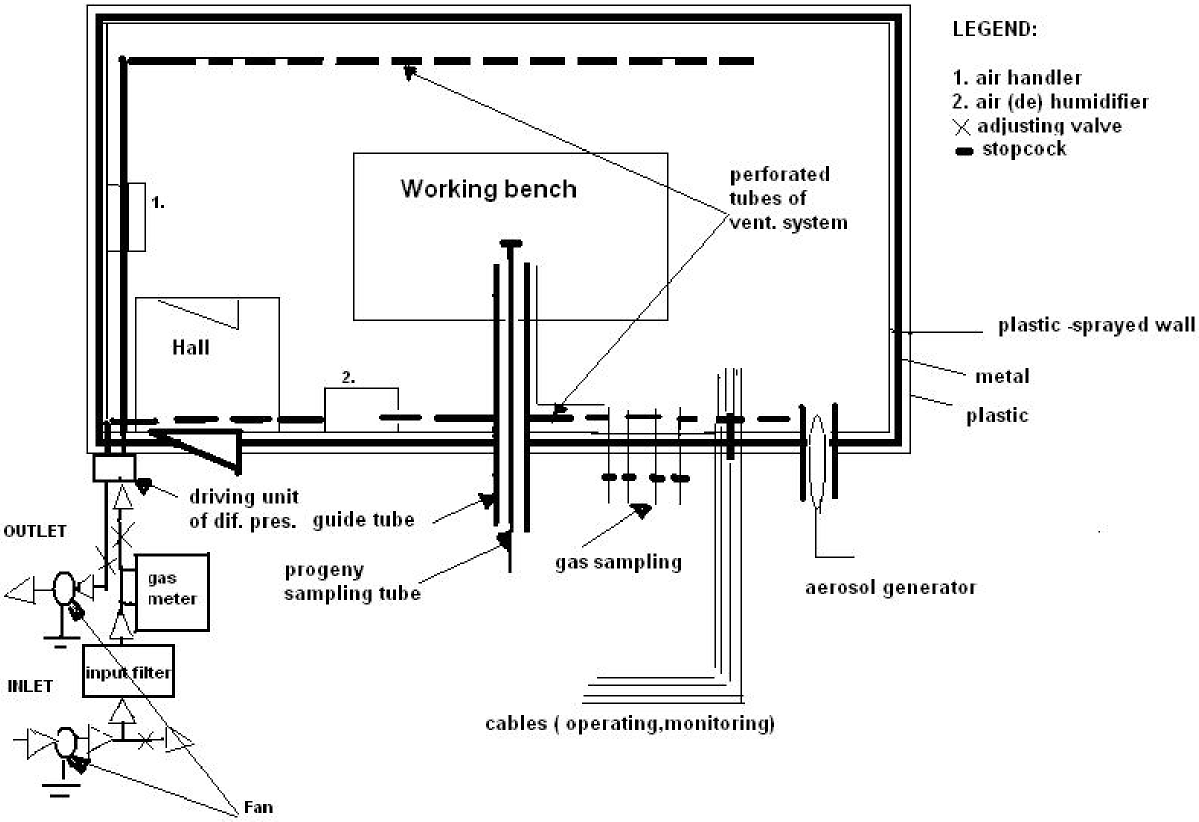


Figure 7. *Schematic view of the NRPI radon chamber*.

Figure 8. *View of empty charcoal container with both holes used as input and output for air flowing into the charcoal (left picture). The whole apparatus (air pump, charcoal container, radon monitor Alphaguard) is presented in right picture.*

5 Theoretical models used for experimental data processing and description of radon reduction in a NRPI chamber using the charcoal trap. Results of experimental tests.

First of all, the simplified model describing the radon capture in charcoal is given. This model has been checked using the experimental data from measurements described in previous chapter. We use a simple model of a penetration of radon through a vessel with a charcoal of the mass *m* (see Fig. 9). If the input activity of radon is C_1 and the flux of the input air with radon is *f*. After sufficiently long time (after achieving a steady state), the output activity of radon C_2 can be expressed as

$$C_2 = C_1 \mathrm{e}^{-\lambda T},$$

where *T* is a retention time of radon in the charcoal (in average, each Rn atom is delayed for the time *T*, in the charcoal) and λ is the radon decay constant ($2.1 \cdot 10^{-6}$ s). The retention time can be expressed as

$$T = k\frac{m}{f}.$$

where *k* is a constant, which characterizes a quality of charcoal to capture radon. The constant *k* is strongly dependant on temperature (see Fig. 10).

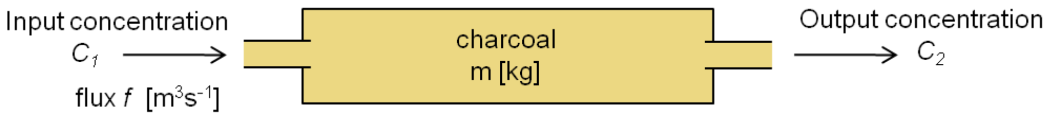


Figure 9. *Penetration of air with radon through a vessel with a charcoal of a mass m. The input radon activity is C_1, the activity of the output radon is decreased to a value C_2.*

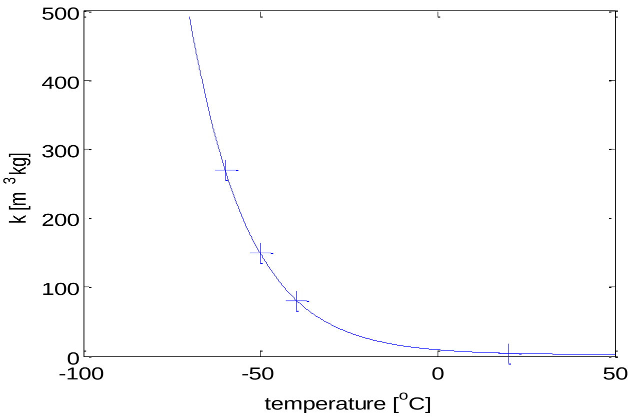


Figure 10. *Dependence of the parameter k characterizing the properties of the charcoal K48 on temperature (measured by the team of Jose Busto, CPPM Marseille).*

5.1 Data processing of Type I experiment

The model of radon suppression in a charcoal trap was used to calculate the factor *k* for different types of charcoal (type 207B 1,5 KI and K48 respectively, under different temperatures). In the Type I experiment, which was described in chapter 3.1 (see Figs. 1, 2 and 3), 0.73 kg of the charcoal (type 207B 1,5 KI) was used. In the Fig. 11, the blue line describes the development of the input activity $C_1(t)$ in time and the green line the radon activity $C_2(t)$ measured in the output air. In the experiment, the air was penetrated through the charcoal vessel with the flux 0,5 l/min. The initial pulse of radon activity was caused with radon accumulated in the radon source before the starting of the experiment. After achieving steady state, output radon activity was suppressed with factor C_1/C_2 = 0,81. It corresponds to the charcoal quality factor k = 1.1 m^3/kg (measured for temperature 25°C). From Fig. 11, the retention time of radon in the charcoal can be estimated to T ~ 32 h. This value corresponds to the suppression factor C_1/C_2 = 0,79, which is in good agreement with value obtained from measurement of final stationary state.

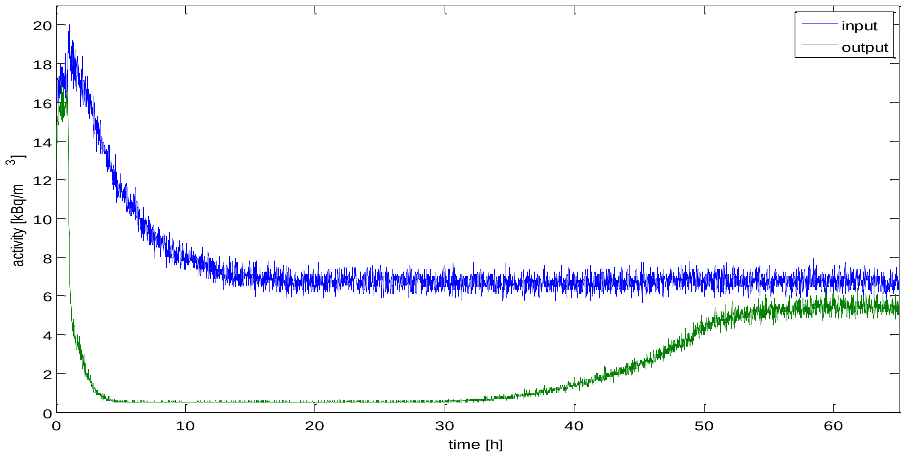


Figure 11. *Input (blue line) and output (green line) radon activity measured in the type I experiment with charcoal type 207B 1,5 KI, (0.73 kg of charcoal, flux 0.5 l/min).*

In the analogous experiment type I, we used 2.1 kg of the different charcoal, type K48. In the experiment, the air was penetrated through the charcoal vessel with the flux 0.5 l/min. After achieving steady state (see Fig. 12), output radon activity was suppressed with factor C_1/C_2 = 0.11. It corresponds to the charcoal quality factor k = 4.2 m^3/kg (valid for the temperature 25°C). From Fig. 12, the retention time of radon in the charcoal can be estimated to T ~ 230 h. This value corresponds to suppression factor C_1/C_2 = 0.18, which is in good agreement with the value obtained from the measurement of final stationary state. The temperatures during first two experiments were similar (around 25 °C). This means that the ability of charcoal K48 to capture radon is much higher compared to charcoal 207B 1,5 KI.

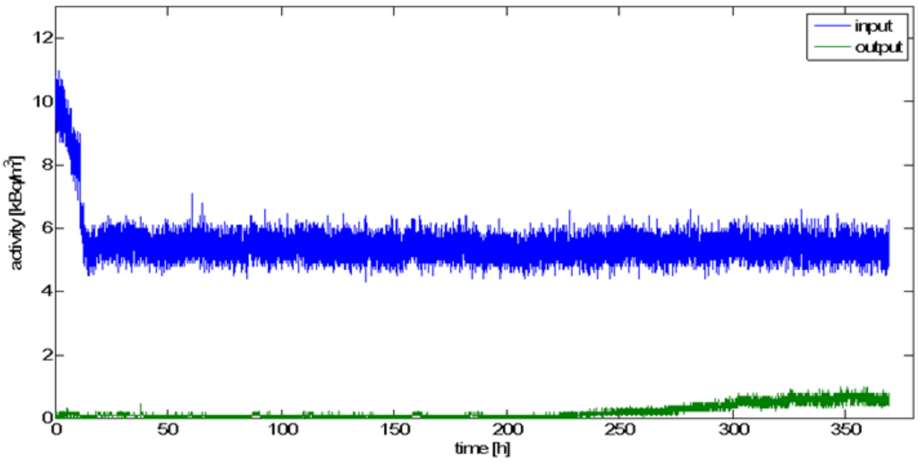


Figure 12. *Input (blue line) and output (green line) radon activity measured in the type I experiment with K48 charcoal (2.1 kg of charcoal, flux 0.5 l/min).*

K factor strongly depends on temperature. The test with K48 charcoal was repeated using again 2.1 kg, however the flux of penetrating air was higher – 1 l/min and the experiment was performed with the average temperature of 1,.5 °C and the relative humidity of the air 49.3%. After achieving of steady state, output radon activity was suppressed with factor C_1/C_2 = 0.20 (see Fig. 13). It corresponds to the charcoal quality factor k = 6.1 m^3/kg (valid for temperature 19,5 °C). From Fig. 13, the retention time of radon in the charcoal can be estimated to T ~ 200 h. This value corresponds to suppression factor C_1/C_2 = 0,22, which is in good agreement with the value obtained from the measurement of final stationary state.

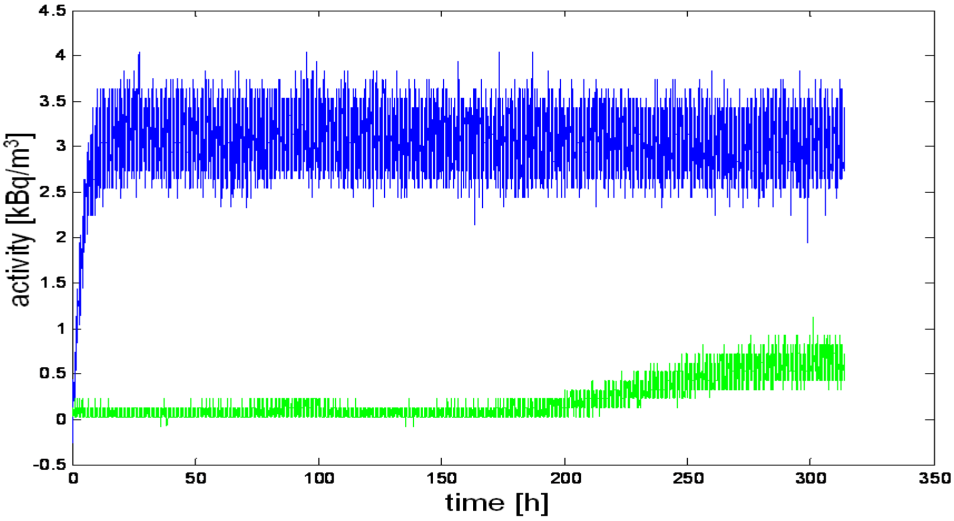


Figure 13. *Input (blue line) and output (green line) radon activity measured in the type I experiment (2.1 kg of charcoal, flux 1 l/min).*

5.1.1 Theoretical description of radon reduction in a building (chamber) using the charcoal trap

To process data obtained in Types II and III experiments it was necessary to develop a simple model of radon behaviour in the chamber (building). Steady state of radon inside a building with a volume V is assumed. The number N_1 of Rn atoms in the building corresponds to the radon activity of C_1. A flux Φ of Rn atoms penetrating into the building is in equilibrium with Rn atoms decay rate λN_1 and outgoing radon flux $\nu_1 N_1$ due to the ventilation ν_1 (s^{-1}). The typical value of ventilation parameter for old buildings is ~0,2/h and for modern well isolated buildings ~0,1/h. For modern buildings in Sweden, the ventilation should be 0,5/h. This equilibrium in the steady state can be described with the equation:

$$\Phi - \lambda N_1 - \nu_1 N_1 = 0,$$

or using the radon activity C_1 as

$$\Phi - V C_1 - \nu_1 \frac{C_1 V}{\lambda} = 0.$$

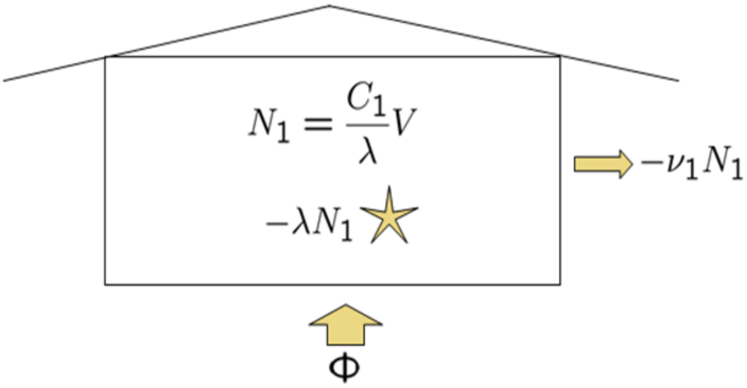


Figure 14. *Illustration of steady state of radon with activity C_1 inside a building with volume V. Number of radon atoms in the building is labelled by N_1. A radon flux incoming into a building is labelled by Φ and is in equilibrium with outgoing radon flux $\nu_1 N_1$ and radon decay rate λN_1.*

The charcoal trap is used inside the building. The air with the activity C_2 circulates through a vessel with charcoal by the air flux f. Speed of elimination of Rn using the charcoal trap can be expressed as

$$\Phi_C = \frac{C_2 f}{\lambda}\left(1 - e^{-\lambda\frac{km}{f}}\right).$$

Next, the stationary state is described. Therefore, the following equation must be valid:

$$\Phi - \lambda N_2 - \nu_2 N_2 - \Phi_C = 0,$$

or using the radon activity C_2 as

$$\Phi - V C_2 - \nu_2 \frac{C_2 V}{\lambda} - \frac{C_2 f}{\lambda}\left(1 - e^{-\lambda\frac{km}{f}}\right) = 0,$$

where v_2 is ventilation parameter of the building after starting using the charcoal trap (in general $v_1 \neq v_2$).

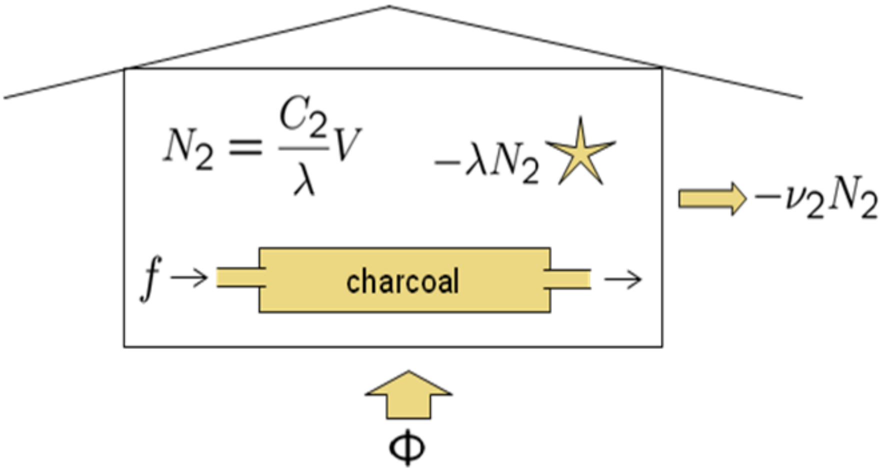


Figure 15. *Illustration of steady state of radon with activity C_2 inside a building with volume V, using a charcoal trap. The air circulated through a charcoal trap with flux f. Number of radon atoms in the building is labelled by N_2. Radon flux incoming into a building is labelled by Φ and is in equilibrium with outgoing radon flux νN_2 and radon decay rate λN_2.*

By combining both equations describing the equilibrium before and after using of charcoal, a formula for expressing radon concentration suppression is obtained (see appendix 2):

$$\frac{C_2}{C_1} = \frac{1}{\frac{\lambda + \nu_2}{\lambda + \nu_1} + f\frac{1 - \mathrm{e}^{-\lambda\frac{km}{f}}}{V(\lambda + \nu_1)}}.$$

In the limit of infinite air flux *f*, the radon suppression can be expressed as

$$\lim_{f\to\infty} \frac{C_2}{C_1} = \frac{1}{\frac{\lambda + \nu_2}{\lambda + \nu_1} + \frac{\lambda k m}{V(\lambda + \nu_1)}}.$$

If the inverse problem needs to be solved – to specify the minimum mass *m* of charcoal necessary for the decrease of radon concentration from C_1 to C_2, the following formula is found:

$$m = -\frac{f}{\lambda k}\ln\left(1 - \frac{(\lambda + \nu_1)V}{f}\left(\frac{C_1}{C_2} - \frac{\lambda + \nu_2}{\lambda + \nu_1}\right)\right),$$

which is valid for the flux of circulating air fulfilling the condition

$$f > (\lambda + \nu_1)V\left(\frac{C_1}{C_2} - \frac{\lambda + \nu_2}{\lambda + \nu_1}\right).$$

In the limit of infinite flux *f*, the minimal mass of the necessary charcoal is

$$\lim_{f\to\infty} m = \left(1 + \frac{\nu_1}{\lambda}\right)\frac{V}{k}\left(\frac{C_1}{C_2} - \frac{\lambda + \nu_2}{\lambda + \nu_1}\right).$$

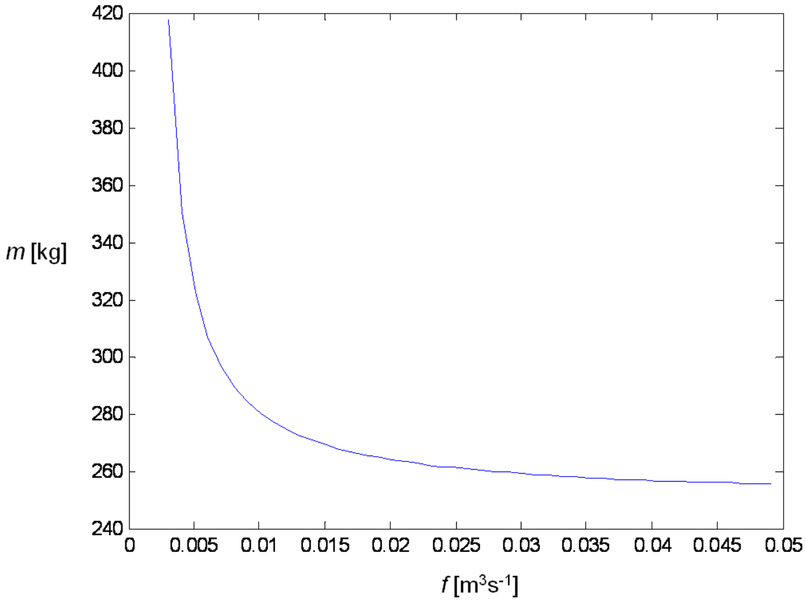


Figure 16. *The necessary mass of charcoal for different fluxes of the circulating air for V = 250* m^3 *(one floor house),* $C_2/C_1 = 5$ *(e.g. suppression from 500* Bq/m^3 *to 100* Bq/m^3*), k =4* m^3/kg *(typical value for K48 charcoal at room temperature), and* $v_1 = v_2 = 0/h$ *(no air exchange in the house).*

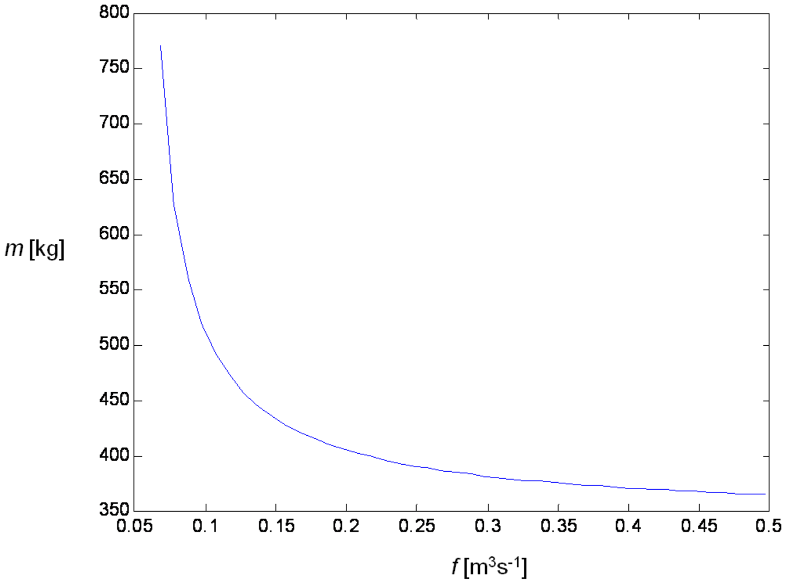


Figure 17. *The necessary mass of charcoal for different fluxes of the circulating air for V = 250* m^3 *(one floor house),* $C_2/C_1 = 5$ *(e.g. suppression from 500* Bq/m^3 *to 100* Bq/m^3*), k =4* m^3/kg *(typical value for K48 charcoal at room temperature), and* $v_1 = v_2 = 0.2/h$ *(typical air exchange in the house).*

The radon suppression factor strongly depends on the ventilation parameters v_1, v_2. It is illustrated in Figs. 16 and 17. If the initial activity C_1 was measured in the building with high ventilation parameter v_1, the incoming flux of radon Φ is much higher than for the building with the same C_1

but low ventilation parameter v_1. Therefore, for such building much higher amount of charcoal (flux of circulating air) is necessary to achieve the same radon suppression.

5.2 Data processing of Type II experiment

The obtained formulas were compared with the results of conducted experiments (chapters 4.2 and 4.3). In the experiment described in chapter 4.2 (see Fig. 4), we used the stainless steel vessel (volume V = 142 l). The air in the barrel was circulated through a charcoal trap (0.73 kg of 207B 1,5 KI charcoal, flux f = 1 l/min). The factor of radon reduction measured during test was obtained as C_2/C_1 = 0.12 (C_1 is initial radon activity with radon trap off, C_2 is final radon activity with radon trap on). Using theoretically calculated value C_2/C_1 = 0.14 (for corresponding quality factor of the charcoal k = 1.32 m^3/kg) it shows good comparison between theory and experimental tests.

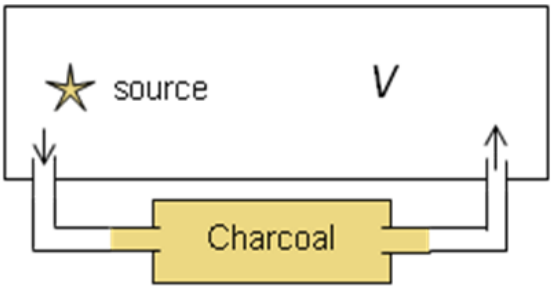


Figure 18. *Scheme of the Type II experiment with the stainless steel vessel with the radon source and the charcoal trap outside of the vessel (see Figs. 4 and 6 in chapter 4.2).*

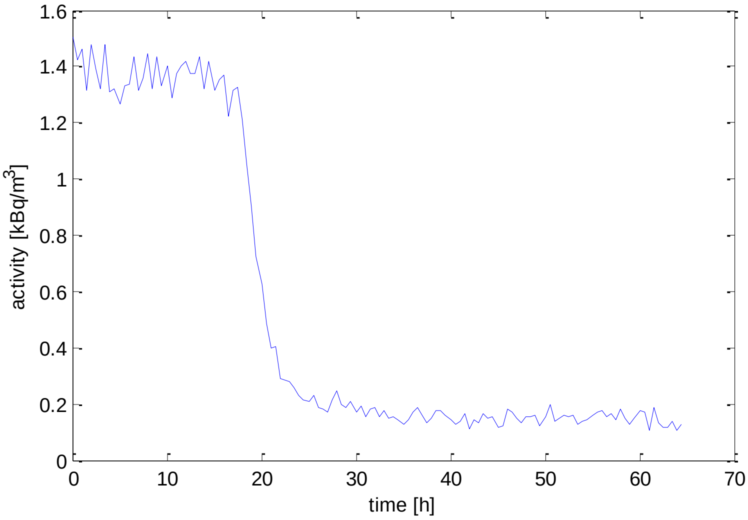


Figure 19. *Radon activity measured in the Type II experiment*.

5.3 Data processing of Type III experiments

Type III experiments were performed in the testing chamber with the volume V = 45 m^3 (see chapter 4.3). The air in the chamber was circulated through a charcoal trap (70 kg of 207B 1,5 KI charcoal, flux f = 1 l/min, temperature 23 °C, ventilation factor v_2 = 0.023/h, see Fig. 20). The factor of radon reduction measured during test was obtained as C_2/C_1 = 0.2 (C_1 is initial radon activity with radon trap off, C_2 is final radon activity with radon trap on). Using theoretically calculated value C_2/C_1 = 0.21 (for corresponding quality factor of the charcoal k = 1.32 m^3/kg for 23°C) it shows again nice comparison between theory and experimental test. This experiment confirms that fivefold radon reduction in the testing chamber with negligible ventilation is achievable with our charcoal trap. The situation is different for higher ventilation factors – see results of next experiment.

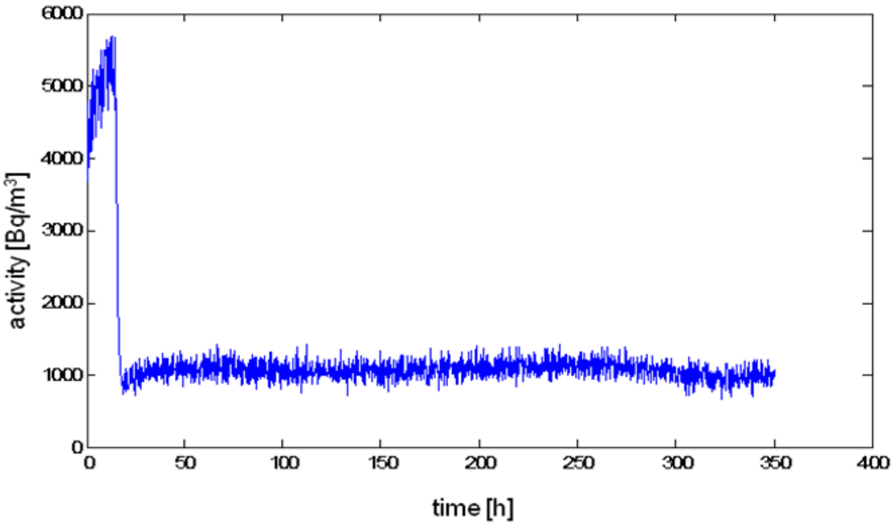


Figure 20. *Radon activity measured in the Type III experiment with ventilation factor* v_2 *= 0.023/h (at NRPI 45* m^3 *chamber).*

The next experimental test was prepared in the same testing chamber as the previous experiment. The air in the chamber was circulated through a charcoal trap (65 kg of K48 charcoal, flux f = 360 l/min, temperature 23 °C, ventilation factor v_1 = v_2 = 0,14/h before and after starting the air circulation through the charcoal trap). The factor of radon reduction C_2/C_1 =0.74 was obtained from experimental data (see Fig. 21). Using theoretically calculated value C_2/C_1 = 0,79 (for corresponding quality factor of the charcoal k = 3,7 m^3/kg for 23°C) it shows again good comparison between theory and experimental test. As expected, the radon reduction caused by the charcoal trap is less efficient due to the high ventilation, which reduces the radon concentration before the operation of the charcoal. From this it is indicated that the charcoal trap is more efficient in spaces with poor ventilation.

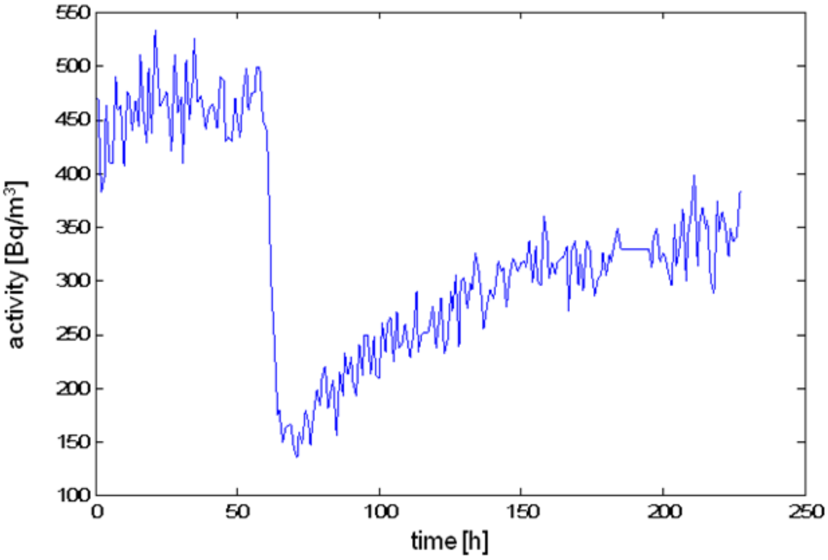


Figure 21. *Radon activity measured in the Type III experiment with ventilation factor* v_2 *= 0.14/h (at NRPI 45* m^3 *chamber).*

A comment on the used theoretical models is given in 6.2.

6 Definition of technical parameters of future prototype.

6.1 Estimation of possible prototype testing at NRPI.

Based on the obtained results of the first stage of the common Czech-Sweden project, next step will provide the construction of prototype and its testing under real working conditions (high radon content in the air, 500 or 300 Bq/m^3 with ventilation factor v_2 = 0.1/h) in radon chamber at NRPI (Prague). The purpose of the construction of the prototype and the testing (different temperatures, long term stability, different types of charcoal) is to obtain the setup which allows to define needed mass of charcoal, working temperature and air flux to suppress the radon activity in the chamber from 500 (or 300) Bq/m^3 to 200 (or 100) Bq/m^3 in the radon NRPI chamber for different ventilation factors and to obtain the experience with such device.

The technical parameters of prototype (mass of charcoal, needed temperature) are based on many conditions. The NRPI chamber has volume of 45 m^3. Based on the curve on Fig. 17 there is a minimal air flux through charcoal trap. For NRPI chamber and the suppression of radon activity from 500 Bq/m^3 to 100 Bq/m^3 it is approximately 19.4 m^3/h. The following tables (Tables 1 and 2) show the needed mass of charcoal for different temperatures of air going through charcoal trap and for other important parameters (air flux, ventilation factor).

		Temperature [°C]							
		+25	+10	0	-10	-20	-30	-40	-50
Ventilation factor h [h^{-1}]	*Air flux [m^3/h]*	Needed mass of charcoal for given temperature							
0	10	56		21			4.3		
0	20	54	32	21	13	7	4		
0.1	10	Too low air flux							
0.1	20	2629	1577	1012	611	354	200	111	61
0.1	30	1187	712	457	276	160	90	50	28

Table 1. Needed mass of charcoal for different temperatures of air and different running conditions (ventilation factor, flux of air into the chamber) for radon suppression at NRPI chamber (45 m^3). The suppression 5 (e.g. from 500 Bq/m^3 to 100 Bq/m^3) was taken into account.

		Temperature [°C]							
		+25	+10	0	-10	-20	-30	-40	-50
Ventilation factor h [h^{-1}]	*Air flux [m^3/h]*	Needed mass of charcoal for given temperature							
0.10	20	505	303	194	117	68	38	21	12
0.10	30	416	268	172	104	60	34	19	10
0.15	20	942	565	363	219	127	72	40	22
0.15	30	732	440	282	170	99	56	31	17

Table 2. Needed mass of charcoal for different temperatures of air and different running conditions (ventilation factor, flux of air into the chamber) for radon suppression at NRPI chamber (45 m^3). The suppression factor 3 (e.g. from 300 Bq/m^3 to 100 Bq/m^3) was taken into account.

Based on the calculated data in Tables 1 and 2 it is possible to propose the future prototype which should be installed at radon chamber of NRPI. Taking into account the realistic air flux into the chamber and suppression factor of radon on the level of 5 it is necessary to built radon trap with the mass of charcoal up to 300 – 400 kg, temperature of the air through charcoal trap tuned between +20°C and -30°C with the air flux around 20 m^3/h. Simplified scheme of the apparatus is following: dryer (dew point = -40°C), air pump fan (up to 20 m^3/h), tunable cooling system of the air with recuperation unit (up to -30°C), charcoal vessel (for 300 – 400 kg) and humidifier. Such device should be installed at NRPI and tested for a long time with different types of charcoal or zeolits under different conditions to obtain the experience with long term running of the apparatus (suppression of radon for different air fluxes mainly). Experience with energy consumption of such device is needed. Testing will be based on the results of experimental tests, mainly for steady state or measurement with several clean charcoal traps. To test different air fluxes; independence of degree of charcoal saturation; to study pollutants captured in charcoal; geometrical shape of charcoal vessel to obtain optimal air flux.

A comment on the used theoretical model is given in 6.2.

6.2 Comment on theoretical models

Theoretical models and approaches used to evaluate experimental results obtained described in 6.1 are only appreciative and illustrative because the by-pass fraction through the adsorption columns is neglected, the reduction by radon decay is overestimated, the amounts of AC given in Tab. 1 and 2 in part 5 of the Final Report are underestimated. Evaluation overwhelming the above mentioned shortcomings is more complicated but the conclusions are in principle in agreement with the simplified evaluation and predictions.

The rigorous evaluation of the experimental results and prediction of the efficacy of mitigation by an AC device needs:

1. Analytical solutions for the time course of the release of radon from the AC column given by the theory of adsorption of radon on AC, described as a set of compartments with linear reaction in series, where the decay of radon is treated as an intrinsic fraction of removal (not as a correction factor),
2. The theory determines how to get the mean residence time of radon in the AC column from the experimental data,
3. The theory of adsorption gives also analytical solutions for the cumulative activity of radon in the column or its time course to be able to calculate the gamma dose near the AC bed – see Appendix 3,
4. Special operational conditions are required for optimal regime of the adsorption given by the van Deemter relation which have to be tested for each experiment,
5. Balance relations for steady state situations have to be formulated allowing to consider all possible inputs and outputs in air of the mitigated room and the AC column,
6. Transitional time courses between the steady states of 100% adsorption and radon break-through can be evaluated by regression analysis using the logistic function (or others) to obtain the mean residence time of radon in the AC column,
7. There are two types of application of the AC (type A: cycling a period at 100% adsorption during one day followed by a desorption regime, type B: continuous regime with radon break-through with a lower efficacy determined by the decay of radon during its residence time in the AC column) the evaluation of which are different

The experiments realized in NRPI had a character of pilot experiments with the AC column at room temperature. They show the typical time courses at different regimes of operation, have been provided sometimes not long enough to determine the mean residence time of radon in the AC column, have been provided with insufficient care against by-pass of radon, sometimes with too intensive flow rate repeatedly resulting in high by-pass of radon or devaluated by humidity. But all the experimental results could be explained by adequate and plausible theoretical models.

Therefore (preliminary**)** *prediction of the efficacy η* of an AC device can be given for both types of application of the adsorption process. Special requests (minimal efficacy, maximal amount of AC, minimal mean residence time of radon in the device, etc.) result in conditions on needed flow rate and/or temperature and dimensions of the AC bed for different ventilation rates. This is described in the report as an example for requested 80% efficacy of radon mitigation for a small and great volume to be mitigated.

A common result is that

- the dynamic adsorption of radon as a mitigation measure to reduce indoor radon is feasible
- at higher ventilation rates the efficacy has a saturation needing increased adsorption coefficient by cooling,
- cooling of the carbon bed (column) is an ultimate requirement to reach sufficient efficacy,
- optimal conditions for the adsorption process (especially the linear speed of the flow) are related also with the dimensions and the shape of the AC bed has to be optimal also,
- good construction of the adsorption column is needed (isokinetic flow through the whole amount of AC, low bypass along the walls of the column, vertical configuration, prevention of air humidity, supplemented with systems of demoisturizing/moisturizing and cooling/warming the IN/OUT air of the AC bed, etc., etc.

Up to now some assumptions have been used in evaluation of the experiments and in the prediction of the efficacy e.g. the constancy and universality of the constants A,B,C in the van Deemter equation for different AC and their temperature dependence. May be statistical methods can be used for the transitional period of the time course better than regression with the logistic function (see: WC Gaul et al., Dynamic adsorption of radon by activated carbon, Health Phys. 88, 4, 371-378, 2005). Also have to be assessed how far can be deviated the operational conditions from the optimal regime. All this shows that with evaluation using experimentally derived characteristics of the used AC and with results obtained on a good constructed prototype device more precise predictions can be developed for a commercially effective mitigation device.

6.3 Required energy for cooling charcoal

1. It is found that activated carbon increases the absorption of radon gas in air if the batch of activated carbon is lowered in temperature to a level of -70ºC.
2. One commercial equipment found at the market could be a so called 2-stage refrigerant circuit. This choice of system will be associated with some difficulties connected in the heat exchanging surface active carbon and refrigerant.
3. A 2-stage refrigerant circuit has at least components as follows:

   First level:

- A heat exchanger necessary to evacuate the amount if heat from the batch of carbon, in this case, a coaxial evaporator.
- A compressor between the evaporator and the condenser in the first stage.
- A condenser, to release the heat from the batch of carbon added with heat from the compressor in this first step.

- A valve between high- and low pressure in the refrigerant circuit.
- A refrigerant, most suitable is HFC 408b. Temperature in the evaporator, refrigerant side will be approximately -80ºC.

  <u>Second level:</u>
- Second level start with the condenser from the first level, equal to the evaporator second level.
- A compressor.
- An aircooled condenser.
- An expansionvalve or capillary tube, border between high- and low pressure side.
- A refrigerant, HFC 404a, circulating in this second level.
- Both stages has electrical connections to regulation circuits, safety equipment.

4. Heat needed to be evacuated from the batch:

   Mass: 100 kg

   Specific heat: 1,3kJ/kg, K

   Temperature difference: start 20ºC, end -70ºC, equals 90 K

   Q= 100 x 1,3 x 90 / 3600 = 3,25 kWh

   Assume a perfect situation when heat from the carbon batch releases to the evaporator without problems and with high heat transfer coefficients between surfaces, 3,25 kW of cooling capacity will be needed during 1 hour.

   The amount of energy needed in the compressor will approximately be as high as the heat from the batch of carbon.

   The second level, the evaporator has to evacuate at least the heat of 6,5 kWh. Finally the condenser re-cools this last step and will handle a heat of 8-9 kWh.

6.3.1 Comment on needed cooling device

Due to real conditions, the evaporator has to be designed with a surface or capacity, probably two times needed in theory. 100 kg of activated carbon represents a certain volume. It is not recommended to process all the volume at once. It is better to treat a smaller volume, one at a time, which will assure a manageable situation.

7 Prediction of operational conditions to reach requested radon mitigation efficacy

Prediction of conditions at which 80% efficacy of radon mitigation for a large/small volume by dynamic adsorption of radon on AC provided as cycling system (type A) or continuously (type B) can be obtained from the rigorous description of the dynamic adsorption process in following way.

7.1 Limits of adsorption device type A

The conditions of a long enough residence time $T_{\min}$ (at least 24 h) and of a required efficacy $\eta_{\min}$ lead to two conditions for the removal coefficient of the AC device $Q_{T,\min}$ and $Q_{\eta,\min}$.

$$Q \geq Q_{T,\min} = \frac{K.m}{T_{\min}} \qquad\qquad Q \geq Q_{\eta,\min} = \frac{\eta_{\min}}{1-\eta_{\min}} \cdot \frac{k+\lambda}{(1-\mu)} . V$$

To fulfil them both requires $Q_{T,\min} = Q_{\eta,\min}$ what gives

$$K = \frac{\eta_{\min}}{1-\eta_{\min}} \cdot \frac{k+\lambda}{1-\mu} \cdot \frac{V.T_{\min}}{m} \quad \textbf{or} \quad \Theta = \frac{1}{0{,}052} . \ln \frac{11}{\dfrac{\eta_{\min}}{1-\eta_{\min}} \cdot \dfrac{k+\lambda}{1-\mu} \cdot \dfrac{V.T_{\min}}{m}}$$

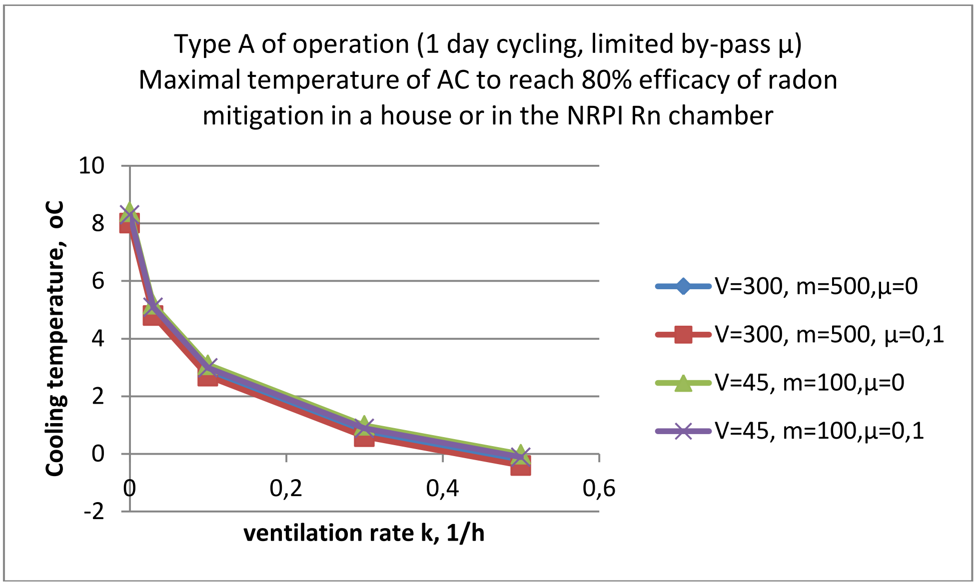
a relation to calculate the requested adsorption coefficient K (m^3/kg) or the relevant temperature Θ (^{0}C) at different ventilation coefficients k. Results are shown in the table and figure below.

V=300, m=500, T=24, 80%

mí	k, 1/h	temp. ^{o}C	K, m3/kg
0	0	8,12	7,2
0	0,03	4,91	8,5
0	0,1	2,80	9,5
0	0,3	0,70	10,6
0	0,5	-0,30	11,2
0,1	0	8,01	7,3
0,1	0,03	4,80	8,6
0,1	0,1	2,70	9,6
0,1	0,3	0,60	10,7
0,1	0,5	-0,40	11,2

80%, V=45, m=100, T=24

mí	k, 1/h	temp. ^{o}C	K, m3/kg
0	0	8,41	7,1
0	0,03	5,20	8,4
0	0,1	3,09	9,4
0	0,3	0,99	10,4
0	0,5	-0,01	11,0
0,1	0	8,30	7,1
0,1	0,03	5,09	8,4
0,1	0,1	2,99	9,4
0,1	0,3	0,88	10,5
0,1	0,5	-0,12	11,1



In all cases the calculated temperature of the AC bed is lower than + 8 ^{0}C

Principal properties and limitations of the type A device therefore are:

- Also in the case of only 80% efficacy of radon mitigation <u>cooling of the AC bed is requested</u>,
- The limiting requirements on cooling and ventilation rates are for this type of operation (in comparison with type B of operation) similar for large and small devices

7.2 Limits of adsorption device type B

The condition of a required efficacy $\eta_{\min}$ and the general relation for the adsorption

$$Q.T = K.m \qquad\qquad Q \ge Q_{\eta,\min} = \frac{\eta_{\min}}{1-\eta_{\min}} \cdot \frac{k+\lambda}{(1-\mu).(1-\delta)} \cdot V$$

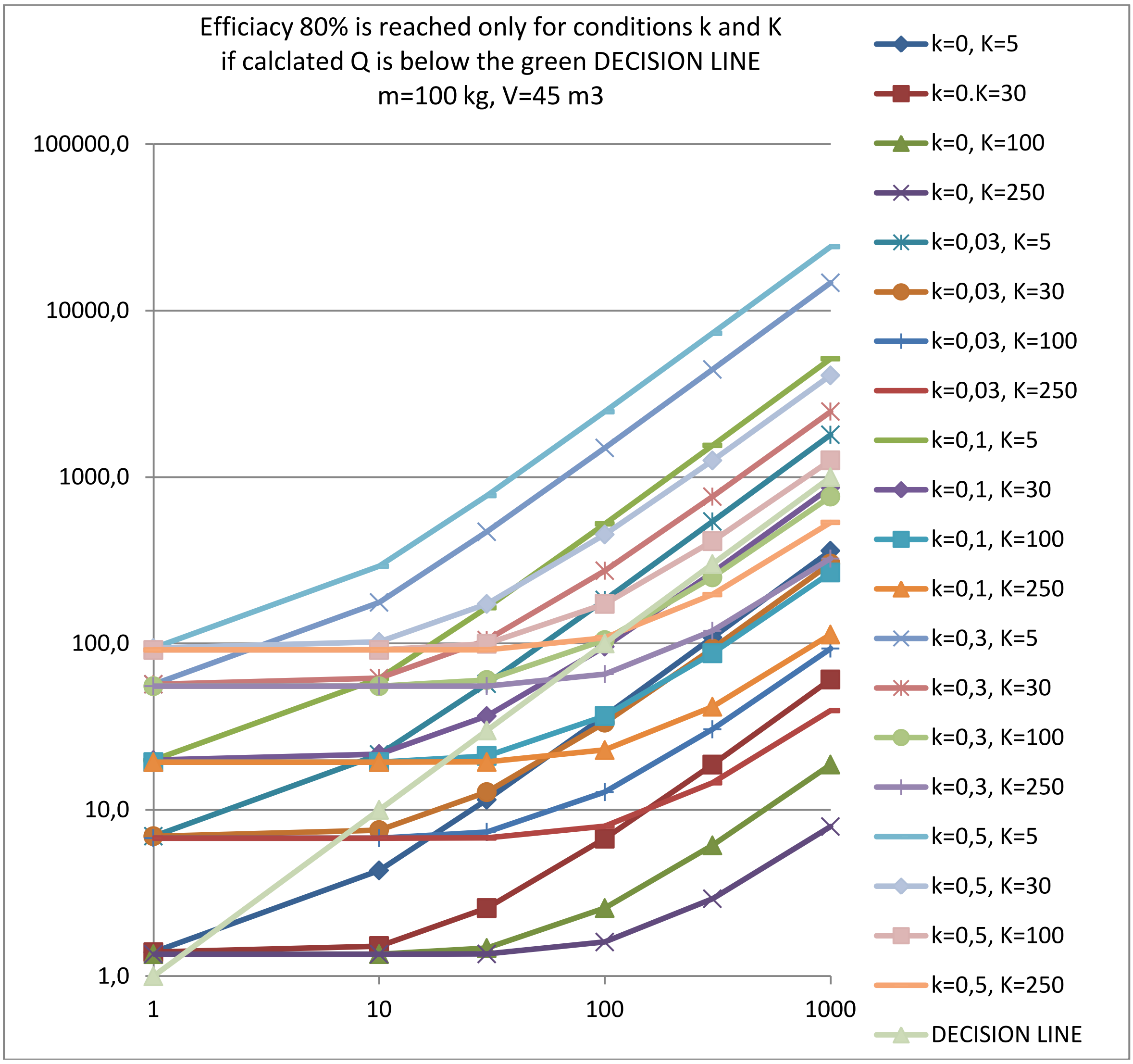
lead to an inequality for the volume flow rate Q

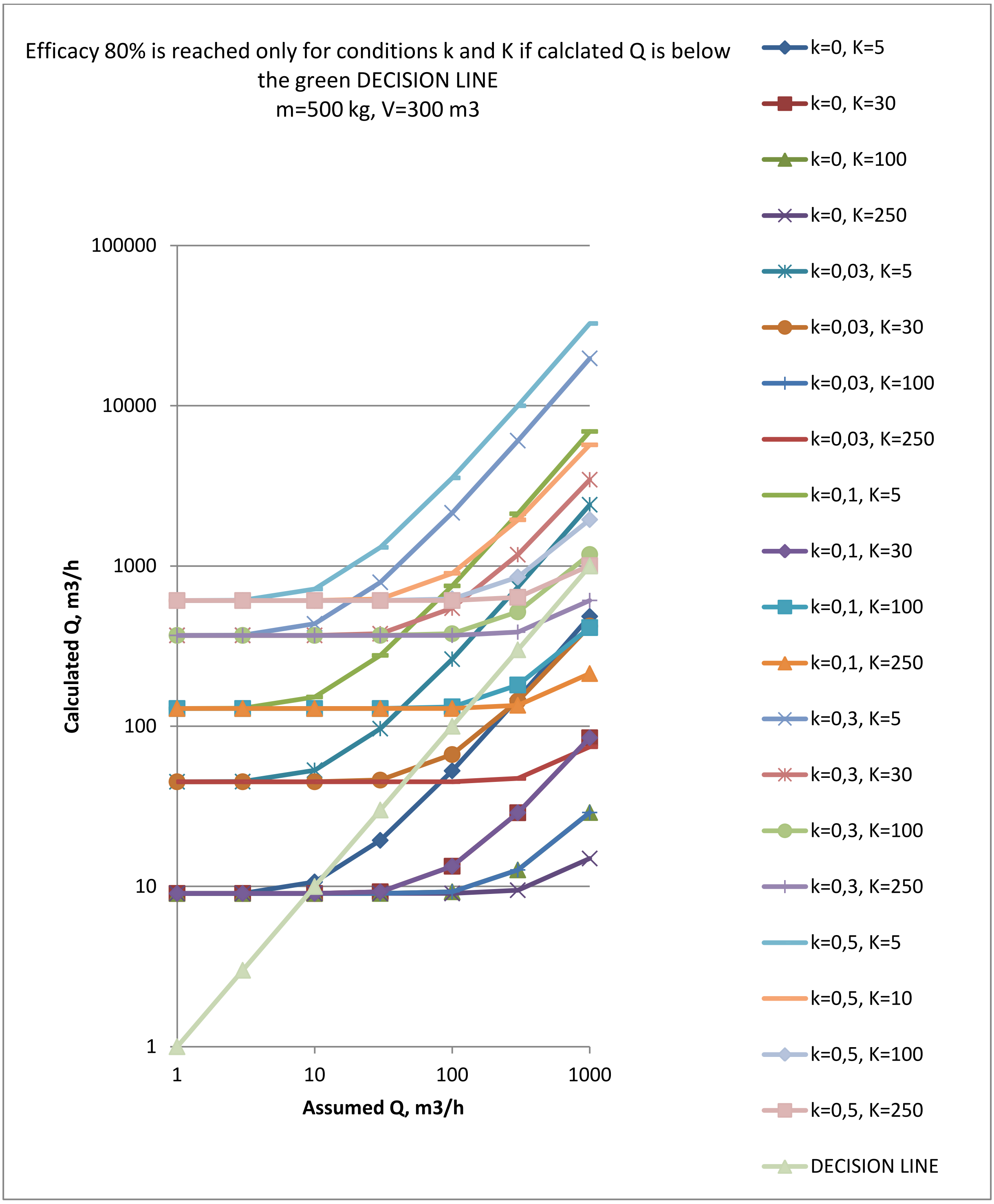
$$Q \ge V.\frac{\eta_{\min}}{1-\eta_{\min}}.\frac{k+\lambda}{(1-\mu).(1-\delta)}$$

$$\text{with} \quad \delta = (1+\xi)^{-n}, \xi = \frac{\lambda.K.m}{n.Q}, n = \frac{L}{H} = \frac{L}{A+B.S/Q+C.Q/S}, S = \pi.d^2/4, L = 2.d$$

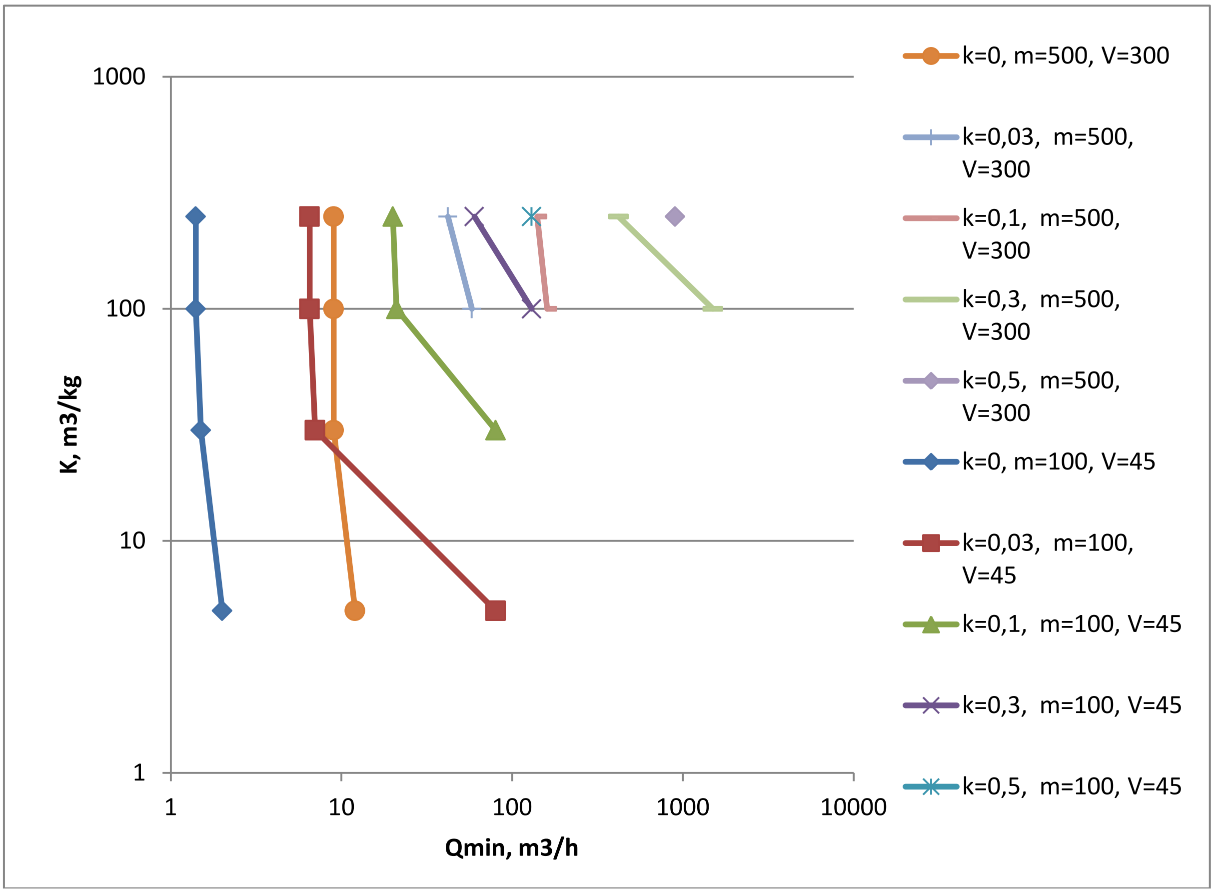
(A,B,C “constants” from the van Deemter equation) which is impossible to solve for explicitly. So first the fraction δ gained by decay of radon in the AC bed has to be calculated for chosen values of *K* and *Q*. From this inequality limiting conditions for the volume flow rate *Q* (or the adsorption coefficient *K* or for the temperature to reach it) at different ventilation coefficients *k* results and results are shown in the table and figure below for $\eta_{\min} = 0,8$ with a gray background in the table and below the decision line on the figure for a great (m=500 kg, V=300 m^3) and small (m=100 kg, V = 45 m^3 – the Radon chamber):

Great room					Calculated Q				
Assumed	assumed				k=	k=	k=	k=	k=
K	Q	n	ξ	1-δ	0	0,03	0,1	0,3	0,5
5	1	84	2,25E-01	1,000	9,05	45	129	369	609
5	3	196	3,21E-02	0,998	9,07	45	129	370	610
5	10	346	5,45E-03	0,847	11	53	152	436	719
5	30	360	1,74E-03	0,466	19	97	277	792	1306
5	100	220	8,56E-04	0,172	53	262	751	2149	3546
5	300	98	6,41E-04	0,061	149	740	2120	6062	10004
5	1000	33	5,70E-04	0,019	485	2413	6913	19769	32625
30	1	84	1,35E+00	1,000	9,04800	45	129	369	609
30	3	196	1,92E-01	1,000	9,04800	45	129	369	609
30	10	346	3,27E-02	1,000	9,04813	45,0	129	369	609
30	30	360	1,05E-02	0,976	9,3	46,1	132	378	624
30	100	220	5,13E-03	0,676	13,4	66,6	191	546	900
30	300	98	3,85E-03	0,314	28,9	143,7	412	1177	1942
30	1000	33	3,42E-03	0,107	84,7	421,9	1209	3457	5704
100	1	84	4,50E+00	1,000	9,0	45,0	129	369	609
100	3	196	6,42E-01	1,000	9,048000	45	129	369	609
100	10	346	1,09E-01	1,000	9,048000	45,0	129	369	609
100	30	360	3,49E-02	1,000	9,048039	45,0	129	369	609
100	100	220	1,71E-02	0,976	9,3	46,1	132	378	624
100	300	98	1,28E-02	0,713	12,7	63,2	181	518	854
100	1000	33	1,14E-02	0,313	28,9	144,1	413	1181	1948
250	1	84	1,13E+01	1,000	9,048000	45,0	129	369	609
250	3	196	1,60E+00	1,000	9,048000	45	129	369	609
250	10	346	2,73E-01	1,000	9,048000	45,0	129	369	609
250	30	360	8,72E-02	1,000	9,048000	45,0	129	369	609
250	100	220	4,28E-02	1,000	9,048888	45,1	129	369	609
250	300	98	3,21E-02	0,955	9,5	47,2	135	387	638
250	1000	33	2,85E-02	0,605	15,0	74,4	213	610	1006


Efficiacy 80% is reached only for conditions k and K
if calclated Q is below the green DECISION LINE
m=100 kg, V=45 m3
100000,0
10000,0
1000,0
100,0
10,0
1,0
1
10
100
1000
k=0, K=5
k=0.K=30
k=0, K=100
k=0, K=250
k=0,03, K=5
k=0,03, K=30
k=0,03, K=100
k=0,03, K=250
k=0,1, K=5
k=0,1, K=30
k=0,1, K=100
k=0,1, K=250
k=0,3, K=5
k=0,3, K=30
k=0,3, K=100
k=0,3, K=250
k=0,5, K=5
k=0,5, K=30
k=0,5, K=100
k=0,5, K=250
DECISION LINE



Values of K and Q fulfilling the condition of sufficient efficacy of 80% are summarised (approximately) in figure given below



Limiting parameters of adsorption coefficient K and volume flow Q to reach 80% efficacy of radon mitigation with 100 kg Ac in a room of 45 m^3 or with 500 kg Ac in a room of 300 m^3

(K=250 m^3/kg at - 60 ^{o}C, K=100 m^3/kg at - 42 ^{o}C, K=30 m^3/kg at - 19 ^{o}C, K=5 m^3/kg at + 15 ^{o}C) From this summarising of results the general conclusions can be given on the feasibility of radon mitigation by dynamic adsorption of radon on AC by type B (continuous operation) to reach 80% of radon mitigation.

Principal properties and limitations of the type B device with continual operation

- To reach the same efficacy as the type A of operation the type B requires higher cooling and higher volume flows
- To reach the same efficacy of radon mitigation in a greater volume needs higher cooling and higher volume flow compared with smaller volumes.

Note: For this prediction values A,B,C from reference KP Strong et al. 1978 have been used which may not be the same for AC K48 and temperatures below zero.

7.3 Conclusion

Radon mitigation by dynamic adsorption on AC is feasible by both types of operation, the main condition of it is the cooling.

8 Estimation of radiation protection needs. Study of role of aerosols.

Based on Czech legislation on radiation protection representing Decree No. 499/2005 Coll. [A] which is in agreement with the Basic Safety Standards of IAEA the radiological risk connected with use of AC bed filters should be considered from point of view:

8.1 Active charcoal (AC) bed as a radioactive source

The Decree classify radioactive sources according different criteria and specify disposal conditions for their holders. To avoid difficulties with “radiation protection point of view” below specify limits should be fulfilled during AC bed use in any time.

- disposal of the active charcoal contaminated by radon and its long-lived transformation product Pb-210, where exemption limits are prescribed

radionuclide	Activity A_{ex}, Bq	Mass concentration $a_{m,ex}$, Bq/kg
Rn 222+	10^8	10^4
Pb-210+	10^4	10^4

Note: The sign + means that progeny are present at the level of radioactive progeny

- gamma dose rate at 0,1 m from the surface of the AC bed during the operation or at the end of it, where dose rate of 1µSv/h is decisive.

Since more technical details about AC filtering bed and its operation time are missing, only raw analysis of used AC bed from mentioned classification will be performed. As input data for calculations we were used maximal acceptable amount of active charcoal and overestimated operational time.

8.1.1 Rn 222+

The content of radon in the AC bed depends approximately on the amount of charcoal *m* (kg), dynamic adsorption coefficient *K* (m^3/kg) and the final radon concentration in the air *a* (Bq/m^3) during operation of the AC bed. If the activity *A* of Rn 222+ is estimated according to formula A = K x m x a, thus using maximal and acceptable values for all the decisive quantities the result is A = (5-50) x 500 x 200 = 5 x10^6 Bq and $a_m \leq 10^4$. So, both the activity exemption level and mass concentration level would be fulfilled.

8.1.2 Pb 210+

Activity of Pb 210 from the above mentioned situation can be estimated by the accumulation of Pb 210 after long-term , say one year (***T***) of continuous operation as A_{Pb}=A x (1-exp(λ_{Pb*}T)) = 5 x 10^6 x 0,03 = 15 x10^4 Bq and $a_m \leq 10^4$ Bq/m^3. So, it can be seen that only exemption level is exceeded by factor 15. Having in mind the fact that maximal values for all decisive quantities are used, both exemption levels would be fulfilled in real conditions for Pb 210 also.

8.1.3 Gamma dose rate ($\dot{D}$g).

The gamma dose rates need to be calculated also for a real construction considering the actual shape of the AC bed and shielding material used. For orientation dose rates for the nearly spherical shape of the unshielded AC bed used in our performed experiments type III., with maximal radon gas input activity *A* mentioned above are calculated. Then $\dot{D}$g = 4 x 10^{-12} A (attenuation factor) = 4 x 10^{-12}x 5 x 10^6x 0,3 = 6 µSv/h. Numerical procedure is in detail listed in appendix 1.

Both the activity and the attenuation factor are overestimated by magnitudes of order. In real conditions, this could mean that the actual dose rate could be lower than 1 µSv/h and the radiation risk of irradiation would not be high.

According to Swedish regulations the public cannot be exposed to a radioactive dose exceeding 1 mSv per annum. Based on the calculations above this dose would be exceeded but with the overestimations made in the assumptions requirements could still be fulfilled in real conditions.

Further testing and research is required to establish need of radiation protection.

8.2 Radioactive waste

The Decree also specifies limits for clearance of radioactive waste. In case of active charcoal below mentioned clearance limits for radon long-lived transformation products Pb-210 and Po-210 must not be exceed.

- disposal of the active charcoal contaminated by radon long-lived transformation products Pb-210 and Po-210 , where clearance limits to environment are prescribed

radionuclide	Mass concentration $a_{m,Cl}$ Bq/kg
Pb-210+	3000
Po-210	3000

Note: The sign + has the same meaning as in above mentioned table

Having in mind maximal input parameters of radon accumulated activity in AC bed $A = 5 \times 10^6$ Bq, amount of charcoal m= 500kg, during assumed one-year operational time T**,** then mass concentration of Pb-210 $a_{m,Cl}$ can be calculated as follows: $a_{m,Cl} = A_{Pb} / m = A/m \times (1\text{-}\exp(\lambda_{Pb} \times T)) = 5 \times 10^6 / 500 \times 0{,}03 = 300$ Bq/kg. The results indicated that clearance limit for Pb 210 and evidently for Po 210 also would be fulfilled in real conditions.

According to a proposal on coming regulations in Sweden radioactive waste from households can be handled as waste with no consideration on radioactivity due to small amounts if the activity is lower than 10 kBq/kg (lower than 10 times 1 kBq/kg per nuclide in the uranium and torium series).

8.3 Role of aerosols

The lung equivalent dose H from inhalation of short-lived radon progeny can be written by means of measured time integral of radon concentration as follows:

$$H = \mathrm{DFC} \times \frac{\mathrm{Texp} \cdot \mathrm{F} \cdot \mathrm{av}}{170 \times 3700} \qquad (1)$$

where:
DFC is the dose conversion factor [mSv/WLM];
F is the equilibrium factor;
a_v is the average radon concentration [Bq/m^3];
T_{exp} is the exposition duration [h].

According to currently published calculations by Marsh and Birchall [B], the DFC in Eq. (1) can be expressed as a linear function of unattached fraction of equilibrium equivalent concentration of radon progeny f_p as follows:

$$\mathrm{DFC}(f_p) = 11.35 + 0.43\, f_p \qquad (2)$$

where f_p expressed as the percentage of total potential alpha energy concentration (PAEC) of the radon progeny mixture.

On principle, AC bed filter during operation can reduce both radon gas concentration and also aerosol concentration including its spectra. Having in mind also both following published Pörstendorfer's approximate formula [C]:

$$fp = \frac{414}{Z} \tag{3}$$

where:
Z is average indoor aerosol concentration [p/cm^3]

and previous equations (1) and (2) it is evident that AC filter bed during its operation can affect magnitude of lung equivalent dose H and consequently cause excessive risk from increasing of inhalation dose point of view.

Considering equations (1) and (2) and assuming "the same" breathing rate, the influence of AC bed filter under operation upon changes of inhalation dose can be expressed in terms of relative change of equivalent lung dose rate H_1/H_0 as follows:

$$\frac{H1}{H0} = \eta \, \frac{F1\,(k+fp1)}{F0\,(k+fp0)} \tag{4}$$

with

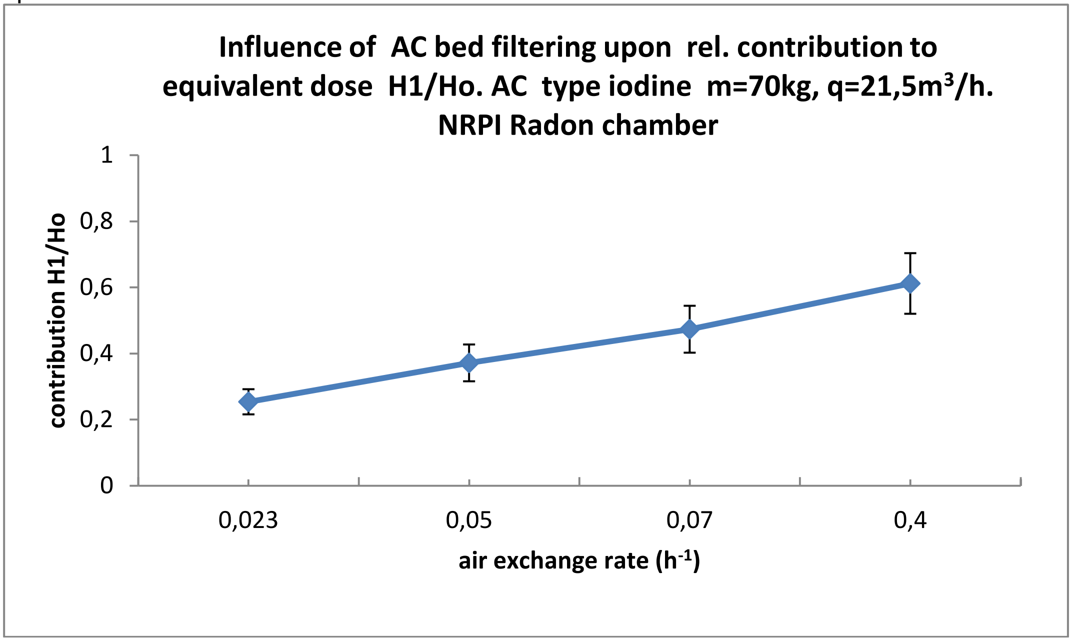
subscripts 0 and 1 representing ambient conditions during filter ON/OFF operation.
k representing the ratio 11.35/0.43 from equation (2).
$\eta = a_{v1}/\, a_{vo}$ representing reduction of average value of radon concentration before and after filter operation.

Since final prototype of AC filtration bed was missing influence its operation upon relative contribution to equivalent lung dose were demonstrated by means of routine used plastic AC bed, described in more detail in previous text (see Experiments type III). Used AC bed contained approximately 70 kg of charcoal type radioiodine and operated with flow rate 21,5 m^3/h. This flow rate corresponded to approximately 0.5 multiple of inner chamber volume exchange rate per hour. Relative humidity, temperature and air exchange rate ranged in usual indoor scopes (40-60 %), (20-25º C) and (0,05 – 0.4/h), respectively.

The air exchange rate was continuously monitored by means of the NRPI continuous monitor of tracer gas nitrous and unattached fraction of radon progeny f_p and equilibrium factor F by means of continuous monitor Fritra 4 as well.

Radon reduction during operation of AC bed ranged from 30% to 70% and the results expressed in form of desired contribution to relative lung equivalent dose calculated according to equation (4) can be seen in the Fig.1. As a reference values F_o,fp_o in equation (4) was chosen 0,3 and 0,09 respectively usually measured in houses. [D],[E].

Fig. 1 The influence of air exchange rate on contribution to equivalent lung dose during operation of AC bed filter in NRPI radon chamber.



The results indicated that application of the AC bed did not cause any excessive risk from inhalation lung equivalent dose point of view and AC bed can be used as a radon remedial tool.

9 Conclusion and future plans

The original proposal (see items in Introduction) is covered in details in previous chapters. The obtained results of the project will mainly be used in the consequent steps.

The next step would be constructing a prototype. Since the crucial point seems to be energy consumption for cooling the charcoal the first step could be to build such a prototype without cooling system. This prototype would be an example of an apparatus that can be placed outdoors, where the cooling could be natural, from the outdoor air, to minimize energy consumption. In the next step the possibility to use a non continuous performance system with charcoal regeneration to increase efficiency should be analyzed. The prototype could be built and tested in the NRPI radon chamber under controlled conditions. It is also possible in a second step to test it under real conditions in a family house, for example in Sweden.

The results from experiments indicate that the charcoal trap is more efficient during low air exchange rate. Hence, it is proposed to aim for poorly ventilated houses with this solution for radon suppressing. As described in chapter 3, there are several cost effective methods to suppress radon from the ground whereas reducing radon concentration in houses where the construction material is the source can be more difficult and costly. Therefore it is suggested to concentrate on the charcoal trap for houses with radon mainly from the construction material as an alternative to installing a mechanical ventilation system.

In continuing experiments the ability for activated charcoal to adsorb not only radon but also pollutants in the indoor air can be tested. If this proves successful it would give the charcoal trap an advantage compared to other radon suppressing methods.

A future plan is also to integrate the charcoal bed system with a device for radon measurement, which could automatically detect radon concentrations and control the charcoal cleaning system.

Appendixes

Appendix 1. Mitigation ratio vs ventilation rate
Appendix 2. The dose rate of gamma radiation near the adsorption device.

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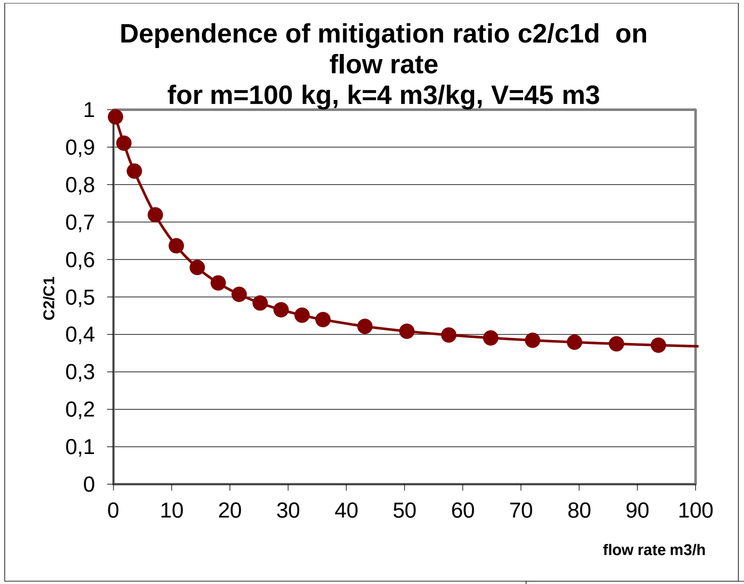
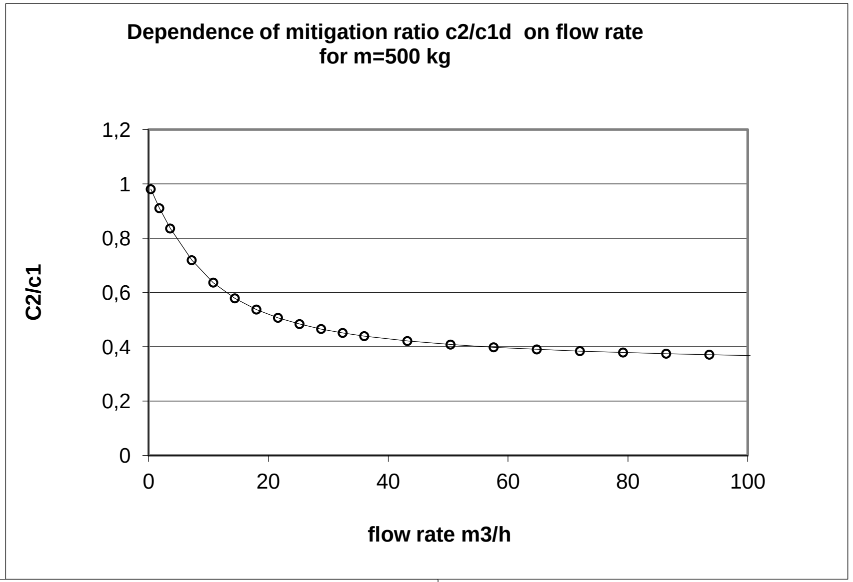
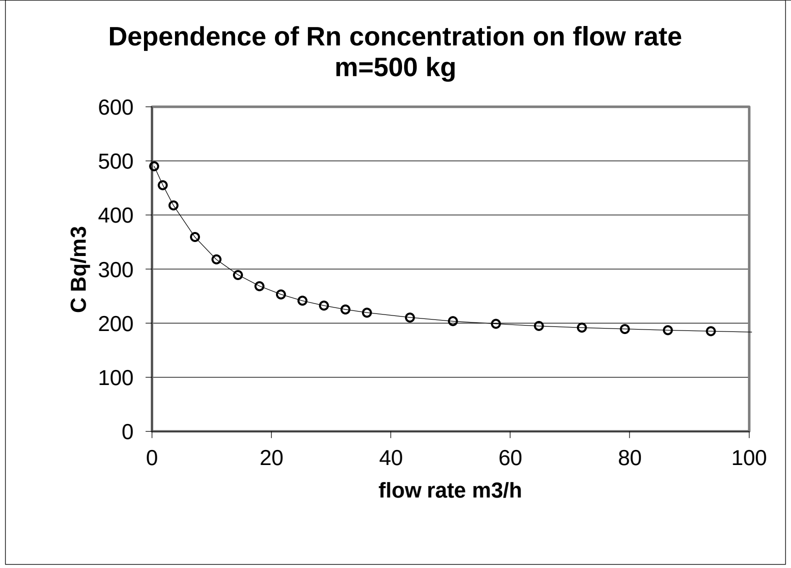
Appendix 1. Mitigation ratio vs ventilation rate

flow rate f,Q (m3/s)	flow rate f,Q (m3/hod)	T (hod)	1-exp(-lamba*T)	denominator	C2 (Bq/m3)	C2/C1 (vent 0)	C2/C1 (vent 0,01)	C2/C1 (vent 0,1)	C2/C1 (vent 0,2)	C2/C1 (vent 0,3)	C2/C1 (vent 0,5)			
0,0001	0,36	0	0	1,00	0	1,00	0,69	0,93	0,96	0,97	**0,98**	**m=**	**500**	**kg**
0,0005	1,8	0	0	1,00	0	1,00	0,35	0,77	0,86	0,90	**0,94**			
0,001	3,6	0	0,0000	1,00	0	1,00	0,28	0,70	0,82	0,87	0,92	**C1=**	**500**	Bq/m3
0,002	7,2	0	0,0000	1,00	0	1,00	0,24	0,66	0,79	0,85	0,90			
0,003	10,8	0	0,0000	1,00	0	1,00	0,23	0,65	0,78	0,84	0,90	**V=**	**45**	m3
0,004	14,4	0	0,0000	1,00	0	1,00	0,22	0,64	0,77	0,84	0,89	**k(K)=**	**10**	m3/kg
0,005	18	0	0,0000	1,00	0	1,00	0,22	0,63	0,77	0,83	0,89	**ventilation rate=**	**0,4**	h-1
0,006	21,6	0	0,0000	1,00	0	1,00	0,22	0,63	0,77	0,83	0,89	**ventilation rate**	**0,01**	
0,007	25,2	0	0,0000	1,00	0	1,00	0,22	0,63	0,77	0,83	0,89	**ventilation rate**	**0,1**	
0,008	28,8	0	0,0000	1,00	0	1,00	0,22	0,63	0,76	0,83	0,89	**ventilation rate**	**0,2**	
0,009	32,4	0	0,0000	1,00	0	1,00	0,21	0,63	0,76	0,83	0,89	**ventilation rate**	**0,3**	
0,01	36	0	0,0000	1,00	0	1,00	0,21	0,63	0,76	0,83	0,89	**ventilation rate**	**0,5**	
0,012	43,2	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,83	0,89			
0,014	50,4	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,83	0,89			
0,016	57,6	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,89			
0,018	64,8	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,89			
0,02	72	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,89			
0,022	79,2	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,89			
0,024	86,4	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,026	93,6	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			

flow rate f,Q (m3/s)	flow rate f,Q (m3/hod)	T (hod)	1-exp(-lamba*T)	denominator	C2 (Bq/m3)	C2/C1 (vent 0)	C2/C1 (vent 0,01)	C2/C1 (vent 0,1)	C2/C1 (vent 0,2)	C2/C1 (vent 0,3)	C2/C1 (vent 0,5)			
0,028	100,8	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,03	108	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,04	144	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,05	180	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,06	216	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,07	252	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,08	288	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,09	324	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,1	360	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,11	396	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,12	432	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,13	468	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,14	504	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,15	540	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,16	576	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,17	612	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,18	648	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,19	684	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,2	720	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,21	756	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,22	792	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,23	828	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,24	864	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			
0,25	900	0	0,0000	1,00	0	1,00	0,21	0,62	0,76	0,82	0,88			


Dependence of mitigation ratio c2/c1d on flow rate
for m=100 kg, k=4 m3/kg, V=45 m3


Dependence of mitigation ratio c2/c1d on flow rate
for m=500 kg


Dependence of Rn concentration on flow rate
m=500 kg

Appendix 2

The dose rate of gamma radiation near the adsorption device

The dose rate $\dot{\boldsymbol{D}}$ [Gy/h] of radon progeny adsorbed on activated charcoal is possible to determine applying the known rule for the dose rate of a point source $\boldsymbol{A}$ [Bq] of Ra 226 in distance $\boldsymbol{r}$ [m] from the source

$$\dot{D} = \Gamma.A / r^2 \ , \tag{4.1}$$

where Γ **= 2,51/-13 (Gy.m^2)/(h.Bq)** is the gamma constant of Ra 226 (in equilibrium with radon and its progeny). The geometrical shape of non-point sources and the self-absorption has to be considered. The equilibrium of the radon progeny in the AC is not the same as in hermetically sealed radium sources but the deviation can be neglected in this orientation study, we think so.

The geometry of the adsorption bed used in the Radon chamber is best approximated by a sphere with an equivalent radius $\boldsymbol{R}$ = 0,247 m, $R_m = R.\rho$ = 123 kg/m^2, (AC ρ = 500 kg/m^3)

The attenuation coefficient of gamma radiation μ = 7,1E-3 m^2/kg in carbon for mean energy 0,78 MeV of radon progeny can be used. So the mean free path of gamma photons in a sphere with radius R = 0,247 m is $\boldsymbol{R}_m.\boldsymbol{\rho}$ = 0,875.

According to the Compendium (RG Jaeger, editor, Engineering Compendium on Radiation Shielding, Vol.1, equ. (6.4-55), 1968) the fluence rate of gamma photons on the surface of a contaminated absorbing sphere is

$$\Phi = S_V.R.(1-(1-e^{-x})/x)/x, \quad \text{kde } x = 2\mu_s.R = 1,754 \tag{4.2}$$

$$\text{so } \Phi = 0,301.R.S_V, \ [\Phi] = \text{cm}^{-2}.\text{s}^{-1}, \ [S_V] = \text{cm}^{-3}.\text{s}^{-1} \tag{4.3}$$

Transformed to dose rate

$$\dot{D} = 3.0,301.\Gamma.A / R^2 = 3,72/-12.A = 5,35/-7 \text{ Gy/h} = 0,54 \ \mu\text{Gy/h}, \tag{4.4}$$

with $A = a.V$ [Bq] activity of radon in the bed in steady state, $a =$ 335 Bq/m^3, V = 45 m^3.

In the same Compendium is (equ. 6.4-53) a numerical relation for the dose rate at the distance $\boldsymbol{a}$ (up to 2 m) from the surface of a sphere

$$\Phi = (S_V.R/\pi).G(p, \mu.R), \quad \text{with } p = 1 + a/R \cdot \tag{4.5}$$

Transformed to dose rate

$$\dot{D} = (3.\Gamma.A/(\pi.R^2)).G(p,\mu.R) = 3,95E-12.A.G(p,\mu.R) = 1,78E-6.G(p;0,875) \text{ Gy/h} \tag{4.6}$$

From the table (Table 6.4.-4.) it is possible to get the shape correction G(p;0,875). In the table below are given dose rates for the actual AC bed used in the Radon chamber. Extrapolation to a = 0 is not sure, also due to that that the shape of the actual adsorption bed is quite different from a sphere), so it is only an orientation number, but near to that calculated directly.

p	a [m]	G(p;0,875)	$\dot{\boldsymbol{D}}$ [µGy/h]
1	0	(0,8)	(0,44)
1,25	0,0625	0,45	0,26
1,5	0,123	0,29	0,17
2	0,25	0,155	0,09
3	0,49	0,066	0,04
5	1,0	0,023	0,013
10	2,2	0,0058	0,004

As an actual example the dose rate from the adsorption bed in Experiment No. 4 CHAMBER with AC K48 (IETP) (ventilation coefficient k = 0,14/h, $\boldsymbol{a}_{\text{stac}}$ = 335 Bq/m^3)is given. The deposited activity $\boldsymbol{A}$ [Bq] of radon is derived in chapter 3

$$A = \sum A_i = \frac{1}{\kappa + \lambda} \cdot \frac{1 - \nu^n}{1 - \nu} . \dot{A}, \text{ with } \dot{A} = Q.a, \ \nu = \frac{\kappa}{\kappa + \lambda} \text{ and } \kappa = n.\kappa_0 = \frac{n.Q}{K.m} \qquad (4.7)$$

With $\kappa = n.Q/(K.m) = 0,00258$ it is possible to use approximate relations for the powers, so $\underline{A = K.m.a = 6,6.65.335 = 144000}$ **Bq** and $\dot{D}$ **= 0,54 µGy/h on the surface of the bed**.

When measuring gamma dose rates in the chamber contaminated with radon progeny in the air and on the walls the contribution to the dose rate from the radon bed has to be known. The Compendium gives fluence rate in the centre of an absorbing sphere (equ.6.4.-56)

$$\Phi = S_V.(1 - e^{-\mu.R})/\mu, \qquad (4.8)$$

which changes without absorption (air) to $\Phi = S_V.R$, therefore the dose rate is

$$\dot{D}_V = 3.\Gamma.A/R^2 = 4\pi.\Gamma.R.a = 2,33/-9 \text{ Gy/h} = 2,3 \text{ nGy/h}, \qquad (4.9)$$

with $A = a.V$ [Bq] the activity of radon in the chamber of 45 m^3, and an equivalent radius $\boldsymbol{R}$ = 2,2 m.

But the Compendium does not give the fluence rate in the centre of the sphere from contamination of the wall $\boldsymbol{b}_S$ [Bq/m^2]. It's possible to derive it as

$$\dot{D}_S = 4\pi.\Gamma.b_S \qquad (4.10)$$

At common conditions (aerosols, ventilation, mixing etc.) the deposit of radon progeny on walls is related with air borne concentration by $\boldsymbol{b}_S = 0,871.\boldsymbol{a}.V/\boldsymbol{S} = 0,64.\boldsymbol{a}$ [Bq/m^2] with $V/\boldsymbol{S} = 0,74$ m. For the Radon chamber is $\boldsymbol{b}_S$ □ $0,645.\boldsymbol{a}$ and the dose rate in the centre from the wall deposit is $\dot{D} = 0,68$ nGy/h.

The ratio of dose rate from the volume and surface activity $\dot{D}_V / \dot{D}_S = 3,4$, Decisive is, of course, is the ratio of this two contributions and the contribution of the radon in AC:

$\dot{D}/(\dot{D}_V + \dot{D}_S) = 180$, so the „background“ of the Radon chamber is negligible. This can be seen partly from the ratio of activities in the radon bed and in the chamber $A_{\text{Rn bed}}/A_{\text{chamber}} = K.\boldsymbol{m}/V_{\text{chamber}} = 9,5$, a next factor of 19 goes to the debit of geometry of concentrated/dispersed sources.

Experimental results for the gamma dose rate

During the experiment in the radon chamber (No. 4) these dose rates (including the background) were measured:

- **0,4 µGy/h** on the surface of the AC bed, range 0,25 – 0,55 µGy/h (compared with the calculated value **0,54 µGy/h**)
- 0,18 µGy/h 2 m apart the AC bed, about the centre of the chamber, range 0,14 – 0,22 µGy/h (here the common background of 0,15 µGy/h dominates)
- 0,16 µGy/h on the walls of the chamber, range 0,14 – 0,18 µGy/h (here the background of 0,1x µGy/h dominates also)

Within a factor of two the measured and calculated (including the estimation of the activity contained in the AC bed) gamma dose rates are in agreement. For better agreement higher concentrations in the Radon chamber are needed.