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Radon associated lifetime risk

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Abstract

Quantification of the risk associated to radon exposure is a major public health issue. Since the 1970s, 13 cohort studies provided results on the exposure-risk relationship in miner populations. Since the 1990s, more than 20 case-control studies evaluated the risk of lung cancer associated to indoor radon exposure in the general population. Nevertheless, due to variations in the study designs, in the characteristics of the studied populations and in factors that modify the exposure-risk relationship (age at exposure, attained age, time since exposure or exposure rate), it is difficult to verify the coherence of published results. Calculation of lifetime excess absolute risks (LEAR) is a way to compare the results of risk coefficients or models derived from different populations when applied to the same scenario of exposure. We present here some LEAR estimates based on the most recent epidemiological results. Different models are applied, derived from both miner studies (BEIR VI, Eldorado, French-Czech models) and indoor studies (European pooling project). The background reference rates are those proposed by the ICRP. Different scenarios of chronic low rate exposure are considered, including those used by the ICRP. Results illustrate the impact of age and time modifiers on the estimated LEAR. Results obtained using different models derived from miner studies are highly coherent. A good agreement is also observed between LEAR estimates obtained from miners and from indoor studies when applied to adapted scenarios. To conclude, calculation of LEAR allows demonstrating a very good coherence in currently available radon associated risk estimates. These results provide support to the elaboration of radiation protection measures regarding radon exposure.

European atlas of natural radiations: status of the indoor and geogenic radon maps

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Abstract

Based on its political and legal mission, in 2006 the JRC started to design the project of a European atlas of natural radiations. As first step a map of indoor radon was envisaged, given the radiological importance of the related exposure pathway. Since a seminal meeting in Prague, autumn 2006, the indoor Rn map is under way, with contributions from so far (August 2009) 15 countries. Individual measurement data are aggregated into a common grid by the participants. Grid data, which consist of grid cells filled with statistics on individual data, are then further processed by the JRC. In the aggregated dataset, no information on individual houses is available. We present the preliminary results in terms of descriptive statistics and maps, and some further results based on modelling steps, like spatial risk estimate. Indoor radon concentration is controlled by geogenic, climatic and anthropogenic factors. Among the latter are house and room types and living habits. In order to assess the hazard, or potential risk of indoor Rn exposure at a location, independent of anthropogenic factors, one needs a standardized quantity which is only controlled by the geogenic (and possibly average climatic) factors. Since a start-off meeting in Oslo, summer 2008, we are developing a harmonized European Rn index which can be estimated from different input data, as available in participating countries. Among these are indoor Rn concentrations, data on Rn in soil gas, geological classes, geochemical data and external dose rate. Currently algorithms are under discussion to convert such multivariate data, different country by country, into one radon index variable. Future steps of the European atlas of natural radiations may be maps of cosmogenic exposure and geochemical maps of natural radionuclides.

The Austrian Radon Programme – Past and future

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Abstract

As early as at the beginning of the 20th century radon measurements in water were conducted in Austria whereas radon measurements in air started in 1949. Several thousand measurements of radon in air in workplaces (caves, mines) and homes were conducted until 1972 by Pohl and Pohl-Rüling. Later measurement campaigns took place in Innsbruck, Salzburg, and Vienna but it was not until 1991 that a systematic and coordinated investigation of the radon situation in Austria began.

The main effort was to establish the Austrian radon map in the framework of a project called The Austrian Radon Project (ÖNRAP) with Harry Friedmann from the University of Vienna as project leader (1992 – 2004). Other main projects were to test various mitigation techniques (SARAH, Maringer, 1996 – 1998) and preventive measures. One project dealt with the influence of building characteristics on the radon concentration and the use of a Blower Door to determine the mean radon concentration of a building (RACODE, Ringer, 1997 – 2001).

Substantial efforts were undertaken to determine the radon exposure in kindergartens, schools, and town halls including the mitigation of the buildings with elevated radon levels.

The knowledge and experience gained by the projects led to the issue of three Austrian standards for radon measurement, mitigation and prevention, and to the issue of a radon information CD and a radon brochure.

In 2006 the Austrian Centre for Radon was established with the aim to better coordinate the radon efforts. Main tasks at present are the setup and maintenance of the official radon website and the design and implementation of the Austrian radon database. Other projects deal with the radon exposure in show caves and tourist mines, the investigation of the house to house variation of radon in a community and the investigation of the causes of that variability, and the determination of radon levels outdoors.

This paper will present and discuss past and future efforts in Austria to determine the radon exposures in homes and workplaces and to reduce the radon risk of the population.

Introduction

“Bergkrankheit” (or mountain sickness), among sixteenth century pitchblende (radium) miners in the Erz Mountains of Germany, was the earliest evidence of the health hazard of inhaled radon and its progeny. However, it was not until the 1920's that the lung disease was attributed to radiation, as opposed to inhaled arsenic (Miller 1990). And it was not until the 1970's that residential exposure to indoor radon began to be considered as a potential public health risk (Nero 1988).

In 1988 Radon was classified as a human carcinogen by the International Agency for Research on Cancer (IARC 1988).

Since the 1980's substantial efforts had been undertaken in many countries to evaluate the radon problem. The annual dose from inhalation of radon gas and its decay products represents typically about one-half of the effective dose received by members of the public from all natural sources of ionizing radiation (UNSCEAR 2008).

This paper describes the studies and projects with respect to radon in Austria in the past, discusses the lessons to learn, and gives a foresight to the future radon strategy.

Radon in Austria until 1991

As early as at the beginning of the 20th century radon measurements in water were conducted in Austria (balneology) whereas radon measurements in air started in 1949. Several thousand measurements of radon in air in workplaces (caves, mines) and homes were conducted until 1972 by Pohl and Pohl-Rüling. Later measurement campaigns took place in Innsbruck, Salzburg, and Vienna but it was not until 1991 that a systematic and coordinated investigation of the radon situation in Austria began (BMGSK 1992).

Radon in Austria after 1991

At the beginning of the 1990's publications from EU, ICRP, WHO, and IAEA gave an international framework to the radon issue (EU 1990, ICRP 1990, WHO 1993, ICRP 1993, IAEA 1996).

In 1991 a project with the aim to evaluate the radon situation in Austria and to provide a concept with respect to a national radon programme was conducted (BMGSK 1992).

Based on EU 1990 and ICRP 1990 the Austrian Radioprotection Commission passed a recommendation concerning ‘action levels for indoor radon’ in 1992 (BMGSK 1994). Key elements of that recommendation are

- action levels for existing and new buildings (400 and 200 Bq/m³, respectively)
- the recommendation to set up a radon potential map of Austria
- the recommendation to set up guidelines for mitigation and prevention
- the recommendation to set up a folder to inform the population

In the following legislative matters and the major projects and studies are outlined.

Radon in Austrian legislation and standards

Indoor radon is dealt with in the recommendation of the Austrian radiation protection commission as mentioned above and is not subject to specific legislation.

On the other hand, radon in work places is regimented by the Radiation Protection Law 2006 and the Natural Radiation Sources Ordinance 2008. The Ordinance applies to the following four working areas: water supplies, underground work places in mines, tunnels, etc., show caves and tourist mines, and radon spas. So far, the response of the concerned companies to the legal requirement to induce an evaluation of the radon exposure to the staff was very weak.

A series of Austrian Standards (ÖNORM S 5280 Radon) has been issued dealing with Part 1: Measuring methods and their range of applications, Part 2: Technical precautionary measures in the case of buildings and Part 3: Remedial measures on buildings.

The Austrian Radon Project (ÖNRAP, 1992-2004, Friedmann)

The main project was the establishment of the Austrian radon map (Friedmann 2005). Radon measurements were conducted in about 16,000 living and sleeping rooms in Austrian dwellings. The results were normalised to a standard situation (no basement, ground floor level, ...) and therefore the normalised data are an indicator for the radon potential, or in other words, the probability to measure a certain radon level in a specific dwelling in a municipality. Fig. 1 shows the Austrian radon potential map.

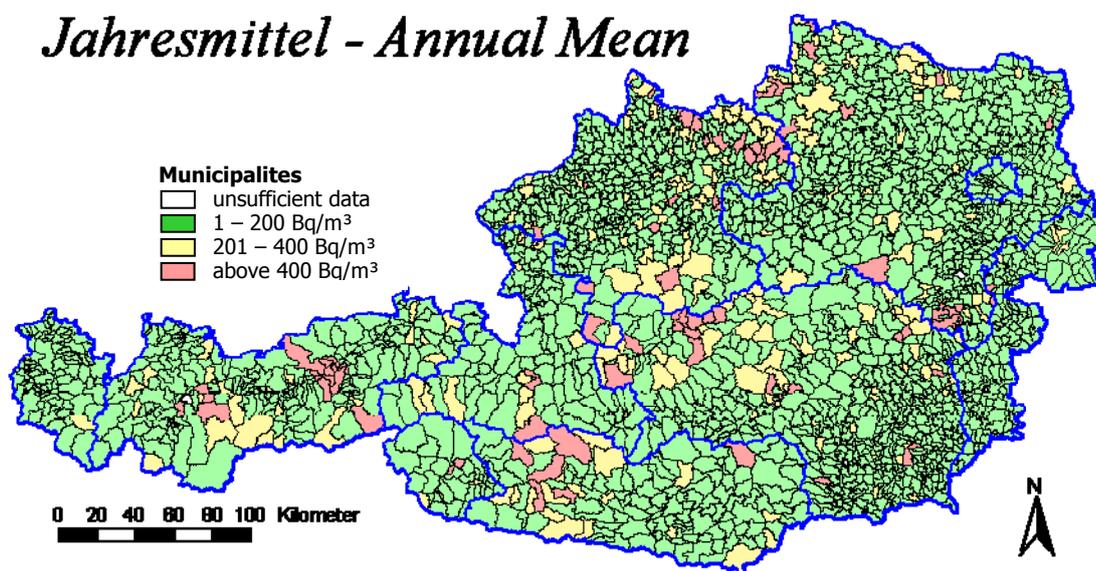


Fig. 1. The Austrian radon potential map.

Radon surveys and mitigations in kindergartens, schools, and town halls

The radon levels in about 800 kindergartens, 350 schools, and 450 town halls have been determined in Austria (mainly in the province of Upper Austria) in the last 10 years. 2,6% of all kindergartens and schools and 1,6% of all town halls showed mean radon levels above 1000 Bq/m³ and 5,9% (kindergartens, schools) and 12% (town halls)

above 400 Bq/m³. In total about 130 buildings needed to be mitigated (or are in the process of mitigation since the priority was linked to the radon level) (Ringer 2002, Maringer 2004, Ringer 2004, AOOELR 2009).

Radon in low energy and passive houses (2009-2011, Ringer)

Airtight building shells, low air exchange rates and specific construction and heating technologies like air-soil heat exchanger gave rise to the concern that radon levels may be elevated in low energy and passive houses. A project is currently investigating the effect of those new building types on indoor radon. This project is a subtask of the EU-project “Radon Prevention and Remediation (RADPAR)”.

(<http://web.jrc.ec.europa.eu/radpar/index.cfm>)

Complete radon survey in three communities (2009-2011, Ringer)

The aims of the project are to study the dwelling to dwelling variation within a municipality, to evaluate the influence of building characteristics and geology, to verify the results of the Austrian Radon Project, to train local building professionals to mitigate dwellings, and to raise awareness with respect to radon within the municipalities and beyond. For that purpose the radon and thoron concentration of every single dwelling in three municipalities with elevated radon potential is to be measured. Furthermore, the soil gas concentrations in the main geological formations in this area will be determined.

After a public information event and after the distribution of the track etch detectors, presently, the long-term radon and thoron measurements are conducted (January – July 2010).

Mitigation of dwellings with elevated radon levels (SARAH, 1996–1998, Maringer)

This study served to test mitigation methods adapted to typical Austrian houses, to gain experience, and to evaluate typical mitigation costs.

Three dwellings with elevated radon levels were mitigated by applying sub-slab depressurisation, sub-house depressurisation and sub-slab ventilation, respectively, as mitigation method.

The main results are given in Table 1.

Table 1. Main results of the mitigation project.

	Gutau	Königswiesen	Traun
method	sub-slab depressurisation	sub-house depressurisation	sub-slab ventilation
mean radon concentration before mitigation (Bq/m ³)	500	900	600
mean radon concentration after mitigation (Bq/m ³)	250 (passive) 50 (active)	180	360
cost (EURO)	14000	7000	400
specific radon reduction costs (€/m ² Bqm ⁻³)	0.23	0.11	0.015

Radon Potential Determination by Controlled Building Depressurisation (RACODE, 1997–2001, Ringer)

In this study a Blower Door (BD) was used to mechanically depressurise houses in a controlled and reproducible manner to determine the radon entry rate. Furthermore, diagnostic tests like “Opening A Door” or “Guard Zone” were carried out to characterise the leakage pattern (i.e. Effective Leakage Area ELA and flow exponent n) of the house. With these data and (simplified) modelling mean indoor radon concentrations are deduced and compared with the results of long term passive radon measurements.

Besides the determination of the mean radon concentration this new method should be useful for the rapid assessment of the effectiveness of mitigation measures if the same kind of measurements at defined pressure conditions are performed before and after mitigation (Ringer 2005).



Radon in work places

With respect to radon exposure in work places major studies – apart from those studies in kindergartens, schools, and town halls as described above – concerned water supplies, tourist mines and show caves.

The results show that the radon concentrations in the water supplies were lower as expected, being in 55% of all measurement sites below 1000 Bq/m³, in 91% below 5000 Bq/m³, and with a maximum value of 38700 Bq/m³. This leads to exposures that are below 2 MBqh/m³ (corresponding to approx. 6 mSv/a) in 42 water supplies. However, for the remaining three water supplies maximal occupational exposures due to radon of 2.8 MBqh/m³ (~ 10 mSv/a), 15 MBqh/m³ (~ 50 mSv/a), and 17 MBqh/m³ (~ 56 mSv/a), respectively, were determined. These water supplies were mitigated. Mitigation measures were: evacuation of the outlet air of the vaporizer by means of a fan, installation of a fan in the exhaust air duct of the compensating reservoir, sealing of drain shafts, mechanical ventilation of the office. In all water supplies the radon exposure was reduced to below 0.8 MBqh/m³ at a cost of approx. € 750,- to € 1.000,- (Ringer 2006, Ringer 2008).

For the purpose of determining the radon exposure of guides and of evaluating the determining factors on the radon concentration, such as climate, structure and geology, long-term time-resolved measurements over 12 months have been carried out in 6 tourist mines and 2 show caves - with 5 to 9 measuring points each - to obtain the course of radon concentration throughout the year. First results are presented in Ringer 2009. The final report is expected by the end of 2010.

Information of the public

A number of folders and brochures has been published to inform the public on the radon issue. One folder deals with radon in water supplies.

Furthermore, a Radon-CD was produced which presents basic information on radon in a multimedia way and a specific radon website was set up by the Ministry for Environment (www.strahlenschutz.gv.at) in addition to the existing Austrian Radon Project website (<http://homepage.univie.ac.at/harry.friedmann/Radon/welcome.htm>).

Presently, a centralised, web-based radon database is being developed. The purpose is to gather all indoor radon related data like measurements, mitigations, preventive measures, building characteristics etc. in one single database. These data are periodically evaluated to monitor the radon situation in Austria and to provide up-to-date information to the public.



The Austrian Centre for Radon

Based on the Radiation Protection Law the Austrian Centre for Radon was established in 2006 within the Competence Centre of Radioecology and Radon of the Austrian Agency for Health and Food Safety. The principal aim is to coordinate the radon efforts in Austria.

Present tasks are the design and implementation of the above mentioned Austrian radon database and the setup and maintenance of the official radon website. Other main projects are mentioned in this paper (radon in show caves and tourist mines, radon in low energy and passive houses, complete radon and thoron survey in three municipalities).

Discussion

As described in the preceding chapters, an important number of projects and studies has been conducted over the last 20 years in Austria. These efforts served to quantify the radon problem and to find solutions. Radon prone areas were identified, research on the factors determining the indoor radon concentration resulted in a better understanding of

the relevant building characteristics, efficient remedial and preventive measures were tested and established, extensive surveys in kindergartens, schools, town halls, water supplies and show caves and tourist mines led to a reduction of the radon risk of the concerned individuals. The knowledge gained was used for legislative matters, for the setup of Austrian Standards, for information material for the public. Finally, the Austrian Centre for Radon was established to better coordinate and concentrate the radon efforts.

But: What was the actual impact on the radon exposure in Austria, how many lives have been saved?

So far, the impact in terms of radon risk reduction was very little. Priority was given to provide help (i.e. information, measurement, mitigation) to those with a high individual radon risk (i.e. high radon levels at home or at work). However, only approximately 0.07 % of the 70,000 buildings which are expected to exceed the action level of 400 Bq/m³ for existing buildings have been mitigated so far! Even worse, due to missing legal requirements to implement preventive measures in new buildings (at least in radon prone areas) the number of radon resistant new buildings is negligible. Bearing in mind that the total building stock increased by over 70 % in the last 40 years in Austria this was clearly a missed opportunity to decrease the collective radon risk.

Finally, despite folders, brochures, websites, and a radon CD public awareness is still very low.

Future tasks

Following the arguments of the previous chapter and with a view to recent publications and drafts on the radon issue (WHO Radon Handbook 2009, ICRP Radon Statement November 2009, EU BSS draft, IAEA BSS draft), the prime future tasks can be identified as:

- There is the need of a binding and executable legislation together with clear assignment of responsibilities to federal and local authorities as this is a prerequisite for an effective radon policy
- Implementation of compulsory preventive measures in building codes as this is an essential and cost-effective measure to reduce the collective radon risk
- Surveys in town halls and other public buildings in all radon prone areas to raise radon awareness of so-called multipliers (local politicians, local administrations)
- Frequent information campaigns to raise awareness of the population
- Extensive measurement campaigns to identify the buildings with elevated radon levels; as a consequence this will require training of building professionals for mitigation
- Integration of the radon issue in school and academic education (builders, engineers, architects, physicians)
- Improvement of the existing radon potential map (further indoor measurements, correlation with geology)

The future tasks should be shaped in a national strategy which also explains its implementation with respect to competent authorities and responsibilities, required financial resources, and evaluation and monitoring of the radon situation.

Conclusions

20 years of substantial efforts led to a widespread knowledge with respect to radon prone areas, factors determining indoor radon levels, remedial and preventive measures, radon in schools, kindergartens, town halls, water supplies, and show caves in Austria. Austrian radon standards and various information material for the public were issued.

However, the impact of these efforts in terms of lives saved or reduction of the mean radon risk was very low so far.

Therefore, in order to convert this knowhow into reduced health risk a number of measures are required like radon specific legislation including the clear assignment of responsibilities, implementation of preventive measures in building codes, further surveys and measurement campaigns to identify high radon buildings, frequent information campaigns, training of builders, engineers, and architects, and the improvement of the existing radon potential map for Austria. A national radon strategy which includes above tasks has to be set up.

References

- AOOELR. Radon in Oberösterreich: Untersuchungen in oö. Amtsgebäuden. Amt der Oberösterreichischen Landesregierung, Direktion Umwelt und Wasserwirtschaft, Abteilung Umweltschutz/Strahlenschutz (Eds). Endbericht; April 2009
- BMGSK. Radon in Österreich: Bestandsaufnahme bisheriger Untersuchungen und Konzepte für ein weiteres Vorgehen hinsichtlich eines nationalen Radonprogrammes. In: Forschungsberichte des Bundesministeriums für Gesundheit, Sport und Konsumentenschutz, Sektion III; 1992
- BMGSK. Empfehlung der Strahlenschutzkommission betreffend "Richtwerte für die Radonkonzentration in Innenräumen". In: Radon in Österreich 1993. Forschungsberichte des Bundesministeriums für Gesundheit, Sport und Konsumentenschutz, Sektion III; 1994
- Friedmann H. Final Results of the Austrian Radon Project. Health Physics, vol. 89(4), pp. 339-348; 2005
- ICRP. 1990 Recommendations of the International Commission on Radiological Protection. Publication 60. Annals of the ICRP Vol. 21 No. 1-3; 1990
- ICRP. Protection Against Radon-222 at Home and at Work. Publication 65. Annals of the ICRP Vol. 23 No. 2; 1993
- ICRP. Statement on Radon. ICRP Ref 00/902/09.
[http://www.icrp.org/docs/ICRP_Statement_on_Radon\(November_2009\).pdf](http://www.icrp.org/docs/ICRP_Statement_on_Radon(November_2009).pdf);
November 2009
- International Agency for Research on Cancer. Man-made mineral fibres and radon. IARC Monographs on the evaluation of carcinogenic risks to humans. Vol. 43. Lyon; 1988
- Maringer FJ, Ringer W, Kaineder H, Hofstädter C, Nadschläger E, Sperker S. Results and Conclusions from the Upper Austrian Radon and Indoor-Pollution Study in

- Kindergartens and Schools. In: Proceedings of „11th International Congress of the International Radiation Protection Association“, Madrid, 23 - 28 May 2004
- Miller E W. Radon Hazard: A Historical Perspective. In: Environmental Radon: Occurrence, Control, and Health Hazards. Majumdar S K Schmelz R G and Miller E W. Ed. The Pennsylvania Academy of Science, Easton, PA, USA; 1990
- Nero A V. Radon and Its Decay Products in Indoor Air: An Overview. In: Radon and its Decay Products in Indoor Air. ed. Nazaroff W W and Nero A V. John Wiley & Sons; 1988
- ÖNORM S-5280-1. Radon – Measuring methods and their range of applications. Österreichisches Normungsinstitut; 2008-05-01
- ÖNORM S-5280-2. Radon – Technical precautionary measures in the case of buildings. Österreichisches Normungsinstitut; 2003-03-01
- ÖNORM S-5280-3. Radon – Remedial measures on buildings. Österreichisches Normungsinstitut; 2005-06-01
- Ringer W, Bernreiter M, Kaineder H, Maringer FJ, Karg V, Nadschläger E. Radonbelastung in Oberösterreichischen Kindergärten. In: Proceedings 18. ÖSRAD Tagung „Konsequenzen der EU-Richtlinie 96/29/EURATOM für die radiologische Umweltüberwachung“, 6. Juni 2002, Wien; 2002
- Ringer W, Bernreiter M, Kaineder H, Maringer FJ. Radon concentrations during working time vs. total average radon concentrations in Austrian kindergartens and schools. In: Proceedings of „11th International Congress of the International Radiation Protection Association“, Madrid, 23 - 28 May 2004
- Ringer W, Kaineder H, Maringer FJ, Kindl P. Determination of the Radon Potential of a Building by a Controlled Depressurisation Technique (RACODE). In: The Natural Radiation Environment VII, Eds.: McLaughlin, Simopoulos, Steinhäusler, Elsevier; 2005. p. 221-231
- Ringer W, Simader M, Bernreiter M, Aspek W, Kaineder H. Occupational Radiation Exposure in Upper Austrian Water Supplies and Spas. In: Proceedings of Second European IRPA Congress on Radiation Protection: From Knowledge to Action, Paris, 15. – 19. Mai 2006
- Ringer W, Simader M, Bernreiter M, Kaineder H. Mitigation of Three Water Supplies with High Radon Exposure to the Employees. Radiation Protection Dosimetry 2008; 130(1), 26-29; doi: 10.1093/rpd/ncn126.
<http://rpd.oxfordjournals.org/cgi/reprint/ncn126?ijkey=ycEeGfG9uOVeAaV&keytype=ref> (free PDF)
- Ringer W, Gräser J, Aspek W, Gschnaller J. Radon in Austrian Tourist Mines and Show Caves. In: Proceedings of 6. Gemeinsame Tagung des Österreichischen Verbandes für Strahlenschutz ÖVS mit dem Fachverband für Strahlenschutz FS: Leben mit Strahlung - von den Grundlagen zur Praxis, Alpbach, 21. – 25. September 2009
- UNSCEAR. Annex E: Sources-to-effects assessment for radon in homes and workplaces. UNSCEAR 2008 Report to the General Assembly (to be published)
- WHO. Handbook on Indoor Radon. ISBN-13: 9789241547673 or
http://whqlibdoc.who.int/publications/2009/9789241547673_eng.pdf; 2009

Norway's new national radon strategy

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Abstract

A multidisciplinary working group, including the Norwegian Radiation Protection Authority (NRPA), was initiated in May 2007 by the Norwegian Ministry of Health and Care Services to suggest a coordinated national effort to reduce radon exposure. Their findings were that since radon levels in Norwegian dwellings are log-normally distributed, most of the radon cancers are induced at low levels. They estimated that 70 % of the annual lung cancers in Norway induced by radon occur at levels below 200 Bq/m³. A successful radon strategy therefore needs to reduce not only high but also moderate radon levels. Radon exposure occurs in all categories of buildings i.e., individual risk comes from the sum of exposures from different buildings; work and leisure. The working group's findings lead to the Norwegian government publishing a new national strategy for radon in July 2009. The strategy seeks to reduce the sum of all exposures and is directed at all categories of buildings. The national strategy aims to achieve radon levels (a) that are as low as practically achievable and (b) that are below given maximum limits. It is divided into the following sections – radon in: land planning, construction of new buildings; existing dwellings, communities with extreme radon problems, public buildings (including schools and kindergartens) and in work places. The NRPA has been appointed by the Norwegian government to coordinate the implementation of the new national radon strategy in the period 2010–2014. Furthermore, the NRPA has changed its recommendations concerning radon, based on scientific evaluation of the current literature and in accordance with the new national strategy. These changes include ALARA and new action and maximum recommended radon levels of 100 Bq/m³ and 200 Bq/m³, respectively. This presentation will present the radon strategy, its justification and the planned implementation.

Introduction

Radon (Rn-222) is a radioactive noble gas produced continually in bedrock material and soils as part of the uranium-238 decay series. Both soil air and groundwater can therefore contain radon. It has a relatively short half-life (3.82 days) and is therefore potentially mobile before it undergoes radioactive decay. Generally, when discussing radon and health effects, one implicitly refers to α -emissions from radon gas and selected daughter nuclides, notably Po-218 and Po-214 (half-lives of approximately 3 minutes and 160 microseconds, respectively).

Increased mortality of metal miners working in the Erz Mountains, central Europe, due to unspecified respiratory illnesses was observed as early as in the 1500s. Recognition that lung cancer was to blame came in the late 1800s, with radon being proposed as the likely cause for the lung cancers in the 1920s. Today, radon is one of the most studied human carcinogens and was recognised as such by the International Agency for Research on Cancer in 1988¹, based on the 11 largest studies on miners (60 000 individuals) which have also been evaluated by the Biological Effects of Ionizing Radiation panel (BEIR VI, 1999).

Radon typically enters buildings from the underlying ground, especially during colder periods as heating a building creates a pressure gradient sucking soil air into the building via cracks and apertures in its foundation. Inhalation of radon and its decay products leads to the deposition of α -particles in the respiratory system. The α -particles have a high linear energy transfer and are quickly stopped by surrounding body tissue. This leads to lots of energy being deposited within very small areas and the inherent high relative biological effectiveness of α -emissions. The final endpoint from received doses is lung cancer; indeed radon is recognised as the second largest cause for lung cancer after active smoking. Strong evidence exists that a single α particle can cause complex clustering damage to a cells DNA and induce major genomic changes e.g. mutation (BEIR VI, 1999). The risk attributed to radon exposure is therefore assumed as a linear relationship with no threshold and no dose-rate dependence.

Several studies have more recently investigated indoor radon and lung cancer, notably three large pooled analyses (Lubin et al., 2004; Darby et al., 2005; Krewski et al., 2006). Importantly, the pooled analyses also made corrections for the smoking habits of study individuals. The pooled analyses show a linear relationship between radon exposure and the risk of developing lung cancer, also at low/moderate exposure levels i.e. applicable to the general population. The risk of radon-induced lung cancer increased with exposure and is proportional to the indoor radon concentration and the exposure time. Moreover, the pooled analyses confirmed there is no lowest threshold radon concentration where no risk occurs. The risk is greatest for smokers and former smokers, though never-smokers can also develop lung cancer as a result of radon exposure. Specifically, the pooled analyses have shown:

- the relative increase in lung cancer risk from a given radon exposure is the same for smokers and non-smokers
- the absolute radon risk is higher for smokers compared to non-smokers
- the majority of lung cancers induced by radon exposure are caused by a synergy effect between smoking and exposure to radon and these lung cancers could have been avoided if the individual either had not chosen to smoke or had not been exposed to radon.

In total, the studies of miners coupled with pooled analyses present strong scientific evidence that exposure to radon leads to an increased risk of lung cancer. Other health effects that have been associated to radon exposure include leukaemia in children, cardiovascular disease, stomach cancer, multiple sclerosis (MS) and skin cancer. However, such studies often rely on differing methodologies producing conflicting

¹ <http://monographs.iarc.fr/ENG/Monographs/vol43/volume43.pdf>

results and conclusions such that to date there is no scientific consensus for either proving or disproving such health effects are associated to radon exposure.

The Norwegian Experience

Increased focus on radon nationally and internationally led to The Norwegian Ministry of Health and Care Services initiating and leading a multi-sector working group in autumn 2007 to report on the challenges faced and available mitigation measures regarding radon (*arbeidsgruppen for samordnet innsats mot radon*). The working group consisted of delegates from the Ministry of the Environment, the Norwegian Labour Inspection Authority, the National Office of Building Technology and Administration, the State Housing Bank, the National Institute for Public Health, the Norwegian Directorate of Health and The City of Oslo; the Norwegian Radiation Protection Authority (NRPA) acted as secretariat.

Radon concentrations measured in Norwegian homes are approximately log-normally distributed; most Norwegians are exposed to low to moderate radon levels in the home (Fig. 1).

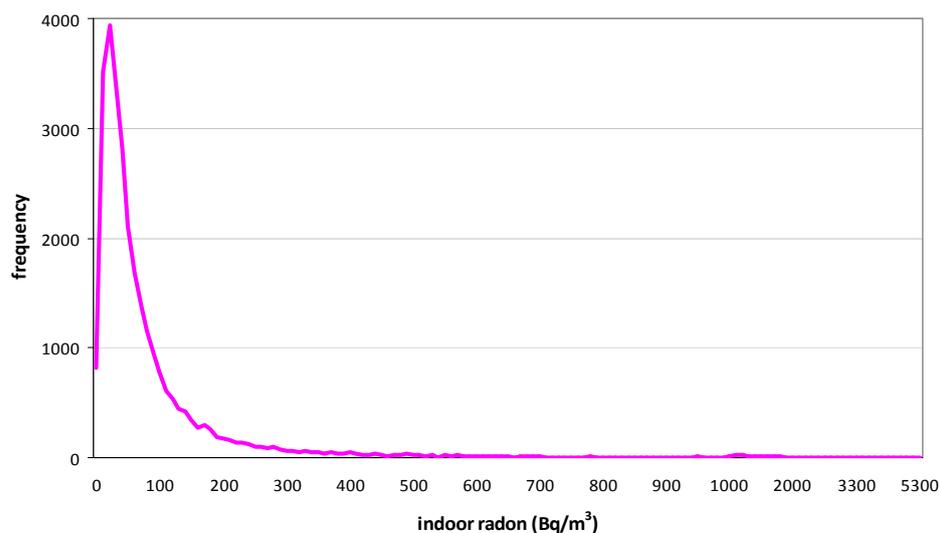


Fig. 1. Results from a national radon mapping campaign in 2000-2001. One radon measurement per dwelling, calculated as the annual average. Notice change of scale intervals on x-axis at indoor radon concentrations >1000 Bq/m³; Total number of dwellings measured approximately 29 000. [StrålevernRapport 2001:6] available on www.nrpa.no (in Norwegian).

However, preliminary calculations based on the approach used by Darby et al., (2005) adjusted for the difference between the assumed average indoor radon concentrations in the United Kingdom and Norway (59 Bq/m³ versus 88 Bq/m³) have shown that approximately 300 people die each year in Norway from radon-induced lung cancer. Due to the distribution of indoor radon concentrations it has been estimated that approximately 70 % of these radon-induced lung cancer deaths occur at indoor radon concentrations below 200 Bq/m³. To reduce the number of radon deaths substantially therefore requires that radon concentrations are reduced in all buildings, not just in the highest risk areas as all reduction of radon concentration and exposure time will have a

favourable impact on health. Taking the population as a whole, health benefits from reducing indoor radon exposure can be considerable, even if only a modest reduction is achieved, so long as the reduction applies to a large number of buildings.

The multi-sector working group ended in the spring of 2009, when it formally submitted its report to the Ministry of Health and Social Care Services. The report and recommendations form the basis the Norway's new national strategy for the reduction of radon exposure in Norway, published 1 July 2009.

The national radon strategy

The national strategy is a tool for management and coordination of radon-prevention work in many sectors and shall be implemented in the five-year period 2009-2014. The strategic goals stated in the strategy are that the Norwegian government will:

- Work towards reducing radon levels in all types of building and premises to below the stated limits
- Contribute to reducing radon exposure in Norway as low as reasonably achievable.

As low as reasonably achievable implies that radon exposure should be reduced as much as reasonably possible, not only to a level just below the stated maximum limit. The choice of strategic goals is based on the knowledge that the risk from radon is proportional to exposure with no lower safe threshold value, such that all reduction of radon exposure will yield a health benefit. Radon can be present in all types of building and premises, and efficient prevention of radon risk therefore implies that radon levels must be reduced generally across society. The strategic goal of achieving as low radon levels as reasonably achievable is supplemented with legally binding limits where appropriate. This will ensure that the authorities have a basis for effective enforcement and compliance.

New indoor radon limits for certain types of building have been adopted (100 Bq/m³, action required; 200 Bq/m³, maximum) which are in line with the current recommendations from the World Health Organisation (WHO 2009), the Nordic Radiation Protection Authorities² and are supported by the NRPA.

Sub-strategies are proposed for work on:

- Radon in land planning
- Radon and the construction of new buildings
- Radon in existing dwellings
- Norwegian communities exposed to especially serious radon problems
- Radon in buildings and premises to which the general public are admitted
- Radon in the workplace

Stated goals and suggested measures for each sub-strategy are briefly described as follows:

² <http://www.nrpa.no/dav/a4c7e5d25d.pdf>

Radon in land planning

Here, the stated goal is:

- Radon must be emphasised in a systematic and sufficient way in all land planning.

A principal challenge for the work of local authorities in land planning in relation to radon will be to classify the land in relation to the radon hazard. Measures suggested in the national strategy include studying the relationship between radon hazard and geological conditions, as well as which requirements must be set for radon protection of buildings in relation to different degrees of radon hazard. A map-based tool for use in assessing radon hazard when planning land use at local and regional levels is suggested as well as establishing routines and systems that ensure that data concerning the building ground and geology, radon in household water supplies from drilled wells, building construction and radon in the indoor air are collected, both from the public and private sectors. These data should be made available for relevant local, regional and central authorities for administrative/management purposes. Identifying the occurrence of local areas with permeable surficial sediments/deposits and radium-rich bedrock is stipulated, as such areas are of importance with regard to radon levels in Norway.

Radon and the construction of new buildings

Here, the stated goal is:

- New buildings that are being constructed in Norway must have indoor radon concentrations that are as low as reasonably achievable and always less than 200 Bq/m³.

This target can be achieved by setting specific requirements for anti-radon measures in all new buildings in the technical regulations pursuant to the Planning and Building Act. Specific requirements would include the use of radon barriers (e.g. a membrane), or the required ventilation of the ground below the building. It is difficult to estimate values for indoor radon concentrations in structures before they have been completed and taken into use. However, by setting requirements for preparing the buildings foundations such that it is possible to use active ventilation of the ground, it will be easier to carry out subsequent initiatives with ventilation/pressure modification to reduce the radon concentration to an acceptable level if the indoor radon levels are deemed too high in the finished building. Radon surveys should be carried out in all new buildings when they are taken into use. Specific measures include the possibility of establishing standardised methods/minimum requirements for radon-preventive measures to be used when constructing new buildings and premises. Supplementary guidance material will be necessary, generated by the National Office of Building Technology and Administration in collaboration with the NRPA. Such user-oriented guidelines that describe the regulatory framework and clarify the areas of responsibility for radon when constructing new buildings will be important for both builders and the local authorities supervising development.

Radon in existing dwellings

Here, the stated goal is:

- The proportion of dwellings with indoor radon concentrations exceeding 200 Bq/m³ must be considerably reduced by 2020. The average indoor radon concentration must be reduced considerably by 2020, and a large proportion of dwellings must have achieved as low radon levels as reasonably achievable.

Different measures other than legal initiatives are the desired option to motivate and encourage homeowners to carry out radon surveys and technical preventive measures in their own homes. One condition for achieving the targets is that the radon-reducing building engineering methods are cost-efficient, safe and reliable. The development of better expertise and increased capacity for carrying out radon-reduction methods within the building industry will also be important. Specific suggested measures include undertaking systematic studies of radon in dwellings situated in all municipalities, the development of standardised radon-reducing measures for existing dwellings and generating campaigns to inform the population about radon: health risks, surveys and the implementation of remedial measures in dwellings. An additional proposal currently under review is the inclusion of radon measurements/status in home buyer reports.

Norwegian communities exposed to especially serious radon problems

Here, the stated goals are:

- All Norwegian communities in "radon extreme areas" are mapped.
- Acceptable health conditions for the inhabitants of such communities are ensured through the introduction of necessary measures.

Extreme indoor radon concentrations can be measured in some buildings situated in specific areas in Norway. A large proportion of the buildings may have high radon values in such areas, including extreme values up to 50 000 Bq/m³ in a few cases. Several such areas have been documented, but because the majority of Norwegian buildings have not yet been surveyed for radon, the possibility of finding other radon extreme areas during future surveys cannot be excluded. Such areas require special measures and follow-up, such as intensive information and survey campaigns when indications exist that a high radon hazard is present and assessing the need for individual assessment and medical follow-up, if necessary, of persons who have been exposed to very high radon concentrations over long periods.

Radon in buildings and premises to which the general public are admitted

Here, the stated goals are:

- The proportion of buildings with indoor radon concentrations above the maximum limit (200 Bq/m³) is to be reduced considerably by 2020.
- The average indoor radon concentration is to be reduced considerably by 2020, and a large proportion of buildings have achieved as low radon levels as reasonably achievable.
- All schools and kindergartens have radon concentrations below the stated maximum limit.

The focus in this sub-strategy has been placed upon schools and kindergartens especially; the combination of obligatory presence and young individuals is deemed as a need for especially stringent requirements. The NRPA has completed an estimation of the costs involved in measuring all schools and kindergartens for radon and completing mitigation measures were appropriate (NRPA report, in press). The cost estimates were based upon the newly drafted legal limits for such buildings (100 Bq/m³ action and 200 Bq/m³ maximum), national statistics archive data and cost estimates received from recognised companies in the radon sector. Total costs were estimated as 50 MNOK for all kindergartens, primary and secondary schools [approximately 6.3 million €]. Other categories of public buildings will also be important however, such as hospitals, shopping malls, office buildings, hotels, restaurants, banks, commercial buildings, jails etc. Such buildings are often large and they contribute to the radon exposure of a large number of individuals. Those who are exposed to radon in such areas have no possibility of knowing that they have been exposed, or be in a position to reduce the exposure levels themselves.

Radon in the workplace

Here, the stated goal is:

- Norwegian workplaces shall have building and equipment conditions that ensure radon concentrations are suitable for a fully adequate working environment, based on consideration of employees' health, safety and the working environment.

Radon gas is the greatest source of exposure for ionising radiation amongst all Norwegian employees together. The working environment is already regulated with regard to other potential health risks such as asbestos and indoor climate, and initiatives outlined within this sub-strategy will also have a positive impact by reducing employees' exposure to radon. Together with the previous sub-strategy it is seen as important to study and devise standardised radon measurement techniques and anti-radon measures in different types of building as well as contributing to the development of knowledge about radon measurement techniques and anti-radon measures in large buildings generally.

Implementation of the national radon strategy

To implement the strategy's wide-ranging and ambitious goals the Ministry of Health and Social Care Services appointed the NRPA to establish a coordination group that would follow up the strategy. The coordination group includes participants from sectors that have policy instruments relevant to radon that will be able to suggest and produce radon mitigation measures. The group have met to discuss an overall plan for implementation as well as the establishment of specific working groups which will concentrate on different areas such as: land planning & radon mapping; radon in existing dwellings; radon in the workplace and radon-related communication & information. This process is on-going.

Three specific pilot studies are also underway. The NRPA are funding a project working together with SINTEF Byggforsk³ to establish suggested standard practice for a radon measurement protocol in large buildings, specifically schools. The results from this pilot study will enable a more widespread measurement campaign in schools during the 2010-2011 measurement period. The NRPA is also collaborating with the Geological Survey of Norway (NGU)⁴ on a project designed to suggest a standardised method for measuring/classifying building raw materials (crushed stone and aggregates are first priority) with respect to their potential to cause elevated indoor radon concentrations, typically when used as fill materials around the foundation of new buildings. One of the goals from this project is to realise the establishment of a national system where radon information is available on-line from the producer, enabling consumers to base their decision on the potential radon risk. Lastly, the NRPA has initiated a pilot radon measurement study in dwellings that previously adopted radon mitigation methods during a 1999–2003 national subsidy campaign, to assess the long term effectiveness of different mitigation techniques used in Norwegian housing.

Regulatory amendments which will contribute to implementing the strategy

Changes have already entered into force 1 July 2009 in the Planning and Building Act (with regard to planning regulations) in which radon risk areas, or areas with potential risk, are to be given special consideration during land planning. Municipal authorities will now be required to include radon risk in risk and vulnerability analyses undertaken prior to new urban development. Furthermore, new radon requirements were adopted in the Planning and Building Act (with regard to building regulations) in March 2010. The new requirements include the introduction of legally binding indoor radon limits for new buildings (100 Bq/m³, action required; 200 Bq/m³, maximum). The new regulation also stipulates the use of anti-radon construction techniques, such as inter alia a membrane, and incorporating passive ventilation in the building foundations (which can be “activated” if necessary by installing a suction fan).

Another Norwegian regulation which is important regarding implementation of the strategy is currently in the process of being amended, namely the Radiation Protection Regulations. The new requirements include legally binding limits (100 Bq/m³, action required; 200 Bq/m³, maximum) for indoor radon in kindergartens, schools and rented accommodation, and are expected to be adopted in June this year, entering into force in 2014. The first of the pilot projects mentioned above is designed to help establish standard measurement techniques that will enable enforcement of these new radon limits.

Lastly, several other regulations are in the early stages of evaluating possible amendments with regard to radon, notably regulations concerning home buyers/sellers information requirements and radon in the workplace.

³ <http://www.sintef.no/Home/Building-and-Infrastructure/>

⁴ <http://www.ngu.no/en-gb/>

NRPA recommendations

The NRPA revised its recommendations with regard to radon in 2009, the new recommendations are summarized as follows:

All buildings should have radon levels as low as reasonably achievable and within the recommended limits:

- Action Limit of 100 Bq/m³
- As low levels as reasonably achievable – mitigation may also be relevant under the action limit
- Maximum Limit of 200 Bq/m³

All buildings should be measured for radon regularly and always following modifications. Radon measurements should be performed as long-term measurements during the winter months using track-etch detectors. Radon mitigation measures in existing buildings should be source specific (aimed at identified radon sources) and seek to achieve as low radon levels as reasonably achievable.

Action Limit of 100 Bq/m³

The action limit is defined as the threshold over which the NRPA recommends that radon mitigation measures are always initiated. If the annual mean indoor radon concentration is over the action limit, the NRPA recommend that effective radon mitigation measures are implemented as soon as possible to reduce radon levels. It is also recommended that radon measurements are repeated after mitigation, to ensure that the effect of measures is sufficient.

Maximum Limit of 200 Bq/m³

The maximum limit is defined as the maximum indoor radon concentration that the NRPA considers should exist in all living rooms in all buildings. If the annual mean indoor radon concentration is over the maximum limit, it is recommended that (repeated) radon mitigation measures are implemented, followed up by control measurements, until indoor radon concentrations are as low as reasonably achievable and below the maximum limit.

The term action limit does not define a threshold where one can conclude that radon levels below it are "safe" levels, or where mitigation is not recommended nor has no purpose. If measurements reveal radon levels below the action limit, but where it is considered possible to achieve a substantial reduction of the levels through specific measures, such measures should be implemented to ensure that radon levels are as low as reasonably achievable.

Conclusion

Norway's new national radon strategy has set out wide-ranging and ambitious goals that will require a coordinated, systematic and sustained effort across several sectors in society. The NRPA is interested in sharing experience and keeping good contacts with other relevant authorities with regard to this work.

References

- BEIR VI, Committee on Health Risks of Exposure to Radon, Board on Radiation Effects Research. HEALTH EFFECTS OF EXPOSURE TO RADON, Commission on Life Sciences, National Research Council, National Academy Press, Washington, D.C., 1999.
- Lubin JH, Wang ZY, Boice JD, Jr., Xu ZY, Blot WJ, De Wang L, Kleinerman RA. Risk of lung cancer and residential radon in China: Pooled results of two studies. *Int J Cancer* 2004, 109(1):132-137.
- Darby S, Hill D, Auvinen A, Barros-Dios J M, Baysson H, Bochicchio F, Deo H, Falk R, Forastiere F, Hakama M, Heid I, Kreienbrock L, Kreuzer M, Lagarde F, Mäkeläinen I, Muirhead C, Oberaigner W, Pershagen G, Ruano-Ravina A, Ruosteenoja E, Schaffrath Rosario A, Tirmarche M, Tomášek L, Whitley E, Wichmann H-E, Doll R. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *BMJ* 2005, 330:223-237.
- Krewski D, Lubin JH, Zielinski JM, Alavanja M, Catalan VS, Field RW, Klotz JB, Létourneau EG, Lynch CF, Lyon JL, Sandler DP, Schoenberg JB, Steck DJ, Stolwijk JA, Weinberg C, Wilcox HB. A combined analysis of North American case-control studies of residential radon and lung cancer. *J Toxicol Environ Health A*. 2006, 69(7):533-97.
- StrålevernRapport 2001:6 (in Norwegian). Indoor radon survey in 114 municipalities. Short presentation of results. Østerås: Norwegian Radiation Protection Authority, 2001.
- WHO 2009, World Health Organisation. WHO handbook on indoor radon: a public health perspective [Eds: Zeeb H and Shannoun F]. ISBN 978 92 4 154767 3. World Health Organization, 2009.

National measurement database in radon research in Finland

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Abstract

STUK has carried out indoor radon measurements in Finnish dwellings since 1980s using alpha-track detectors. Our database contains measurements in 70 000 dwellings in detached houses, 17 000 dwellings in semi-detached and terraced houses and 5 000 flats. Residents are asked to fill in a two-page questionnaire form that contains questions on building characteristics, such as foundation type, ventilation type and radon prevention. Measurement activity is affected by location of residence, as people living in high-radon area are more likely to carry out radon measurements. Representative national and regional average concentrations were estimated by calculating the values in 1x1 km cells, and weighting each cell by the dwelling density. The calculated national average radon concentration in dwellings (excluding flats), 137 Bq/m³, settles in between the representative values of 145 Bq/m³ and 121 Bq/m³ obtained in national random sampling surveys in 1990 and 2006, respectively. Municipal-specific radon map of Finland, as well as curves presenting average radon concentration by construction year, calculated using the dwelling-density weighting method, are presented. Until now, random sampling surveys have been necessary to obtain representative information on radon situation in Finland. The dwelling-density weighting approach opens up an alternative method. The database can be utilised, e.g., in radon prevention and mitigation studies.

Introduction

Radiation and Nuclear Safety Authority (STUK) has carried out indoor radon measurements in Finnish dwellings since 1980s using alpha-track detectors (Castren et al. 1992, Weltner et al. 2002). By the summer 2008, our national database contains measurements in 70 000 dwellings in detached houses, 17 000 dwellings in semi-detached and terraced houses and 5 000 flats. Nowadays most measurements are paid by the residents, but the material includes also measurements ordered by local authorities as well as those included in various STUK surveys and research projects.

Large indoor measurement databases can be used for radon mapping and identifying radon-prone areas (e.g. Miles, 1998). In Finland, a national Radon Atlas was published in 1997 (Voutilainen et al. 1997). An updated Radon Atlas will be published in 2010. On the other hand, national and regional radon statistics, such as average

concentrations and percentage of houses exceeding the action level, are typically determined by representative sampling surveys. There have been two nationwide random sampling radon surveys in Finland with about 3 000 participants in each. The nationwide mean concentrations were 145 Bq/m³ in houses and 82 Bq/m³ in flats during the first survey 1990 - 1991 (Arvela et al. 1993). The respective values were 121 Bq/m³ and 49 Bq/m³ in the other survey in 2006 - 2007 (Mäkeläinen et al. 2009; 2010).

This paper investigates the possibility to calculate the national and regional radon statistics using the database material. At present STUK is carrying over 10 000 measurements per year. Utilising the data that is collected in radon measurements in any case would be a cost-effective means to update the Finnish radon statistics. The obvious problem is that the measurement material is highly unrepresentative. Residents in high-radon areas are more likely to perform the measurement, and also the regional campaigns are usually directed to risk areas. The bias is compensated by calculating the values for 1x1 km cells and weighting the values by the dwelling density in the cell. The results are compared to those obtained in the national random sampling surveys.

Material and methods

The radon measurements in the national database in Finland have been carried out using alpha-track detectors. The method has been described by Reisbacka (2010). The detector is posted to the resident together with a two-page questionnaire form that contains questions on building characteristics, such as construction year, foundation type, ventilation type and radon prevention.

The material of the present paper includes measurements in detached, semi-detached and terraced houses by the summer 2008. Apartments in blocks of flats are not considered.

The resident is instructed to locate the detector in the lowest residential floor, e.g. in the living room or bed room. Only measurements in actual living areas (not in cellars, etc.) of dwellings that were normally inhabited during the measurement were included in the material. Two or more detectors used simultaneously in a same dwelling is considered here as one measurement, with the average of the concentrations taken into account.

Measurements were included if the duration was at least 30 days and no more than 25% of the time had taken place outside the official measurement period, 1 November to 30 April. Annual average radon concentration was calculated using a seasonal correction factor of 0.85. The value was determined as the annual average vs. winter-time concentration ratio in the random sampling survey in 2006 (Mäkeläinen et al. 2009). However, also measurements longer than 272 days were included with the result interpreted as the annual average, without using the seasonal correction factor.

Measurements carried out in the same dwelling at different times were identified based on their address or, in case of insufficient address information, by the resident's statement in connection with the later measurement. A total of 87 457 different dwellings, i.e. 6% of all the dwellings in detached, semi-detached and terraced houses in Finland, were identified.

The location coordinates were determined by address using the StreetMap Finland road network material (ESRI Finland Oy), and data from the Population Register Centre and the National Land Survey of Finland. Some of the houses measured

prior to 1997 were located from paper maps (Voutilainen et al. 1997). The positions of 75 270 dwellings are known accurately enough so that they could be located in a 1x1 km cell. The database contains 86 182 measurements in these dwellings (average 1.14 measurements per dwelling). There was on average 1.14 detectors used in each measurement.

The national and regional average concentrations as well as percentages of dwellings exceeding 200 Bq/m³ were estimated by a dwelling-density weighting method. The values were calculated in 1x1 km cells and each cell was weighted by the number of dwellings (not including flats) in it. The dwelling density information was obtained from the Grid Database of Statistics Finland and is based on the situation on 31 December 2005. The grid data contains no detailed information on dwellings in cells that contain only one building. These cells include 1.3% of the Finnish population, and they were assumed to contain one dwelling, if there were inhabitants in the cell. A total of 1.4 million dwellings in 103 004 cells were included in the analysis. There was at least one measured dwelling in 21 258 cells. These measured cells included 73% of all the dwellings. The other cells were given the average concentration and percentage exceeding 200 Bq/m³ from the nearest measured cell, or average of the values if there was more than one measured cell at the same distance. Each cell was included in the municipality where the centre of the cell is located.

The material of the present paper was compared to the 2 267 dwellings in detached, semi-detached and terraced houses completing the representative random sampling survey in 2006. The newest houses are underrepresented in the present material because the measurement is often made many years after the construction (Figure 1). The main difference in building characteristics is that the material contains clearly more hillside houses than the random sampling survey (Table 1). Other than that, there is no significant difference in the distributions of foundation types. This is assuming that the houses without a basement with an unknown foundation type do have the same percentage of slab-on-ground foundations as the other houses without a basement. There is no significant difference in ventilation types either (Table 2).

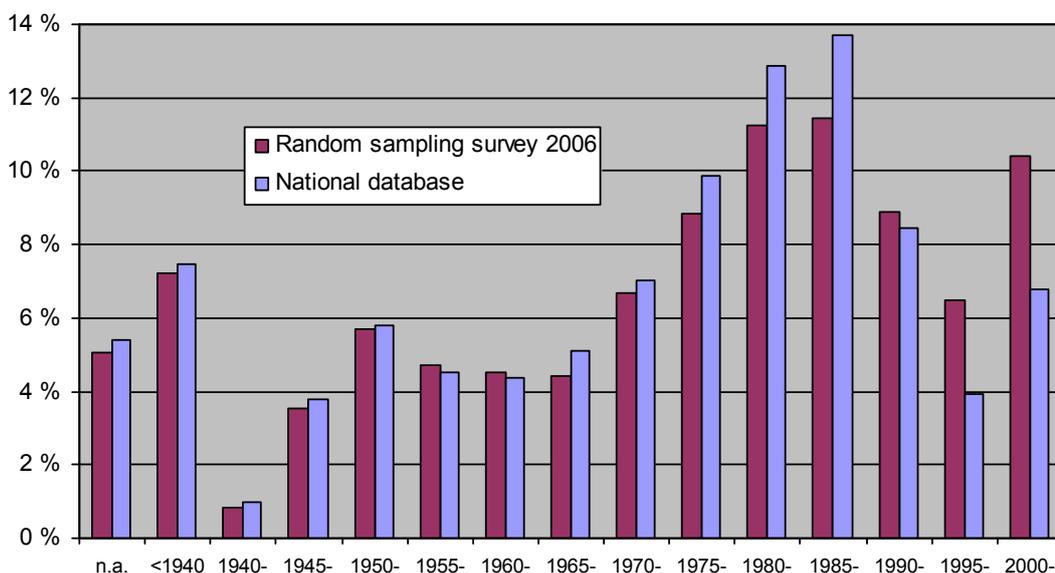


Figure 1. Dwellings in detached, semi-detached and terraced houses by construction year.

Table 1. Foundation types according to the questionnaire form filled in by the resident.

Foundation type	National database	Random sampling survey 2006
No basement, slab-on-ground foundation *	15% (39%)	33% (40%)
No basement, other type of foundation *	7% (18%)	18% (21%)
No basement, foundation type unknown	34%	10%
Cellar or partial cellar	22%	25%
Hillside house	21%	14%
Total (foundation type known)	52 179	2 060

*percentage in parentheses assuming the class *No basement, foundation type unknown* has the same *slab-on-ground* frequency than the other no basement-houses.

Table 2. Ventilation types according to the questionnaire form filled in by the resident.

Ventilation type	National database	Random sampling survey 2006
Natural	62%	58%
Mechanical exhaust	19%	19%
Mechanical supply and exhaust	19%	23%
Total (ventilation type known)	69 499	2 070

All in all, the comparison shows no indication that factors not related to the location of the house would cause significant distortion in the present material.

Results

The average radon concentration of the 75 270 dwellings included in the material is 227 Bq/m³, if the first measurement in each dwelling is considered (Table 3). The estimated average concentration in all the 1,4 million dwellings in detached, semi-detached and terraced houses, determined by weighting the values calculated for 1 km² cells by the dwelling density, is 137 Bq/m³.

There is 7 703 dwellings with multiple measurements. Typically, the latter measurement is carried out to verify the success of the radon mitigation, initiated by a high concentration in the first measurement. Therefore the average concentration is clearly lower (128 Bq/m³), if the latest measurement in each dwelling is considered.

Table 3 shows also the results of the random sampling surveys. According to the survey of 2006, the average concentration in houses constructed after 1991 is not any lower as compared to that in older houses (Mäkeläinen et al., 2009). The difference between the surveys (145 Bq/m³ in 1991 vs. 121 Bq/m³ in 2006) is partly due to the higher outdoor temperature during the latter survey. Also the houses built before 1991 and having radon mitigation done after 1991 may have contributed to the difference.

The national average radon concentration and the percentage exceeding 200 Bq/m³ obtained in the present work settle in between those from the two surveys.

Table 3. The average radon concentration and percentage of dwellings exceeding 200 Bq/m³ in Finland (flats are not included).

Source	Number of measured dwellings	Average, Measured dwellings (Bq/m ³)	Average, All dwellings	>200 Bq/m ³ , Measured dwellings (%)	>200 Bq/m ³ , All dwellings
Database, highest value in each dwelling	75 270	233	139 ^a	31.5	16.9 ^a
Database, first meas. in each dwelling	75 270	227	137 ^a	31.0	16.6 ^a
Database, latest meas. in each dwelling	75 270	199	128 ^a	28.5	15.5 ^a
Database, lowest value in each dwelling	75 270	194	127 ^a	28.0	15.2 ^a
Random sampling survey 1990	2 096		145		17.9
Random sampling survey 2006	2 267		121		15.1

^a Calculated by the dwelling-density weighting method.

There are 20 provinces in Finland having 9 000 – 230 000 dwellings each (flats not included). The weighting of the database material (first measurement in each dwelling) by dwelling density results in most cases in slightly higher radon values as compared to the random sampling survey in 2006 (Figure 2). Six provinces with the highest concentrations constitute a continuous high-radon area that is indicated in Figure 3.

Until now, the municipal-specific radon maps of Finland have presented the indoor radon situation concerning the measured dwellings (Figure 3a). On the other hand, the municipal radon averages calculated by the dwelling-density weighting method are shown in Figure 3b. The largest difference between the maps concerns the municipality of Kajaani. The average of the 713 measured dwellings is 405 Bq/m³, and the estimate given by the dwelling-density weighting method is 120 Bq/m³. The difference is due to a 3 km² local high-radon area that was extensively measured because of the high concentrations found there in the 1980s. This area includes only 5% of the 9 700 dwellings in detached, semi-detached and terraced houses in Kajaani, but as much as 45% of those measured.

The complete data of 75 270 dwellings was divided to smaller subsets to study how the number of measured dwellings affect the result obtained by the dwelling-density weighting method. A total of 376 subsets with 200 dwellings each were created. Any single dwelling was included in only one of the sets. Similarly, 250 sets of 300 dwellings, 150 sets of 500 dwellings etc. were made. The smaller the subset size, the higher the expectation value of the national average concentration calculated from the

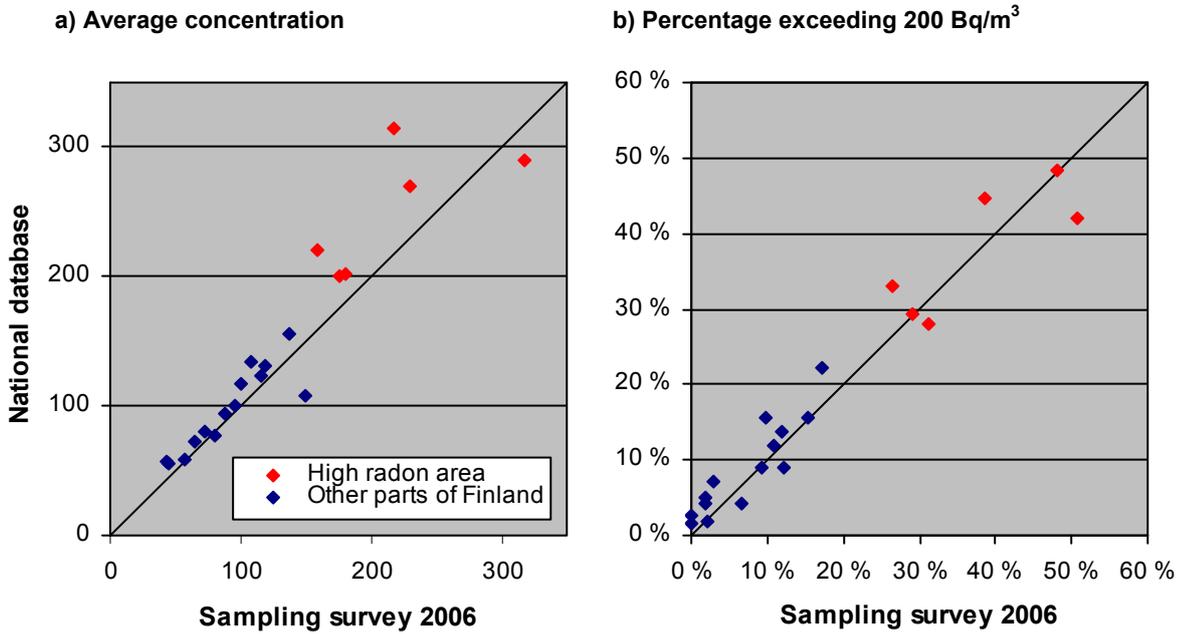


Figure 2. Radon in Finnish dwellings (not including flats). Values obtained from the national database by dwelling-density weighting method (first measurement in each dwelling) compared to the random sampling survey in 2006. Each point represents one of the 20 provinces of Finland.

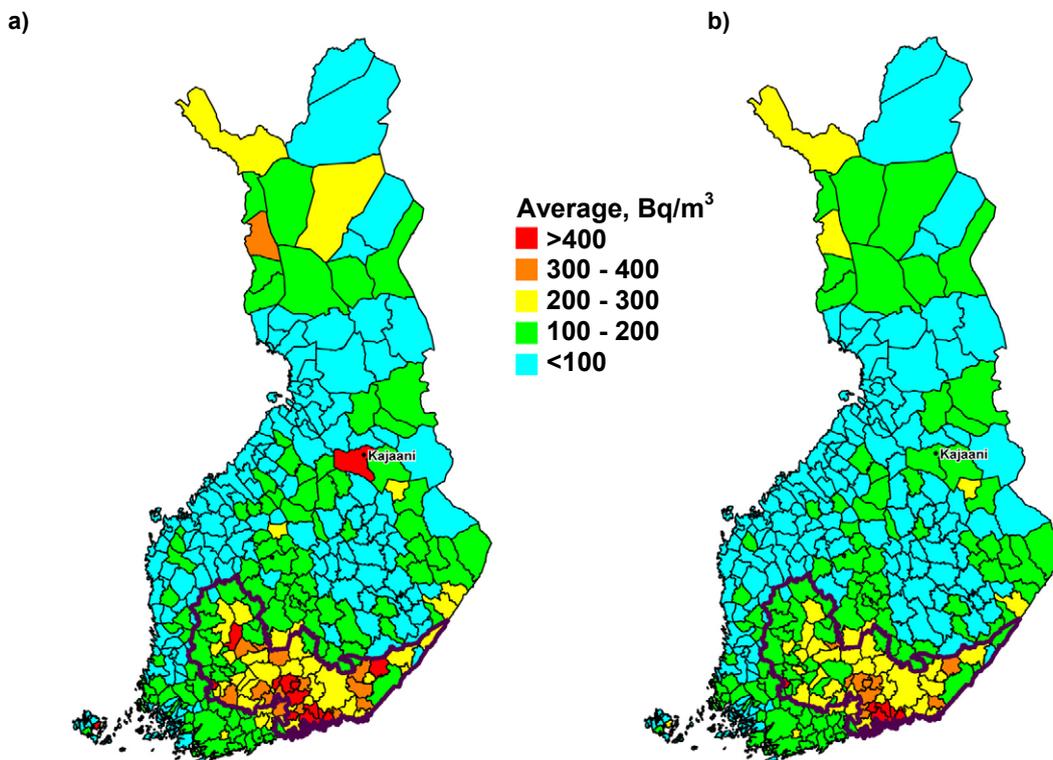


Figure 3. Radon by municipalities in dwellings (not including flats). a) Measured dwellings and b) All dwellings, estimated by the dwelling-density weighting method. First measurement in each dwelling is considered. High-radon area (six provinces with the highest average concentration) is separated by a violet line.

subset (Figure 4). The expectation value deviates less than 5% from the value 137 Bq/m³ obtained using all the 75 270 dwellings, if at least 5 000 dwellings are included. In an extreme case of making the estimate from one dwelling only, the expectation value equals the average of the measured dwellings (227 Bq/m³). The relative standard deviation among the concentration averages calculated using the different subsets is $3.6 \cdot n^{-0.6}$, as fitted in the data shown in Figure 4, where n is the number of dwellings used in the calculation. The fitted relative standard deviation is 0.4% for the complete data of 75 270 dwellings.

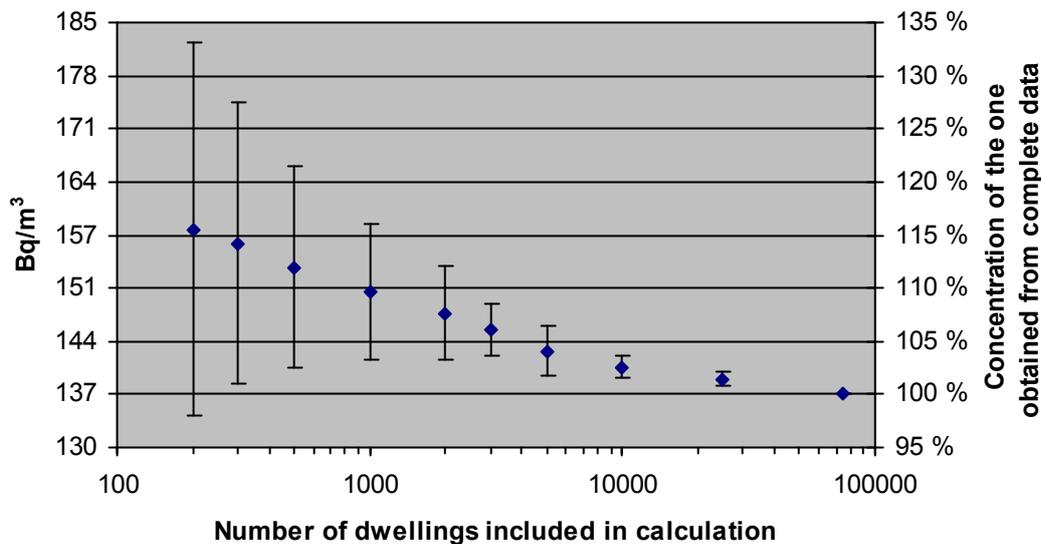


Figure 4. Average radon concentration in Finnish dwellings (not including flats) calculated by the dwelling-density weighting method. Uncertainty is given as \pm one standard deviation. First measurement in each dwelling is considered.

The material contains 71 216 dwellings with a known year of construction, indicated by the resident. They were divided to sets of 1 000 (or 3 000) by the construction year. The dwellings with the same year were put in random order. The national radon average was calculated for each set using the weighting factors from the same grid data base (valid December 31, 2005) for all the sets. Thus, the analysis is simplified in a way that it does not consider the fact that houses are not built in the same 1 km² cells each year. The concentration trend of recently build houses is rather similar than the one by the random sampling survey in 2006 (Figure 5). The concentrations of older houses follow more closely the random sampling survey in 1990, being clearly higher as compared to the survey in 2006.

The oldest dwellings in the last set of 3 000 measurements were constructed 2002, that is 6 years before the latest measurements included in the material. The time gap between the construction year and the time when the estimate is available can be shortened by using smaller sets, with an expense of decreased accuracy. The oldest dwellings in the last group of 1 000 measurements were constructed 2005.

The national average concentrations calculated from these chronological datasets are 147 Bq/m³ (1000 dwellings per set) and 143 Bq/m³ (3 000 dwellings per set). These

values are slightly lower respectively, than the corresponding expectation values 150 Bq/m³ and 145 Bq/m³ shown in Figure 4 for randomly chosen sets. Thus the chronological subsets overestimate the national average concentration (137 Bq/m³) slightly less than the randomly chosen subsets.

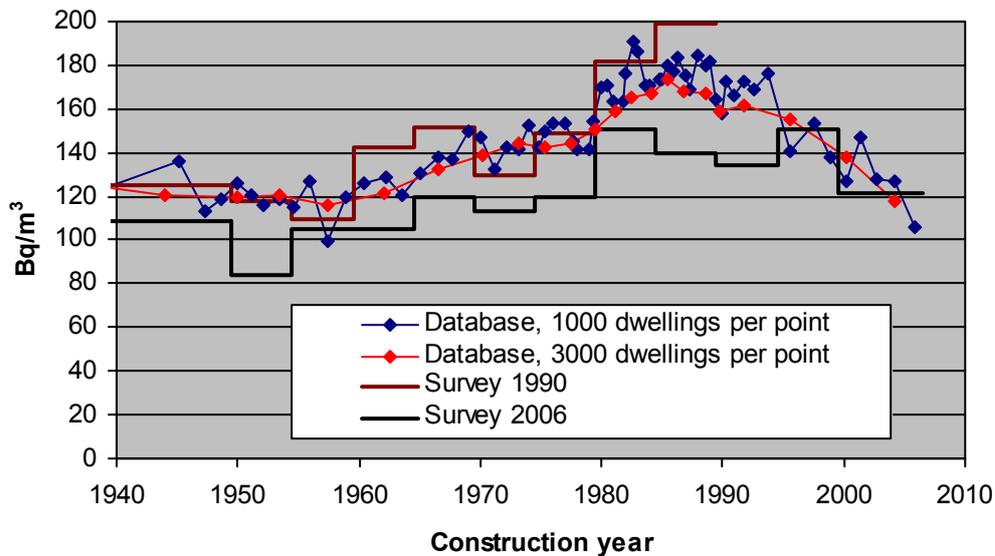


Figure 5. Average radon concentration in dwellings (not including flats) in Finland. The values calculated from the national database (first measurement in each dwelling) using the dwelling-density weighting method are compared to the results of the random sampling surveys in 1990 and 2006.

The average radon concentration of the Finnish houses was the highest in the 1980s and 1990s. The increasing trend before the 1980s was mainly due to the increased popularity of the slab-on-ground foundation type. On the other hand, three main reasons have been identified for the decrease in radon concentrations since the 1990s; i) increased popularity of the crawl-space foundation type, ii) mechanical supply and exhaust ventilation strategy is used in practically all the new houses and iii) radon-safe construction practices have become common (Mäkeläinen et al. 2009). Figure 6 shows, that the recent decreasing trend is the strongest in the high-radon area. This suggests that the radon-safe construction practices, being much more common in the high radon area, are a major contributor to the decreasing trend.

Discussion

The difference in radon concentration between the measured dwellings and the other dwellings seems to be caused mainly by factors related to the location of the house, such as soil gas radon content and soil type. These factors can be compensated for by the dwelling-density weighting method described in this paper. The number of measured dwellings in our database is large enough for producing municipality-specific results, although more work is needed to estimate the minimum amount of measurements needed for reliable results. The material can also be used, e.g., for monitoring radon situation in new houses by construction year. The sensitivity of the

results to grid size needs to be studied. There is also a 0,25x0,25 km grid database that can be used, if the 1x1 km grid appears to be too coarse producing significant inaccuracy.

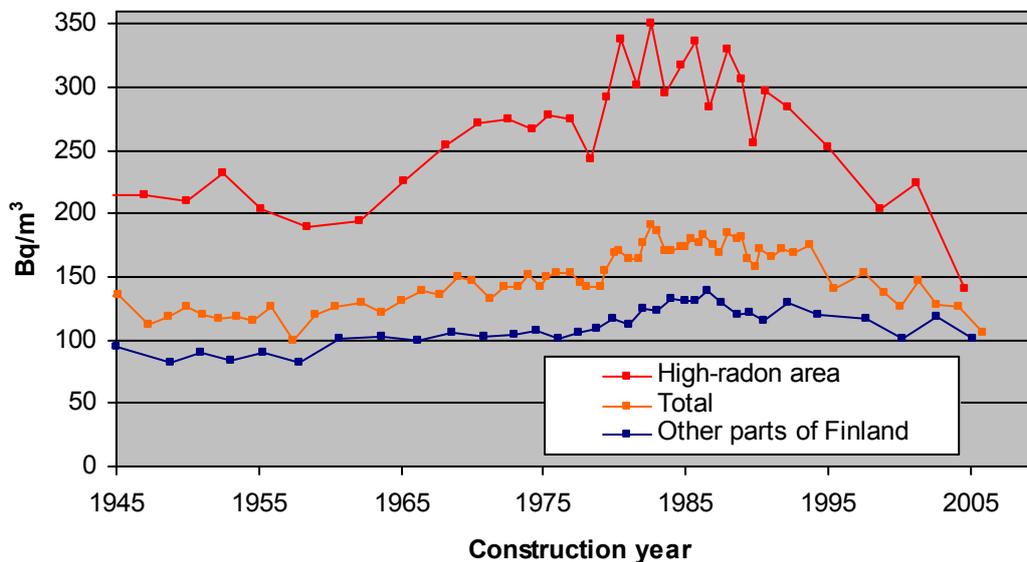


Figure 6. Average radon concentration in dwellings (not including flats) in Finland calculated from the national database (first measurement in each dwelling) using the dwelling-density weighting method. The high-radon area is indicated in Figure 3.

This paper considers only dwellings in detached, semi-detached and terraced houses, but it is important also to study blocks of flats. This is because the average radon concentration in the lowest floor flats with either soil or rock directly beneath them (no cellar etc.) is as high as in houses (Mäkeläinen et al. 2009). Since the number of measured flats is small (4 908), the radon statistics can not be produced with the same elaborateness as can be done in case of houses. The dwelling-density weighting approach requires some modifications when applied to the flats. Measurement is recommended especially for the lowest-floor apartments and consequently they are overrepresented in our material. Another factor causing overrepresentation of high concentrations is that a high value in one apartment often results in measuring also the other apartments in the same building.

Radon measurements are primarily intended to determine if mitigation is needed. Therefore residents are instructed to carry out the measurement in the lowest floor with living areas, because the concentration is usually higher there than in the upper floor. The abundance of lowest-floor measurements was not compensated for in this work. The effect of the radon detector location on the detected concentration needs to be analysed, if the concentration people actually are exposed to is to be accurately determined.

Conclusions

The regional and national average radon concentrations and percentages exceeding 200 Bq/m³ were estimated by a dwelling-density weighting method using the measurement results in 75 270 dwellings with a known location. The results agree with those from national random sampling surveys with a reasonable accuracy. Until now, random sampling surveys have been necessary to obtain representative information on radon situation in Finland. The dwelling-density weighting approach opens up an alternative method. The new approach is cost-effective, as it utilises data that is collected in any case. The large number of measurements enables also presentation of municipality-specific radon situation.

Our future plans include utilisation of the national measurement database more widely in radon research. Measurement results, combined with the building characteristics data collected by a questionnaire form, can be utilised, e.g., in radon prevention and mitigation studies.

References

- Arvela H, Mäkeläinen I, Castrén O. Otantatutkimus asuntojen radonista Suomessa (Residential Radon Survey in Finland. In Finnish, abstract in English). STUK-A108. Helsinki: Radiation and Nuclear Safety Authority; 1993.
- Castren, O. Arvela H, Makeläinen I, Voutilainen, A. Indoor radon survey in Finland: Methodology and applications. *Radiation Protection Dosimetry* 1992; 45 (1-4): 413-418.
- Miles, J. Development of maps of radon-prone areas using radon measurements in houses. *Journal of Hazardous Materials*. 1998; 61 (1-3): 53–58.
- Mäkeläinen I, Kinnunen T, Reisbacka H, Valmari T, Arvela H. Radon suomalaisissa asunnoissa - Otantatutkimus 2006 (Radon in Finnish dwellings - Sample survey 2006. In Finnish, abstract in English). STUK-A242. Helsinki: Radiation and Nuclear Safety Authority; 2009.
- Mäkeläinen I, Valmari T, Reisbacka H, Kinnunen T, Arvela H. Indoor Radon and Construction Practices of Finnish Homes from 20th to 21st Century. Third European IRPA Congress, 14-18 June 2010, Helsinki, Finland; 2010.
- Reisbacka H. Radon Measurement Method with Passive Alpha Track Detector at STUK, Finland. Third European IRPA Congress, 14-18 June 2010, Helsinki, Finland; 2010.
- Voutilainen A, Mäkeläinen I, Pennanen M, Reisbacka H, Castrén O. Radon Atlas of Finland. STUK-A148. Helsinki: Radiation and Nuclear Safety Authority; 1997.
- Weltner A, Mäkeläinen I, Arvela H. Radon mapping strategy in Finland. *International Congress Series* 2002; (1225): 63-69.

Reducing lung cancer incidence by health campaigns: A review of the uptake, health benefits and cost effectiveness of Smoking Cessation and Radon Remediation Programmes in Northamptonshire, UK

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Abstract

The greatest risk factor for lung-cancer is smoking, the second largest factor being raised radon levels at home. Initiatives to stop smoking and reduce domestic radon levels have met with some success, but in both cases a significant proportion of those affected fail to respond. The two risk factors combine, so that those who smoke and live in a house with high radon levels are at higher risk than if exposed to only one of the two threats. There is the potential for combined public health campaigns to better target those affected.

Our group has studied both the smoking cessation and radon remediation programmes in Northamptonshire, UK, considering the costs and health benefits of each, and, using postal questionnaires, recording the demographics of participants. Our analysis suggests that the demographics of the two groups are significantly different. Those who remediate tend to be older, include fewer smokers and have fewer children.

The health benefits from stopping smoking are greater than those from radon remediation, and the smoking cessation programme costs less per lung-cancer averted. In addition, the continuing reduction in smoking prevalence in the UK will reduce the effectiveness of radon remediation campaigns.

This paper discusses the synergy between the programmes, and argues that there is merit in an integrated approach to these health campaigns, and in particular to extending smoking cessation programmes to include advice on reducing the risks from radon.

Introduction

Smoking is the most significant risk factor for lung-cancer. Since this became known, education and health campaigns have been conducted to reduce smoking prevalence. In

England, smoking prevalence has dropped from 45% in 1974 to 28% in 1998, declining further to 21% in 2008 (Dept. of Health, 2010).

Radon, a naturally-occurring radioactive gas, is the second most significant risk for lung-cancer after tobacco smoking. High levels of radon were first identified in uranium mines, but more recently, it has been established that significant levels are found in the built environment, and case-control studies have shown an associated increase in lung cancer in the public from radon in their homes (AGIR, 2009; BEIR VI, 1999; Darby et al., 2005).

Northamptonshire, a county in central England, is one of the areas in the UK where a significant proportion of homes have radon levels over the UK domestic Action Level of $200 \text{ Bq}\cdot\text{m}^{-3}$ (Bradley et al., 1997). Radon levels can be tested simply, and, if raised radon levels are found, remediation work, usually involving the introduction of a sump and attached pump to extract radon to outside and costing around £750 (around 825€), will reduce radon levels nearly always well below the Action Level. Over the last 18 years, campaigns to measure and reduce radon in homes have been implemented through the local councils' environmental health departments. Despite publicity, only around 40% of householders have tested radon levels in their home, and of those who discover raised levels, only 15% remediate their homes (Chow et al., 2007). Our group has studied the characteristics of those who remediate their homes, and has shown that they are older, have fewer children, and include fewer smokers than the general population (Denman et al., 2004).

The risks from radon and smoking are considered to be sub-multiplicative (BEIR VI, 1999), and so smokers, who are most at risk from radon, are not being targeted by current radon remediation campaigns. This led our group to consider the local smoking cessation initiatives, and whether these might be valuable in reducing radon-induced lung cancers. Our initial work showed that the smoking cessation programme in Northamptonshire has added value compared to cessation programmes in areas with lower radon levels. In addition, there is greater health benefit for a smoker living in a high-radon house from quitting smoking than from remediating the house and continuing smoking (Groves-Kirkby et al., 2008).

In England, smoking cessation programmes are commissioned by the local Primary Care Trust (PCT), part of the National Health Service (NHS), with the assistance of General Practitioners (GPs). Our group has recently studied the characteristics of those who join and participate in smoking cessation programmes.

This paper compares those who remediate and those who quit smoking, and considers the characteristics of each group, and their similarities and differences. It also compares the cost-effectiveness of each programme, and considers the impact of the steady reduction of smoking prevalence in England. These results can inform future public health initiatives to improve the response to both risks.

Material and methods

All houses in the radon remediation series were remediated by a single company following UK Radon Council good practice (The Radon Council Ltd, 1995). In early 2002, additional personal information to make the individual risk assessments was obtained by postal questionnaires sent to all the houses in the study. The questionnaire included questions about all of the residents in the house, including age, occupation,

smoking habits and the time each spent inside the house on a recent day; detailed results from this study have been reported previously (Denman et al., 2004).

Participants of the Northamptonshire PCT Smoking Cessation Programme were contacted by telephone in 2007 to ask about their quit status. During the call, participants were invited to complete a written questionnaire, and if they agreed, this was posted to them with a stamped addressed envelope for return. The answers were entered into a bespoke Access database, using double entry and record comparison to ensure data accuracy.

The results from the smoking cessation programme were assessed by examining the bivariate relationships between the main outcome measure (whether the respondent indicated that they continued to have quit smoking), and the socio-demographic factor under consideration, using Chi-squared tests. The results from the remediators were compared to the smoking cessation scheme participants in a similar analysis.

A separate exercise analysed demographic data from 4,626 smokers registering with the Northamptonshire Smoking Cessation Service during 2004-2005 and setting personal quit-dates. Smoking status was validated at 4 weeks by carbon monoxide monitoring, and at 26 and 52 weeks by telephone questionnaire (unvalidated, self-reported). Using age, gender, smoking status and postcode of residence (surrogate for domestic radon concentration) derived from this cohort as input data for the European Community Radon Software (ECRS) tool (Degrange et al., 2000), estimates of the lung-cancers averted in the quitting cohort were generated, permitting preliminary analysis of the relative cost-effectiveness of radon remediation and smoking cessation.

Results

In the radon remediation series, 122 questionnaires were sent, and 73 householders replied (59.8%). The houses contained 162 occupants, an average of 2.22 per house (range 1 to 5). These included 138 adults and 24 children. 1 household did not give personal data on the occupants, leaving 72 houses with 160 occupants suitable for further analysis. Householders had been living in the house for an average of 16.2 years (range 0.8 to 45.9 years). 3 households (6 occupants) had moved in since remediation. 6 households contained smokers, 3 indicated that around 100 cigarettes a week were smoked in the house, 2 suggested 30 cigarettes, while one household smoked 4 cigars a week. In addition, one respondent indicated that only a young adult in their household smoked, but did so only outside the house. 10 of the 160 occupants (6.25%) indicated that they were current smokers. In 2 households, both adults smoked. The remaining 4 households who smoked contained 5 non-smokers who would be subject to passive smoking risk in addition to the radon risk.

In the smoking cessation series, some 482 4-week quitters were identified from the Northamptonshire PCT Stop Smoking Service. These smokers had successfully quit at 4 weeks, as assessed by the Department of Health criteria, during the period 1st July 2006 to 30th September 2006. The sample population had previously consented to be followed up at one year, as part of routine data collection to ascertain their current quit status, and were asked, during this telephone contact if they would provide some further information in a written questionnaire for research. Some 317 questionnaires were sent out. Completed questionnaires were received from 103 quitters (32%), 68 of whom confirmed that they had not smoked since, while 35 had relapsed. 77 lived with a

partner, or parent, while 63 had children under 18 living at home, while a further 17 had children over 18 at home.

There are statistically significant differences in family size between remediators, quitters, and the national population. Remediators' family size is smaller, and more likely to be 2, less than that of the national population ($p < 0.001$), while the distribution of family sizes for quitters differs to that of both remediators ($p = 0.006$) and the national population ($p = 0.011$), with the quitters generally having larger family sizes.

The length of time that people had spent in their current house was also studied, and compared to National Statistics. The results are shown in Table 1. Separate data was obtained for <1 year and >40 years but the frequencies were too low for valid statistical analysis and they were therefore combined to form those shown in the Table. Although it appears that remediators have been in their current home longer than the national average, this is not statistically significant ($p = 0.110$). However, it is statistically significant that quitters are more likely to have been in their current house for a shorter time than both remediators and the national population ($p = 0.036$, and $p = 0.033$ respectively).

Table 1. Length of Time in Current Home.

Time in Current House	England, Home Owners 2001/2	Radon	Quitters
t < 3 years	2,755,000	5	18
3 < t < 5 years	1,424,000	6	15
5 < t < 10 years	2,416,000	13	27
10 < t < 20 years	3,525,000	20	19
t < 20 years	4,174,000	26	24
Total	14,294,000	70	103

From the questionnaires, analysis of the ages of responders indicates that the remediators tend to be older than quitters, and for the radon remediators there is a clear peak in the age range 60 to 80 years, which is also seen in Figure 1. However, the difference between remediators and quitters is not statistically significant at the 5% level ($p = 0.185$).

The age distribution of all occupants of remediated houses and of houses with quitters is shown in Figure 1, together with a comparison with the age distribution of the Northamptonshire population. The differences in this case are highly statistically significant (all have $p < 0.001$). This is presumably related to the statistically different family sizes in each group, noted above.

The questionnaire sent to those on the smoking cessation programme also permitted comparisons between those who had remained quitters for a full year, and those who had relapsed since the previous assessment at 4 weeks. Table 2(a) shows that the continuing quitters were more likely to have children under 18 at home. This is statistically significant, with $p = 0.002$. Those who relapsed were more likely to have children over 18 at home, as in Table 2(b). This is also statistically significant ($p = 0.003$). Continuing quitters are also more likely to be living with a partner or parent, see Table 3, with this finding being significant at the 5% level ($p = 0.046$).

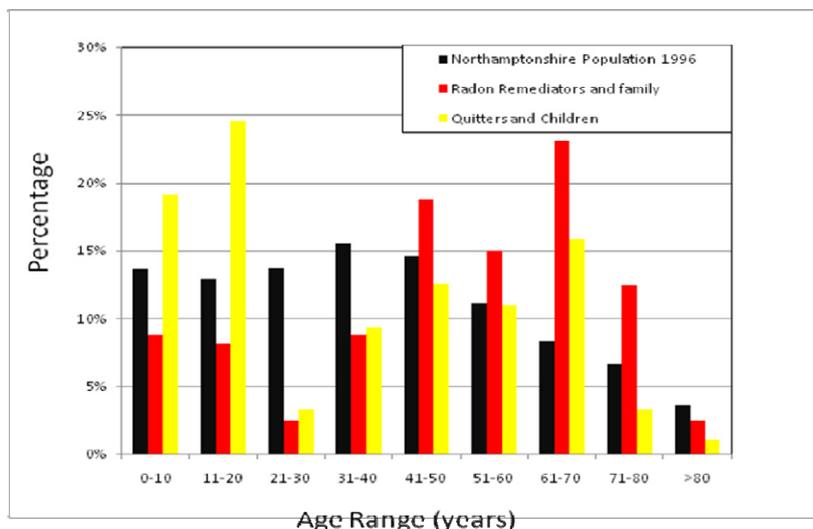


Fig. 1. Age Distribution of local population, occupants of remediated homes, and of houses with quitters.

Table 2. Association between quit status and having children at home (a) under 18 and (b) over 18.

Table 2(a)

Status	Children under 18 at home	
	Yes	No
Relapsed	14	21
Still not smoking	49	19
Total	63	40

Table 2(b)

Status	Children over 18 at home	
	Yes	No
Relapsed	11	24
Still not smoking	6	62
Total	17	86

Table 3. Association between quit status and living with partner or parent.

Status	Parent or Partner in home	
	Yes	No
Relapsed	22	13
Still not smoking	55	13
Total	77	26

Of the initial cohort of 4,626 quitters participating in the cost-effectiveness study, only 435 remained tobacco-free after 52 weeks. Using the ECRS software, loss of life-expectancy and excess lung-cancer incidence were modelled for each individual in the study, assuming that they: (i) continued smoking, (ii) quit smoking at the time of the study and (iii) had never smoked, in each case for zero radon exposure and the mean annual level in their home imputed from their postcode of residence. Preliminary results

are summarised in Table 4. The average life-year saving among ex-smokers in the Northamptonshire radon environment is 1.21, being the difference between the average smoking-attributable life-year losses of 1.93 and 0.72 for smokers and ex-smokers respectively, compared with 1.10 in a radon-free environment.

Table 4. Cost-Effectiveness Comparison.

Smoking Cessation Study		Radon Remediation Study	
Population	462		127
Attributable Lung Cancers	55.22		6.84
Total cost (service+medication)	£1,156,515	Total remediation cost	£746,725
Total cost per quitter	£2,503		
Cost per life-year saved	£2,069		£8,047

Discussion

UK Smoking Cessation Programmes place emphasis on quitting at an early age, as the British Doctors Study (Doll et al., 2004) showed that those who quit successfully by 35 years avoid much of the excess mortality risk due to smoke, those who quit successfully by 50 avoid about half the risk, and those at 60 avoid one third the mortality risk. The age of the occupants when radon remediation is carried out is similarly important, as the degree of risk from radon depends on the total time spent exposed in the home together with the average radon level in the house prior to remediation.

In our study, an analysis of the ages of responders indicates that, although remediators appear to be older than both quitters and the Northamptonshire population, this difference is not statistically significant at the 5% level. However, the age distribution of quitters together with their partners and children has a statistically lower age profile than the population, which is in itself lower than remediators and their families. This contrasts with the relative risk to other occupants in the home, since the reduction in health risk when radon is reduced is similar for each member of the family, while for the smoker, the risk to other family members is the lesser one of passive smoking, assuming they do not smoke, or none, if the smoker smokes outside.

In addition, our study shows that remediators have smaller families than quitters, and have lived in their current homes longer. Therefore participants on the smoking cessation programmes represent a different target population from those who remediate, so there is a potential to extend the reach of a radon remediation initiative.

The questionnaire to quitters also asked about the quitters' knowledge of radon, and whether radon, amongst many other factors, played any role in the decision to quit. These results, reported elsewhere (Groves-Kirkby et al., 2008), showed that few respondents regarded radon as a significant decision factor, and that the direct health concerns as a result of smoking were much more significant as factors affecting the decision to quit.

Smoking cessation programmes have been in operation for longer than radon remediation programmes, and there has been extensive analysis of their efficacy,

reflected in many more publications. As a result, smoking cessation programmes have evolved to improve their operation, and to target remaining smokers.

The age profile of UK smokers has changed significantly since 1970 (Dept. of Health, 2010), dropping significantly so that people aged 20 to 24 smoke more than any other age group, which is consistent with the age profile of quitters in our study. There is a considerable literature on other characteristics of smokers, and the relative success of different smoking cessation techniques, and the likelihood of relapse.

Solberg et al. (2007) studied the educational background of young adult smokers (age 18 to 24 years) in the US, and concluded that the level of interest in quitting, number of quit attempts, and relapse rates did not depend on educational level, although higher educational level was associated with a lower proportion of smokers. Macy et al. (2007), studying a similar group, showed that 33% of long-term quitters who had quit for over 1 year, had relapsed by 5 years. They were less likely to relapse if they were married to a non-smoker, had only one parent who smoked, or worked in a smoke-free building. Tucker et al. (2005), also studying young smokers and quitters (23 to 29 years), found that smokers were more likely to have higher rates of substance abuse, illegal activity, poor mental health and victimisation, but these factors were less relevant to quitting than social transitions and interpersonal factors, race, ethnicity, and health status. Other studies have shown that quitters were more likely to relapse if they had higher emotional distress, higher nicotine dependence, higher alcohol consumption, and more medical problems (Augustson et al., 2008), and increased post-quit anger (Patterson et al., 2008). However, Freund et al. (1992) report that recent hospitalisation and a diagnosis of heart disease increases the likelihood of cessation.

Mills et al. (2008) questioned smokers attending US Emergency Departments and found that 37.8% (441/1168) had children. They found that smokers with children were more interested in quitting, and more confident in doing so. Our study supports these findings, with 61.2% (63/103) of those entering the smoking cessation programme having children under 18 at home, rising to 72.1% (49/68) for continuing quitters at one year. Interestingly, our study shows that, if the children are over 18 then the converse is true – that the parent is more likely to have relapsed.

Smoking cessation programmes have developed over the years, but it is proving increasingly difficult to reduce smoking rates further, and Twigg et al. (2009) suggest that a heterogeneous range of different programmes will be required to reach 'hard-to-engage' populations. Bauld et al. (2008) compared two types of cessation programme in Glasgow – a group scheme with GP support, and a pharmacy-based scheme – and showed that the demographics of those recruited to each scheme was somewhat different, with a higher proportion of those aged 16 to 40 attending the pharmacy-based scheme. There was also a significantly higher proportion of people with children, whilst the group scheme had an increased percentage of females. The quit rate at 4 weeks was higher for the group scheme. They showed that those who were more socially deprived were less likely to quit, which concords with other studies, which also note that those in socially deprived areas are more likely to smoke (Twigg et al., 2009). Of the factors considered in our study, Bauld et al. (2008) found a significantly higher cessation rate in those with partners/spouses ($p = 0.046$), but only in the group scheme; whereas those with children had a significantly lower cessation rate ($p = 0.003$) but only in the pharmacy scheme. It should be noted that this study was conducted for 4-week quitters,

whilst our study was of long-term (1-year) quitters, and many authors note that there is a large relapse rate over the first year. For example Zhou et al. (2008), in a major international study, note a relapse rate close to 80% in the first quarter, with 60% of the remainder relapsing in the next quarter. Zhou et al. also note that relapse rates vary between countries, with subjects in USA and Canada more likely to relapse than those in France, Spain and UK. Others more likely to relapse include those who have failed to quit before, those with cessation-related sleep disturbance, and with heightened anxiety.

Despite these concerns, smoking prevalence in England has steadily reduced over many years, and the Department of Health have published an initiative to reduce smoking prevalence to 10% in 2020 (Dept. of Health, 2010). This target is ambitious, but Canada and Victoria, Australia, both demonstrate falling prevalence rates and already have smoking prevalence below 20%.

Our study indicates that it would be possible to extend the response to the health risks of radon if quitters were provided with safety and remediation information during their interaction with smoking cessation programmes in areas affected by radon.

It should be noted, however, that quitting smoking also saves money, whilst the householder needs to spend money to remediate if raised levels are found. It is interesting to note that, in their questionnaire responses, quitters placed the cost issue as the 7th most significant factor in their decision to quit smoking – below the direct health risks, but above family pressure, and the knowledge of radon (Timson et al., in preparation).

Among smokers in Northamptonshire, individual and population mortality increases with smoking status and radon exposure, with smoking accounting for 5 to 8 times more life-years lost than radon. Quitting smoking is expected to reduce life-years lost to avoidable lung-cancer by 121 years per 100 quitters at a cost of £2,069 per life-year saved. If the same group were to remediate their homes while remaining smokers, the intervention would reduce life-years lost to lung-cancer by 21 years for every 100 remediators at a cost of £8,047 per life-year saved. For ex-smokers and non-smokers with comparable radon exposure, remediation would reduce life lost to lung-cancer by 10 years per 100 remediators and 3 years per 100 remediators respectively, at costs of £17,000 and £62,000 per life-year respectively.

The effect of smoking prevalence is important in radon remediation programmes. For example, AGIR (2009) estimate that, for an annual build of 200,000 new homes in the UK, installation of radon-proof membranes will currently avert 4.4 lung cancers per year. Applying the current relative risks for radon in smokers and non-smokers, this would drop to 2.5 lung cancers per year by 2020 if the UK achieves its 10% smoking rate target.

Conclusions

This study has confirmed that the higher motivation to quit in smokers with children at home, noted by Mills et al. (2008), converts into a higher percentage of smokers with children entering our smoking cessation programme initially and then a statistically significant higher proportion of such smokers continuing to quit at one year. Conversely, the presence of young adults over 18 in the home increases the likelihood of relapse before one year. The presence of a partner or parent in the home decreases the likelihood of relapse.

The study also indicates that those joining a smoking cessation programme differ considerably from remediators, and in particular have significantly larger families, while remediators have lived in the same house for a longer time. Thus they represent a different target group, who do not currently consider radon as a significant risk.

Finally, although the quantitative analysis of cost-effectiveness remains incomplete, it is apparent that in a radon affected area, the cost per life-year saved from a smoking cessation campaign may well be significantly less than that arising from a radon remediation campaign.

There is thus the potential to extend the response to the health risks of radon if provided with safety and remediation information during their interaction with the smoking cessation team in radon Affected Areas.

The approach of radon remediation programmes in England and Wales to date has been through local Environmental Health departments and targeted at remediating the home. However, this analysis suggests that there is scope for the National Health Service to take up this concern, to target smokers and to benefit from the greater experience of running smoking cessation programmes. In addition, the falling smoking rates suggests that the balance between smoking cessation programmes and radon remediation programmes in lower radon areas should be coordinated in order to achieve the best value for money, and highest benefits.

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References

- Advisory Group on Ionising Radiation (AGIR). Radon and Public Health. Docs. Health Protection Agency, RCE-11, June 2009. ISBN 978-0-85951-644-0.
- Augustson EM, Wanke KL, Rogers S, Bergen AW, Chatterjee N, Synder K, Albanes D, Taylor PR, Caporaso NE. Predictors of sustained smoking cessation: a prospective analysis of chronic smokers from the alpha-tocopherol beta-carotene cancer prevention study. *Am J Public Health* 2008; 98 (3): 549-55.
- Bauld L, Chesterman J, Ferguson J, Judge K. A comparison of the effectiveness of group-based and pharmacy-led smoking cessation treatment in Glasgow. *Addiction* 2008; 104: 308-316. Doi:10.1111/j.1360-0443.2008.02246.x.
- BEIR VI: Committee on Health Risks of Exposure to Radon, 1999. Health Effects of Exposure to Radon. National Academic Press, Washington DC, ISBN 0-309-05645-4.
- Bradley EJ, Lomas PR, Green BMR, Smithard J. Radon in dwellings in England: 1997 Review. National Radiological Protection Board Report R293; NRPB, Chilton, UK. 1997.
- Chow Y, Green BMR, Zhang W, Meara J. Radon health equity audit - is the radon programme fair? Health Protection 2007 University of Warwick. 2007.
- Darby S, Hill D, Auvinen A, Barros-Dios JM, Baysson H, Bochicchio F, et al. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *Brit. Med. J.* 2005; 330: 223-227.

- Degrange JP, Birchall A, Haylock R, Janssens A, Levy FP, Marsh J, Muirhead CA. European Commission software tool for radon risk calculation and evaluation of countermeasures. Proc. 10th International Congress of the International Radiation Protection Association, Hiroshima Japan. 2000.
- Denman AR, Groves-Kirkby CJ, Phillips PS, Tornberg R. Using the European Community Radon Software to estimate the individual health benefits of a domestic radon remediation programme, *J. Radiol. Prot.* 2004; 24 (1): 83-89.
- Department of Health. A smokefree future. <http://www.dh.gov.uk/publications>. Document 299072, 1 February 2010.
- Doll R, Peto R, Boreham J et al. Mortality in relation to smoking: 50 years observations on male British doctors. *Brit. Med. J.* 2004; 328: 1519.
- Freund KM, D'Agostino RB, Belanger AJ, Kannel WB, Stokes J. Predictors of smoking cessation: the Framlington Study. *Am. J. Epidemiol.* 1992; 135: 957-64.
- Gray A, Read S, McGale P, Darby S. Lung cancer deaths from indoor radon and the cost effectiveness and potential of policies to reduce them. *Brit. Med. J.* 2009; 338: a3110, doi:10.1136/bmj.a3110
- Groves-Kirkby CJ, Denman AR, Timson K, Shield G, Phillips PS, Rogers S. Radon, tobacco and lung cancer – the significance of smoking cessation programmes. *Health Protection Matters* 2008; 12: 40-44.
- Macy JT, Seo DC, Chassin L, Presson CC, Sherman SJ. Prospective predictors of long-term Abstinence versus relapse among smokers who quit as young adults. *Am. J. Public Health* 2007; 97(8): 1470-5.
- Mills AM, Rhodes KV, Follansbee CW, Shofer FS, Prusakowski M, Berstein SL, et al. Effect of household children on adult ED smokers' motivation to quit. *Am. J. Emerg Med.* 2008; 26(7): 757-762.
- Patterson F, Kerrin K, Wileyto EP, Lerman C. Increase in anger symptoms after smoking cessation predicts relapse. *Drug Alcohol Depend* 2008; 95(1-2): 173-6.
- Solberg LI, Asche SE, Boyle R, McCarty MC, Thoele MJ. Smoking and cessation behaviors among young adults of various educational backgrounds. *Am. J. Public Health* 2007; 97 (8): 1421-6.
- The Radon Council Ltd. The radon manual: a guide to the requirements for the detection and measurement of natural radon levels, associated remedial measures and subsequent monitoring of results. Shepperton: The Radon Council Ltd.; 1995.
- Timson K, Shield G, Phillips PS, Rogers S, Eckberg M, Groves-Kirkby CJ, Denman AR. Risk of suffering respiratory disease is a key influence in motivating smokers to quit smoking in Northamptonshire (in preparation).
- Tucker JS, Ellickson PL, Orlando M, Klein DJ. Predictors of attempted quitting and cessation among young adult smokers. *Prev. Med.* 2005; 41(2): 554-61.
- Twigg L, Moon G, Szatkowski L, Iggulden P. Smoking cessation in England: intentionality, anticipated ease of quitting and advice provision. *Social Science and Medicine* 2009; 68 (4): 610-619.
- Zhou X, Nonnemaker J, Sherrill B, Gilsenan AW, Coste F, West R. Attempts to quit smoking and relapse: factors associated with success of failure from the ATTEMPT cohort study. *Addictive Behaviours* 2009; 34, (4): 365-373.

A model describing indoor concentrations of thoron and its decay products

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Abstract

In the past, the radioactive noble gas thoron (^{220}Rn) was thought to occur only in negligible concentrations. But recently, increased thoron concentrations were found in traditional Chinese and Indian mud buildings, where their contribution to the inhalation dose of the dwellers can be in the order of magnitude of the dose from radon (^{222}Rn). Moreover, the WHO's Radon Handbook of 2009 advises dose reductions also with relatively moderate exposures, for which even average additional thoron concentrations can be crucial. Therefore, a model of the occurrence of thoron and its decay products indoors was developed.

The solution of the differential equations which describe the sources and sinks of the nuclides of the thoron decay chain yielded a theoretical relation between the concentrations of the nuclides in the unattached and the attached state, which are important for inhalation dosimetry. Several differences to existing radon models could be identified. Transfer coefficients occurring in the differential equations were determined experimentally. For this purpose various atmospheric conditions were adjusted in a small-scaled traditional mud dwelling, which had been erected in a laboratory at Helmholtz Zentrum München. Because of the prevalence of increased thoron concentrations in homes with mud as building material, special emphasis was given to study thoron exhalation from mud structures.

To validate the model, model predicted concentrations of thoron and its decay products of real Chinese and Indian mud dwellings were compared to measured concentrations in those rooms. The model makes possible to assess exposures of dwellers to thoron and – combined with a dose model – to calculate their inhalation doses in dependence on their living habits from easily measurable constructional properties of the dwelling. The model predicts significant exposures for residents of buildings with mud construction elements in other countries as well.

Introduction

Need for a thoron model

The radioactive noble gas radon and its decay products have been known as indoor health risks for several decades as they can cause a significant dose to the respiratory tract and other tissue. Only recently, the connection between the exposure to radon and an increased incidence of lung cancer with a linear dose-response relation even below 200 Bq m^{-3} was shown in epidemiological studies (Darby et al. 2005, Krewski et al. 2005). These findings, among others, induced the World Health Organization to advise measures for the mitigation of exposures also with relatively moderate concentrations of radon and its decay products (WHO 2009).

The radon isotope ^{220}Rn (thoron) occurs in most houses mainly from the building material as its half-life is only 55.6 s. For dwellings made of brick or concrete, it contributes to the inhalation dose of the dwellers in the order of 10–20% of the dose caused by all radon isotopes (UNSCEAR 2000). Therefore, previous studies focused on the exposure to the prevalent isotope ^{222}Rn (called radon in the following) whereas thoron was examined only rarely or as a side-aspect of radon measurements (e.g. Stranden 1980, Steinhäusler 1996). In the light of the proposed reduced reference levels (WHO 2009), the dose contribution by thoron gains importance for the total indoor exposure in such dwellings.

Moreover, in the last years occurrences of increased thoron concentrations have been discovered in dwellings made of unfired mineral building materials as adobe and mudbricks (Sreenath Reddy et al. 2004). The contribution of thoron and its decay products to the inhalation dose of people living in the traditional caves which are dug into the loamy soil of the Central-Chinese Loess Plateau has been found to be up to 50% (Shang et al. 2005).

Therefore a characterization of the influence of indoor parameters on the occurrence of thoron and its decay products is required. The model for the calculation of the concentrations of radon and its decay products in mines which was formulated by Jacobi (1972) and was adapted to arbitrary indoor atmospheres by several contributors (Knutson 1988, Porstendörfer 1994) can be used as a base. However, the decay chain of thoron differs from that of radon in several essential properties such as the decay modes and half-lives of the respective nuclides, which causes various significant changes in the model structure. Additionally, several transfer coefficients between the compartments of the thoron model cannot be adopted from the radon model but must be determined separately.

This study presents results from a self-contained indoor thoron compartment model (Meisenberg and Tschiersch 2010) illustrates the reasons for necessary differences to the radon model. Useful instructions for the metrology of thoron are deduced from the model predictions. Types of houses in which increased thoron concentrations can be expected are presented.

Relevant properties of thoron and its decay products

Thoron with its short half-life of 55.6 s cannot penetrate foundations which can usually be found in most modern buildings. On the other hand, a comparatively small thickness such as that of walls and ceilings can be sufficient to cause significant exhalations of

thoron. Therefore the building material and thus a part of the building is the major source of indoor thoron. Hence, a thoron model must incorporate the exhalation of the gas and the influences on it.

The spatial distribution of thoron in a room is not homogeneous but features increased concentrations close to thoron exhaling surfaces. Therefore its concentration cannot be specified by a single value but must be characterized depending on the position in the room.

As with radon and its decay products, the dose after inhalation of the radioactive nuclides of the thoron decay chain is mainly caused by their alpha-particle emission. Thus the exposure to thoron can be assessed by the potential alpha-particle concentration *PAEC*, which is the total energy of the alpha-particles emitted by the decay products per volume. Therefore, a thoron model must specify the influence of indoor parameters to this quantity, which can differ from that on the activity concentration of the nuclides.

The contribution of the single decay products to the potential alpha-energy concentration of the thoron decay chain does not only depend on their position in the decay chain but also on their half-life. The long-lived ^{212}Pb ($T_{1/2} = 10.6$ h) contributes almost the complete portion (91.3%) whereas the contribution of ^{212}Bi ($T_{1/2} = 1.01$ h, 8.7%) is much smaller but can still be relevant. The contributions of ^{216}Po , ^{212}Po (because of their short half-lives) and ^{208}Tl (only beta-decay) are negligible.

The half-lives of the significant nuclides ^{212}Pb and ^{212}Bi are much longer than that of the nuclides in the radon decay chain. Thus, radioactive decay is less important as a sink whereas possible other sinks such as air exchange influence the concentrations of the nuclides more strongly.

Similar to those of radon, the decay products of thoron originate as single airborne atoms or ions (which cluster water molecules around them) but can also attach to aerosol particles or deposit onto surfaces. The exposure to unattached and attached decay products yields different contributions to the dose in the different parts of the respiratory tract whereas deposited decay products do not add to the exposure of people. Beside the different relevant nuclides, a thoron model must take into account these three states. Additionally, the activity size distribution of the attached decay products is another relevant input parameter for dose calculations.

With these properties, a suitable structure of a model for the indoor occurrence of thoron and its decay products is shown in Figure 1.

Material and methods

Experimental mudbrick room and real rooms

Increased concentrations of indoor thoron have been found in dwellings made of unfired mineral building material such as mud (Sreenath Reddy et al. 2004, Shang et al. 2008). For the determination of the transfer coefficients of the thoron model, a room was erected from mudbricks at Helmholtz Zentrum München. It features dimensions of $l = 2.8$ m, $w = 1.5$ m, and $h = 1.8$ m, a volume of 7.1 m³, and a semi-cylindrical vault; thus it represents at a reduced scale a type of dwellings which is common on the Central-Chinese Loess Plateau. The mud of the inner plaster, which is commercially

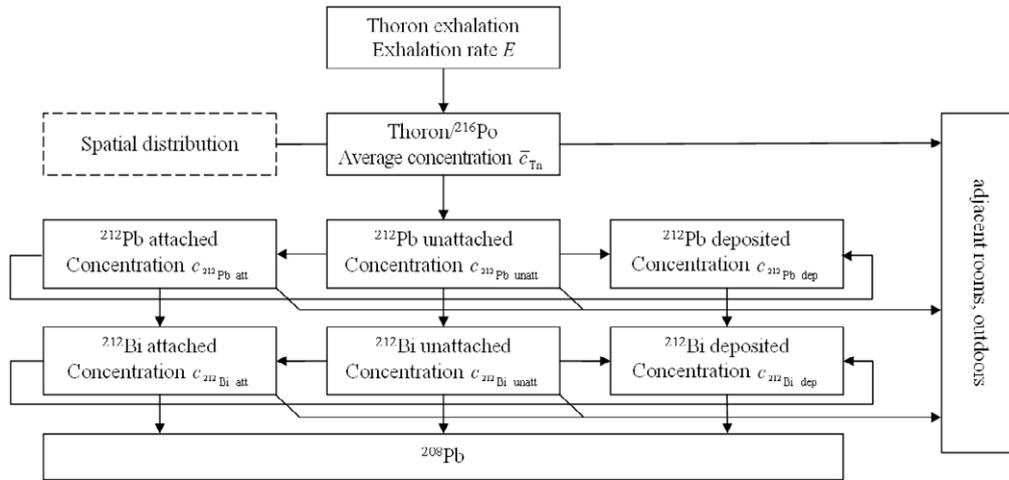


Fig. 1. Structure of the model describing the indoor concentration of thoron and its decay products.

available (Claytech, Germany), was mixed with thorium-rich granite to increase the exhalation of thoron for higher precision of short-time measurements; its specific ^{232}Th activity is about 50 Bq kg^{-1} .

For a validation of the measurement results from the experimental room, measurements were also performed in mudbrick dwellings on the Central-Chinese Loess Plateau and in northern India.

Measurement of thoron concentrations and exhalation rates

Thoron concentrations were measured with the common radon and thoron measurement device Rad-7 (DurrIDGE, USA), which uses the electrostatic deposition of newly formed thoron decay products. It conveys air with a volume flow rate of about 1 L min^{-1} from the end of an inlet tube.

Thoron exhalation rates were measured by means of the equilibrium concentration which is reached in a closed accumulation chamber (Tuccimei et al. 2006). In contrast to radon, leakages and back-diffusion do not need to be taken into account because of the short half-life of thoron. Samples for which the exhalation rate was measured were sealed with thoron-proof lacquer on all sides but one.

Measurement of concentrations of thoron decay products

Working level monitors (commercially available from Tracerlab, Germany; Peter 1994) were used for the measurement of unattached and total thoron decay product concentrations. The decay products were deposited on a sampling substrate with an air flow rate of about 150 L h^{-1} . Their decay was measured online by alpha spectrometry.

For the deposition and measurement of the total thoron decay product concentration, a cellulose nitrate filter was used as the sampling substrate. A wire screen with a mesh size of $625 \mu\text{m}$ was applied as the sampling substrate for the measurement of unattached decay products (Meisenberg and Tschiersch 2009). With the given air flow rate, this screen features a negligible deposition probability for attached decay products whereas unattached decay products are sampled with an efficiency of about 40%.

Further measurement methods

Specific activities of ^{232}Th in solid samples were measured by gamma spectrometry using its gamma-emitting decay products in equilibrium with it.

Air exchange rates of rooms were measured by one-time release of CO_2 as a tracer gas to the indoor air. The concentration of the homogeneously spread CO_2 decreased by air exchange with clean ambient air. The rate of decrease is the air exchange rate.

Aerosol number concentrations were measured with a condensation particle counter (3022A, TSI, USA) with a lower cut-off diameter of 7 nm and an air flow rate of 18 L h^{-1} .

Results and Discussion

Exhalation of thoron from mud

The exhalation rate E of thoron was measured at various samples of mud such as bricks, plaster, and rammed earth. A dependency on the specific ^{232}Th activity A_{spec} , which can be approximated by a linear function, was found (Figure 2):

$$E = (0.031 \pm 0.003) \text{ kg m}^{-2} \text{ s}^{-1} \cdot A_{\text{spec}}$$

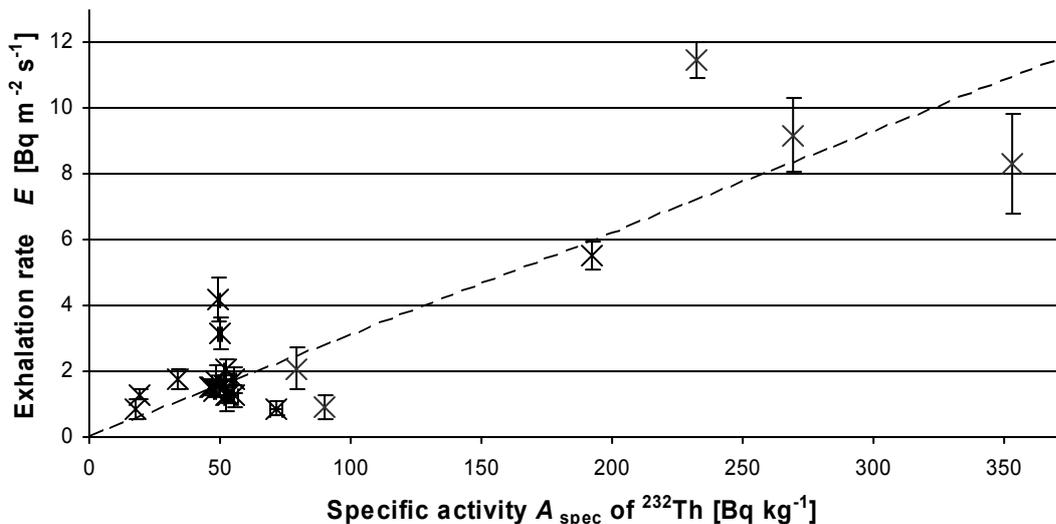


Fig. 2. Exhalation rate of various mud samples from Europe and Asia as a function of their specific ^{232}Th activity as well as the line of linear regression.

For the determination of the diffusion length of thoron in mud, the exhalation rate was measured at two samples from which a few millimeters of mud were removed between each measurement of the series. The exhalation rate remained constant until thicknesses of less than 2 cm were reached.

At several samples of mud, the exhalation rate after firing the sample was compared with that in the unfired state. For this purpose, the samples were fired at a temperature of $900 \text{ }^\circ\text{C}$ for three days. The exhalation rates were reduced on average to only $6.4 \pm 5.1\%$ of the initial value.

Although a distinct influence of the specific ^{232}Th activity in the mud on the exhalation of thoron was observed, even ordinary ^{232}Th activities can lead to increased concentrations of indoor thoron and its decay products: Samples of mudbricks and plaster from the Central-Chinese Loess Plateau featured specific activities of $53 \pm 7 \text{ Bq kg}^{-1}$ on average, whereas specific activities of 60 Bq kg^{-1} on average (with values up to 310 Bq kg^{-1}) were found in natural building stones from Europe (EC 1999).

The short diffusion length in the mud causes a significant thoron exhalation even from thin layers of mud as plasters. However, fired bricks and clinkers do not seem to be a relevant source of thoron; there, the pores are obstructed by the partly melted minerals.

Spatial distribution of thoron

In the experiment room, the concentration of thoron was measured at several distances from a thoron-exhaling wall. Several measurement series were performed at different air exchange rates. In all measurement series, a decrease of the concentration within a few centimeters was found; with increasing air exchange rates from 0.1 h^{-1} to 4.5 h^{-1} the slope of the decrease became smoother whereas with even higher air exchange rates the gradient increased again. With an air exchange rate of only 0.1 h^{-1} almost no thoron could be found in the middle of the room whereas with higher and still realistic air exchange rates concentrations of up to 15% of the concentration directly at the wall were observed (Figure 3).

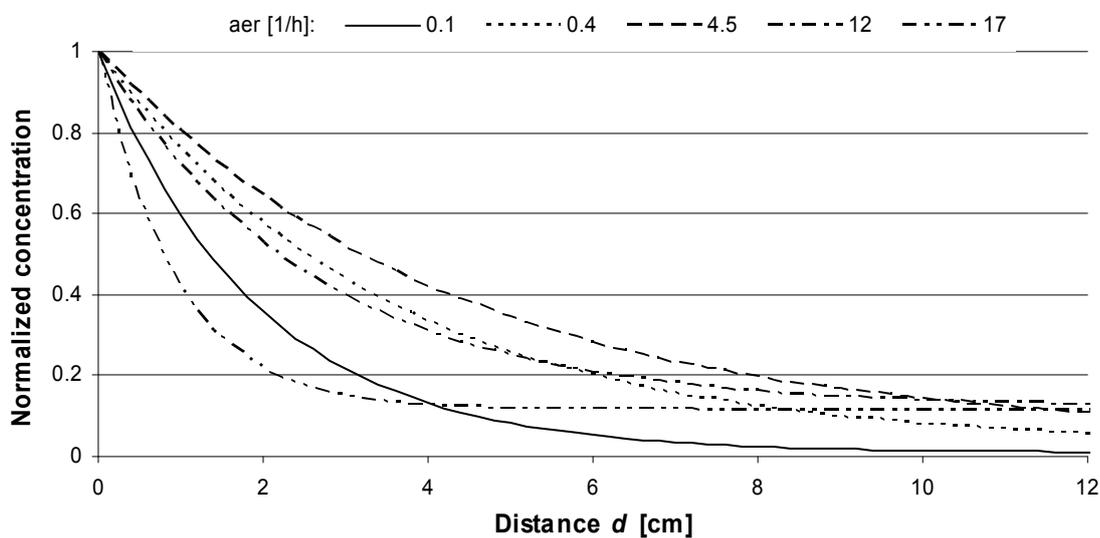


Fig. 3. Concentrations of indoor thoron (relative to the value directly at the wall) as a function of the distance from a thoron-exhaling wall at different air exchange rates aer.

The concentration profile at the lowest air exchange rate is governed by the diffusive transport of the gas. The Gaussian error function describes the spatial distribution of particles which are transported by diffusion if their source spans over one half-space as it is the case with thoron from a wall. When this function is fitted to the measured data, the diffusion length of thoron in air can be determined as $2.6 \pm 0.2 \text{ cm}$.

The thoron concentration especially in the middle of the room is strongly influenced by the mixture of the air – in this case caused by air exchange.

Concentration of the thoron decay products

Concentrations of the thoron decay products were measured at different air exchange rates a_{er} in the experimental room. Figure 4 presents the results by means of the equilibrium factor F , which is the concentration of the decay products weighted by their contribution to the $PAEC$ relative to the average concentration of thoron.

The strong influence of the air exchange on the equilibrium factor and thus on the decay product concentration can be seen; this influence as well as that of possible further sinks is promoted by the small decay constant λ of 0.065 h^{-1} of ^{212}Pb as the most important decay product. The values obey a $\lambda/(\lambda+a_{er})$ relation. Usual air exchange rates in modern dwellings are in the range from below 3 to about 10 h^{-1} (i.e. F in the range from 0.02 to 0.006) with a trend to lower values of less than 1 h^{-1} in low-energy houses ($F = 0.06$). Typical values for the radon decay chain are in the range from 0.4 to 0.2 (Porstendörfer 1994).

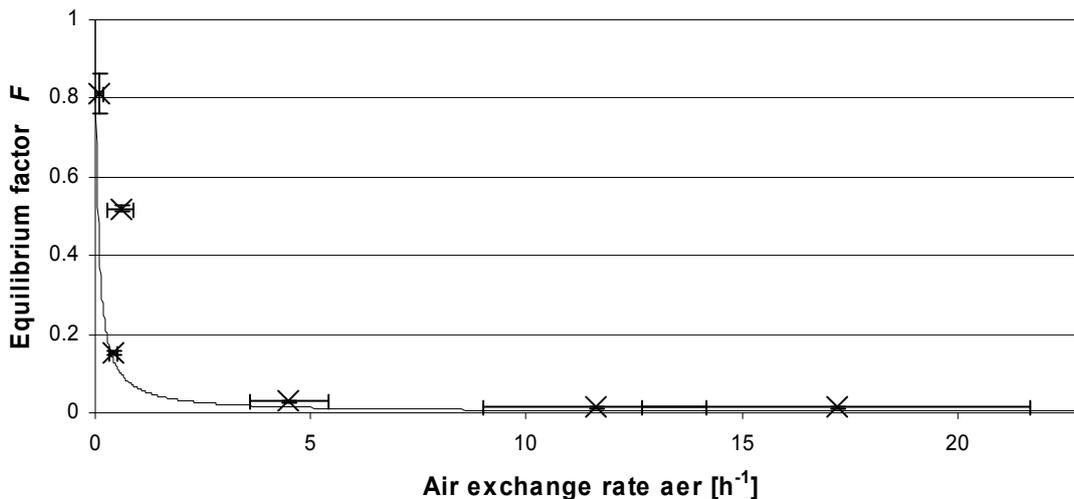


Fig. 4. Equilibrium factor of the thoron decay chain as a function of the air exchange rate: Measurement results from Chinese (X) and from Indian (\diamond) dwellings and fitted curve.

Unattached fraction of the decay products

The unattached fraction of the thoron decay products was measured in the experiment room at different aerosol concentrations as its most important influence (Figure 5). The air exchange rate during the measurements was 0.1 h^{-1} . Similar to the equilibrium factor, this parameter plays an important role for the unattached fraction because of the long half-lives of the thoron decay products.

The observed values are much smaller than those of the radon decay products with values between 0.05 and 0.20 for usual indoor conditions (aerosol concentrations between 1000 and 20000 cm^{-3} ; Porstendörfer 1994). With higher air exchange rates, however, a greater unattached fraction can be expected because of the shorter lifetime of the decay products in the room.

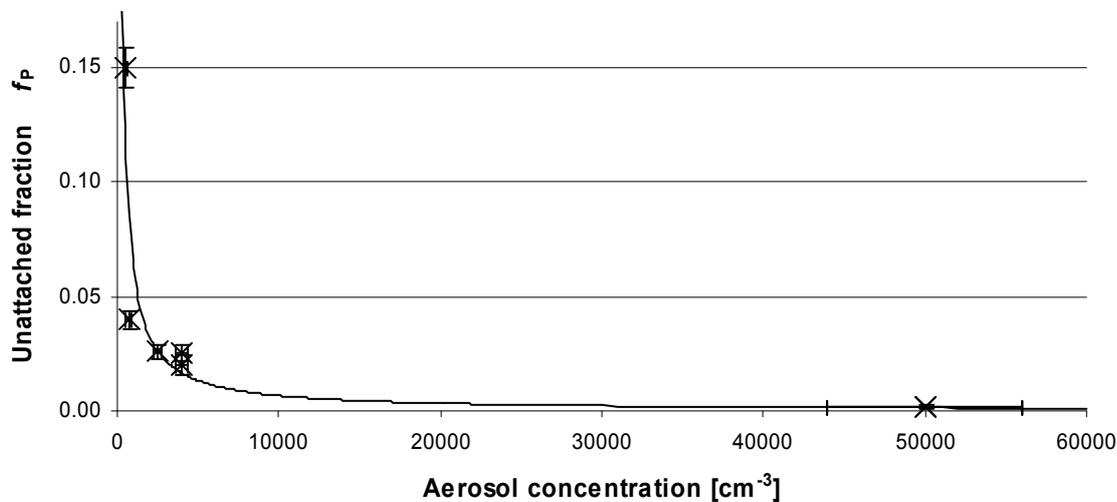


Fig. 5. Unattached fraction as a function of the aerosol concentration and fitted curve.

Conclusions

Consequences on the metrology of thoron exposures

For the assessment of the exposure of people to radioactive gases, the relevant quantities for the calculation of the inhalation dose must be measured. Both for radon and thoron, these are the concentrations of the airborne decay products. For radon, however, a single indoor measurement of the gas can usually provide a satisfying estimate of the inhalation dose.

For thoron, two reasons impede the use of gas measurements for the assessment of the exposure to the decay products: Firstly, the thoron concentration is not homogeneous and does not even feature a constant profile with different indoor atmospheric conditions. Thus, a single measurement at one position cannot give information about the average thoron concentration in the room. Secondly, air exchange plays such an important role as a sink of the long-lived thoron decay products that their concentrations can vary by about one order of magnitude with different air exchange rates. Thus, even the average thoron concentration is not a significant quantity for the decay product concentration if the air exchange rate is unknown.

Therefore, the measurement of the decay product concentration itself is essential. Separate measurements of the concentrations of ^{212}Pb and ^{212}Bi and of the unattached and the attached state are helpful but less important. The development of cheap and simple passive detectors for the decay products is desirable.

Calculation of inhalation doses

Recently, inhalation dose coefficients for the nuclides of the thoron decay chain were published (Li et al. 2008). With these values, their concentrations in mudbrick dwellings of the Central-Chinese loess plateau can yield annual effective doses in the range of up to 2 mSv if a daily indoor stay of 10 h is assumed. Even with a small aerosol concentration of 6000 cm^{-3} , more than half of the dose is contributed by attached ^{212}Pb . Unattached ^{212}Pb and, even less, attached ^{212}Bi add the remaining part.

A calculation of expected concentrations of thoron and its decay products in European mud dwellings shows that they can cause similar doses also there.

Indication for potentially increased thoron exposures

As increased concentrations of thoron and its decay products were found mostly in buildings of unfired mineral building material such as mud, a survey of thoron exposures should initially focus on such buildings. In Europe, unfired mud is a traditional building material for timber-framing buildings but also gains attention as an ecological material in modern indoor architecture. As overviews over the content of ^{232}Th in building materials exist (e.g. EC 1999), indication of areas of mud with high concentrations of ^{232}Th is given.

Air exchange is an effective sink of the long-lived thoron decay products. Therefore, rooms which feature small air exchange rates are prone to high concentrations of the decay products in particular. The refurbishment of traditional buildings aiming at reduced energy consumption might increase the number of rooms where both small air exchange rates and mud as the building material are present.

The concentrations of thoron (averaged over a room) and of the decay products are proportional to the ratio of the area of the thoron-exhaling surfaces to the room volume. Therefore, small rooms, in which this ratio is greater, are more susceptible to increased concentrations than large rooms.

References

- Darby S, Hill D, Auvinen A, Barros-Dios JM, Baysson H, Bochicchio F, Deo H, Falk R, Forastiere F, Hakama M, Heid I, Kreienbrock L, Kreuzer M, Lagarde F, Mäkeläinen I, Muirhead C, Oberaigner W, Pershagen G, Ruano-Ravina A, Ruosteenoja E, Rosario AS, Tirmarche M, Tomásek L, Whitley E, Wichmann HE, Doll R. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *British Medical Journal* 2005; 330: 223–226.
- European Commission. Radiation protection 112 – Radiological protection principles concerning the natural radioactivity of building materials. Luxembourg: European Commission, Directorate-General for Environment, Nuclear Safety and Civil Protection; 1999.
- Jacobi W. Activity and potential α -energy of $^{222}\text{radon}$ - and $^{220}\text{radon}$ -daughters in different air atmospheres. *Health Phys* 1972; 22: 441–450.
- Knutson EO. Modeling indoor concentrations of radon's decay products. In: Nazaroff WW, Nero AV (Eds.). *Radon and its decay products in indoor air*. New York: Wiley-Interscience; 1988. p. 161–202.
- Krewski D, Lubin JH, Zielinski JM, Alavanja M, Catalan VS, Field RW, Klotz JB, Létourneau EG, Lynch CF, Lyon JI, Sandler DP, Schoenberg JB, Steck DJ, Stolwijk JA, Weinberg C, Wilcox HB. Residential radon and risk of lung cancer: A combined analysis of 7 North American case control studies. *Epidemiology* 2005; 16: 137–145.
- Li WB, Tschiersch J, Oeh U, Hoeschen C. Lung dosimetry of inhaled thoron decay products. In: *Proceedings of IRPA 12*. 2008 Oct 19–24; Buenos Aires, Argentina. International Radiation Protection Association; 2008.

- Meisenberg O, Tschiersch J. Online measurement of unattached and total radon and thoron decay products. *Applied Radiation and Isotopes*; 67: 843–848.
- Meisenberg O, Tschiersch J. Thoron in indoor air: modeling for a better exposure estimate. *Indoor Air* 2010 (submitted).
- Peter JE. Analysis of radon and thoron daughter concentrations in air by continuous alpha spectroscopy. *Radiation Protection Dosimetry* 1994; 56: 267–270.
- Porstendörfer J. Properties and behaviour of radon and thoron and their decay products in the air. *Journal of Aerosol Science* 1994; 25: 219–263.
- Schmidt V, Hamel P. Measurements of deposition velocity of radon decay products for examination of the correlation between air activity concentration of radon and the accumulated Po-210 surface activity. *Science of the Total Environment* 2001; 272: 189–194.
- Shang B, Chen B, Gao Y, Cui H, Li Z. Thoron levels in traditional Chinese residential dwellings. *Radiation and Environmental Biophysics* 2005; 44: 193–199.
- Shang B, Tschiersch J, Cui H, Xia Y. Radon survey in dwellings of Gansu, China: the influence of thoron and an attempt for correction. *Radiation and Environmental Biophysics* 2008; 47: 367–373.
- Sreenath Reddy M, Yadagiri Reddy P, Rama Reddy K, Eappen KP, Ramachandran TV, Mayya YS. Thoron levels in the dwellings of Hyderabad city, Andhra Pradesh, India. *Journal of Environmental Radioactivity* 2004; 73: 21–28.
- Steinhäusler F. Environmental ^{220}Rn : a review. *Environment International* 1996; 22: S1111-S1123.
- Stranden E. Thoron and radon daughters in different atmospheres. *Health Physics* 1980; 38: 777–785.
- Tuccimei P, Moroni M, Norcia D. Simultaneous determination of ^{222}Rn and ^{220}Rn exhalation rates from building materials used in Central Italy with accumulation chambers and a continuous solid state alpha detector: influence of particle size, humidity and precursors concentration. *Applied Radiation and Isotopes* 2006; 64: 254–263.
- UNSCEAR. Sources and Effects of Ionizing Radiation, Annex B: Exposures from natural radiation sources. Vienna: United Nations Scientific Committee on the Effects of Atomic Radiation; 2000.
- World Health Organization. WHO Handbook on Indoor Radon: A Public Health Perspective. Geneva: World Health Organisation; 2009.

First results of measurements of equilibrium factors F and unattached fractions f_p of radon progeny in Czech dwellings

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Abstract

The unattached fraction of radon decay product clusters f_p and equilibrium factor F are dose relevant parameters in all dosimetric approaches to dose calculation. In the past, three year weekly continuous measurements of unattached and attached activities of radon daughter product and air exchange rate were carried out during heating season in thirty occupied typical Czech family houses.

The results indicated significantly different weekly averages of equilibrium factor F and f_p for houses located in towns compared to villages. Due to this fact, approximately 10% average increase of equivalent lung dose rate was estimated in the detriment in towns.

Average values of equilibrium factor F and f_p were 0.40 and 8.6% in urban houses and 0.32 and 10.7%, respectively in rural houses.

Based on measurements of mean values of f_p , average effective dose conversion coefficients per WLM were estimated at 15.0 mSv/WLM in urban houses and 15.9 mSv/WLM in rural houses, respectively.

Introduction

The unattached fraction of radon decay product clusters f_p and equilibrium factor F are dose relevant parameters in all dosimetric approaches to dose calculation. Direct measurements of f_p and F under different ambient conditions allow a comparison of influence of ambient conditions to relative dose contribution [4].

The results of sensitivity analysis applied to the classical Jacobi–Porstendörfer room model [5] generally describing dynamics of both unattached and attached short-lived radon progeny in the room indicate ACH (air exchange rate), deposition on surfaces q_f and attachment rate to aerosols X of unattached radon daughter product as the key quantities influencing most strongly the behaviour of observed values f_p and equilibrium factor F in a room. The most important role in processes affecting values of deposition q_f and attachment rate X plays, besides ACH , predominantly aerosol size distribution and total aerosol concentration.

In the past, three year weekly continuous measurements of unattached and attached activity concentration of each radon progeny and of ACH were performed during heating season in thirty occupied typical Czech family houses.

Primarily, the purpose of the present paper is to introduce the results of direct measurements of F and f_p under different living conditions and to estimate the influence of these conditions to dose contribution.

We also focused on the calculation of the key model parameters X , q_f and ACH in measured houses in order to independently estimate the most probable values of F and f_p by means of the room model and to compare them with those obtained from direct measurements.

Since there are well known practical and principal problems arising from long-term measurement of aerosols in occupied dwellings with any SMPC (Scanning mobility particle sizer) caused by evaporating of wide spread butyl alcohol saturator used in particle condensation nuclei counters into the room, aerosol particle size distribution and aerosol concentration were not systematically directly measured. Nevertheless, aerosol concentration Z could be estimated indirectly from measured values f_p by means of Porstendörfer's approximate formula ($f_p = 414/Z$) [3].

Material and methods

All measurements were conducted in thirty occupied typical Czech or two-storey family houses from October to March during heating season. The houses were chosen randomly and they were equipped with central heating system. Originally, we intended to divide them according to assumed different ambient living conditions from the aerosol concentration and its size distribution standpoint in structure as follows: towns – villages, smokers – non smokers. Unfortunately, after finishing all measurements we had to distinguish only basic living conditions according to the house location i.e. town – village and newly according to daily time period.

To detect the assumed influence of different occupant's indoor activities and outdoor changes (traffic density, weather conditions etc.) on behaviour of observed parameters f_p and F we divided each daily 24 hours taking measurement time period into "day" taking from 6 a.m. to 6 p.m. and into "night" taking from 6 p.m. to 6 a.m., respectively. Exposure duration took minimally one week in each house.

Measurement instruments

For measurement of unattached and attached activity concentration of each short-lived radon daughter progeny, we used continuous monitor Fritra 4 (SMM – Prague, CZ). Monitor Fritra 4 has built-in memory buffer allowing more than 4000 records taking each 120 minutes. This measuring interval included ten minutes sampling and 110 minutes taking computational procedure with implemented four alpha counting intervals providing minimum detectable activity (MDA) for each radon progeny in following ratio (^{218}Po : ^{214}Pb : ^{214}Bi) = (1: 0.6: 0.5) stepwise $40 \text{ Bq}\cdot\text{m}^{-3}$, $12 \text{ Bq}\cdot\text{m}^{-3}$, $15 \text{ Bq}\cdot\text{m}^{-3}$. The MDA for measured radon concentration was estimated to about $15 \text{ Bq}\cdot\text{m}^{-3}$. Unattached activity concentration of each radon progeny was measured from the screen with mesh 300 and cut-off diameter $d_{50} = 4 \text{ nm}$ and the attached activity concentration of each radon progeny from the Millipore filter type AA, $0.8 \text{ }\mu\text{m}$ placed behind the screen.

The description of monitor Fritra 4 alone in more details and quality assurance from measurement of unattached and attached activity concentration for each radon progeny and from measurement indoor average aerosol concentration standpoint is given elsewhere [2].

Radon measurements were performed by means of well-known continuous monitor Alphaguard (Genitron, D) certified at the German reference chamber at the PTB in Braunschweig. During all measurements, we used its 60 minutes measuring diffusion mode. The both monitors were placed mostly in living rooms at each house.

Theoretical background

i) Equilibrium factor F and f_p as dose relevant parameters

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:

$$H = DFC \cdot \frac{T_{\text{exp}}}{170} \cdot F \cdot \frac{a_v}{3700} \quad (1)$$

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 calculations by Marsh and Birchall [4] the DFC in eq. (1) can be expressed as a linear function of unattached part of equilibrium equivalent concentration of radon progeny f_p as follows:

$$DFC(f_p) = 11.35 + 0.43 f_p \quad (2)$$

with f_p expressed as the percentage of total PAEC.

Finally, considering eq. (1) and (2) and assuming “the same” breathing rate, the influence of two different ambient conditions to dose can be expressed in terms of relative change of equivalent dose rate H_1/H_0 as follows:

$$\frac{H_1}{H_0} = \frac{F_1 \cdot (k + f_{p,1})}{F_0 \cdot (k + f_{p,0})} \quad (3)$$

with subscripts 0 and 1 representing two different ambient conditions and k - representing the ratio 11.35/0.43 from eq.(2).

ii) Attachment rate X , deposition rate q_f and air exchange rate ACH

The attachment rate X and deposition rate q_f (plate-out) and ACH can be calculated in principle simultaneously from measured unattached and attached activity concentration of each radon daughter progeny by means of an algebraic inversion of the model [2] expressed for room in steady state as follows:

$$\begin{aligned}
 a_{j,f} &= \lambda_{i-1} (a_{j-1,f} + R_{j-1} a_{j-1,a}) / (ACH + \lambda_j + q_f + X) \\
 a_{j,a} &= (ACH \cdot a_{j,o} + (1 - R_{j-1}) \lambda_j a_{j-1,a} + X a_{j-1,f}) / (ACH + \lambda_j + q_a) \\
 a_{0,i} &= (Q_{Rn} + ACH a_{0,o}) / (\lambda_0 + ACH)
 \end{aligned} \tag{4}$$

with initial conditions $a_{0,i} = a_{0,i,f}, a_{0,i,a} = 0, a_{j,o,f} = 0$

a_j - activity concentration of j-th radon daughter product [Bq m^{-3}]

λ_j - decay constant of j-th radon daughter product [h^{-1}]

R_j - fraction of recoiled atoms of j-th nuclide from aerosol particles

1st subscript $j = 0, 1, 2, 3, 4$ stepwise $^{222}\text{Rn}, ^{218}\text{Po}, ^{214}\text{Pb}, ^{214}\text{Bi}, ^{214}\text{Po}$

2nd subscript i, o - denotes indoor/outdoor

3rd subscript f, a - denotes unattached/attached activity j-th radon daughter product

Q_{Rn} - sum of radon entry rates into a house [$\text{Bq m}^{-3} \text{h}^{-1}$]

Attachment rate

Under realistic indoor conditions, the observed attachment rate X in a room in „steady state” can be approximately calculated only on the base of measurement of unattached and attached activity concentration ^{218}Po as follows [3].

$$X = \frac{a_{1ia}}{a_{1if}} \lambda_1 \tag{5}$$

where

a_{1ia}, a_{1if} are attached and unattached concentrations, respectively ^{218}Po [Bq m^{-3}]

λ_1 is decay constant ^{218}Po [h^{-1}]

or in case of measurement the proper aerosol size distribution as follows:

$$X = \int_0^\infty \beta(d) Z(d) dd \tag{6}$$

where

$\beta(d)$ - attachment coefficient of attached radon progeny to aerosol as a function of particle diameter d [$\text{cm}^3 \text{h}^{-1}$]

$Z(d)$ - aerosol size distribution [cm^{-3}]

According to [1] attachment coefficient $\beta(d)$ can be calculated as follows:

$$\beta(d) = \frac{2\pi D_0 d}{\frac{8D_0}{dv_0} + \frac{d}{2\delta_0}} \quad (7)$$

where

D_0 is diffusion coefficient $6.8 \cdot 10^{-2} \text{ cm}^2 \text{ s}^{-1}$

v_0 is mean thermal velocity $1.72 \cdot 10^4 \text{ cm}^{-1}$

$\delta_0 = d/2 + s_0$ with $s_0 = 4.9 \cdot 10^{-6} \text{ cm}$ is the mean free path of the unattached decay product clusters.

Plate-out

According to the model, the deposition rate q_f of unattached daughter products can be calculated approximately under realistic indoor conditions ($ACH \ll X + \lambda_1$) as follows:

$$q_f = \lambda_1 \frac{a_0}{a_{1f}} - (\lambda_1 + X) \quad (8)$$

with all symbols as in previous text.

Air exchange rate

Under the assumptions of the model introduced by the set of eq. (4), the ACH can be calculated both by means of an algebraic inversion given previously and by means of numerical iterations applying the set of eq. (4).

On the basis of our previous experiments carried out in the radon chamber of NRPI (National Radiation Protection Institute), we developed the code calculating ACH in principle as follows:

Input data for the code were measured lower and upper limit of ratios activity concentrations stepwise $Rn/^{218}\text{Po}$, $^{214}\text{Pb}/^{218}\text{Po}$, $^{214}\text{Bi}/^{218}\text{Po}$ and lower and upper limit estimates of X , q_f and ACH . The code provides stepwise outputs in a form of sets of required parameters X , q_f , ACH and recoil R fulfilling all input conditions. The most probable value of ACH was chosen from the set in which the values X and q_f matched the best to values X and q_f , calculated according to eq. (5) and eq. (8) respectively on the basis measured values of attached and unattached concentration of ^{218}Po . A large number of tests previously performed under the defined ACH in the NRPI radon chamber indicated overall agreement of calculated and true values of ACH up to acceptable 30%.

iii) Statistical evaluation

The differences between measurements were evaluated using the Student test and assuming log-normal distribution.

Results and discussion

The results of confirmatory data analysis from all measured houses ($N=30$) in the form of weekly geometric means (GM), corresponding standard deviation (GSD), 95% confidence interval (95% CI) for desired quantities of interest and p-value are summarized in Table 1 and Table 2.

In Table 1 are shown results of the analysis applied to measured data for compared time periods day – night. From Table 1 by means of p-values can be seen that all quantities of interest are not significantly different, except ACH .

The observed statistically significant approximate average 30% increase of ACH during day compared to night was not surprising. Due to this fact, a higher indoor aerosol concentration coming from outdoor air is assumed and implicitly higher attachment rate X (see eq. (6)) is expected and also measured.

The results of attachment rate X calculated according to eq. (5) can be approximated by their basic parameters ($GM = 24 \text{ h}^{-1}$, $GSD = 1.63$) for time period day and ($GM = 20 \text{ h}^{-1}$, $GSD = 1.41$) for time period night, respectively. These results agree fairly well with published data. According to [1], attachment rate X is ranging from 20 h^{-1} to 50 h^{-1} in poor ventilated houses ($ACH < 0.5 \text{ h}^{-1}$) without additional aerosol sources.

Considering eq. (6) and the average attachment coefficient $\beta(d) = 0.005 \text{ cm}^3 \text{ h}^{-1}$ published by Porstendörfer in case of poor ventilated houses ($ACH < 0.5 \text{ h}^{-1}$) without additional aerosol sources, we can expect average indoor aerosol concentration $Z \approx 4800 \text{ cm}^{-3}$ during day and $Z \approx 4000 \text{ cm}^{-3}$ during night, respectively.

The results of measured deposition rate q_f calculated according eq. (8) can be approximated by their basic parameters ($GM = 23 \text{ h}^{-1}$, $GSD = 1.48$) for time period day and ($GM = 22 \text{ h}^{-1}$, $GSD = 1.35$) for time period night, respectively. These measured results agree relatively well with published by other authors 40 h^{-1} [7], 10 h^{-1} [3], 30 h^{-1} [10].

According to already cited [1] typical published average values F and f_p in indoor air range between 0.2 - 0.4 and 0.05 - 0.20, respectively for "normal" aerosol conditions $Z \approx (1000 - 20\,000) \text{ cm}^{-3}$ with mean values of $F = 0.3$ and $f_p = 0.096$. These results are in good agreement with our measured results f_p ($GM = 0.099$, $GSD = 1.58$), F ($GM = 0.35$, $GSD = 1.31$) found for time period day and f_p ($GM = 0.107$, $GSD = 1.47$), F ($GM = 0.36$, $GSD = 1.32$) found for time period night.

In Table 2 are shown results of the analysis applied to measured data for compared locations town – village. From p-values in Table 2 can be seen that all quantity of interest are significantly different except deposition q_f and the fact that observed mean values F , f_p , X and q_f agree very well with the published data mentioned in previously.

In our opinion, the higher average value F and logically lower average value f_p in indoor air in towns compared to villages are caused mainly by higher average aerosol concentration probably in consequence of different indoor activities. This fact is indicated by dramatically higher values of attachment rate X in towns compared to villages and statistically significant lower average value ACH approximately about 30%.

If we consider the above mentioned average attachment coefficient $\beta(d) = 0.005 \text{ cm}^3 \text{ h}^{-1}$ published by Porstendörfer, eq. (6) and measured means of attachment rates X

from Table 2, we are able to estimate average indoor aerosol concentration $Z \approx 5200 \text{ cm}^{-3}$ in case of towns and $Z \approx 3600 \text{ cm}^{-3}$ in case of villages. From Table 2 can be also seen that measured average value ACH is ranges around $(0.3 - 0.4) \text{ h}^{-1}$ in case of both towns and villages.

If we consider Porstendörfer's approximate formula $f_p = 414/Z$ mentioned previously (see Introduction) and measured average values of f_p calculated for different observed conditions from Table 1 and Table 2, we can estimate average value of indoor aerosol concentration as follows:

- $Z \approx 4800 \text{ cm}^{-3}$ in case of towns and $Z \approx 4000 \text{ cm}^{-3}$ in case of villages respectively
- $Z \approx 4200 \text{ cm}^{-3}$ for time period day and $Z \approx 3900 \text{ cm}^{-3}$ for time period night.

These results indicate very good agreement of both approaches used to estimate average aerosol concentration Z i.e. by means of measured attachment rate X and f_p , respectively and also implicitly a good accuracy of measurements of unattached and attached activity concentrations of radon daughter product by means of monitor Fritra 4.

Since average value f_p in measured urban houses were 8.6 % and 10.6 % in rural houses then with respect to eq.(2) lung dose sensitivity factor $DFC = 15.0 \text{ mSv/WLM}$ should be applied in case of urban houses and $DFC = 15.9 \text{ mSv/WLM}$ in case of rural houses, respectively. Further, according to [4], the lung dose sensitivity factor DFC contributes to more than 99% of the effective dose per WLM and therefore the above mentioned values of DFC can represent very well the effective dose conversion coefficient per unit WLM.

To verify the Jacobi–Porstendörfer model (see eq.4) from the prediction of F and f_p point of view, in Figs. 1 and 2 are illustrated results of comparison of measured values F and f_p with those calculated by means of the room model on the basis of input data, i.e. average values X , q_f and ACH (taken from Table 1 and Table 2) for investigated ambient conditions. For all calculations, average value of recoil $R = 0.5$ [1] was used. The results indicate a very good agreement between directly measured values of F and f_p and calculated by means of the room model.

Assuming "the same breathing rate" the influence of our different investigated ambient conditions (denoted 0 and 1 respectively) to relative changes of the equivalent lung dose rate H_1/H_0 is illustrated in Fig. 3.

In Fig. 3 is seen the average value of H_1/H_0 calculated for proper observed ambient conditions applying eq. (1-3) and combined standard uncertainty acquired by application of the Law of Propagation of Uncertainty to eq.(3).

About 10% significant relative increase of the equivalent lung dose rate in case of towns compared to villages was found. On the other hand, difference in contribution to relative lung dose rate in case of observed conditions day – night was not statistically significant.

Table 1. Results of confirmatory analysis of weekly average values f_p , F , X , q_f and ACH over time periods day and night.

Quantity (units)	Period	GM	GSD	95% CI	p- value
f_p	Day	0.099	1.58	0.04	0.247
	Night	0.107	1.47	0.05	0.231
p = 0.494					
F	Day	0.35	1.31	0.20	0.60
	Night	0.36	1.32	0.21	0.63
p = 0.533					
X (h^{-1})	Day	24	1.63	9	64
	Night	20	1.41	10	40
p = 0.130					
q_f (h^{-1})	Day	23	1.48	11	50
	Night	22	1.35	12	40
p = 0.653					
ACH (h^{-1})	Day	0.41	1.59	0.16	1.04
	Night	0.30	1.82	0.09	0.99
p = 0.024					

F , f_p denote equilibrium factor and unattached fraction of equivalent equilibrium concentration, respectively

X , q_f denote attachment rate and deposition rate of unattached radon progeny
 ACH denotes air exchange rate.

Table 2. Results of confirmatory analysis weekly average values of f_p , F , X , q_f and ACH for location town and village.

Quantity (units)	Location	GM	GSD	95% CI	p- value
f_p	Town	0.086	1.58	0.04	0.247
	Village	0.107	1.40	0.05	0.231
p = 0.003					
F	Town	0.40	1.25	0.26	0.63
	Village	0.32	1.31	0.19	0.55
p = 0.002					
X (h^{-1})	Town	26	1.61	10	67
	Village	18	1.37	10	34
p = 0.001					
q_f (h^{-1})	Town	23	1.41	12	46
	Village	22	1.42	11	44
p = 0.661					
ACH (h^{-1})	Town	0.30	1.91	0.08	1.09
	Village	0.40	1.56	0.16	0.97
p = 0.046					

The quantities f_p , F , X , q_f and ACH have the same meaning as in previous Tab.1.

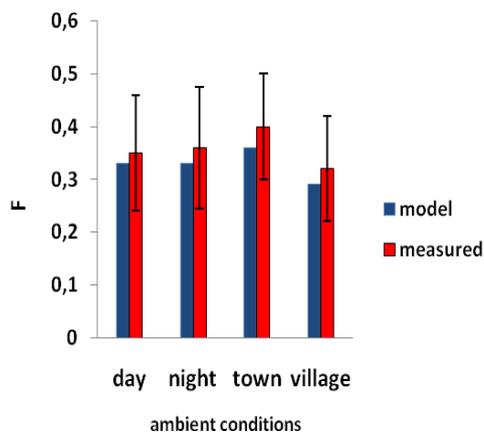


Fig. 1. Results of comparison of equilibrium factor F calculated via the room model and directly measured, respectively (with GSD).

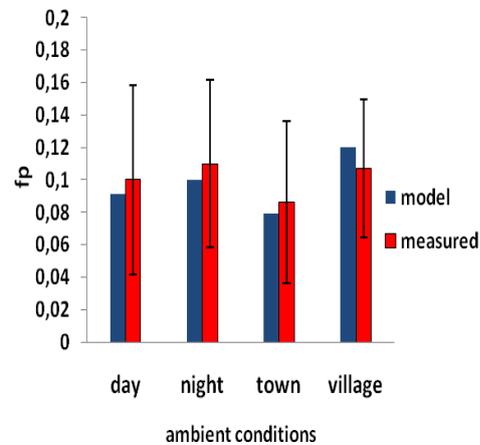


Fig. 2. Results of comparison of f_p calculated via the room model and directly measured, (with GSD)

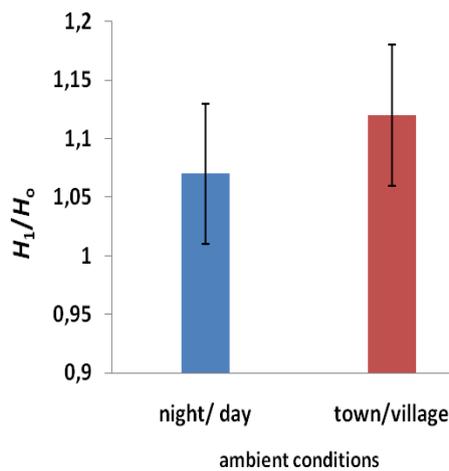


Fig. 3. Average relative contribution to lung equivalent dose rate H_1/H_0 under different ambient conditions and the corresponding combined standard uncertainty.

Conclusions

The results of weekly continuous measurements of radon concentration and unattached and attached concentrations of each short-lived radon progeny in thirty randomly chosen Czech family houses during heating season indicated statistically significant difference of weekly averages equilibrium factor F and f_p for urban houses compared to rural. The log-normal distribution of weekly means f_p and F is represented in case of towns as follows: f_p (GM= 0.086, GSD = 1.58), F (GM = 0.40, GSD = 1.25) and f_p (GM = 0.107, GSD= 1.40), F (GM = 0.32, GSD = 1.31), respectively in case of villages. Due to this fact approximately 10% average increase of equivalent lung dose rate was calculated in the detriment of towns.

The difference in mean values f_p and F during observed time period day - night was not statistically significant.

The effective dose conversion coefficients per WLM were estimated to 15.0 mSv/WLM for towns and 15.9 mSv/WLM for villages, respectively.

Both key parameters of the Jacobi-Porstendörfer room model, i.e. attachment rate X and plate-out q_f of unattached radon progeny ranged from 10 h⁻¹ to 60 h⁻¹ with the mean around (20 – 25) h⁻¹.

The air exchange rate ranged from 0.1 h⁻¹ to 1 h⁻¹ with the mean approximately around (0.3 – 0.4) h⁻¹ and its statistically significant average 30% decrease during the night compared to day was observed.

The average indoor aerosol concentration was significantly higher in towns ($Z \approx 5000 \text{ cm}^{-3}$) compared to villages ($Z \approx 4000 \text{ cm}^{-3}$). On the other hand, difference between mean indoor aerosol concentration during observed time period day ($Z \approx 4200 \text{ cm}^{-3}$) was not statistically significant in comparison to night time period ($Z \approx 3900 \text{ cm}^{-3}$).

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References

1. CEC Report EUR 14411EN. Fifth International Symposium on the Natural Radiation Environment. Brussels – Luxembourg: ECSC-EEC-EAEC; 1993.
2. Jilek K, Thomas J, Brabec M. QA-programme for radon and its short-lived radon progeny measuring instruments. *Radiat. Protection Dosimetry* 2008; 130(1):4347.
3. Knutson EO, George AC, Frey JJ, Koh BR. Radon daughter plate-out, Part II. *Health Phys.* 1983; 45(2): 445-452.
4. Marsh JW, Birchall A. Sensitivity analysis of the weighted equivalent lung dose per unit exposure from radon progeny. *Radiat. Protection Dosimetry* 2000; 87(3):167-178.
5. Porstendörfer J. Behaviour of radon daughter products in indoor air, *Radiat. Protection Dosimetry* 1984; 7(1-4):107-113.
6. Porstendörfer J. Influence of physical parameters on doses from radon exposures, In: Burkart W, Sohrabi M, Bayer A (Eds.). *Proceedings on 5th International Conference on High Levels of Natural radiation and radon areas.* 2000 Sept 4-7; Munich, Germany, Elsevier 2002. p. 149 – 160.
7. Porstendörfer J, Reineking A, Becker KH. Free fractions, attachment rates, and plate-out rates of radon daughters in houses. In: Hopke P (Ed.). *American Chemical Society Symposium Series* 1987, Vol. 331: p. 85-300.
8. Reineking A, Porstendörfer J. The unattached fraction of short-lived radon decay products in indoor and outdoor environment, *Health Phys.* 1990; 58:715-727.
9. Thomas J, Jilek K, Brabec M. Inversion of the Jacobi- Porstendörfer room model for the radon progeny – *Nukleonika* 2010, in press.
10. Wicke A, Porstendörfer J. Radon daughter equilibrium in dwellings. In: Vohra KG, Mishra UC, Pillau KG, Sadasivan S (Eds.). *Natural Radiation Environment,* Eastern Wiley Limited; 1982. p. 481-488.

A comparison of one and three month radon measurements in Ireland

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Abstract

Indoor radon concentrations are subject to high temporal variation that can make short term measurements of radon unreliable and difficult to interpret. Oscillations in radon concentrations can be smoothed by carrying out long-term measurements using CR-39 alpha track detectors, with a typical measurement period of three months or more. Short term radon measurements can be unreliable when used to predict how average long term radon concentrations within a building compare with the Reference Level. Ideally, the measurements would be carried out over a full year as this would provide the most accurate result. However, householders are often reluctant to wait so long for results and detectors left in place for so long are commonly lost. Furthermore, there is evidence to suggest that the sensitivity of a detector may change over such a long period of time, increasing the uncertainty associated with the result. Currently in Ireland, radon measurements are carried out over a minimum period of three months. This is a compromise between the need for a long exposure period to provide a reliable estimate of the long-term mean radon concentration and the problems associated with year-long measurements. The Radiological Protection Institute of Ireland (RPII) have recommended that radon be included in the conveyancing process but recognise that a 3 month measurement period may create too much of a delay when householders are likely to require a radon result in a shorter timeframe. This project compares the results of one month measurements with three month measurements using CR-39 alpha track detectors. Statistical analysis of the results from 662 homes around Ireland are reported.

Introduction

Radon is a naturally occurring radioactive gas which originates from the decay of uranium present in rocks and soils. When radon surfaces in the open air, it is quickly diluted to harmless concentrations, but when it enters an enclosed space, such as a house or any other building, it can sometimes accumulate to relatively high concentrations. In air, radon decays quickly to produce radioactive particles that, when inhaled, are deposited in the airways and in the lungs. These result in a radiation dose which, over a long period of time, may lead to lung cancer. International Agency for

Research on Cancer (IARC) has classified radon as a class 1 carcinogen (IARC, 1988). Worldwide exposure to radon in homes is linked to 3% to 14% of lung cancers, depending on the average radon concentration in the country and method of calculation. (WHO, 2009). In Ireland the average indoor radon concentration is 89 Bq/m^3 which is the eight highest in the world. (Fennell *et al.*, 2002, WHO, 2009). When risk estimates for indoor radon are applied to Ireland some radon can be linked to some 10 to 15% of all cases of lung cancer in Ireland and it is the second most significant cause of lung cancer after smoking (RPII and NCRI 2005).

Over 91,000 homes in Ireland are predicted to have radon concentrations above the national Reference Level of 200 Bq/m^3 . This equates to over 7% of the national housing stock. (Fennell *et al.*, 2002). In 2006, the RPII recommended that radon measurements, and where necessary, remediation at the time of sale and/or purchase of buildings is an appropriate mechanism to reduce the collective dose from radon in Ireland. (RPII, 2006). There are currently some 4000 radon measurements carried out in Ireland each year and there are 1.9 million dwellings in the country. (Department of Environment, Heritage and Local Government (DEHLG), 2008, RPII, 2009). Therefore it could take over 400 years for the present housing stock to be measured and for those houses predicted to have high radon levels to be identified. In 2007, the number of second-hand homes purchased was almost 38,000 (DEHLG, 2007) therefore if a radon measurement was linked to the conveyancing of houses each house in the country could be tested for radon within about 40 years.

Current radon measurement practice in the RPII is to use CR-39 alpha track detectors over an exposure period of at least three months in conjunction with the application of a seasonal correction factor (Colgan *et al.*, 2008; RPII, 2008). Normal practice is to send two detectors with each measurement pack; one to be placed in a bedroom and one in a living area (RPII, 2008). The average of both rooms is seasonally adjusted and it is this seasonally adjusted average which is compared to the Reference Level. One potential difficulty with linking radon to conveyancing is the need for a three month measurement period as householders are often unwilling to wait so long. Consequently some countries have introduced shorter "screening" measurements for use during conveyancing. (Ibrahimi and Miles, 2009). Extrapolating from shorter measurements to an annual average introduces uncertainties into the result and these will normally be much larger than the uncertainties caused by counting and calibration errors on the detectors [Miles, 2001]. Therefore it is prudent only to use short term screening measurement in selected circumstances, such as conveyancing, and only when the relationship between the short term measurements and the standard long term measurement is known. This study was, therefore carried out to determine this relationship and to investigate possibility of using a one-month "screening" measurement during conveyancing to determine whether a house is above or below the Reference Level.

Material and methods

This project was run in two phases. Phase 1 was carried out during 2008. The RPII contacted 102 customers who had recently applied for a standard radon measurement and invited them to instead participate in this study free of charge. All of those contacted agreed to participate and the households were distributed all over Ireland.

Initial analysis of the detectors revealed that 89% of the three month detectors had radon levels less than 200 Bq/m³. The dataset did not contain sufficient data for higher radon concentrations therefore phase 2 of the project sought to obtain data on the relationship between three month observations and one month observations at higher radon concentrations. The RPII contacted 840 customers who had previously measured radon levels above 200 Bq/m³ in their homes. Those contacted were from areas all over Ireland.

In order to make the reply process as easy as possible, the invitation letter had a response slip at the bottom for people who wished to participate, with spaces to add a contact phone number, an email address and a signature. Also enclosed was a freepost envelope to return the response to the RPII. 612 people replied agreeing to participate in the project (a response rate of 73%). This response rate was unexpectedly high. Experience in the UK of response rates to radon surveys has been in the range of 20 – 40%, depending on the areas being targeted (Kendall *et al.*, 2005). The high response rate for this research could be due to how easy it was to respond to the letter.

For both phases of the project, measurement packs were sent to all volunteers. Each measurement pack contained:

- Personalised letter: thanking for participation and setting out instructions for detector placement and return
- Two short-term detectors (labelled: Bedroom 1M; Living area 1M)
- Two long-term detectors (labelled: Bedroom 3M; Living area 3M)
- 1 month record sheet: to record the dates the detectors were placed and removed for the 1 month period
- 3 month record sheet: to record the dates the detectors were placed and removed for the 3 month period
- 2 freepost return envelopes

After the one and three month periods had elapsed, each participant was reminded to return the two relevantly labelled detectors and record sheet. This was done firstly by a phone call; if there was no answer, they were sent either an email or letter instead.

The RPII offers a commercial radon measurement service using alpha track detectors comprising a two part polypropylene holder and a CR-39 (poly allyl diglycol carbonate) detection plastic. Details of detector processing are given in Fennell *et al.*, 2002. The standard radon measurement service offered by the RPII (3 month radon measurement) is subject to stringent quality control procedures and is accredited to ISO 17025 by the Irish National Accreditation Board. Although the one month measurements would not be accredited, they were subjected to the same stringent quality control procedures during this project.

Results

As already described the measurement procedure provided four radon concentration results for each household: living area 1 month, bedroom 1 month, living area 3 month and bedroom 3 month. Mean values for each household were calculated for the one month results and the three month results.

To ensure a high level of confidence in the results, both phases of the study covered all counties of Ireland and contained both high and low radon concentrations. Although the measurement regime was designed to ensure that detectors were in place

for set periods of one month and three months, detectors were returned from some households with longer measurement periods. It was decided that observations such as these could mislead the estimation process. In addition for some households useable measurements were not obtained for all four detectors. After eliminating those households with measurement periods greater than one and three months and those with fewer than four results, results from a total of 622 homes were available for analysis. The data consisted of 93 households in Phase 1 and 529 households in Phase 2.

As mentioned the analysis of the Phase 1 data proved to be inconclusive so we will report on two data sets. One formed with all data from Phase 1 and Phase 2. The second formed from merging data from Phase 1 and Phase 2 but with what were deemed to be extreme values that is $>9000 \text{ Bq/m}^3$, removed.

A linear regression model was fitted to the data to determine if a useful relationship could be established between one month and three month measurements. It is known that radon concentrations can be modeled well by the lognormal distribution if they have been corrected by subtracting a background average value of outdoor radon concentration and that predictions using this assumption are more accurate than models based on untransformed measurements (Gunby *et al.*, 1993, Fennell *et al.*, 2002 and Murphy and Organo, 2008). Fennell *et al.* (2002) reported 6 Bq/m^3 as being representative of the average outdoor radon concentration in Ireland. Consequently all subsequent modelling was performed on radon levels in which the background level of 6 Bq/m^3 was firstly subtracted from the radon levels before the levels were log-transformed to provide a better fit to a normal distribution.

1.1 Regression analysis

1.1.1 All data from both phases of the project

The merged data set comprised all of the data from phase 1 and phase 2 of the project 622 observations, 529 from phase 2 and 93 from phase 1. As was previously described the measurements in phase 2 were deliberately chosen from higher radon areas. Figure 3.1 plots the background corrected log-transformed results from the one month radon measurements against the log-transformed three month radon measurements for this merged data set. As can be seen in this plot, where the phase 1 measurements are clustered on the bottom left corner of the graph, there was an increased variance among the one month measurements in phase 1 compared to phase 2. However, even with this added variability it is clear from Figure 3.1 that there is still a strong linear association between the one month measurements and the corresponding three month measurements. Indeed the correlation coefficient for this merged data set is $r = 0.935$.

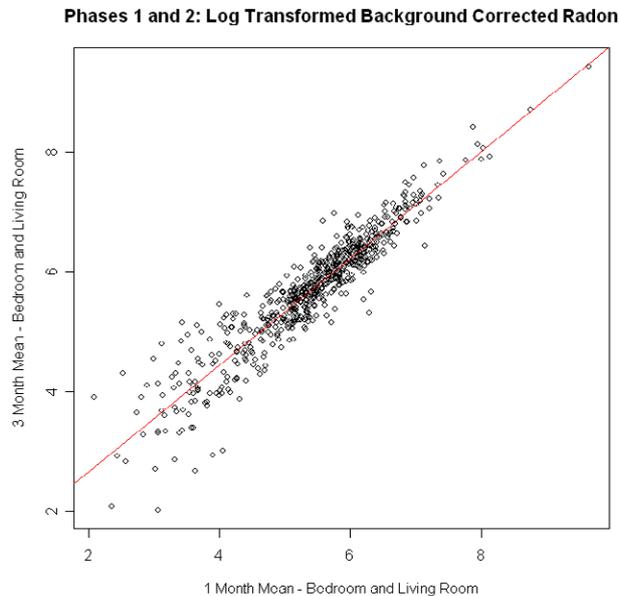


Figure 3.1. Log-transformed household mean 1 month radon concentration vs. log-transformed household mean 3 month radon concentration [all data from both phases of the project].

Table 3.1 describes the fit of the linear regression model that was fitted to this data set. The ANOVA F test P-value which is less than 2.2×10^{-16} and the t-tests of the significance of the regression parameters (P-value $< 2.0 \times 10^{-16}$) all indicate that the simple linear regression model is a good fit to the data. The coefficient of determination is $R^2 = 87.41\%$ indicating that approximately 87% of the variation in the one month measurements can be explained by the linear association between the one month measurements and the three month measurements.

Table 3.1. Simple linear regression analysis of log-transformed household mean 1 month radon concentration vs. log-transformed household mean 3 month radon concentration [all data from both phases of the project].

	Parameter Estimate	Standard Error	T-statistic	P-Value
Intercept	0.881	0.074	11.86	$< 2.00 \times 10^{-16}$
Slope	0.891	0.014	65.62	$< 2.00 \times 10^{-16}$
Source	DF	Sum Sq	Mean Sq	4306.3 $< 2.2 \times 10^{-16}$
Log 3 month	1	523.62	523.62	
Error	620	75.39	0.12	
Total	621	599.01		
	R-Sq = 87.41%	R-Sq(adj) = 87.39%		

Figure 3.1a contains a Histogram and a QQ plot of the residuals from these plots. While the histogram shows that the residuals are symmetrically distributed, the QQ-plot displays a certain deviation from normality at the two ends of the plot indicating that the regression residuals are somewhat more dispersed than would be expected from a normal distribution. Having said this, a Kolmogorov-Smirnov test of normality on these

residuals gave a p-value of 0.085 thus failing to reject the null hypothesis of normality for the residuals at significance level 0.05.

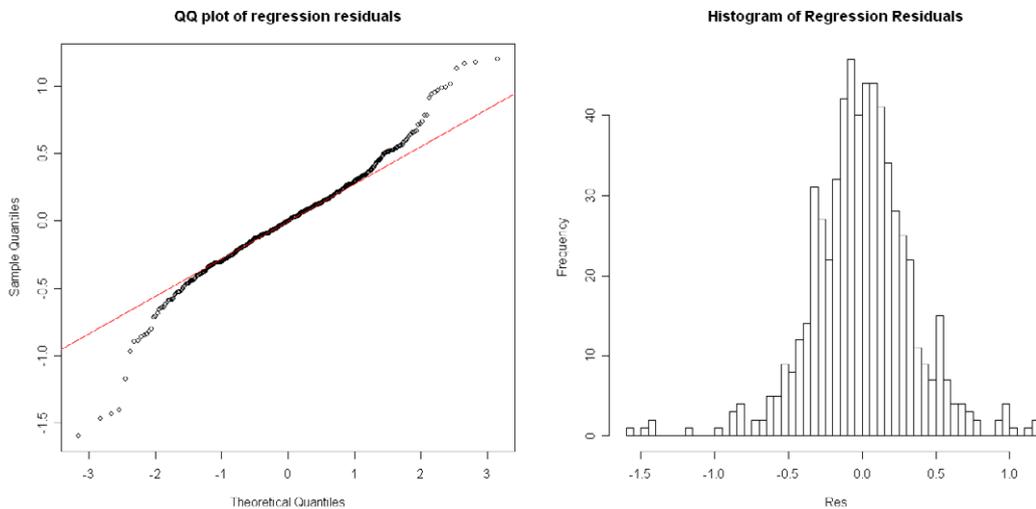


Figure 3.1a. Residuals from the Log-transformed household mean 1 month radon concentration vs. log-transformed household mean 3 month radon concentration [all data from phase 1 and 2 of the project.

1.1.2 Data from both phases of the project with two extreme results (greater than 9,000 Bq/m³) removed

Two very extreme results (>9,000 Bq/m³) were removed and the merged data set reanalysed to examine whether these two results had acted as influential observations. Figure plots the background corrected log-transformed results from the one month radon measurements against the background corrected log-transformed three month radon measurements. The correlation coefficient was computed to be 0.932.

Table 3.2 describes the fit of the linear regression model that was fitted to this data set. The ANOVA F test P-value which is less than 2.2×10^{-16} and the t-tests of the significance of the regression parameters (P-value $< 2.0 \times 10^{-16}$) all indicate that the simple linear regression model is a good fit to the data. The coefficient of determination is $R^2 = 86.9\%$ indicating that approximately 87% of the variation in the one month measurements can be explained by the linear association between the one month measurements and the three month measurements.

The parameter estimates changed slightly when the two extreme observations were removed indicating that these observations did not unduly influence the model fit.

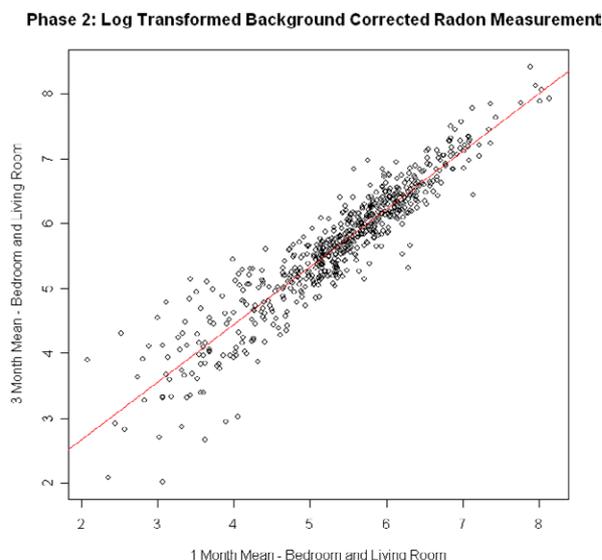


Figure 3.2. Log-transformed household mean 1 month radon concentration vs. log-transformed household mean 3 month radon concentration [data from both phases of the project with two extreme results ($> 9,000 \text{ Bq/m}^3$) removed].

Table 3.2. Simple linear regression analysis of log-transformed household mean 1 month radon concentration vs. log-transformed household mean 3 month radon concentration [data from both phases of the project with two extreme outliers removed].

	Parameter Estimate	Standard Error	T-statistic	P-Value
Intercept	0.880	0.076	11.59	$<2.00 \times 10^{-16}$
Slope	0.891	0.014	64.04	$<2.00 \times 10^{-16}$
Source	1.10	0.00502	(1.08, 1.13)	1.10
Log 3 month	DF	Sum Sq	Mean Sq	F-statistic
Error	1	500.25	500.25	4101
Total	618	75.39	0.12	$<2.2 \times 10^{-16}$
	619	575.64		
	R-Sq = 86.9%	R-Sq(adj) = 86.88%		

Figure 3.2a contains a Histogram and a QQ plot of the residuals from these plots. The removal of two observations would not greatly influence these residuals and indeed the histogram and the QQ-plot are almost identical to those found on the full merged data set again indicating that the regression residuals are somewhat more dispersed than would be expected from a normal distribution. But once again, a Kolmogorov-Smirnov test of normality on these residuals gave a p-value of 0.087 thus failing to reject the null hypothesis of normality for the residuals at significance level 0.05.

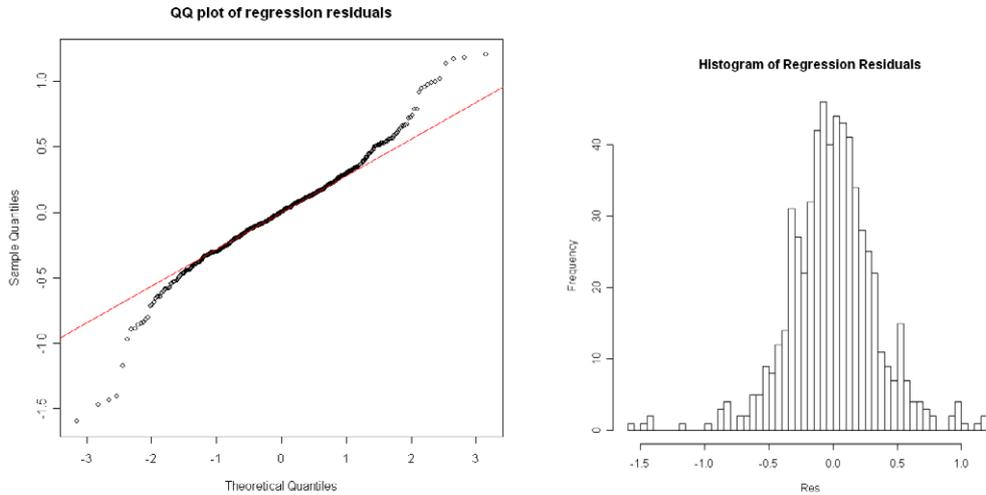


Figure 3.2a. Residuals from the Log-transformed household mean 1 month radon concentration vs. log-transformed household mean 3 month radon concentration [Data from phase 1 and 2 of the project with two extreme observations removed].

1.2 Setting upper and lower threshold levels

The regression models which were fit to the data sets enable us to predict a three month radon concentration on the basis of a one month measurement. We have seen that the regression models fit well so these predictions can be viewed as reliable. The predictions are, however, just point estimates and as such are subject to uncertainty. We can quantify this uncertainty by producing confidence intervals rather than point estimates. The aim of this modelling is to establish two separate bounds on the one month measurement. The first is a lower threshold such that any one month measurement that is below this threshold can be confidently viewed as indicating that a three month measurement taken on the same house would be lower than the 200 Bq/m³ Irish National Reference Level. The second threshold that must be computed is an upper threshold such that a one month measurement exceeding this threshold would produce a three month measurement exceeding 200 Bq/m³. The lower and upper thresholds can be computed from the regression model using standard 95% one sided prediction intervals for the background corrected log transformed radon levels which are exponentiated and have had the background of 6 Bq/m³ added back. Hence to find the threshold levels we solve the following inequalities for the upper threshold (X_U) and the lower threshold (X_L).

$$200 < 6 + \exp \left(\hat{\beta}_0 + \hat{\beta}_1 \log(X_U - 6) - t_{95\%} s \right) \sqrt{1 + \frac{1}{n} + \frac{(\log(X_U - 6) - \bar{X})^2}{SS_{XX}}}$$

$$200 > 6 + \exp \left(\hat{\beta}_0 + \hat{\beta}_1 \log(X_L - 6) + t_{95\%} s \right) \sqrt{1 + \frac{1}{n} + \frac{(\log(X_L - 6) - \bar{X})^2}{SS_{XX}}}$$

where X_T are the upper or lower threshold levels, $\hat{\beta}_0$ and $\hat{\beta}_1$ are the estimates of the intercept and slope from the regression, s is the estimate of the standard deviation of the error terms in the regression model, n is the sample size, $t_{95\%}$ is a one sided 95% critical

value of the t distribution \bar{X} is the mean of the background corrected one month measurements and $SS_{xx} = \sum (x - \bar{x})^2 = s_x^2(n-1)$ is the sum of squares of the background corrected one month measurements.

Table 3.3 summarises the lower and upper thresholds (Bq/m^3) of the equivocal result region for the two the datasets described above. Outside of these ranges, one month radon concentrations derived from the datasets can be regarded as definitive indicators of mean annual levels below or above the Irish National Reference Level of 200 Bq/m^3 with 95% confidence. Results falling between these thresholds are regarded as equivocal, and would require a measurement for a three month period in order to estimate a more accurate mean annual level.

Table 3.3 Upper and lower threshold levels (95% CI) for one month radon measurements using alpha track detectors.

Dataset used for analysis	95% Confidence level	
	Lower threshold (Bq/m^3)	Upper threshold (Bq/m^3)
All data from both phases of the project	89	234
Data from both phases with 2 extreme results (>9,000 Bq/m^3) removed	89	235

Discussion

Many international studies have investigated the possibility of reducing the standard radon measurement period with alpha track detectors from three months to a one month period or less (Quindos *et al.*, 1992, Bowring, 1992, Klotz *et al.*, 1993, Chen, 2003, Groves-Kirkby *et al.*, 2006, Ruano-Ravina *et al.*, 2008 and Ibrahimi and Miles, 2009). However, none of these studies were based in Ireland and so cannot be assumed as directly applicable. Climatic conditions, as well as seasonal and dwelling-occupancy factors influence the amount of radon that may emanate from the ground and enter buildings (Sundal *et al.*, 2007). These reasons pointed to the need for an indigenous study covering the whole of the country of Ireland.

Groves-Kirkby *et al.* (2006) found threshold values of $109 - 478 \text{ Bq/m}^3$ for one month alpha track detectors. However, the study had only 18 data-points for the one month measurements and the authors warned that the one and three month results in their study should be treated with caution due to the low number of data-points (Groves-Kirkby *et al.*, 2006). Ibrahimi and Miles (2009) investigated the accuracy of two-week radon measurements using alpha track detectors and found threshold levels of $170 - 300 \text{ Bq/m}^3$. However, their results were based on measurements made in 59 homes in the UK. Although the research suggest a tighter range of threshold levels than what is currently in use for the screening detector service in the UK (current threshold levels are $100 - 400 \text{ Bq/m}^3$), (Ibrahimi and Miles, 2009). In order to ensure a high level of confidence in the results of this study, it covered all counties of Ireland and had a sufficient spread of both high and low radon concentrations. A total of 622 short and long term measurements were available for analysis.

Conclusions

At time of writing this report a formal recommendation has yet to be made on how this study will be used to support the RPII's aim to link radon to the conveyancing of properties in Ireland (RPII, 2006). While the results summarised in table 3.3 are encouraging further work is needed. Before being in a position to recommend a threshold range the RPII will take account of new seasonal correction factors for Ireland. (Burke *et al.*, in press). In addition, the RPII are likely to recommend conservative round numbers for the threshold band.

References

- Bowring CS. Short-term radon measurements in buildings. *Journal of Radiological Protection* 1992; 12 (4): 239-241.
- Burke Ó, Long S, Murphy P, Organo C, Fenton D, Colgan PA (in press). Estimation of seasonal correction factors through Fourier decomposition analysis – a new model for indoor radon levels in Irish homes. *Journal of Radiological Protection*, (in press).
- Chen J. Estimate of annual average radon concentration in the normal living area from short-term tests. *Health Physics* 2003; 85 (6): 740-744.
- Colgan PA, Organo C, Hone C, Fenton D. Radiation doses received by the Irish population. RPII 08/01. Dublin: Radiological Protection Institute of Ireland; 2008.
- Department of Environment, Heritage and Local Government, Annual Housing Statistics Bulletin, 2007. www.environ.ie.
- Department of Environment, Heritage and Local Government, Annual Housing Statistics Bulletin, 2008. www.environ.ie.
- Fennell SG, Mackin GM, Madden JS, McGarry AT, Duffy JT, O' Colmáin M, Colgan PA, Pollard D. Radon in Dwellings, the Irish National Radon Survey. RPII-02/1. RPII, 2002. www.rpii.ie.
- Groves-Kirkby CJ, Denman AR, Crockett RGM, Phillips PS, Woolridge AC, Gilmore GK. Time-integrating radon gas measurements in domestic premises: comparison of short-, medium- and long-term exposures. *Journal of Environmental Radioactivity* 2006; 86: 92-109.
- Gunby JA, Darby SC, Miles JCH, Green BMR, Cox DR. Factors affecting indoor radon concentrations in the United Kingdom. *Health Physics* 1993; 64 (1): 2-12.
- IARC (1988). Man-made mineral fibres and radon. IARC Monographs on the evaluation of carcinogenic risks to humans, Vol. 43. IARC, Lyon.
- Ibrahimi F and Miles J. An etched track detector for short-term screening measurements of radon. *Journal of Radiological Protection* 2009; 29: 139-146.
- Kendall GM, Green BMR, Miles JCH, Dixon DW. The development of the UK radon programme. *Journal of Radiological Protection* 2005; 25: 475-492.
- Klotz JB, Schoenberg JB, Wilcox JB. Relationship among short- and long-term radon measurements within dwellings: influence of radon concentrations. *Health Physics* 1993; 65: 367-374.
- Miles JCH. Temporal variation of radon levels in houses and implications for radon measurement strategies. *Radiation Protection Dosimetry* 2001; 93 (4): 369-375.

- Murphy P, Organo C. A comparative study of lognormal, gamma and beta modelling in radon mapping with recommendations regarding bias, sample sizes and the treatment of outliers. *Journal of Radiological Protection* 2008; 28: 293-302.
- Quindos LS, Fernandez PL, Soto J. Short- vs. Long-term indoor radon measurements. *Health Physics* 1991; 61 (4): 539-542.
- Radiological Protection Institute of Ireland. Action plan to identify and remedy Irish houses with radon concentrations above the national reference level. RPII, 2006. www.rpii.ie.
- Radiological Protection Institute of Ireland. Measurement protocol for determination of the annual average radon gas concentration in domestic dwellings. RPII, 2008. www.rpii.ie.
- Radiological Protection Institute of Ireland, National Cancer Registry of Ireland. Health risks due to exposure to radon in homes in Ireland - Joint statement by the Radiological Protection Institute of Ireland and National Cancer Registry of Ireland. Dublin: RPII, 2005. www.rpii.ie.
- Radiological Protection Institute of Ireland. Personal Communication, 2009.
- Ruano-Ravina A, Castro-Bernárdez M, Sande-Meijide M, Vargas A, Barros-Dios JM. Short- versus long-term radon detectors: a comparative study in Galicia, NW Spain. *Journal of Environmental Radioactivity* 2008; 99: 1121-1126.
- Sundal AV, Jensen CL, Ånestad K, Strand T. Anomalously high radon concentrations in dwellings located on permeable glacial sediments. *Journal of Radiological Protection* 2007; 27: 287-298.
- World Health Organisation. WHO Handbook on Indoor Radon: A Public Health Perspective. WHO, 2009. www.who.int.

Radon hazard evaluation based on measurements of indoor air and gamma measurement surveys in combination with bedrock and drift geology mapping

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Abstract

During the last 10 – 15 years, The Norwegian Radiation Protection Authority has carried out several surveys of radon in indoor air. These data have been useful for the overall evaluation of radon risks at the local level, and they have been used both for estimations of average radon exposure and, to a certain extent, to identify radon-prone areas. According to the new radon strategy (2009) in Norway, the local authorities will need to consider the radon hazard in connection with area planning, and if necessary impose restrictions or local regulations regarding new building constructions in very high risk areas. The Geological Survey of Norway and the Norwegian Radiation Protection Authority have established a combined approach to mapping of radon in Norway, based on direct measurements of radon in indoor air, bedrock and drift geology, and the mapping of uranium/radium in the ground using airborne gamma-measurement surveys. This work resulted in the release of overview radon awareness maps covering the most densely populated areas in Norway around the capital city Oslo. The performance of the hazard evaluations was tested in an area centered around the municipality of Gran, and was shown to be able to enclose most of the high risk areas. Areas already known to be associated with elevated radon hazards were confirmed, and additional potential high risk areas not yet confirmed by indoor radon measurements were identified. The Norwegian Geological Surveys have recently carried out new air-borne gamma measurement surveys in areas south-west of Oslo. Corresponding datasets on indoor radon are available, and includes areas known to be strongly affected by radon. A test of the combined approach in this area will be independent of the earlier studies, and will be used for additional testing and refinement of the method that has been established. The results of this work so far will be presented.

Indoor radon and construction practices in Finnish homes from the 20th to the 21st century

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Abstract

Indoor radon is the second leading cause of lung cancer in Europe. In order to reduce the exposure to radon, it is necessary to understand the structural features of buildings that affect radon concentrations. These features vary with the year of completion of the building.

A population-based random sample study was performed in the homes of 2,882 people. Radon measurements were made using alpha track detectors. Information on the structure of the dwellings was collected using a questionnaire filled in by the residents.

The weighted national mean of indoor radon concentration in single-family and row houses was 121 Bq/m³ and in blocks of flats 49 Bq/m³. The national mean was 96 Bq/m³.

According to our study, the radon concentrations in new single-family and row houses began to rise after the 1960s, and continued to rise until steadying during the 1980s and 1990s, decreasing thereafter to the level of the 1970s. These changes can be explained by changes in building methods.

Before 1965, the prevailing house type was one with a basement with no direct entrance into the living area. This solution reduced the radon entry into the living area. Thereafter, a slab-on-ground foundation, which promotes radon-bearing air entering the house, became the most common foundation. A more radon-resistant foundation, crawl space was popular during 1950s. Its popularity decreased thereafter and increased again after 2000.

Since the year 2000, mechanical supply and exhaust ventilation has been installed in most new dwellings. This reduces the entry of radon due to smaller pressure differences. In addition, the use of radon prevention techniques in new building has become more common because of new building codes.

The changes in the Finnish construction practice from the 20th to the 21st century have had clear consequences, which can be seen in indoor radon concentrations. After a slow awakening to radon awareness in the 1980s, research, guidance and legislation have resulted in the current downward trend in indoor radon concentrations.

Introduction

Indoor radon exposure increases the risk of lung cancer in a residential environment (Darby et al. 2005). The most important reason for high radon concentrations in dwellings is the radon-bearing soil air that flows into the building. Gaps between the slab and foundation walls, permeable materials used in foundations and a high underpressure increase radon concentration. Indoor radon exposure can be reduced by identifying and mitigating dwellings with high concentrations, and by radon prevention techniques in new building.

Regulations concerning indoor radon for the health protection and building control authorities in Finland are working reasonably well and are on a good level on the world scale. According to Decree 944/92 by the Ministry of Social Affairs and Health, the indoor radon concentration should not exceed 400 Bq/m³, whereas new buildings should be built so that 200 Bq/m³ is not exceeded (Ministry of Social Affairs and Health, 1992). In addition, Part D2 of the National Building Code of Finland (Indoor climate and ventilation of buildings) sets 200 Bq/m³ as a reference value for the planning of new buildings (Ministry of Environment, 2004). Since 2004, according to Regulation B3, radon should be taken into account in new building throughout the country (Ministry of Environment, 2004). A radon technical plan should be included in the building licence application. This plan can only be exceptionally ignored when building in areas where exceeding 200 Bq/m³ seldom occurs.

Material and methods

The results of this study are based on the random sample study by STUK, in which 6,000 Finns were selected using simple random sampling from the Finnish population registry (Mäkeläinen et al. 2009).

The radon measurements were made using alpha track detectors in two half-year periods, the first from April to November 2006 and the second from November 2006 to April 2007. Information on dwelling construction was collected using questionnaires filled in by the inhabitants. Fifty-seven per cent of the selected population accepted the call to participate, and 48 per cent completed a valid measurement; 58 per cent (2,267) of the residents living in houses (single-family and row houses) and 31 per cent (599) of those living in blocks of flats completed valid measurements.

The annual mean of radon concentration for each dwelling was calculated as an arithmetic mean weighted by the lengths of the two measurement periods. The final national statistics were calculated by weighting the annual means using the number of inhabitants of houses and flats in each province.

Results

Annual mean of radon concentration

The weighted average for annual means of radon concentration was 96 Bq/m³ for all dwellings, 121 Bq/m³ for houses and 49 Bq/m³ for flats. The medians were 56 Bq/m³, 75 Bq/m³ and 36 Bq/m³ respectively. Radon concentration notably varies regionally. Häme and South-Eastern Finland (the provinces of Itä-Uusimaa, Päijät-Häme, Kymenlaakso, Kanta-Häme, Pirkanmaa and South Karelia) constitute a continuous high

radon area in which a quarter of all Finnish house inhabitants reside. In this area the mean radon concentration in houses was 201 Bq/m³ and in the rest of Finland 96 Bq/m³.

Effect of the year of completion of building on the radon concentration

Radon concentrations in new buildings are connected to the construction practices of their time. They were at their lowest in houses built during the 1950s (Fig.1). During the 1960s and 70s the radon concentrations started to rise, being almost double at the beginning of the 1980s compared with houses built during the late 50s. Thereafter, the radon concentrations in new houses have decreased, and since the year 2000 the radon concentrations in new houses has been at the same level as in houses built in the 60s and 70s.

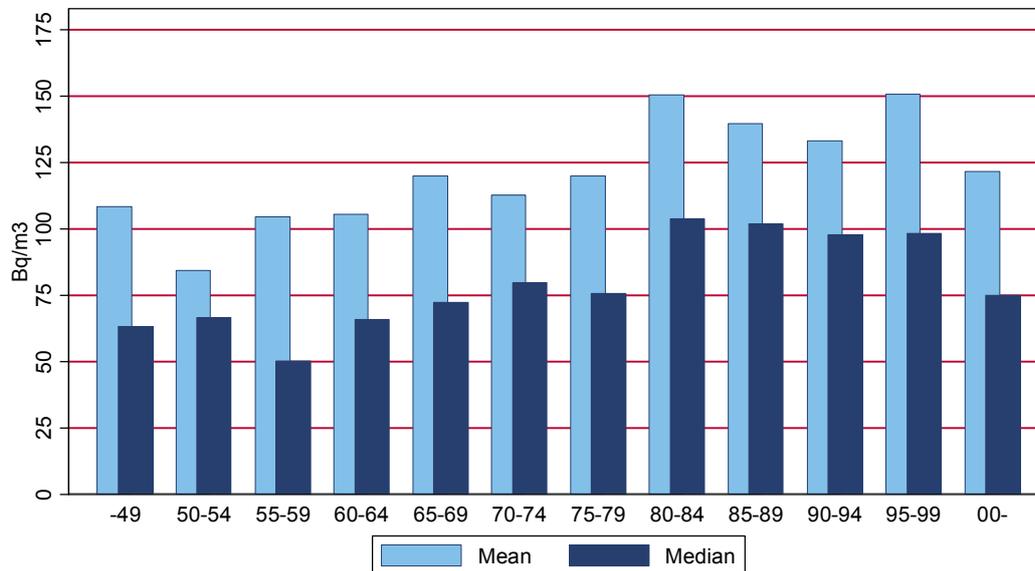


Fig. 1. Means and medians of annual average radon concentration in houses according to the year of completion of the building.

Effect of foundation type on radon concentration

Houses were divided into three types according to the ground contact of the foundations. Both hillside houses and houses with a cellar have basement walls backing onto the ground. In a hillside house, one wall is on ground level and the wall facing it is at least partly backing onto the ground. In houses with a cellar, all walls are ground-contact walls. The third type is a house without a basement that mostly has a slab-on-ground or crawl space foundation. The inhabitants selected the figure most like their house type in the questionnaire.

Until the beginning of the 1960s the most common type was a house with a cellar (Fig. 2). Thereafter, houses without a basement became most common. Since the 70s, a hillside house has been more common than a traditional house with a cellar.

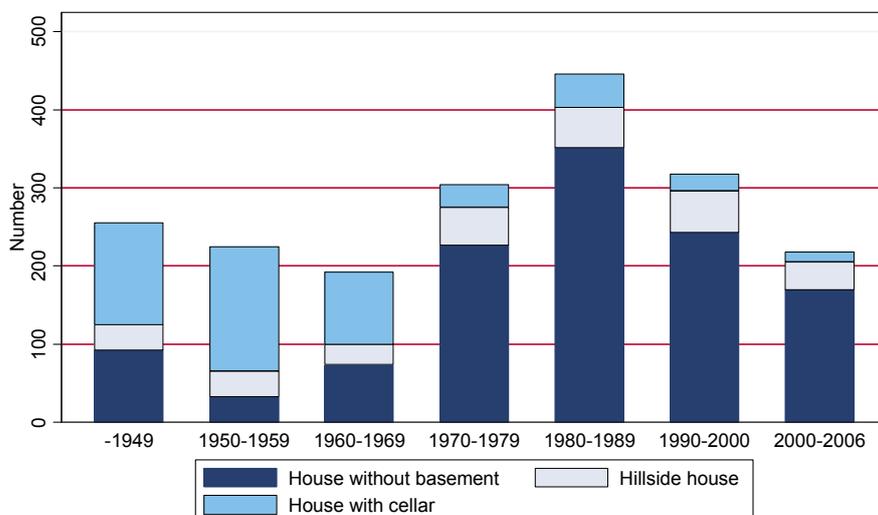


Fig. 2. Numbers of house types in the study data according to the year of completion of building.

The highest radon concentrations are in houses with a basement (hillside houses and houses with a cellar) built in the 1990s and later, having medians of 156 and 152 Bq/m³ (Table 1). Concerning houses completed before the 1990s, hillside houses have higher concentrations than other types (median 92 Bq/m³), but houses with a cellar are the lowest (median 66 Bq/m³). On the other hand, radon concentrations in houses without a basement are almost at the same level regardless of building year (medians 77 and 78 Bq/m³).

Table 1. Type of house and radon concentration.

House type	All houses*			Built before 1990			Built in 1990-2006		
	Count	Mean Bq/m ³	Median Bq/m ³	Count	Mean Bq/m ³	Median Bq/m ³	Count	Mean Bq/m ³	Median Bq/m ³
House without a basement	1253	119	76	775	118	77	412	117	78
Hillside house	288	156	102	193	143	92	89	191	156
House with a cellar	519	117	66	454	111	66	35	183	152

*Including those with building year missing

In houses with a basement, walls backing onto the ground increase radon leaks into the dwelling without proper sealing. If the staircase to the lowest floor is open, radon-bearing air from downstairs mixes with the air in the rest of the dwelling. On the other hand, if the entrance to the basement is normally closed or the entrance to the lowest floor is only from the outside, radon-bearing air cannot so easily enter the upper floors. This is the case in the older houses with a basement, where only 22 per cent had an open staircase (Table 2). Another factor increasing radon concentrations in new houses with a basement is probably the higher proportion of light-weight concrete blocks used as ground-contact wall material: 71 per cent in the newer houses compared with 16 per cent in the older ones with a basement. In the new houses, the basement

floor is also more often used as a living area: 57 per cent in the newer houses and 26 per cent in the older ones. The residents were asked to carry out the measurement on the lowest floor with a living area as the concentration there is usually the highest. This also results in higher concentrations in the new houses.

Table 2. Houses with a basement: Radon and entrance type from the upper floors to the basement level.

Entrance to the lowest floor	All houses with a basement*			Built before 1990			Built in 1990-2006		
	Number	%	Median Bq/m ³	Number	%	Median Bq/m ³	Number	%	Median Bq/m ³
Open staircase	200	28	117	127	22	103	68	64	163
Staircase and door	390	55	65	350	61	65	19	18	179
Only from outside	119	17	78	95	17	76	20	19	117
All	709	100	78	572	100	71	107	100	157

House without basement and radon

A house without a basement has been the most common foundation type in houses since the 1960s. The two most used foundation types in this house type are slab-on-ground and crawl space (Fig. 3). When slab-on-ground laid between the foundation walls is used, radon-bearing soil air gets in through the gap between the foundation wall and the slab unless the gap and feed-throughs are sealed. The crawl space foundation is fairly radon-resistant if radon leaks are stopped by sealing the foundation joints and feed-throughs, and ventilation of the base floor is arranged.

Crawl space as a foundation type was very common before 1960 (Fig. 3). Its popularity decreased thereafter, but, according our data, since the year 2000 it has been getting more popular than ever since the 1950s. Whereas the percentage of crawl space houses was only 4 per cent during the 1970s, it has risen to approx. 20 per cent in houses built after 2000.

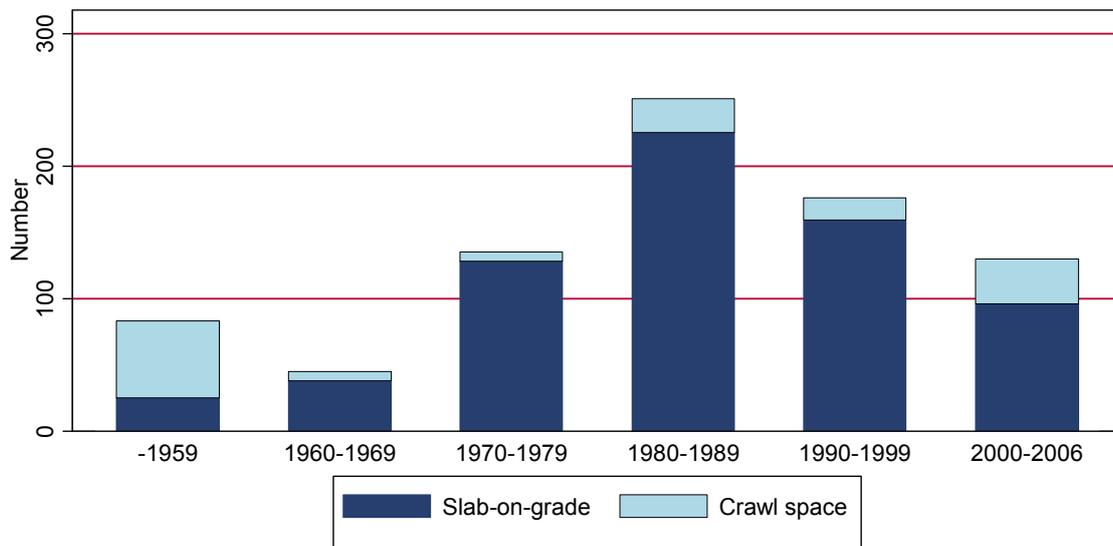


Fig 3. Numbers of slab-on-ground and crawl space foundations in houses according to the year of completion of building.

Differences in radon concentrations between these types are clearly seen (Table 3). Radon concentrations are higher in houses with slab-on-ground foundations built both before and after 1990.

Table 3. Foundation types slab-on-ground and crawl space in houses without a basement.

Foundation type	All houses with a basement			Built before 1990			Built in 1990-2006		
	Count	Mean Bq/m ³	Median Bq/m ³	Count	Mean Bq/m ³	Median Bq/m ³	Count	Mean Bq/m ³	Median Bq/m ³
Slab-on-ground laid between foundation walls	688	132	94	415	134	96	251	130	93
Crawl space	150	61	44	96	59	48	49	60	38

Cast concrete was a clearly more radon-resistant option (medians 75 Bq/m³ and 58 Bq/m³) than light-weight concrete blocks (medians 136 Bq/m³ and 106 Bq/m³) in both older and newer houses. Light-weight concrete blocks are very permeable, and when used as building material for foundation walls, radon-bearing soil air can easily flow through them from the soil into the dwelling. In houses with slab-on-ground foundations built before 1990, 31 per cent had light-weight concrete blocks used in the foundation walls, but for those built thereafter, the percentage was already 66 (Table 4). Radon concentrations were higher in the older than in the newer houses regardless of the material of the foundation walls. However, because the proportion of foundation walls made of light-weight concrete blocks is smaller in the older houses than in the new ones, the radon concentration in all the houses with slab-on-ground has not changed much (medians 96 Bq/m³ and 93 Bq/m³, Table 3).

Table 4. Material of foundation walls and radon in houses with slab-on-ground foundations.

Material of foundation walls	Built before 1990			Built in 1990-2006		
	Number, proportion (%)	Mean Bq/m ³	Median Bq/m ³	Number, proportion (%)	Mean Bq/m ³	Median Bq/m ³
Cast concrete	237 (69%)	114	75	74 (34%)	91	58
Light-weight concrete blocks	105 (31%)	158	136	146 (66%)	150	106

Ventilation type and radon

Ventilation types were compared in houses without a basement with slab-on-ground foundations because the group is large enough and does not have temporal confounding factors, as was seen in the last chapter. The data shows that mechanical exhaust ventilation is the most disadvantageous ventilation type with regard to radon (Table 5). This ventilation type increases the underpressure of the dwelling and radon leaks from the soil. The situation in the houses with natural ventilation is only slightly better. The mechanical supply and exhaust ventilation is best with regard to radon. This was as expected: a well-adjusted supply and exhaust system ensures a sufficient air exchange rate, and reduces the underpressure and, consequently, radon leaks into the building.

Mechanical supply and exhaust ventilation has become more popular in new houses. In single-family houses, the change to this system started in the 1980s. In row houses the change has been slower. These changes are one cause of the reduction in radon concentrations observed since 1990 (Table 4).

Table 5. Ventilation type and radon concentration in houses without a basement with slab-on-ground laid between foundation walls.

Ventilation type	All houses			Built before 1990			Built in 1990-2006		
	Count	Mean Bq/m ³	Median Bq/m ³	Count	Mean Bq/m ³	Median Bq/m ³	Count	Mean Bq/m ³	Median Bq/m ³
Natural	284	143	97	244	140	98	28	183	104
Mechanical exhaust	141	148	115	68	136	104	69	163	137
Mechanical supply and exhaust	230	110	76	78	118	81	147	104	75

Radon prevention in new building

Guidance on radon prevention in new building has been available since 1994 (Ministry of Environment, 1994). This first guide was replaced by the RT Building Information File published in 2003 (Building Information Ltd., 2003). The guides recommend sealing the joints between the foundation wall and floor slab and walls backing onto the soil with bitumen felt, sealing the feed-throughs, and installing radon piping as a

preparatory measure. The goal is a low radon concentration using only passive sealing. If, however, the radon concentration in the house is measured as more than 200 Bq/m³, activation of the radon piping by installing a fan on the roof is needed. Activating the fan sucks radon-bearing air from the soil under the slab.

Radon piping has been installed in 64 per cent of houses with slab-on-ground foundations built after 1995 in the high radon areas of Häme and South-Eastern Finland. The percentage of similar houses in the rest of Finland was 14. Sealing of the foundation constructions was not so common: 18 per cent in the high radon area and 14 per cent in the rest of Finland. Both installing radon piping and sealing of foundation constructions were performed in the high radon area and the rest of Finland in 11 and 4 per cent of dwellings respectively.

Radon prevention is clearly more common in the high radon area. The prevention measures showed some reduction in radon concentration, especially in the high radon area, but the numbers of dwellings were too small for conclusions.

Conclusions

Radon concentrations in new houses have increased from the 1950s to the 1980s, and have decreased thereafter, especially since the year 2000. The recent decrease is caused by several reasons, one being the growing percentage of houses with crawl space foundations. Crawl space is a radon-resistant construction if the flow of radon-bearing air into the dwelling is stopped by sealing the base floor and feed-throughs, and by taking care of the ventilation of the crawl space.

Mechanical supply and exhaust ventilation has become the most common ventilation system in new houses, and this has also reduced radon concentrations. The third cause of the reduction in radon concentrations in new dwellings is the use of radon prevention in new building, which has become more popular, especially in high radon areas. The installation of radon piping systems is common in high radon areas; sealing of ground-contact constructions has not been used as often as was expected.

Although radon concentrations in new buildings have decreased, there are also factors that are against the downward trend. Houses with a basement have high radon concentrations. In both hillside houses and houses with a cellar, the proportion of dwellings having living areas on the basement floor has increased, and the entrance from the upper floor to the basement floor is more and more often an open staircase. In addition, the growing use of permeable light-weight concrete blocks as a building material for foundation and basement walls instead of cast concrete has increased radon concentrations.

Part 3 of the National Building code of Finland, which concerns the foundations, came into force in the year 2004. The code requires radon prevention in all buildings. The radon concentration in the completed building should be below 200 Bq/m³. When the provisions are widely implemented, the reduction in radon concentrations in new buildings is expected to continue.

References

- Building Information Ltd. Radon Prevention, RT 81–10791 (LVI 37–10357) (in Finnish Radonin torjunta). Helsinki 2003.
- Darby, S, Hill, D., Auvinen, A., ym. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *British Medical Journal* 2005, 330, 23–227.
- Mäkeläinen I, Valmari T, Reisbacka H, Kinnunen T, Arvela H. Radon suomalaisissa asunnoissa Otantatutkimus 2006 (Radon in Finnish dwellings - sample study 2006; in Finish; abstract in English). STUK-A242. Helsinki: Radiation and Nuclear Safety Authority; 2009.
- Ministry of Environment. Radon prevention in single-family and row houses Radon-technical planning of ground-contact constructions (in Finish: Radonin torjuminen pien- ja rivitaloissa. Maanvastaisten rakenteiden radontekninen suunnittelu.) Guide 2 1993, Ministry of Environment, Helsinki, 1994
- Ministry of Environment. The National Building Code, part B3, Foundations - Regulations and Guidelines 2004 (in Finnish and Swedish; unofficial translation into English); www.ymparisto.fi
- Ministry of Environment. The National Building Code, part D2, Indoor climate and ventilation of buildings - Regulations and Guidelines 2004 (in Finnish and Swedish; unofficial translation into English); www.ymparisto.fi
- Ministry of Social Affairs and Health. Decree 944/92 by the Ministry of Social Affairs and Health on reference value for indoor radon concentration in dwellings (in Finnish: Sosiaali- ja terveysministeriön päätös asuntojen huoneilman radonpitoisuuden enimmäisarvoista. n:o 944/92). Helsinki 1992.

Geochemical case study of sediment samples from Olkiluoto, Finland – assessment of radon emission

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Abstract

In order to define the naturally-occurring radioactive materials that are source of radon in natural environments, a comprehensive analytical (geochemical, physical and chemical) methodology was employed to study sediment samples from overburden glacial formation in Olkiluoto (W Finland). Techniques such as gamma-spectrometry, emanation measurements, sequential chemical extraction, scanning electron microscopy (SEM), electron microprobe analyses (EMPA) and inductively-coupled plasma mass spectrometry (ICP-MS) were used to determine the potential source of radon. Samples are representing a typical Finnish red-ox profile formed on glacial sediments deposited around 9,000 years ago. In Olkiluoto samples activity concentration of ^{238}U , ^{226}Ra and ^{228}Ra show no significant trend in a function of depth secular equilibrium between ^{238}U and ^{226}Ra occurred only in the samples collected from the reductive zone. In the oxidized horizon higher radium than uranium activity concentration was measured. In this horizon the $^{226}\text{Ra}/^{238}\text{U}$ is 1.4. In Th decay chain secular equilibrium occurred between ^{232}Th and ^{228}Ra . Radon productions and emanation factors are very low, varying between 0.01 – 0.03 Bq/(kg h) and 0.04 – 0.08, respectively. The uppermost sample collected from the oxidized horizon has the highest radon production and emanation factor. This sample has the highest ^{226}Ra content (52 Bq/kg), as well. The sequential extraction revealed that in the oxidized zone more exchangeable Ra is present than in the reductive zone. In general, more radium was leached (ca. 20% of the total) easily than uranium and thorium, except in the deepest sample, where 30% of the total uranium was leached easily. Monazite, xenotime, zircons, apatite and U-Th-silicates were identified in the samples as the main sources of uranium, thorium and radium. These minerals were partly weathered in the uppermost horizons and mainly fresh in the deeper ones.

The radon situation in Swedish dwellings based on recent measurements

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Abstract

Gammadata has been measuring radon levels in Sweden and abroad since the late 1980's and is one of the largest suppliers of CR-39 based radon detectors in Europe. Our extensive database includes several hundreds of thousands of measurements. This makes it possible for us to derive several conclusions of the radon situation in Sweden. We present radon levels measured in single family dwellings and their dependence on several factors such as the type of ventilation and foundation of the measured dwellings.

Introduction

Due to the relatively large problem with high radon levels in dwellings in Sweden an examination of which factors increase or decrease the risk for radon levels above the action level is of interest. In the past years radon measurements in dwellings have been available for the general public through offers sent out to all house owners within several municipalities making the selection of measurement locations much more random than previously. This increases the possibility of using data from a measurement database to draw general conclusions concerning radon levels.

We have selected to examine single family dwellings comparing ventilation, foundation, and construction year. The data used is based on the information provided by the person performing the measurement. For single family dwellings we assume that the majority of the information concerning the building is correct.

Since a large portion of the measurements in our database are incomplete concerning information about the building certain combinations of construction year and foundation and ventilation yield very few data. Those results containing fewer than 30 measurement points have been removed from this examination in order to reduce the risk of single measurements of extreme values having a large effect on the result.

In Sweden we have three sources of radon in dwellings, the ground, the building material and the water. Water is the least common source and hence we disregard its effect on the radon level indoors in our analysis. The building material that can provide radon levels above the action level is a light concrete which is based on alum-shale. This material was widely used in the 50's through the 70's. In the 50's and 60's as much as half the buildings constructed contained some amount of alum-shale concrete (G.A. Swedjemark), The production of this material was stopped 1975 but houses built

in the years following can also contain it. Since this material is common only in Sweden we have based our analysis solely on those measurements where there is a notation that the dwelling does not contain alum-shale.

Construction year of the building

Examining the radon levels in single family dwellings can be used as a general quality measurement of the different house constructions in different eras. To examine this we divide into 10 year periods thereby assuming no major reformations in house constructions were made during each time period. A clear relationship between the year a building is constructed and the radon level is evident, see table 1:

Table 1. radon levels in private dwellings depending on year of construction.

Year of construction	Number measured	Average radon level	Highest measured level	Percentage above 200 Bq/m ³
1800-1899	4263	149	6759	16,6
1900-1919	8235	150	>12200	17,7
1920-1929	7826	154	6510	19,5
1930-1939	12949	142	8410	18,5
1940-1949	15174	157	8240	23,5
1950-1959	24866	177	8910	30,0
1960-1969	43229	197	16220	34,5
1970-1979	45412	172	>24500	28,3
1980-1989	21426	111	17050	13,8
1990-1999	10963	71	10960	6,5
2000-2008	12132	59	5050	4,7

In table 1 it is clear that the period ranging from 1950-1979 an increase in the radon level measured is noted compared to previous years. This time period also coincides with an increase in building rate of houses.

Foundation and ventilation

The question arises whether certain combinations of constructions produced in certain time periods are more likely to experience radon problems than others. The house constructions selected for examination includes both the foundation of the house as well as the ventilation type. The four most common foundation types in Sweden are as follows; basement, crawlspace, slab, and split level house, in no particular order. The selected ventilation types are as follows; natural ventilation, mechanical exhaust, and mechanical supply and exhaust air ventilation (most often used together with heat recovery).

In general we find that houses containing basements or split levels in combination with natural ventilation are responsible for the highest radon levels.

Looking at natural ventilation and the radon level dependence for different years and different house foundations it is clear that split level dwellings tend to have the highest radon levels, see figure 1. Until the 1970's the basement was constructed to contain garage, storage areas, laundry rooms, furnaces etc and were therefore not used as living space. In an annual average calculation only living areas are included. Therefore, in dwellings with the original construction high levels of radon can be present in the basement which are ventilated away before reaching the living space

upstairs as it is normally separated from the basement by a door. This is most likely the reason why houses containing basements tend to have lower levels of radon compared to split-level houses where living areas are placed partially underground (C. Boox)

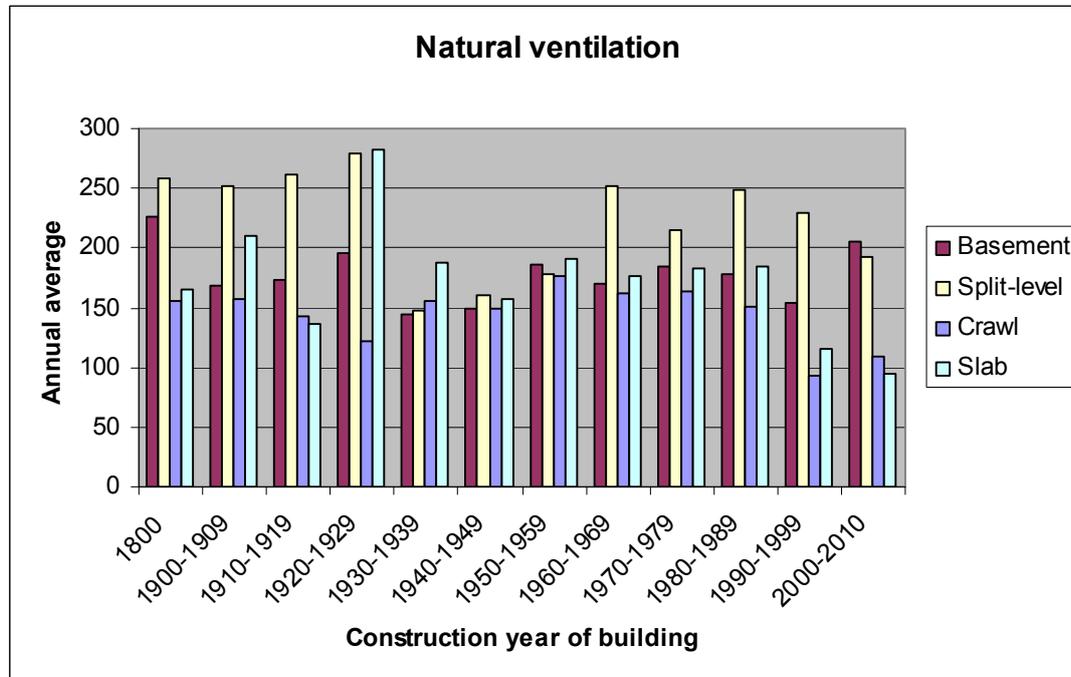


Fig. 1. Annual average radon levels measured in dwellings with natural ventilation which are constructed in the eighteen hundreds until present day and the dependence on house foundation.

For dwellings up until the past 10 years, crawl space tends to have lower levels than the rest. An interesting feature is that slabs as well as crawlspace constructions manufactured in the past 20 years show a marked improvement of radon levels as compared to older constructions and when compared to basements and split-levels of all years. It is disappointing that the same level of improvement is not seen in modern basements and split-levels. Another interesting feature is the increase in radon levels seen in slab constructions of the 1920's. This may in part be due to the concrete used at this time period, a lack of funds after the first world war tended to increase the dilution of concrete with fillings such as rock which in effect made the material more porous. Also, in the beginning of the 1900's concrete slabs were not of the same type of construction as today, the main function at those times was to have a more practical floor rather than no floor at all so the slabs were quite thin and not insulated from the ground below.

The same comparison for mechanical exhaust and mechanical supply and exhaust is shown in figures 2, and 3 below.

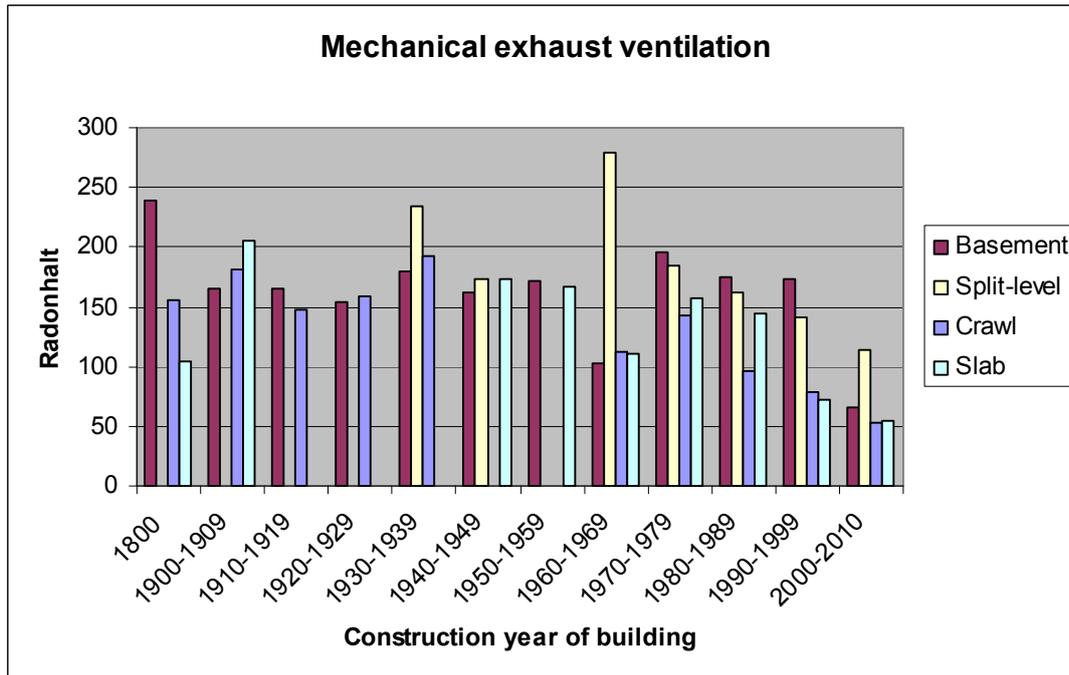


Fig. 2. Annual average radon levels measured in dwellings with mechanical exhaust ventilation which are constructed in the eighteen hundreds until present day and the dependence on house foundation.

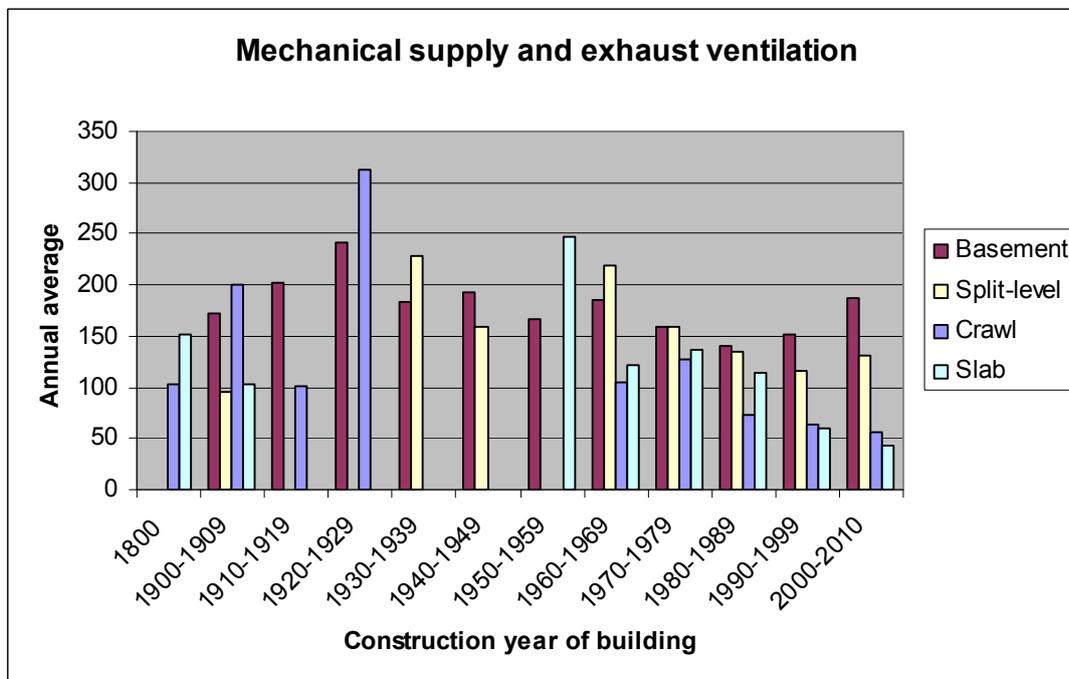


Fig. 3. Annual average radon levels measured in dwellings with mechanical supply and exhaust ventilation which are constructed in the eighteen hundreds until present day and the dependence on house foundation.

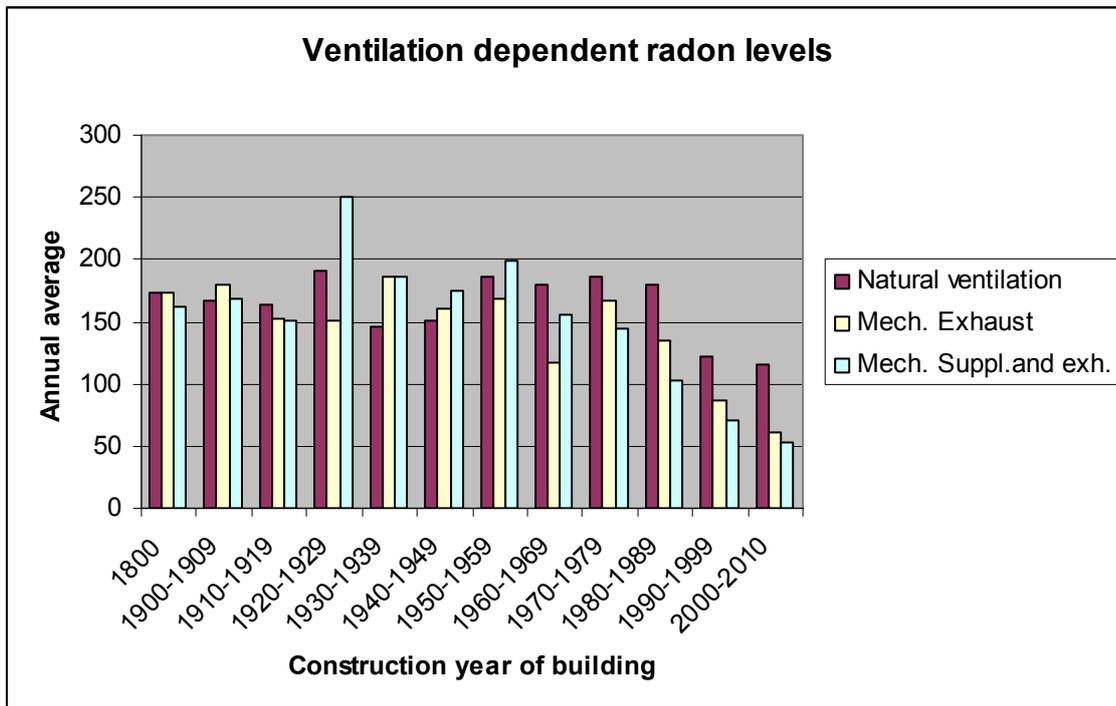


Fig 4. Radon levels in single family dwellings depending on type of ventilation and building construction year.

Mechanically ventilated dwellings have seen a clear improvement in radon levels starting in house constructions in the 1980's up until the present. Part of the reason may be an increased use of mechanical ventilation in the original building construction. Mechanical exhaust has been used in Sweden starting in the 1930's while mechanical supply and exhaust air ventilation with heat recovery started being used in the 1970's (H. Adolphson). For natural ventilation, improvements are seen in buildings from the 1990's and onward. For mechanical exhaust and supply ventilation this means that in buildings manufactured previous to 1970's the system was installed afterwards. Although this installation can be assumed to have led to an improved ventilation in the dwelling it has no apparent great effect on the radon level as compared to natural ventilation in these data. In several cases it is evident that mechanical ventilation rather has the opposite effect on the radon level which supports the general notion that using mechanical ventilation does not automatically mean low radon levels (something which our customers informs us of regularly as well). However this does not mean that installation of mechanical ventilation for radon reducing purposes is not effective. As mechanical ventilation is used as a form of remediation it may well be that several of the dwellings included in this data have reduced from an even higher radon.

Another reason that natural ventilation may have a disadvantage over mechanical is that during the energy crisis of the 1970's the general population was encouraged to reduce their energy consumption by improving insulation in their houses. This is well known to have caused an increase in radon levels (B. Clavensjö) as well as a reduction in ventilation. Therefore it is possible that part of the reason why natural ventilation tends to have higher radon levels is that it no longer is working according to the original construction because the amount of fresh air intake has been reduced.

Conclusions

A modern building with a slab or crawlspace construction together with mechanical ventilation is the best construction according to this study in order to minimize radon levels in single family dwellings. The new WHO recommendations are that radon levels in dwellings should be below 100 Bq/m³. When examining figure 4 above it is noteworthy that the modern buildings with natural ventilation in this study tend to have an average above the WHO recommendation. We therefore propose that mechanical ventilation in combination with slab or crawlspace should be recommended for future construction of single family dwellings

References

- H. Adolphson, C.G. Hellgren, Ventilation i äldre byggnader, Statens Fastighetsverk, 2009
- C. Boox, Bjerking AB, discussions
- B. Clavensjö, G. Åkerblom, 2007: Radonboken, Formas, T2:2007, ISBN 978-91-540-5987-4
- G. A. Swedjemark, The history of radon from a Swedish perspective, Radiation Protection Dosimetry, 2004, Vol. 109, No. 4, pp. 421-426

Radon concentrations in newly built homes in Norway

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Abstract

Since 1997 requirements on radon in new buildings have been included in building regulations and guidelines in Norway. A large survey of radon in dwellings were carried out in Norway in the period 2000-2001 and the percentage of homes with radon concentration above 200 Bq/m³ was estimated to 9 % (Strand et al. 2001). These homes were mainly built before the 1997 Building Regulations but little has been known about the effects of the regulations and guidelines on the newly built homes.

During the winter season 2008 the Norwegian Radiation Protection Authority carried out a nation-wide survey including 750 randomly selected dwellings built in the period 2000-2007 to investigate to what extent radon is still a problem in the new housing stock. The survey showed that the 1997 Building Regulations in force at the time of the survey, and the guidelines supporting it, had very limited effect on the radon concentration in the newly built dwellings.

Previous to this study it was assumed that the awareness on radon affected areas could be higher in municipalities strongly affected by this problem. Therefore, another survey was also carried out in seven selected municipalities where extensive radon problems had been found in earlier studies. In two municipalities, 50-60 % of the new dwellings had annual mean radon concentrations above 200 Bq/m³. In one of the municipalities, all 10 newly built homes had radon concentrations below 200 Bq/m³. In the remaining 4 municipalities, the fraction of radon concentrations above 200 Bq/m³ was in the range 10-30 %. The conclusions were that the requirements in the 1997 Building Regulations and supporting guidelines had very little effect on radon concentrations in newly built homes.

New building regulations have been adopted after the finishing of this study and will take effect from 1 July 2010. The new building regulations include specific requirements for the use of radon barriers and preparing the building foundations such that it is possible to actuate active ventilation of the ground, if necessary, after finishing the building.

Introduction

The Norwegian Radiation Protection Authority (NRPA) has carried out several radon surveys during the last twenty years and radon is far the largest contributor to annual radiation dose to the public in Norway. There is no known threshold concentration below which radon exposure represent no risk of developing lung cancer. Exposure to radon in homes has been estimated to cause approximately 300 lung cancer deaths each year in Norway.

Radon gas from the ground enters homes through cracks and openings in the foundation of the building. In July 1997 the building regulations in Norway for the first time required planning of building constructions to avoid enhanced health risk by contaminants in the ground, which included radon. A maximum level for indoor radon concentrations was not given in the 1997 regulations. However, 200 Bq/m³ was the recommended maximum level in the guidelines supporting the regulations, issued by The National Office of Building Technology and Administration and supported by NRPA.

In 2008 two surveys were carried out by NRPA in order to get knowledge about the radon levels in newly built homes, constructed in the period 2000-2007. In the nation-wide survey, the homeowners were randomly selected. In the other survey all relevant homeowners in seven municipalities, known to have extensive radon problems, got an invitation to take part.

The goal of the surveys was to explore whether the radon concentrations in recently built homes are low, and below the maximum level of 200 Bq/m³, as recommended in the guidelines. Further, the goal of one of the surveys was to study radon levels in newly built homes in municipalities where previous surveys had shown extensive radon problems.

Material and methods

Indoor radon concentrations can vary considerably due to changes in weather conditions and ventilation rates etc. In Norway, long-term integrated radon measurements during heating season are preferred for assessing the annual average radon concentration. The NRPA recommend a measurement period of at least two months and all results should be seasonally adjusted.

Before building a new home a planning permission is required. Addresses for all estates given planning permission from the year 2000 to the start of the project in the autumn 2007 were ordered from the Norwegian land register. Almost 280 000 addresses were received. Planning permission is also required before reconstruction of homes and construction of other buildings, e.g. tool or car sheds. For this reason a lot of homes constructed outside the period of interest (2000-2007) were also measured. These measurements had to be rejected from the study later in the process.

For practical reasons only addresses which was identical to the homeowners address was included in the surveys, excluding homes hired out.

For the nation-wide survey addresses were randomly selected. For the municipal survey all addresses of newly built homes were selected. The municipalities of Drangedal, Grane, Nes (in the county of Buskerud), Skjåk, Tana, Ullensvang and Ulvik were included in the survey (figure 1).



Fig. 1. The seven selected municipalities with extensive radon problems included in the 2008 municipal survey.

In February 2008, an invitation was sent to approximately 2750 homeowners with an offer to participate in the two surveys; 2500 homeowners in the nation-wide survey and 250 in the municipal survey. Enclosed to the letter of invitation the homeowner could find two CR-39 etched track radon detectors, full instructions for placement of the detectors, a questionnaire and a pre-paid envelope for the return of detectors.

The homeowners were asked to place one detector in the main living area and one in a bedroom. Further they were asked to fill in the questionnaire which should be returned together with the detectors. The questionnaire included detailed information about the point of measurements, building construction, ventilation, etc. The data in this study will be further analysed and published at www.nrpa.no in a NRPA report in English.

The overall response rate in the two surveys was approximately 49 %. However, approximately 36 % of the measurements had to be rejected because the homes were constructed outside the period of interest (2000-2007).

Results and discussion

Nation-wide survey

Measurements from a total of 758 randomly selected homes constructed in the period 2000-2007 were used in the nation-wide survey. The results from the survey are given in table 1.

The mean annual radon concentration for all categories of homes constructed in the period 2000-2007 is estimated to 66 Bq/m^3 . 8 % of the homes have at least one measurement exceeding the recommended upper level of radon concentration of 200

Bq/m³. Taking the uncertainties of the measurements into account this is practically the same result, 9 %, as estimated for the Norwegian housing stock mainly built before the introduction of radon requirements in the 1997 Building Regulations.

The mean annual radon concentration is known to vary for different categories of homes. The results for the different categories for this survey are given in table 1 showing that detached homes have got the highest mean annual radon concentration, and the highest percentage of homes above 200 Bq/m³. The measured terraced homes have lower mean radon concentration than the measured detached homes.

Horizontally separated dwellings in two-family homes also showed high mean annual radon concentration and a high percentage above 200 Bq/m³, but based on the result of only 24 homes.

Blocks of flats or multifamily homes have got the lowest mean annual radon concentration, 33 Bq/m³, and 1 % of the homes above recommended maximum level of 200 Bq/m³. The reason for this is that most of the flats do not have direct contact with the ground.

Table 1. Results from the 2008 nation-wide survey of homes constructed in the period 2000-2007.

Building category	Number of homes	Mean (Bq/m ³)	Maximum (Bq/m ³)	Homes above 200 Bq/m ³ (%) ¹
All categories	758	66	2670	8
Detached homes	320	90	2670	12
Terraced homes	139	66	1254	9
Horizontally separated dwellings in two-family homes	24	71	782	8
Blocks of flats or multifamily homes	236	33	368	1
Unknown	39	59	823	8

¹Homes with at least one of the two measurements above 200 Bq/m³

²Annual mean radon concentration

Municipal survey

Measurements from a total of 102 homes constructed in the period 2000-2007 were used in the municipal survey. The results from the survey are given in table 2.

Table 2. Results from the 2008 municipal survey of homes constructed in the period 2000-2007.

Municipality	Number of homes measured	Mean (Bq/m ³) ⁽²⁾	Maximum (Bq/m ³) ⁽²⁾	Homes above 200 Bq/m ³ (%) ⁽¹⁾
Drangedal	24	352	1900	58
Grane	10	43	150	0
Nes (Buskerud)	15	167	510	60
Skjåk	20	131	900	20
Tana	12	63	220	16
Ulvik	5	129	330	20
Ullensvang	16	100	420	25

¹Homes with at least one of the two measurements above 200 Bq/m³

²Annual mean radon concentration

The seven municipalities were known to have extensive radon problems. The mean annual radon concentration for all categories of homes is estimated to 166 Bq/m³. In this survey, the mean annual radon concentrations were varying between 43 Bq/m³ and 352 Bq/m³ for the seven municipalities. All measurements in the municipal survey were made in detached homes (100 homes) or terraced homes (only 2 homes).

For comparison the mean annual radon concentrations for the seven municipalities are shown in the bar graph (figure 2) together with two bars representing all homes and the detached homes, respectively, in the nation-wide survey.

In the municipalities Drangedal and Nes (Buskerud), 58 % and 60 % of the homes, respectively, at least one of the two measurements in the home indicated an annual mean radon concentration above 200 Bq/m³. However, in Grane no homes were identified as being above the reference level given in the guidelines to the building regulations.

For comparison the percentages of homes with at least one measurement above 200 Bq/m³ in the seven municipalities are shown in the bar graph (figure 3) together with two bars representing all homes and the detached homes, respectively, in the nation-wide survey.

Further analysis have to be done to get a better understanding of why new homes still have high radon concentrations in areas well known to have extensive radon problems. However, the total results indicate that the building regulations have not had the wanted impact on the radon problem in the majority of the high risk municipalities investigated.

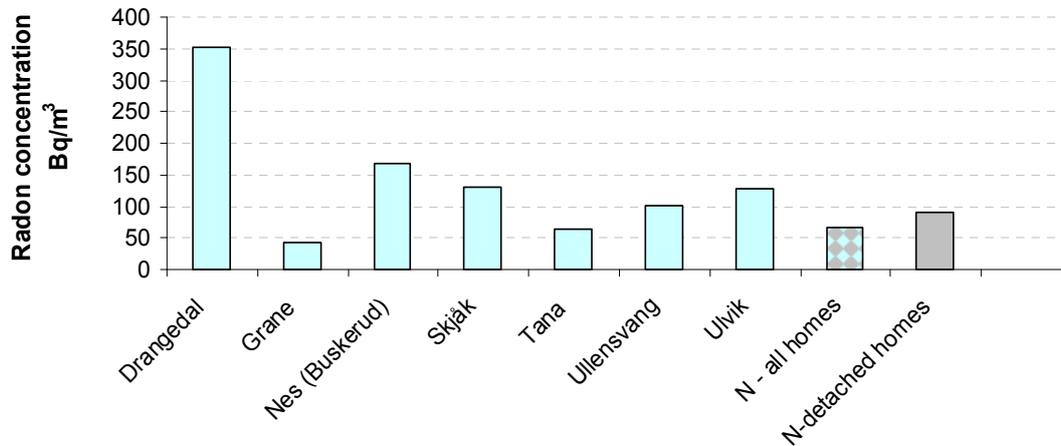


Fig. 2. The mean annual radon concentration in the seven municipalities compared with the mean radon concentration in all the homes and all the detached homes in the nation-wide survey.

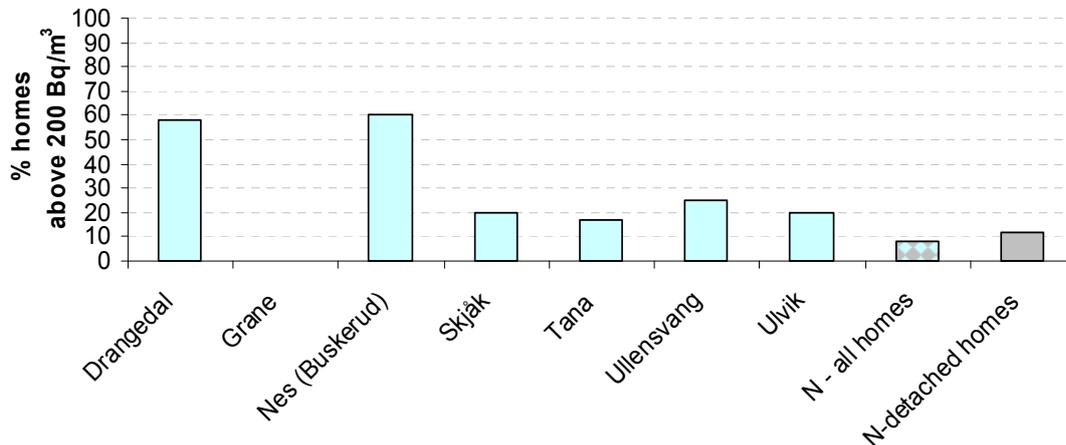


Fig. 3. The percentage of homes with at least one measurement above the maximum upper level of 200 Bq/m³ compared with the percentage in all the homes and all the detached homes in the nation-wide survey.

Conclusions

Both the nation-wide and the municipal surveys carried out in this study indicate that a significant portion of the newly built homes in Norway have radon concentrations above the recommended maximum level of 200 Bq/m³. The building regulations, which came into force in July 1997, do not seem to have had any particular influence on the radon concentration in the Norwegian housing stock.

New building regulations have been adopted after the finishing of this study and will take effect from 1 July 2010. The new building regulations include specific requirements for the use of radon barriers and preparing the building foundations such that it is possible to actuate ventilation of the ground, after finishing the building. The new requirements include the introduction of legally binding indoor radon limits for new buildings (100 Bq/m³, action level; 200 Bq/m³, maximum). Because the requirements in the new regulations are more specific than the 1997-regulations it will hopefully keep the radon concentrations below the upper maximum level of 200 Bq/m³ and further reduce the mean annual radon concentration in the coming new housing stock.

References

Strand T, Ånestad K, Ruden L, Ramberg G B, Jensen C L, Wiig A H, Thomesen G. Indoor radon survey in 114 municipalities. Norwegian Radiation Protection Authority, 2001. StrålevernRapport 2001:6 : 14 pp (in Norwegian)

Short-term measurements of radon concentration in dwellings

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Abstract

Radon concentrations in dwellings are known to vary from day to day depending on weather conditions and occupant lifestyle. Consequently, short-term measurements (STM) of a few days are generally less representative of the annual mean radon concentration than long-term measurements (LTM) performed over several months. On the other hand, STM may be used as screening techniques for testing radon levels. The aim of this study was to develop a screening method based on STM to provide fast and reliable indications of radon levels in dwellings.

Radon concentrations were measured in 184 dwellings in Switzerland over a 3 month period using alpha-track detectors (Radtrak). Together with LTM, STM were performed at 3 time points, i.e. at the beginning, the middle and the end of the 3 month period, using activated charcoal canisters (Picorad) exposed during one day. A statistical comparative analysis of LTM and STM in those dwellings was performed to derive the screening method.

Results obtained with STM overestimated, on average, by 35% those obtained with LTM, with a standard deviation of 65%. This was explained by the reduced ventilation applied during STM. The variability of STM at the three different time points was characterized by a standard deviation of 24%. Based on those results, the following screening method was proposed considering an action level of 400 Bq/m³:

- (a) if results of STM are less than 110 Bq/m³, the annual mean radon concentration is below 400 Bq/m³ with a confidence level of 95%;
- (b) if results of STM are above 970 Bq/m³, the annual mean radon concentration exceeds 400 Bq/m³ with a confidence level of 95%;
- (c) if results of STM range between 110 and 970 Bq/m³, LTM are required to determine whether the dwelling is above or below 400 Bq/m³.

This method was validated for several dwellings. We conclude that STM provide valuable information on radon levels in dwellings to determine if further LTM are necessary. In Switzerland, this STM screening method is primarily used in real estate transactions.

Introduction

Radon exposure is the main component of the radiation dose to the Swiss population and the leading cause of lung cancer after smoking. As part of preventive healthcare, the Radiological Protection Ordinance set in 1994 a yearly average limit of 1000 Bq/m³ and introduced a guidance value of 400 Bq/m³ for the concentration of radon gas in Swiss dwellings. A major objective of the ongoing national radon programme is then to identify dwellings where radon concentration exceeded the legal limit of 1000 Bq/m³ and ensure that remediations are performed. To determine radon concentrations, the Swiss Federal Office of Public Health (FOPH) recommends measurements over a 3 month period using dosimeters, during the heating period. Most of the usual dosimeters like alpha-track detectors and electret ionization chambers are used for such long-term measurements (LTM). In Switzerland, those dosimeters are available from approved measuring laboratories.

Since radon concentration fluctuates from day to day depending on atmospheric conditions and occupant lifestyle, short-term measurements (STM) of a few days are less likely than LTM over several months to represent the yearly average radon concentration in dwellings (U.S. Environmental Protection Agency, 2009). Nevertheless, if results are needed quickly, it is widely accepted that STM may be used as screening techniques for a rapid initial testing of radon levels, especially if radon concentration is likely to be significantly higher than the national average value. For instance, there is often limited time to deal with radon in case of real estate transaction and people are asking more and more about radon levels before they buy or rent a home.

The aim of this study was to develop a screening method based on STM to provide fast and reliable indications of radon levels in dwellings. For this purpose, we first aimed at testing STM as compared to LTM that reflect a better average radon concentration. A strategy of screening measurement based on the reliability of STM was then derived and assessed.

Material and methods

As part of a measurement campaign, radon concentrations were measured in 184 dwellings of the canton of Vaud in South West of Switzerland over a 3 month period using alpha-track detectors (Radtrak). The canton is located by the Lake Geneva and at the foot of the Jura Mountain where elevated indoor radon levels were observed. Together with LTM, single STM were performed at 3 time points, i.e. at the beginning, the middle and the end of the 3 month period, using activated charcoal canisters (Picorad) exposed during one day. Each single STM was performed simultaneously with two Picorad detectors in order to assess their reproducibility. Detectors were always placed in the lowest inhabited area in contact with normal breathing air. Areas with a high air circulation rate were avoided (doors, windows). A statistical comparative analysis of LTM and STM in those dwellings was performed.

In order to assess whether electret detectors (E-Perm SST) can be used alternatively to activated charcoal canisters for STM, both types of detectors were exposed simultaneously in a home-made radon chamber during 1, 2 and 3 days. Measurements were limited to a period of 3 days to avoid saturation of activated charcoal canisters. The obtained radon concentrations were then normalized to the

reference concentration in the radon chamber measured with an AlphaGuard monitor traceable to the international standard. Moreover, the same experiment was conducted in situ, in a house with high radon levels ($\sim 1500 \text{ Bq/m}^3$). Performances of both activated charcoal canisters (Picorad) and electret detectors (E-Perm SST) were compared.

Results

Radon concentrations measured with LTM varied between a few Bq/m^3 and 900 Bq/m^3 , with an average of 62 Bq/m^3 . For STM, the average radon concentration was 85 Bq/m^3 . A good reproducibility was found for activated charcoal canisters as showed by the standard deviation of 13% obtained between responses of both dosimeters exposed simultaneously at the same position during a single STM. The dispersion of the three STM performed with both activated charcoal canisters was 24%. Indeed, the Gaussian distribution of the ratio of each single STM to the mean of the three STM given in Fig. 1 is characterized by a mean of 1.00 and a standard deviation of 0.24. This dispersion characterizes the temporal variability of radon concentration and represents the reliability limit of STM.

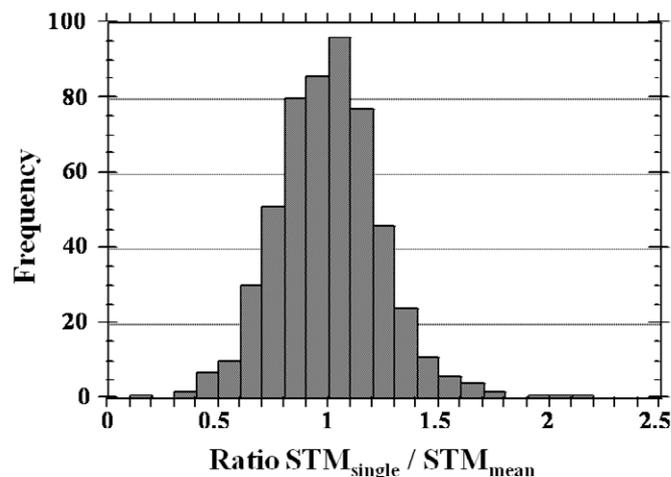


Fig. 1. Distribution of the ratios between the single STM and the mean of three STM (beginning, middle and end of the period). Results of each single STM correspond to the average of radon concentrations measured simultaneously with two activated charcoal canisters.

The distribution of the ratio between each single STM and the LTM was considered Gaussian with a mean (μ) of 1.35 and a standard deviation (σ) of 0.65 (see Fig. 2). The overestimation of 35% obtained with activated charcoal canisters can be explained by ventilation restrictions imposed before and during the STM. Based on this Gaussian distribution ($\mu = 1.35$ and $\sigma = 0.65$), it is possible to calculate the probability P that the LTM exceeds a given action level AL using the radon concentration C obtained from STM. The following expressions are then derived:

$$5\% = P\left(\frac{C}{AL} < (\mu - 1.64 \cdot \sigma)\right) = P(C < 0.28 \cdot AL)$$

$$95\% = P\left(\frac{C}{AL} < (\mu + 1.64 \cdot \sigma)\right) = P(C < 2.42 \cdot AL)$$

Thus, considering a given action level AL, the probability that the LTM is below L_{INF} , defined as $0.28 \cdot AL$, is of 5%. In other words, the probability that the LTM is above L_{INF} is of 95%. Similarly, there is a probability of 5% that the LTM is higher than L_{SUP} , defined as $2.42 \cdot AL$. Values of L_{INF} and L_{SUP} are given in Table 1 for three different action levels.

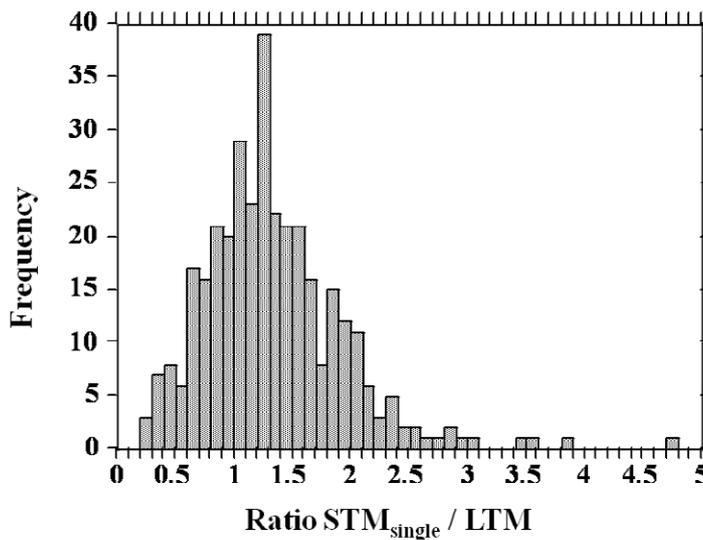


Fig. 2. Distribution of the ratios between the single STM and the LTM.

Table 1. Values of L_{INF} and L_{SUP} according to different action levels.

Action Level [Bq/m ³]	L_{INF} [Bq/m ³]	L_{SUP} [Bq/m ³]
200	60	480
400	110	970
1'000	280	2'420

Results obtained with electret detectors (E-Perm SST) and activated charcoal canisters (Picorad) are compared in Fig. 3 for both measurement conditions, i.e. in the radon chamber and in the existing house. Each point corresponds to the average radon concentration measured with two dosimeters normalized to the reference concentration obtained with the AlphaGuard monitor during the measurement period (1, 2, 3 or 7 days). A very good agreement was observed for electret detectors, always within $\pm 10\%$ except for the one-day measurement in the radon chamber (-12%). A relatively good agreement was also found for activated charcoal canisters with a maximum deviation of -22% for the one-day measurement in the radon chamber and +38% for the three-day in situ measurement.

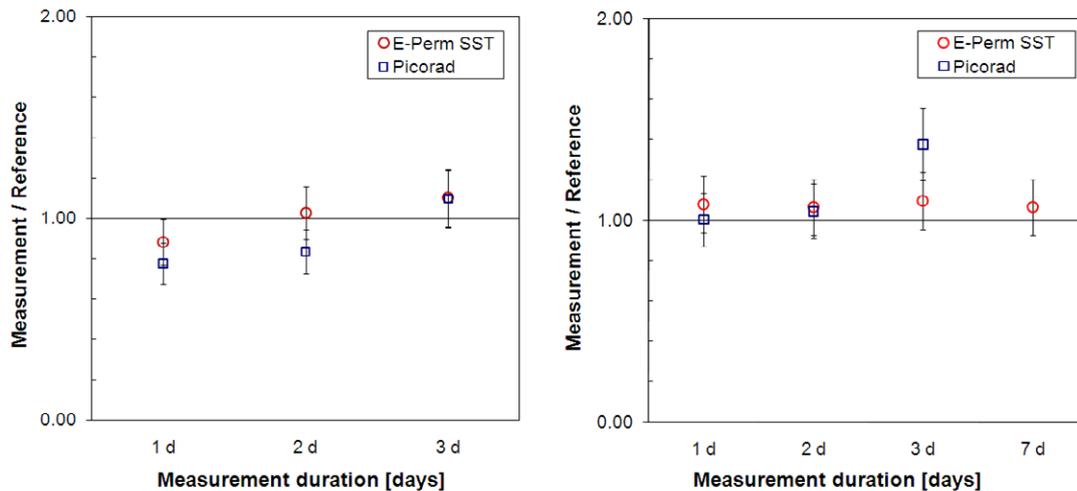


Fig. 3. Comparison of radon measurements with electret (E-Perm SST) and activated charcoal (Picorad) detectors. Measurements were performed in a radon chamber (left) and in an existing house (right) with a radon concentration of about 1500 Bq/m³. Each measurement corresponds to the average of radon concentrations measured simultaneously with two detectors.

Discussion

Based on these results, we propose a screening method based on STM to provide fast and reliable indications of radon levels in dwellings. For the measurements, windows and doors should be kept closed at least 12 hours before starting the measurement and during the whole measurement period. The recommended duration of measurement is 2 days using activated charcoal canisters (Picorad) and at least 2 days using electret detectors (E-Perm type SST). Note that electret detectors can be quickly evaluated immediately at the end of a measurement and thus are somewhat more appropriate than activated charcoal canisters for STM. Results of STM are then interpreted as follows, for a given action level (values of L_{INF} and L_{SUP} are given in Table 1):

- if the result of STM is less than L_{INF} , the yearly average radon concentration is below the action level with a confidence level of 95%;
- conversely, if the result of STM is above L_{SUP} , the yearly average radon concentration exceeds the action level with a confidence level of 95%;
- while no additional measurements are required in both cases (a) and (b), if STM range between L_{INF} and L_{SUP} , LTM are necessary to determine whether the radon concentration in the dwelling is below or above the action level.

In the UK, a similar study was conducted by the Department for Environment, Food and Rural Affairs (Phillips P.S et al., 2004). STM were based on a period of one week using charcoal detectors, electret detectors and alpha-track detectors. Results of STM were also compared with 3-month measurements performed with alpha-track detectors. For an action level of 200 Bq/m³, the DEFRA reported similar values of L_{INF} and L_{SUP} as those showed in Table 1, i.e. 68 and 522 Bq/m³ when activated charcoal canisters were used and 59 and 667 Bq/m³ using electret detectors.

Our screening method was validated for several dwellings in Switzerland. In our practice, STM are mainly used in the framework of real estate transactions.

Conclusions

Short-term measurements (STM) are appropriate for a rapid screening test of radon levels in dwellings. In this study, a method based on STM, i.e. two-day measurements using electret detectors or activated charcoal canisters, has been developed to determine, with a confidence level of 95%, if an action level (in Bq/m³) has been exceeded or not and if further long-term measurements are required. In Switzerland, STM are essentially being used in the framework of real estate transactions.

References

- Piller G., Johner H.-U., Classification of Radon Areas in Switzerland, *Radiat. Prot. Dosim* 1998; 78(1):7-9.
- U.S. Environmental Protection Agency. A Citizen's Guide to Radon: The Guide to Protecting Yourself and Your Family from Radon, 2009. Retrieved April 15, 2010, from: <http://www.epa.gov/radon/pubs/index.html>.
- Phillips P.S. et al., *Comparative analysis of weekly vs. three monthly Radon measurements in dwellings*, Department for Environment, Food and Rural Affairs, 2004.

Estimating the health benefits of progeny extraction units as a means of reducing exposure to radon

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Abstract

Radon exposure to the general public can be reduced by preventing entry of radon gas into buildings using a passive radon-proof membrane or an active sump and pump system. However, a significant majority of the radiation dose delivered is from the decay products of radon rather than from the gas itself. These decay products (also referred to as progeny) are present in indoor air, with an equilibrium factor – a measure of the ratio of progeny to radon gas – of between 0.4 to 0.5. As a result, systems which extract radon progeny from the air by filtering have been promoted as means of reducing exposure to the general population.

The European Community Radon Software (ECRS) offers a means of estimating lung-cancer risk associated with an individual's exposure to radon, and includes the possibility of estimating the health risk from different proportions of radon gas and its progeny by varying the value of the Equilibrium Factor. This software was used to estimate the health benefits associated with reduced decay products in differing concentrations of radon gas. The results were compared to health benefits expected if the risk was reduced by the standard method of reducing the radon gas concentration below the Action Level, which in the UK is $200 \text{ Bq}\cdot\text{m}^{-3}$ for domestic properties.

These calculations showed that there is the potential for efficient extraction units to provide the necessary dose and risk reduction where initial average radon gas concentrations are up to $800 \text{ Bq}\cdot\text{m}^{-3}$. However, above $1000 \text{ Bq}\cdot\text{m}^{-3}$, such systems cannot reduce the health risk sufficiently to reach levels comparable to those resulting from radon gas reduction to below the Action Level.

Introduction

The naturally-occurring radioactive gas, radon, is the second most significant risk for lung cancer after tobacco smoking. High levels of radon were first identified in uranium mines but, more recently, it has been established that significant levels are found in the built environment, and case-control studies have shown an associated increase in lung-cancer in the public from radon in their homes (BEIR VI 1999; Darby et al. 2005; AGIR 2009).

Radon decays into other radioactive elements, and two of these, Polonium-218 and Polonium-214, have been shown to deliver a significant proportion of the radiation

dose received by occupants of domestic premises. In a sealed system, radon and its progeny exist in secular equilibrium. In the domestic environment, however, secular equilibrium is never maintained, because progeny are continuously being removed from indoor air by surface deposition and ventilation. The degree of disequilibrium between the radon gas and the progeny is represented by the Equilibrium Factor (EF), which is defined as the ratio of the potential alpha energy concentration (PAEC) of the actual progeny mixture to the PAEC of progeny in secular equilibrium with the radon gas. Thus EF is between 0 and 1, and within domestic buildings is typically in the range 0.4 to 0.5. Although they are intrinsically solid materials, radon progeny can exist in suspension in air, either unattached, or attached to aerosol particles. Porstendörfer (1984) has discussed these processes, including plate-out of particles and the influences on the ratio between radon and progeny.

Although technical solutions to the radon problem in domestic properties have been largely based on prevention of ingress of radon gas from the soil under the influence of the climatically-dependent pressure difference between the interior of the dwelling and the external environment, there has recently been renewed interest in the physical removal of radon progeny by direct filtering of the internal air, thereby reducing the equilibrium factor between radon gas and its solid progeny.

A number of studies by our own group (Marley et al. 1998) and others have confirmed that filters can indeed remove radon progeny from air (Ogorodnikov et al. 1962; Busigin et al. 1980) and their efficacy as respiratory filters in mining has been studied (Wake et al. 1992).

Offermann et al. (1985) reported that an air-cleaner used to control the indoor concentration of respirable particles and radon progeny, especially if fitted with a high efficiency particulate air filter (HEPA-filter), was effective in removing radon progeny, a finding confirmed by Li and Hopke (1991), who reported that air cleaners effectively reduce the median dose due to radon and its progeny, and that air-filtration is more effective than electronic air cleaning. However, while air cleaning can be effective in reducing total radon progeny, concentrations of unattached radon progeny, a dominant factor affecting the dose conversion factor, can increase with air-cleaning. Henschel (1994) reviewed techniques for the purpose of reducing indoor radon concentration, commenting that the effects of air-cleaners on health risk were unclear due to the increase in the unattached fraction. Tokonami et al. (2003) noted that use of an air-cleaner enhances the dose conversion factor critically, since the unattached fraction increases significantly due to aerosol removal. Most recently, Kranrod et al. (2009) showed experimentally that radon progeny dose reduction of the order of 50% was feasible by use of a well-configured air-cleaner.

These uncertainties notwithstanding, there are several devices on the market specifically claiming to reduce the risk from radon^{1,2}. However, the US Environmental Protection Agency (EPA) does not recommend radon remediation using filters (EPA 2010).

¹ http://www.nrpltd.com/radon_gas_filter.php

² <http://www.airpurifiersandfilters.com/radon-air-purifiers.php>

Material and methods

The European Community Radon Software (ECRS) tool (Degrange et al., 2000) performs lung-cancer risk calculations specific to European populations for individual or collective radon exposure profiles. Specifically, the software is capable of generating a range of individual risk-related estimates, including reduced life expectancy and expected age at death, for subjects whose age, sex, smoking habits and domestic radon exposure are known, and can furthermore take into account the equilibrium factor applicable to the environment being investigated. ECRS has therefore been used in the present study to consider whether deploying EF-reducing filtration techniques in homes can produce a significant health benefit to occupants.

In addition to basic demographic, radon exposure and smoking status input parameters, ECRS permits user control of Equilibrium Factor and aerosol parameters. Two Equilibrium Factor tables are provided, attributable to ICRP 65 (ICRP, 1994) and the UK National Radiological Protection Board (NRPB) respectively. Whereas the ICRP parameters, the system default, do not vary with room type, the NRPB data addresses the possible impact of ventilation rate and air smoke content on the equilibrium factor. For the present study, a derivative of the ICRP dataset was used, with identical values of Equilibrium Factor being used throughout the house for each case modeled.

ECRS modeling addresses additional aerosol parameters, representing the overall radon progeny activity-size distribution by a sum of lognormal distributions (modes). For each of these modes, unattached progeny and three attached modes (nucleation, accumulation and coarse), values are given for fraction of total PAEC, dispersion (i.e. geometric standard deviation), and particle size in terms of Activity Median Aerodynamic Diameter (AMAD) for attached particles and Activity Median Thermodynamic Diameter (AMTD) for unattached particles. Two data models are provided, a default Generic House, where the parameters do not vary with room type, and a generalized model, which considers the possible impact of ventilation rate and air smoke content on the aerosol parameters and provides specific room-by-room data. The Generic House option was used in the present analysis.

For the present study, analysis was based on 40-year-old, Non-Smoking and Smoking Males and Females exposed to radon levels of 0, 200, 600 and 1000 Bq·m⁻³, for Equilibrium Factors ranging from 1.0 down to 0.02. Using the results from this analysis, iso-risk plots were generated, identifying the effect of reduction of Equilibrium Factor on individual excess lung-cancer risk. The calculated risks of contracting lung cancer were then compared to the risk at a radon level of 200 Bq·m⁻³ (the UK domestic Action Level) with an Equilibrium Factor of 0.5.

Results

At all levels of Equilibrium Factor and for both sexes, excess lung-cancer risk is linearly proportional ($R^2 > 0.99$) to radon exposure over the range 0 - 1000 Bq·m⁻³ (five times the UK Action Level). Specific Risk factors (incremental risk attributable to 1 Bq·m⁻³ exposure) for 40-year-old Non-Smoking Males and Females are themselves linear in Equilibrium Factor (Figure 1), as is loss of life expectancy consequent on radon exposure (Figure 2).

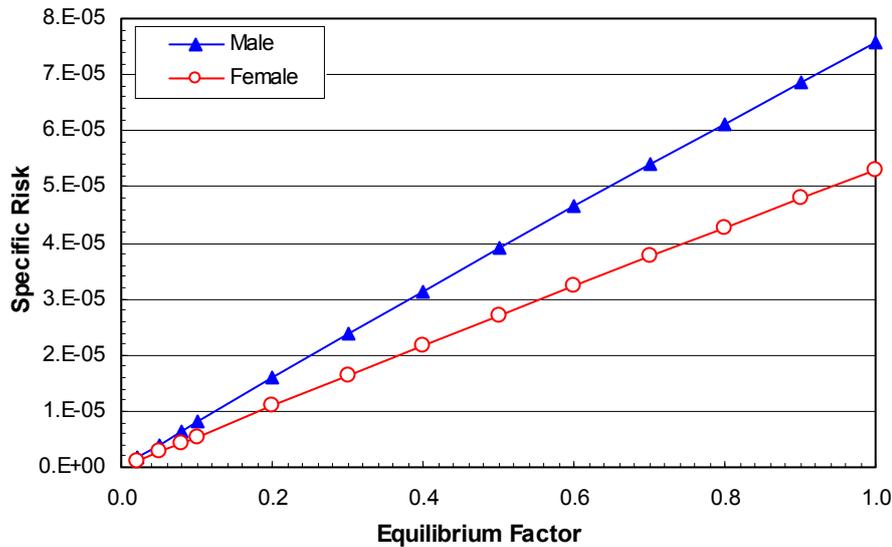


Fig. 1. Variation of excess risk per unit Bq.m^{-3} radon concentration, linear in radon over the range 0 – 1000 Bq.m^{-3} , with Equilibrium Factor for 40-year-old non-smoking Males and Females.

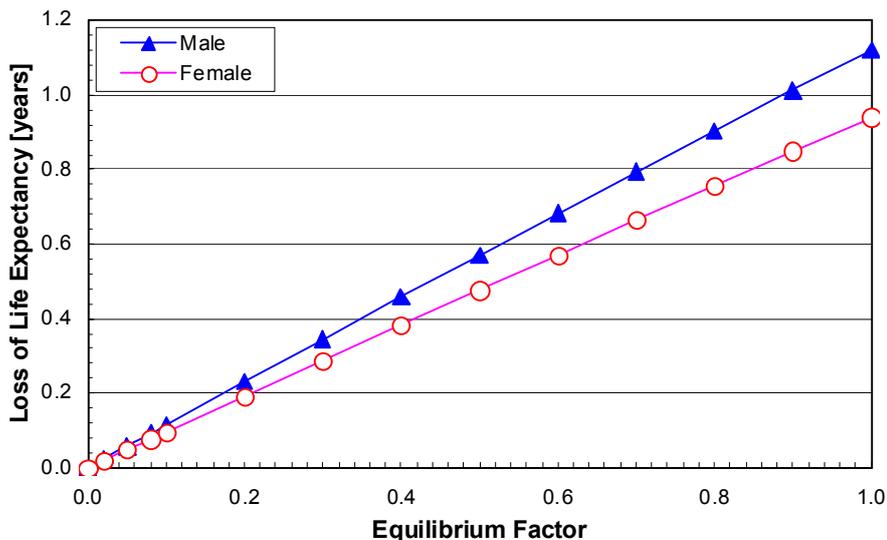


Fig. 2. Loss of Life Expectancy Attributable to Radon Exposure of 1000 Bq.m^{-3} for 40-year-old non-smoking Males and Females.

Excess risk represents the additional risk of contracting lung-cancer directly attributable to radon exposure. This is a complex function of age, sex, radon exposure level and duration, equilibrium factor and smoking status. By way of example, Figure 3 shows the set of iso-risk plots in the exposure-level/equilibrium factor domain, generated for 40 year-old non-smoking males and females with whole-life exposure to the indicated radon concentration levels, spanning the range of excess risks from 0.01 to 0.1 (1% - 10%). Similar families of curves can be generated for individuals of other ages, of different smoking status, and with any desired combination of radon exposure and home occupancy. These all have the same rectangular hyperbolic analytical form,

the product of radon concentration and equilibrium factor being constant for any given level of excess risk.

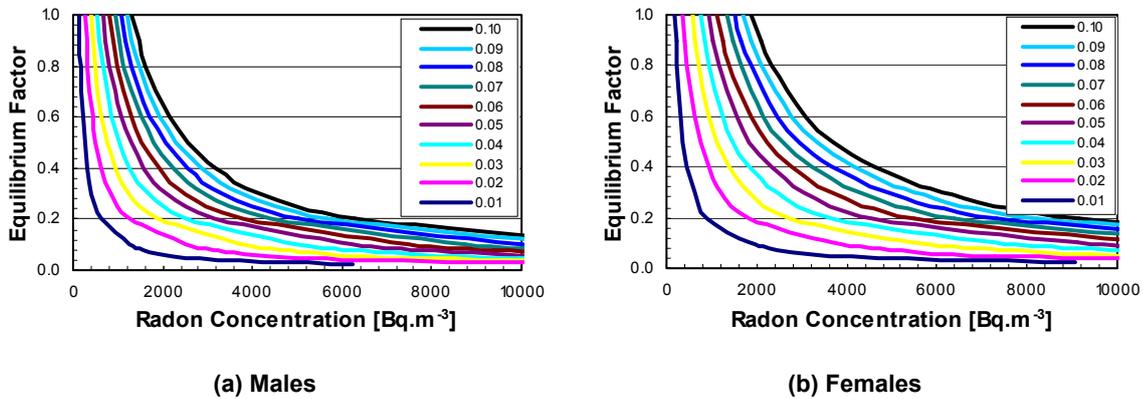


Fig. 3. Iso-Risk Plots for 40-year-old Non-Smokers, Excess Lung-Cancer Risk as parameter.

Discussion

At an exposure level of 200 Bq·m⁻³ with an Equilibrium Factor of 0.5, the current UK Action Level case, the excess risks of contracting lung-cancer are 0.008 and 0.0055 for Males and Females respectively. To facilitate further analysis and discussion, Figure 4 reports the 0.008 risk curve for Male subjects over the typically encountered range of domestic radon concentration levels. A similar curve can be generated for Females, in this case with a risk parameter of 0.0055.

As the figure shows, the iso-risk curves in the EF-radon domain take the analytical form of rectangular hyperbolæ (in this case, characterised by $EF \cdot radon = 106$), a fact readily verified by inspection. Thus, if the Equilibrium Factor in a 200 Bq m⁻³ environment is reduced by a factor of 5 to 0.10, a reduced excess lung-cancer risk situation obtains at all radon levels from zero up to 1000 Bq m⁻³.

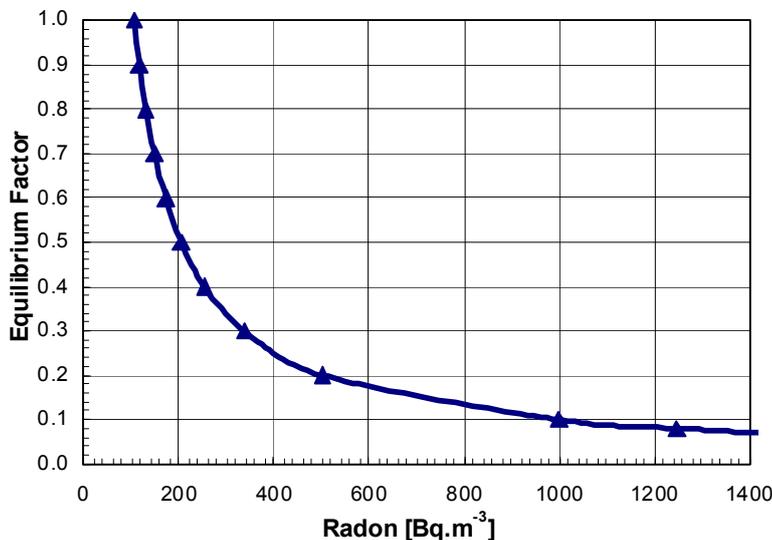


Fig. 4. Iso-Risk Plot (Excess Risk = 0.008) for Males in 200 Bq.m⁻³, EF = 0.5 Environment.

Curling et al. (1990a) developed an optimization model for filter thickness, solidity, and fibre diameter to minimize inhalation dose from radon decay products, based on modified forms of the Porstendorfer-Jacobi (Porstendorfer, 1984) room model and the Jacobi-Eisfeld (Jacobi and Eisfeld, 1980) lung-dose model. The resulting optimal design, a thin filter of low solidity and large fibre diameter, confirmed that significant reduction in the dose rate could be achieved using a filter system. While the theoretical model predicted 80% reduction in the dose rate, with the inherent assumption of movement of 230 room volumes per hour through the fan, initial experimental trials (Curling et al. 1990b) achieved 50% reduction.

Kranrod et al. (2009) confirmed by measurement that an air-cleaner equipped with an HEPA filter and a deodorizing activated carbon filter preferentially removed the attached fraction of radon progeny from the room air, reducing EF to around 71% of its un-filtered value. Because of the differing contributions to the risk from radon gas, attached progeny and unattached progeny, the 71% reduction in Equilibrium Factor achieved in this way again resulted in a 50% reduction in dose. In the case studied, the initial radon gas level was around $300 \text{ Bq}\cdot\text{m}^{-3}$ and the risk to occupants was reduced below that at the Action Level of $200 \text{ Bq}\cdot\text{m}^{-3}$.

Examples in the literature of the Equilibrium Factors achieved in rooms where such filtration systems were operational are limited. Marley et al. (1998) measured $F=0.17$ in a UK hospital operating theatre, while Li and Hopke (1991) found $F=0.134$ in a US house. Reduction of the Equilibrium Factor to around this level in any room where the average radon gas level is below 800 Bq m^{-3} would reduce the risk to occupants sufficiently. If an equilibrium factor of 0.1 could be achieved, then the upper limit would be 1000 Bq m^{-3} , and so this could be regarded as an upper limit for such systems.

The performance of air-cleaners will depend on the air volume passing through the filter, and therefore will depend on the size of the room, the air throughput capability of the system and the characteristics of the filter. Thus it would be expected that an air-cleaner will not achieve as significant a reduction in progeny in a larger room. In addition, the movement of radon gas around the building needs to be considered. Additional units may be required in other rooms, if the radon gas moves slowly enough between rooms to decay and create new decay products, or if the source of radon gas and decay products is in another part of the building and reaches the living room and bedrooms independently.

For this reason, such units cannot be installed in any arbitrary room within a dwelling and be expected to achieve significant health benefits throughout the home. The performance of commercial units needs to be tested in standard conditions to ensure that a sufficient reduction in Equilibrium Factor is achieved. Furthermore, when deployed in a home, the performance needs to be checked. Standard track-etch devices only measure radon gas, and so there will be a need to develop simple assessment devices which measure both radon gas and progeny if these sort of units are to be deployed widely.

Conclusions

The theoretical calculations demonstrated in this paper demonstrate that air filtration units can reduce occupants' risk below the limit implied by the Action Level, provided that the radon gas level in the building is moderately raised above the Action Level. At

increasing radon levels the air filtration units must be more efficient to achieve the required benefit, and above $1000 \text{ Bq}\cdot\text{m}^{-3}$, the unit cannot reduce risk sufficiently to reach the target.

Thus such units may have their place in remediating homes with radon levels up to $800 \text{ Bq}\cdot\text{m}^{-3}$, and may also be of value in homes remediated by other means where the level has been brought down, but not below the Action Level. Kranrod et al. (2009) have confirmed that satisfactory performance of such units can be achieved, at least at $300 \text{ Bq}\cdot\text{m}^{-3}$.

Several practical issues remain before such units can be widely adopted. Firstly the performance of commercial units needs to be evaluated to assess how far they can reduce the Equilibrium Factor in a range of room sizes. Secondly, a simple monitoring system that can measure both radon gas, and progeny, and is comparable to the simplicity of the track etch systems for radon gas, must be developed, so that the health benefit from such units can be proven.

References

- AGIR: Advisory Group on Ionising Radiation. Radon and Public Health. Documents of the Health Protection Agency, Report RCE-11, June 2009. ISBN 978-0-85951-644-0.
- BEIR VI: Committee on Health Risks of Exposure to Radon, 1999. Health Effects of Exposure to Radon. National Academic Press, Washington DC, ISBN 0-309-05645-4.
- Busigin A, van der Vooren AW, Phillips CR. Collection of radon daughters on filter media. *Environmental Science and Technology* 1980; 14 (5): 533-536.
- Curling CA, Rudnick SN, Ryan PB, Moeller DW. Optimization of filtration for reduction of lung dose from Rn decay products: Part I - Theoretical. *Health Phys.* 1990a; 59(3):267-275.
- Curling CA, Rudnick SN, Ryan PB, Moeller DW. Optimization of filtration for reduction of lung dose from Rn decay products: Part II- Experimental. *Health Phys.* 1990b; 59(3):277-285.
- Darby S, Hill D, Auvinen A, Barros-Dios JM, Baysson H, Bochicchio F, et al. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *Br. Med. J.* 2005; 330: 223-227.
- Degrange JP, Birchall A, Haylock R, Janssens A, Levy FP, Marsh J, Muirhead CA, European Commission software tool for radon risk calculation and evaluation of countermeasures, Proc. 10th International Congress of the International Radiation Protection Association, Hiroshima, Japan, 2000.
- Environmental Protection Agency (EPA). Consumer's Guide to Radon Reduction : How to fix your home. Jan 2010. EPA 402/K-10/002
- Henschel DB. Analysis of radon mitigation techniques used in existing US houses. *Radiat. Prot. Dosim.* 1994; 56: 21-27.
- ICRP. ICRP 65, Protection against radon-222 at home and at work. 1994. ICRP Publication 65, Vol. 23, No.2, Pergamon Press.
- Jacobi W, Eisfeld K. Dose to tissue and effective dose equivalent by inhalations of radon-222 and their short-lived daughters. 1980. GSF Report S-626, Springer-Verlag, Munich.

- Kranrod C, Tokonami S, Ishikawa T, Sorimachi A, Janik M, Shingaki R, Furukawa M, Chanyotha S, Chankow N. Mitigation of the effective dose of radon decay products through the use of an air cleaner in a dwelling in Okinawa, Japan. *Applied Radiation and Isotopes* 2009; 67: 1127-1132.
- Li C-S, Hopke PK. Efficacy of air cleaning systems in controlling indoor radon decay products. *Health Physics* 1991; 61(6): 785-789.
- Marley F, Denman AR, Phillips PS. Studies of radon and radon progeny in air conditioned rooms in hospitals. *Radiation Protection Dosimetry* 1998; 76 (4): 273-276.
- Offermann FJ, Sextro RG, Fisk WJ, Grimsrud DT, Nazaroff WW, Nero AV, Revzan KL, Yater J. Control of respirable particles in indoor air with portable air cleaners. *Atmos. Environ.* 1985; 19: 1761-1771.
- Ogorodnikov BI, Kirichenko VN, Basmanov PI, Petryanov IV. The trapping of short-lived radon daughter products by FP fibrous filters. *Atomic Energy* 1963; 15 (3): 230-237.
- Porstendörfer J. Behaviour of radon daughter products in indoor air. *Radiation Protection Dosimetry* 1984; 7 (1):107-113.
- Tokonami S, Matsuzawa T, Ishikawa T, Iimoto T, Yonhara H, Yamada Y. Changes of indoor aerosol characteristics and their associated variation on the dose conversion factor due to radon progeny inhalation. *Radioisotopes* 2003; 52: 285-292.
- Wake D, Brown RC, Trottier RA, Liu Y. Measurements of the efficiency of respirator filters and filtering facepieces against radon daughter aerosols. *Ann. Occup. Hyg.* 1992; 36 (6): 629-636.

Indoor radon anomalies and correlation with geodynamic events: A case study in the Etnean area

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Abstract

More than 50% of the total absorbed dose from natural radiation sources is attributed to radon gas and its daughters (UNSCEAR, 1993). In the last decades, an increasing regulatory and scientific interest concern radon indoor monitoring, because radon and its daughters produces a risk of lung cancer, by inhalation of high concentrations for a long time. The indoor radon transportation is due principally by two different mechanisms: diffusion from soil and building materials and convection flow. The diffusion mechanism depends on the radium concentration in soil and building materials, as well as on the diffusion coefficient; convective flows are generated by a pressure difference between the inside and the outside of a building. Many external factors can also influence the diffusion process: rainfall, freezing and increasing atmospheric pressure decrease the exhalation rate, while increasing temperature can increase it. In this study temperature, pressure and humidity are monitored together with radon concentrations.

In 2006, for a period of four months between winter and spring, both in soil and indoor radon gas, and meteorological parameters, have been monitored continuously in two buildings at St. Venerina, situated on the low eastern flank of the volcano. This area is crossed by the Timpe Fault System (TFS), that are composed of faults mainly trending towards NNW–SSE and NW-SE. The indoor radon anomalies have been studied trough statistical methodology and they have been correlated with the geodynamic events of volcano Etna, recorded during the investigated period. Its values seems to show variations not due to local meteorology, diffusion or convection mechanisms, instead the predominant effect seems to be the geodynamics of the Etnean area. This study is an example that shows how in the active volcano-tectonic areas, the indoor-radon monitoring, based only on seasonality and floor numbers, is not exhaustive to establish the indoor radon levels, and how radon accumulation may depends on several and complex effects, each one able to generate anomalies of its concentration.

Introduction

During his life, man is constantly exposed to many ionizing radiation sources of natural origin, the most important of whose are ^{40}K and the radionuclides produced by the radioactive families of Uranium and Thorium. These elements have been produced at the time of Earth's creation and their decay products are widely distributed in soil, water and air. Of particular interest from the scientific point of view is the presence of radon gas in the air, in particular the isotope ^{222}Rn , produced by alpha decay of ^{226}Ra , which belongs to the decays chain of ^{238}U . Radon is a noble gas, odorless, colorless and tasteless, seven times heavier than air. Since it is chemically inert, it is characterized by great mobility. The World Health Organization (WHO) through the International Agency for Research on Cancer, included the as a group 1 carcinogen - in a list of 75 substances. The new document that the WHO has recently presented about has raised the level of concentration at the national reference value of 100 Bq/m^3 , with an express recommendation to not exceed the limit value 300 Bq/m^3 (WHO HANDBOOK ON INDOOR RADON A PUBLIC HEALTH PERSPECTIVE - 2009), these values should be useful to the national authority to enact the appropriate construction standards. Exposure to radon in dwellings due to the presence of Uranium in soil and building materials is one of the major problems of radio-protection today.

^{222}Rn studies and monitoring showed that this geo-gas can reveal a variety of interesting features, as well as permit a depth comprehension of the Earth's crust.

Relatively recent is a new line of research, that is foretell geodynamic events through the sudden fluctuations of its concentration, the so-called *radon anomalies*, which can be correlated with the geodynamics of the investigated area (La Delfa et al., 2007; Planinic et al., 2005; Vizzini et al., 2006-2007; Zmazek et al., 2005). The link existing between radon in soil anomalies and seismic events, has been explained by the so-called *pore-collapse model* (J.-P. Toutain et al., 1999).

The site

The town of St. Venerina (figure 1) is located on the lower eastern slope of volcano Etna. All the area is exclusively composed of volcanic soils, which refer to lava flows of different ages. From the structural point of view, the territory is characterized, as the entire eastern slope of Mt. Etna, by fault systems with prevailing directions NE-SW and NW-SE, which affect all the area. Some of these tectonic dislocations are well evident by the presence of sharp uneven terrain, the largest of which are called "Timpe".

Based on historical data, some of these faults, are defined "seismogenic", because they are responsible for seismic activities, both in the recent and historical periods. The seismic activity that is originated from these faults, usually affects relatively shallow crustal levels ($h \leq 7 \text{ km}$), with generally modest magnitude of earthquakes. However in periods of volcanic eruptions the related seismic events can reach the highest values recorded in all the Etnean area. What previously said was particularly evident in the well-known disaster occurred in October 29, 2002, during one of the most intense eruptions of Mount Etna, when a seismic swarm, and one great earthquake of magnitude 4.4 (Richter scale) and intensity VIII (MCS scale), with epicenter in St. Venerina, was responsible for considerable damages to persons and dwellings.

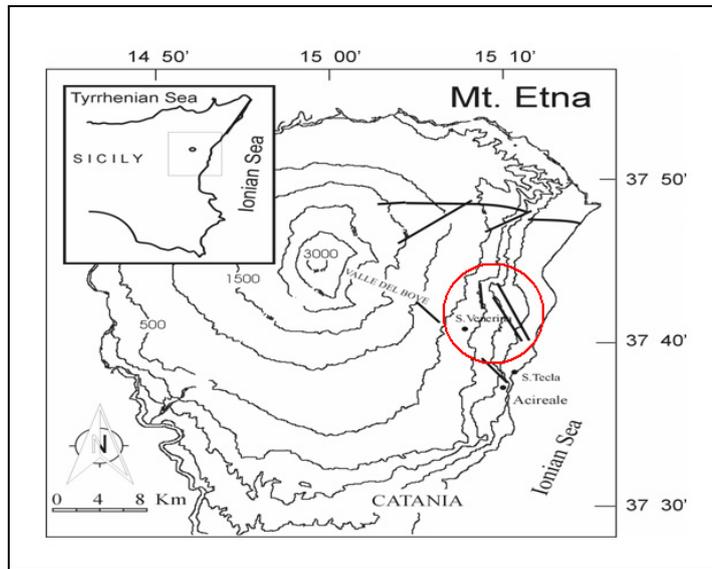


Fig. 1. Map of Mt. Etna and Si.Ge.T. active faults (red circle).

Material and methods

The main contribution of the in soil radon concentrations is due to the emanation process from soil or fractures in the ground. Materials with high Uranium and Thorium contents and which are located near the Earth's surface, can produce a high radon exhalation rate. In this context, Sicily is an island with different specific geological characteristics, offers a variety of lithotypes and therefore of features for building materials. The rocks and soils in all the Etnean area, are characterized by igneous rocks, which have the most Uranium and Thorium contents among the other lithological varieties of the island (metamorphic and sedimentary rocks). Therefore it was considered appropriate to effect a characterization of some rock samples, using gamma spectroscopy, to measure the primordial radionuclides contents. This study, as well as of academic nature, has practical implications on the human exposure to environmental radioactivity, since the rocks sampled in the monitoring sites are those processed and used for the construction of buildings for residential purposes, and this is particularly evident in all the Etnean area and at St. Venerina in particular, where the large part of dwellings are built with volcanic rocks and ash. The samples analysis has been effected revealing the γ -ray emitted by the radionuclides originating from ^{238}U and ^{232}Th decay chains and from ^{40}K , using a HPGe detector with efficiency of 40% and electric cooling. The measurements of radionuclides concentrations are used to determine both the indoor radon concentration and the gamma dose rate (Rizzo et al., 2001).

A benchmark for the radiological risk assessing due to external gamma radiation, is the **Radium equivalent activity**. The meaning of the Radium equivalent activity is to have a single number or index that can describe the γ -output which is originated from different mixtures of Uranium (or Radio), Thorium and ^{40}K in a material. The Radium equivalent activity can be calculated as follows (Beretka and Mathew, 1985):

$$Ra(eq) = A(Ra) + 1.43A(Th) + 0.077A(K)$$

where:

$A(Ra)$ is the ^{226}Ra activity (which is the same as ^{238}U) in Bq/kg

A (Th) is the ^{232}Th activity in Bq/kg

A (K) is the ^{40}K activity in Bq/kg

This equation is based on the assumption that 370 Bq/kg of ^{238}U , 259 Bq/kg of ^{232}Th and 4810 Bq/kg of ^{40}K produce the same dose range. Moreover, the Ra(eq) value of 370 Bq/kg is equal to the annual dose equivalent of 1.5 mSv per year, which represents the highest absorbed dose by a person in a year, caused by the exposure to natural radioactivity coming from building materials. The Radio equivalent activities obtained in the St. Venerina area, oscillate between 221,32 Bq/kg and 246,74 Bq/kg, with an average value of 236,01 Bq/kg, that is well below the threshold limit of 370 Bq/kg.

The Uranium and Thorium contents in rocks in the territory of St. Venerina, don't explain the in soil radon concentrations, more than 20000 Bq/m³, which were recorded in previous studies (La Delfa et al., 2009; Vizzini et al., 2006-2007), and even more the indoor radon concentration fluctuations, from 2 to 5 times than the seasonal average concentrations, which seems to not be linked with seasonality. The radioactivity based on the primordial radionuclides content is indeed a constant value, characteristic of the lithology of the site. Based on these considerations, a punctual investigation in the territory of St. Venerina has been effected, near tectonic structures in the north part of the town, within the so-called geostructural system of Timpe (Si.Ge.T.), that is a faults system oriented NNW-SSE (red circle in figure 1).

The study of seismicity and the possible correlation with radon concentration fluctuations was carried out during the period between 12th January to 12th April 2006.

This temporal range was conveniently chosen as significant for these studies because a change in the seismic and volcanic styles of the volcano has been detected, while the meteorological parameters, both for indoor and in soil radon monitoring, had not drastic changes of their mean values in all the investigated period.

The in soil radon concentrations collected, showed fluctuations which, as known from the literature, are attributable both to changes in meteorological parameters, and to changes due to the dynamics of the volcano (Planinic et al., 2005; Shi Yuchun and Xu Yingfeng, 1994; Zmazek et al., 2005). From the radon gas concentrations and the meteorological parameter data (temperature (°C), pressure (mBar) and relative humidity (%)), recorded every 10 minutes from the active monitoring device AlphaGUARD (GENITRON), the daily average values have been calculated. The in soil experimental data of St. Venerina have been collected in order to identify radon anomalies, precursors of seismic events related to the volcano Etna activity.

The results obtained, which are published in La Delfa et al., 2007, showed that there is a close correlation between in soil radon fluctuations and the geodynamic activity of the volcano. This conclusion is even more reliable because during the monitoring period there haven't been drastic changes in the meteorological parameters, which could affect the radon fluctuations of purely geodynamic nature. From these reasons, it became possible to assume that both the in soil and indoor radon concentration fluctuations, recorded and presented in this study, may be associated to the geodynamic activity of the volcano.

Simultaneously with in soil radon monitoring, indoor measurements have been effected, through another AlphaGUARD in modality of natural gaseous spread, put in a

confined little room located at the ground floor of an ancient uninhabited building, lacking of windows, and located at a distance of about 7 meters from the in-soil operating instrument. There is a 15-20 cm thickness of concrete separating the room from the soil; the building walls are constituted of lava blocks. This building has been chosen because can be considered as representative of the historical centre of the town.

Indoor radon measurements at St.Venerina have been carried out also in a new building (reinforced concrete) from 12th January to 14th April 2006. In particular measurements have been performed in a basement of one edifice far about 50 meters from the site where in-soil active monitor was operating. It was built with the most current seismic criteria after the famous earthquake of magnitude 4.4 (Richter scale) and intensity VIII (MCS scale) in October 29, 2002, previously described. This dwelling can be considered as representative of the new neighborhoods of the town. In this new site indoor radon has been acquired using ORTEC Charcoal Canisters (CC) technique, following the EPA protocol (Gray and Windham, 1987).

The CC, preliminary weighed, had to be exposed, uncovered, in the confined place for 48 hours. The canister gamma activity (the activity of ^{214}Bi and ^{214}Pb radon daughters) was measured by means of NaI (TI) scintillation spectrometer. The typical time between the end of the exposition and the beginning of the measurements was about four hours, which is the time needed to reach the transient equilibrium between parent and γ -emitted daughters. The concentration values expressed in Bq/m^3 were determined through the spectral analysis, exposure time and calibration factor known. Humidity sensors, used for all the investigation period to verify the reliability of the CC methodology (Gervino et al., 2004), have ensured that the humidity was always below 70% throughout the monitoring period.

Results and discussion

Both in soil and indoor radon measurements are shown in figure 2 a, b:

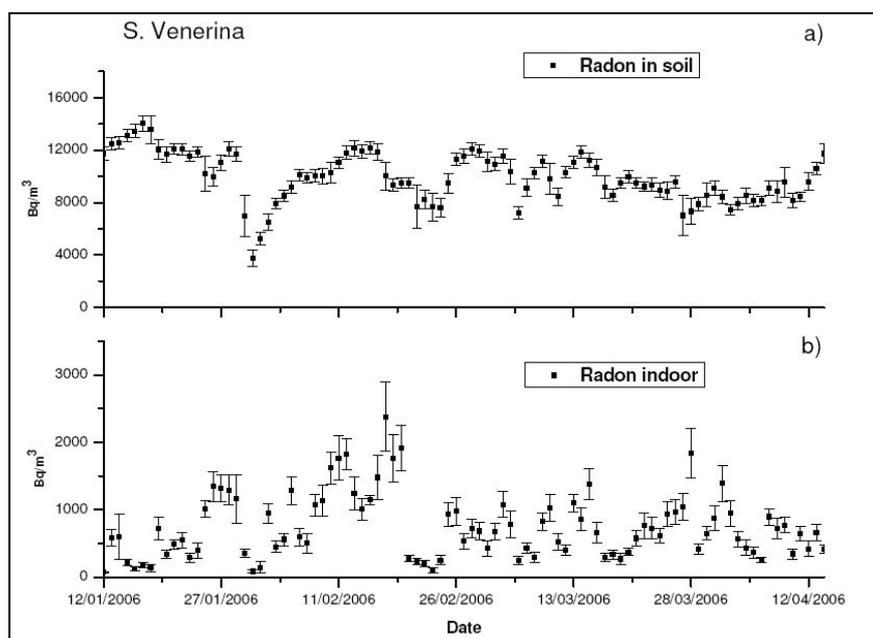


Fig. 2. Both in soil and indoor (old building) radon concentrations.

As it's possible to see, the two trends seems strictly correlated. The indoor meteorological parameters have been also recorded for all the considered period. They are shown in figure 3 as normalized cumulative curves:

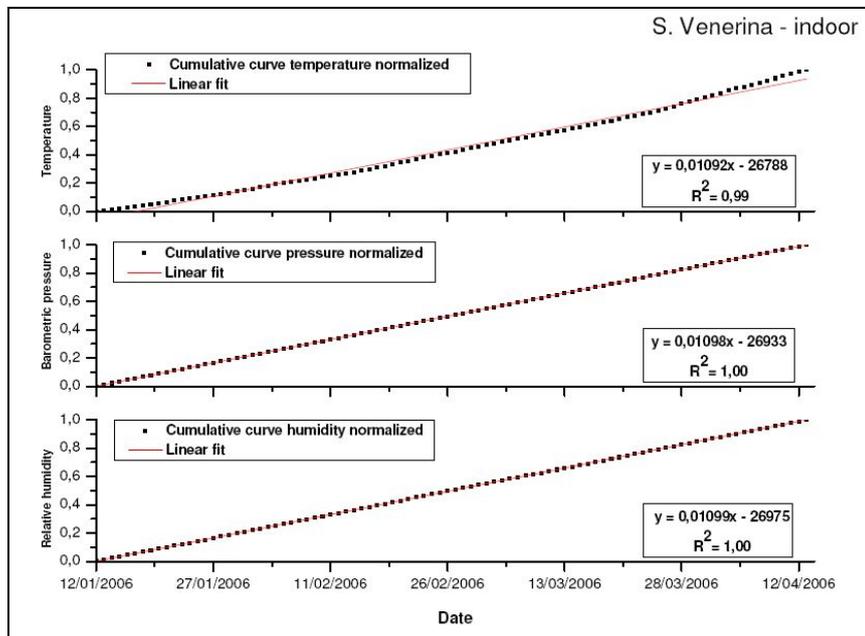


Fig. 3. Normalized cumulative curves of the indoor meteorological parameters.

During the monitoring period, no remarkable variations of meteorological parameters have been observed ($R^2 \geq 0.99$). As it's possible to see, only at the end of the investigation period and at the same time, a little temperature increase and a little humidity decrease have been noticed. These gradual variations are typical of the following spring arrival.

A **cross-correlation** analysis was carried out. It is a standard method of estimating the degree to which two series are correlated. Considering the two series the cross correlation r at delay d is defined as the following function:

$$r(d) = \frac{\sum_i [(x(i) - mx) \cdot (y(i-d) - my)]}{\sqrt{\sum_i (x(i) - mx)^2} \sqrt{\sum_i (y(i-d) - my)^2}}$$

Where the two series are indicated with $x(i)$ and $y(i)$ respectively; mx and my are the arithmetic means of the corresponding series; $d = 1, 2, \dots, N-1$ is the delay in days (the two series represent daily trends).

Result of the cross-correlation is shown in figure 4:

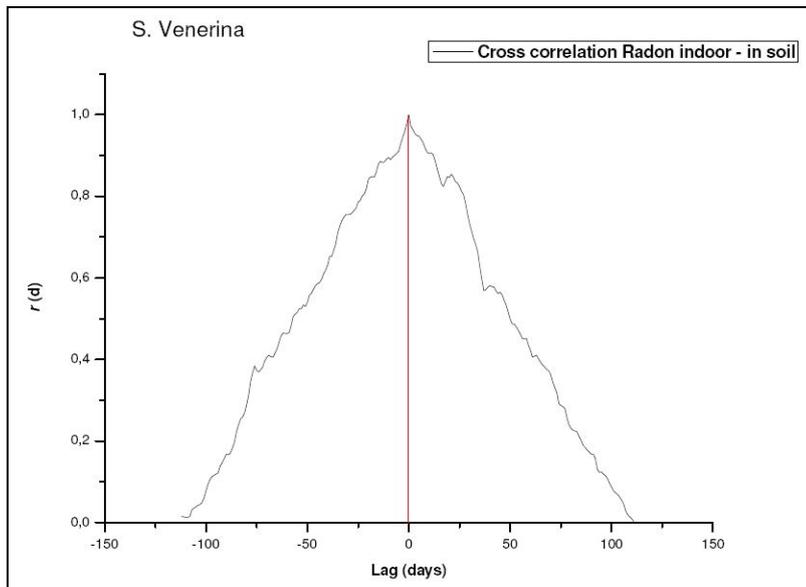


Fig. 4. Normalized cross-correlation between in soil and indoor (old building) concentrations.

As it's possible to see, the maximum correlation is for $d=0$, indicating that indoor and soil radon concentrations have the maximum correlation without delay. Therefore, in old buildings, radon quickly migrates from soil to indoor, reaching values even exceeding those recommended.

Both the indoor radon concentration measurements, that is those detected through the active device AlphaGuard, and those detected through CC, are shown in figure 5 a, b:

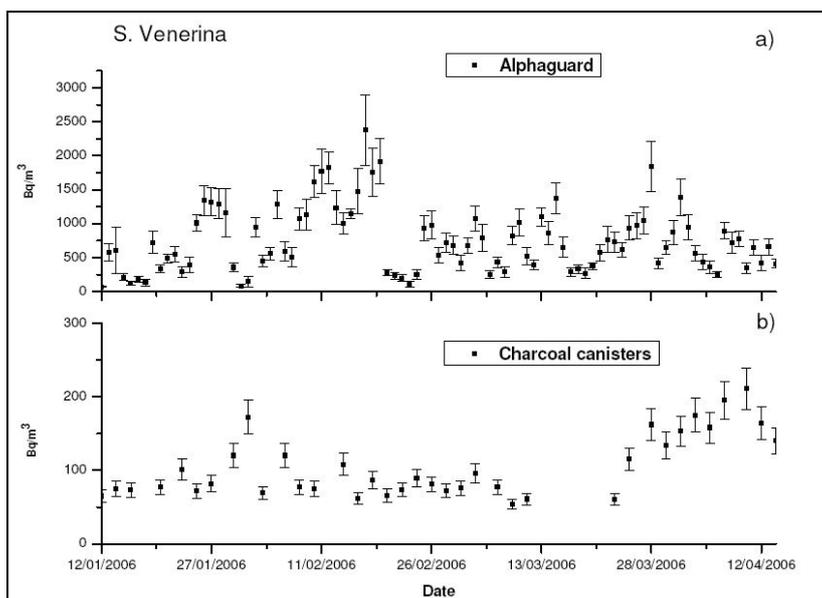


Fig. 5. Both the indoor radon concentration measurements: a) old building, through active device AlphaGUARD; b) new building, through CC detectors.

As previously made for the old building, a cross correlation analysis was carried out. The result obtained is shown in figure 6:

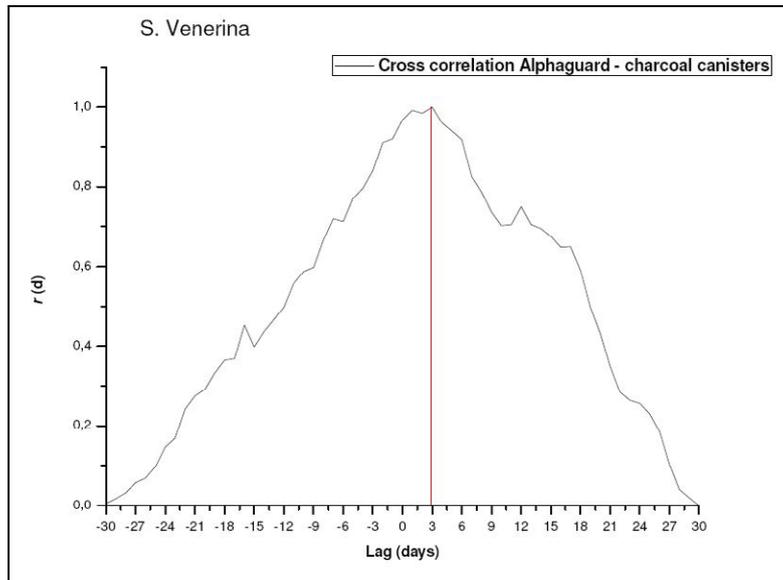


Fig. 6. Normalized cross-correlation between both indoor radon concentrations.

Though one might expect that the new building is able to effectively disperse the radon gas from the subsurface surrounding the building, again in this case, the two trends show a maximum correlation, with a shift of three days, that is inside the radon half-life.

Conclusions

The analysis of rock samples collected throughout the Etna area, have showed that the concentration of primordial radionuclides produce a Radio equivalent activities within the maximum value of 370 Bq/m^3 . The values obtained represent the contribution of natural background radiation due to the lithology of the area. These values don't explain both in soil and indoor radon concentration fluctuations recorded in previous studies and, in particular, in the monitoring period considered in this study. It was verified by La Delfa et al., 2007 that the in soil radon fluctuations, showed in figure 2a, are closely linked to geodynamic of the volcano Etna, and this result is even more reliable, because the weather conditions had not undergone drastic changes for all the time interval considered.

Simultaneously with the in soil radon monitoring, indoor radon concentrations in two different types of dwellings have been monitored (figures 2b and 5b), together with the indoor meteorological parameters (figure 3). The indoor weather parameters have stable trends throughout the monitoring period. The cross-correlation analysis have pointed out that the indoor radon concentrations measured, both in the old and in the new building, show the same fluctuations of the in soil radon concentrations. While in the old building, the maximum correlation is without temporal delay, in the new building has been obtained a temporal delay of 3 days, however inside the radon half-life. These results show that in active volcano-tectonic areas such as St. Venerina, the geodynamics of the area is strictly correlated also with the indoor radon concentrations, and it seems to be the main external factor of indoor accumulation, in periods of stable weather conditions.

This study wants to point out that in geodynamic settings such as the Etnean area, the indoor radon monitorings (effected to estimate the population exposure to radon gas), which are usually made following a criterion exclusively based on seasonality and floor numbers, should be made considering also the geodynamics of the area of interest, possibly extending the analysis in periods of significant seismic and volcanic activities.

References

- Beretka J., Mathew P. J. 1985. Natural radioactivity of Australian building materials, industrial wastes and by-products. *Health Phys.* 48, pp. 87-95.
- Gervino G., Bonetti R., Cigolini C., Marino C., Prati P., Pruiti L.. Environmental radon monitoring: comparing drawbacks and performances of charcoal canisters, alpha-track and E-PERM detectors. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, Volume 518, Issues 1-2, 1 February 2004, Pages 452-455.
- Gray, D.J., Windham S.T., 1987. EERF standard operating procedures for radon-222 measurement using charcoal canisters. U.S. Environmental Protection Agency 520/5-87-005.
- La Delfa S., Immè G., Lo Nigro S., Morelli D., Patanè G., Vizzini F., 2007. Radon measurements in the SE and NE flank of Mt. Etna (Italy). *Radiation Measurements*, 42, 1404–1408.
- La Delfa S., Vizzini F., Patanè G.. False and true anomalies of radon concentration: analysis of different methodologies to a reliable forecast of volcanic phenomena. Proceeding at National Conference A. Rittmann: THE ITALIAN VOLCANOLOGY: STATE OF THE ART AND FUTURE PERSPECTIVES. Nicolosi (CT), Italy. 11–13 June 2009. ISBN 978-88-89972-11-3.
- Planinic J., Radolic V., Vukovic B. (2004). Radon as an earthquake precursor.
- Rizzo S., Brai M., Basile S., Bellia S., Hauser S., 2001. Gamma activity and geochemical features of building materials: estimation of gamma dose rate and indoor radon levels in Sicily. *Appl. Rad. Isot.* 55 pp. 259-265.
- Thomas D., Geochemical precursors to seismic activity. *Pageoph* 126 (1988) 241–266.
- Toutain J.-P., Baubron J.-C., Gas geochemistry and seismotectonics: a review. *Tectonophysics* 304 (1999) 1–27.
- UNSCEAR 1993 report. SOURCES AND EFFECTS OF IONIZING RADIATION. United Nations Scientific Committee on the Effects of Atomic Radiation. UNSCEAR 1993 Report to the General Assembly, with Scientific Annexes
- Vizzini F., Basile S., Brai M., La Delfa S.- Response of an integrated system, for the study of complex phenomena monitored by gas radon. Proceeding at International Workshop: ECOLOGICAL COMPLEX SYSTEMS: STOCHASTIC DYNAMICS AND PATTERNS. Terrasini (Pa), Italy. 22-26 July 2007.
- Vizzini F., La Delfa S., Lo Nigro S., Tringali G. – Radon anomalies at Volcano Etna: Identification methods and correlation with geodynamic events. Proceeding at SEISMIC SEMINAR - Department of Geophysics at Freie Universitat of Berlin, Location: Berlin, Malteserstr. 74 – 100, Bldg. D, room D, 144. 11 October 2006.
- WHO HANDBOOK ON INDOOR RADON A PUBLIC HEALTH PERSPECTIVE. World Health Organization 2009. ISBN: 978-92-4-154767-3.

Yuchun S., Yingfeng X. (1994). Variability of soil radon attributed to meteorologic causes and its application.

Zmazek B., Zivcic M., Todorovski L., Dzeroski S., Vaupotic J., Kobal I. (2005). Radon in soil gas: How to identify anomalies caused by earthquakes.

Influence of environmental factor on radon emanation coefficient

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Abstract

Radon gas is generated from radium in soil and rocks. Radon emanation coefficient is regarded as an important factor affecting the generation of radon from soil and rocks and it depends on various environmental factors such as soil particle size, temperature and moisture saturation. In this study, radon emanation coefficient of Japanese soil samples is measured by accumulation method. We have examined experimentally the dependency of radon emanation coefficient on different soil particle size (from $< 106 \mu\text{m}$ to $> 1000 \mu\text{m}$), temperature (5, 25, 40, 55 °C) and moisture saturation (from 0 to 0.9).

Evaluation of radon risk using GIS (Geographic Information System) techniques in the Central Hungarian Region

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Abstract

A new technique of Wattananikorn et al. (2008) for radon potential mapping based on airborne uranium concentration maps was tested in the Central Hungarian Region. Airborne uranium maps (Tyhomirov, 1965-66 digitalized by Boros, 2009) covering eastern parts of the area were processed and analyzed by standard GIS tools. Soil gas radon concentrations were estimated (Wattananikorn et al., 2008) as well as prospective indoor risk values (Kemski et al., 2001). After the spatial analysis of these data with population maps, the results show different radon risk categories at all settlements (Kohli et al., 1997). GIS analyses were validated by in situ soil gas radon measurements and laboratory analyses of soil samples, as well as radon concentration data in indoor areas. Enough good results were gained proving that tested radon potential estimation method is applicable mainly for selecting settlements needed extended research.

Introduction and objective

Radon (²²²Rn) is responsible for 48% of the total annual effective dose from natural sources of a man living in average environment (UNSCEAR, 2000). The inhalation of this radioactive isotope and its short lived daughters may cause lung cancer potentially (e.g. Bochicchio, 2008 and references therein).

Generally, mapping of radon risk is based on in-situ soil gas concentration (e.g. Gates & Gundersen, 1992; Kemski et al., 2001) or indoor concentration measurements (e.g. Minda et al., 2009). Both methods are expensive and time-consuming to carry out on extended areas but a crude estimation method for radon risk also exists.

Our main aim was modifying and testing this cost-effective and concise procedure which was published recently (Wattananikorn et al., 2008). Other objective was the

classification of all settlements into categories based on the results of tested radon risk mapping/estimation method for gaining which settlements need more extended research.

The studied area

Central Hungarian Region is the most populated area and cultural, educational, financial and political centre of Hungary (Fig. 1A). Hence the idea to predict potentially health deteriorating impacts in the area is widely acceptable. An airborne uranium concentration map (Tyhomirov, 1965-66) of the northern part of the region is available (Fig. 1B) from the middle of the 60's. The digitalized version of this map (Boros, 2009) means the base of the present work.

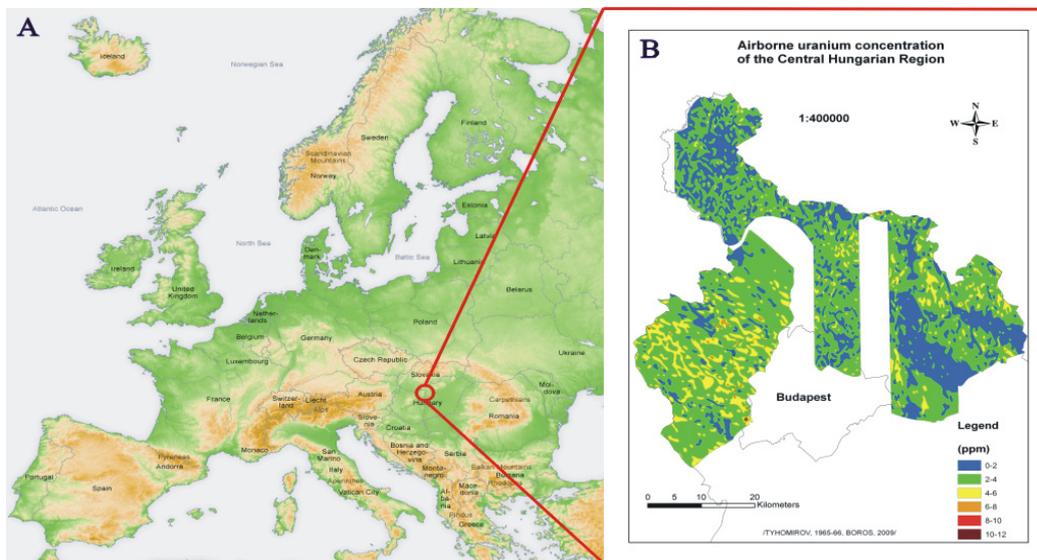


Fig. 1A. Location of Central Hungarian Region in Europe and 1B. Airborne uranium concentration map on the northern part (TYHOMIROV, 1965-66 digitalized by BOROS, 2009).

Methods

Basis of present work is GIS (Geographic Information System) analysis of different databases. The applied software is the ArcGIS 9.3, which can be used for making vector-based maps with geostatistic correction. It also shows the correlation between evaluated and measured databases originated from the following methods (1-4. methods). The complex data processing makes possible testing the estimation of soil gas radon concentration as well as indoor values.

Evaluation of data

1. Soil gas radon concentration was evaluated based on the airborne uranium concentration map of the studied area (Fig. 1B) (Tyhomirov, 1965-66 digitalized by Boros, 2009) and Eq. 1. which was published by Wattananikorn et al. (2008).

$$Eq. 1.: N = 1.92 u,$$

where N is the predicted soil radon concentration in kBq/m^3 and u is the airborne equivalent uranium in ppm. It is based on measurements in Thailand at 14 areas of 7 test sites of three basins which are covered mainly by Quaternary alluvial and terrace deposits. Correlation between soil radon concentration and airborne equivalent uranium was determined considering the standard deviation of measured values. Hence the upper limit of soil radon concentration can be estimated by *Eq. 1.* We assumed that this equation with little changes can be valid in Central Hungarian Region too, although differences in rock type occur. Since differences in permeability values were neglected only a crude estimation can be presented.

2. From the calculated soil gas radon concentration distribution prospective indoor risk values were estimated using *Eq. 2.* (Kemski et al., 2001; Wattananikorn et al., 2008).

$$\text{Eq. 2.: Indoor radon} = 1.91 \text{ Soil radon} - 3.3,$$

where indoor radon is in Bq/m^3 and soil radon is in kBq/m^3 . Its basis is studying of relationship between maximum ground floor indoor radon and soil radon concentrations in Germany. However, construction features and the age of houses should be also taken into account in further work.

After a spatial and geostatistical analysis of estimated indoor data the results show different categories at all settlements on the settlement map (after Kohli et al., 1997). Most hazardous settlements and distribution type can be studied averaging the values in polygons of settlements' areas (from AGROTOPO digital database) and weighting them by their size. More details on 1. and 2. methods can be found in the references.

Method testing

3. Data on constructed soil gas radon concentration map was compared by data at 28 sites of two types of direct measurements in interest of testing the estimation method based on airborne uranium concentration data. These two types of methods signed by a and b can be found below.

a, In-situ soil gas radon concentration measurements were done using RAD7 radon detector and soil probe at an average depth of 75 cm (according to Gates & Gundersen, 1992).

b, Soil gas radon concentrations were evaluated based on radon mass exhalation rate (similar like Sakoda, 2008) and density, porosity measurements in laboratory by using *Eq. 3.* (Szabó, K. Zs., 2009).

$$\text{Eq. 3.: Soil radon} = 100 E_{\text{mass}} \rho / 1000 p \lambda,$$

where soil radon is in kBq/m^3 , E_{mass} is the radon mass exhalation rate in Bq/kg/s , ρ is the density of soil sample in kg/m^3 , p is the porosity in %, λ is the decay constant of radon in $1/\text{s}$. A parallel work is supporting the possibility of using this method for soil gas radon concentration estimations (Szabó, Zs., 2009).

4. Indoor radon concentration data were also tested by a few monthly long measurements with Radosys track etched detectors.

Results and discussion

Soil gas radon concentration

Estimated soil gas radon concentration map (1. method) and values of test measurements (3a. and 3b. methods) are presented on Fig. 2.

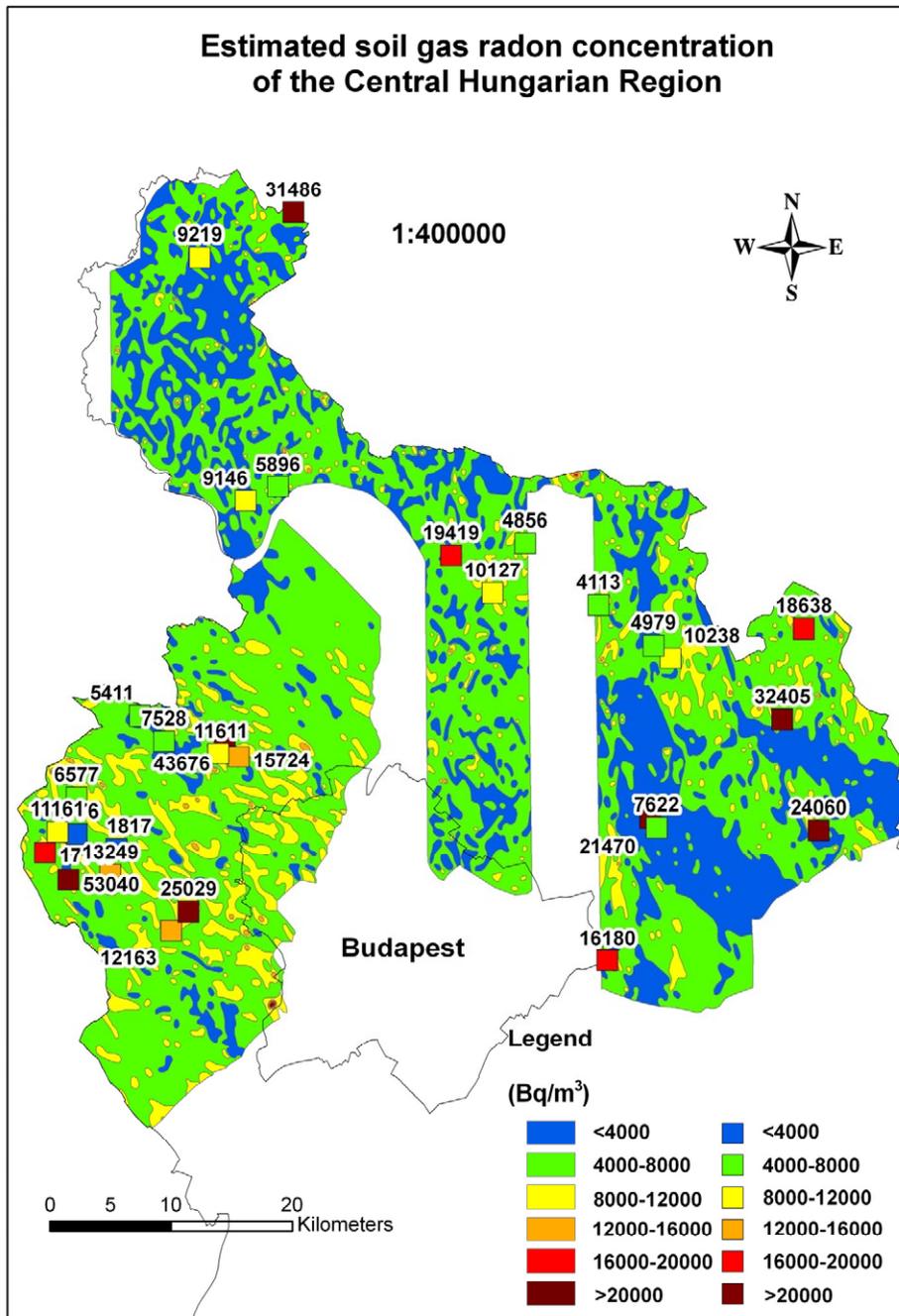


Fig. 2. Constructed soil gas radon concentration map showing the testing points.

The map (Fig. 2.) indicates that the high risk areas are mainly on the limestone and dolomite hills on west side of the region. These areas having higher estimated values of radon concentration should be first explored direct measurements to obtain answer whether they have high risk due to radon. However results of direct measurements show that other areas also can have higher values (e.g. Pesti Plane, Gödöllői hills).

Correlation between estimated and measured values is 0.6 - 0.7 indicating that calculation based on airborne uranium concentration ignores a lot of affecting parameters but can be applied as a crude estimation. However, note that local anomalies cannot be determined.

These results also suggest that a new equation (*Eq. 4.*) should be used instead of *Eq. 1.* in this area (different geological relation) because of the occurred underestimation presumably originated from the differences between permeability values.

$$\text{Eq. 4.: } N = 2.12 u,$$

where N is the predicted soil radon concentration in kBq/m^3 and u is airborne equivalent uranium in ppm. Using this equation most calculated soil gas radon concentration values will be closer to the measured values giving the best estimation.

Indoor radon concentration

Estimated indoor radon risks were calculated for each settlement (2. method). Results are summarized in a histogram on Fig. 3. Number of columns was selected as the $\ln[\text{number of settlements } (n=95)]$.

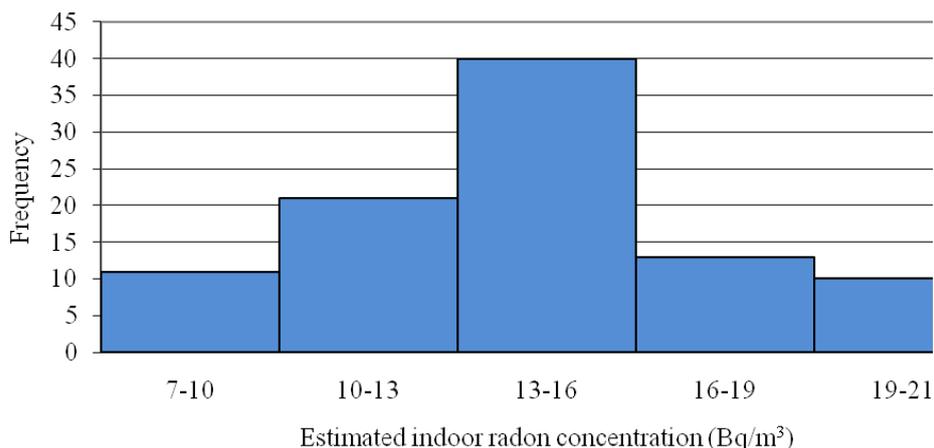


Fig. 3. Histogram of evaluated indoor radon concentrations in dwellings averaged by settlements (n=95).

Values of estimated indoor radon concentration are very low. The procedure has a probability to underestimate indoor radon here as indoor test measurements also indicate (4. method). More direct measurements are necessary to build up a new equation instead of *Eq. 2.*

Results originated from estimation indicate a normal distribution (Fig. 3.). This mainly refers to that average airborne uranium concentrations below settlements have a normal distribution and there are not significant average values for one settlement in the Central Hungarian Region. It is again emphasized that it is necessary to determine the relationship between soil gas and indoor radon concentration at this area too, hence further measurements are needed.

Conclusions

1. A cost-effective method for radon risk estimation based on airborne uranium maps was modified and tested with direct measurements in the Central Hungarian Region.
2. Based on the evaluation high risk areas are mainly on the west side of the region.
3. Since local anomalies cannot be predicted, a correlation of 0.6-0.7 between estimated and measured soil gas radon values is quite reasonable. The calculation based on airborne uranium concentration ignores a lot of affecting parameters but can be applied as a crude estimation. A new equation (*Eq. 4.*) was also built up for this area.
4. Based on the constructed soil gas radon concentration map, it is possible to select settlements for extended research.
5. Values of estimated indoor radon concentrations are very low. The procedure has a probability to underestimate indoor radon.
6. Average airborne uranium concentrations below settlements have a normal distribution.
7. Further testing and corrections of the procedure are needed.
8. GIS techniques are available and well applicable in radon risk estimation.

References

- Bohicchio, F. The radon issue: Considerations on regulatory approaches and exposure evaluations on the basis of recent epidemiological results, *Applied Radiation and Isotopes* 2008; 66: 1561-1566.
- Boros, Á. Evaluation of Radon Risk Factors by using Geographic Information System (GIS) techniques in the area of Central Hungarian Region (in Hungarian), MSc Thesis, Eötvös University, Budapest, Hungary 2009; 87.
- Gates, A. E., Gundersen, L. C. S. Sensitivity of soil radon to geology and the distribution of radon and uranium in the Hylas zone area, Virginia, *Geological Society of America Special Paper* 1992; 271: 17-27.
- Kemski, J., Siehl, A., Stegemann, R., Valdivia-Manchego, M. Mapping the geogenic radon potential in Germany, *Science of the Total Environment* 2001; 272: 217-230.
- Kohli, S., Sahlén, K., Löfman, O., Sivertun, Å, Foldevi, M., Trelle, E., Wigertz, O. Individuals living in areas with high background radon: a GIS method to identify populations at risk, *Computer Methods and Programs in Biomedicine* 1997; 53: 105-112.
- Minda, M., Tóth, Gy., Horváth, I., Barnet, I., Hámori, K., Tóth, E. Indoor radon mapping and its relation to geology in Hungary, *Environmental Geology* 2009; 57: 601–609.

Sakoda, A., Hanamoto, K., Ishimori, Y., Nagamatsu, T., Yamaoka, K. Radioactivity and radon emanation fraction of the granites sampled at Misasa and Badgastein, Applied Radiation and Isotopes 2008; 66(5): 648-652.

Szabó, K. Zs. Study of radon activity in soils from Pest County (in Hungarian), MSc Thesis, Eötvös University, Budapest, Hungary 2009; 67.

Szabó, Zs. Study of radon and thoron distribution in the NE Zsámbék basin (in Hungarian), MSc Thesis, Eötvös University, Budapest, Hungary 2009; 57.

Tyhomirov, A. Airborne radiometric maps of Hungary., ELGI 1965-66

UNSCEAR Report, Annex B, Exposures from natural radiation sources, United Nations, New York 2000; 74.

Wattananikorn, K., Emharuthai, S., Wanaphongse, P. A feasibility study of geogenic indoor radon mapping from airborne radiometric survey in northern Thailand, Radiation Measurements 2008; 43: 85-90.

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Deposition and clearance of inhaled radon progenies in the central airways

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Abstract

Most of lung cancers of former uranium miners developed in the central airways. Current computational fluid dynamics calculations indicate high local deposition densities in this region. However, cellular burdens of radon progenies deposited in the deeper regions of the lung and cleared up by the mucociliary escalator may also contribute to the health effects in the large central airways. The surface of airway generations increases with airway generation number, thus, it looks a reasonable supposition that the dose of the deeply deposited and up clearing radon progenies may significantly contribute to the total dose in the large airways.

In this work, the deposition distribution of inhaled radon progenies in the respiratory system was computed by the newest version of the stochastic lung model. A clearance model was developed to simulate the up clearing fractions of attached and unattached radon progenies. The stochastic lung model was applied also to compute the surface of the airways. Finally, the surface activity densities of the primarily deposited and upcleared fractions have been calculated and compared at airway generation level for different breathing patterns.

The main input data of the clearance model are the followings: deposition data, velocity of the mucus in each airway generation, surface area of the airways and the half lives of radon progenies.

Based on the results, the radiation burden per unit surface area in the central airways is the highest in the first few airway generations mostly due to the deeply deposited and up cleared radon progenies. Comparing the amounts of the primary deposited and the up cleared radon progenies in the large airways one can conclude that the burden of the up cleared fraction is higher than that of the primary deposition. The results suggest that a possible reason for the preferential occurrence of radon induced lung cancer in the central airways may be, besides the primary deposition, the contribution of the up clearing radon progenies.

Introduction

Large scale histopathological studies have demonstrated that radon induced lung carcinomas of former uranium miners occurred predominantly in the large bronchi, especially in airway generations 3-5. Computational fluid dynamics calculations yielded high primary deposition density values in this region of the thoracic airways. At the same time, the dose contribution of the deeply deposited and up clearing radon progenies in these large bronchial airways is usually neglected. By the increase of generation number the total surface of airway generations highly increases and the deposition efficiency does not decrease remarkably with generation number, thus the dose contribution of the up clearing radon progenies may be significant in the large airways.

The objective of this study is to compute the generation number specific primarily deposited and the up cleared particle fractions to establish their relative contribution to the resultant surface activity in the large bronchi.

Methods

In the present work, the primary deposition distributions of the inhaled radon progenies were computed in the whole respiratory system by the newest version of stochastic lung deposition model (SLM) originally developed by [Koblinger and Hofmann \(1990\)](#). Particle deposition simulations were performed at four different breathing conditions characteristic of sleeping, sitting, light exercise and heavy exercise physical activities. Functional residual capacity, tidal volume, and breathing cycle times characteristic of an adult man during the four types of activities were derived from [ICRP66 \(1994\)](#) publication.

A new bronchial clearance model has been elaborated to simulate the up clearing fractions of particles deposited in the deeper airway generations. Particles trapped by the high viscosity mucus were assumed to move together with the mucus layer. Mucus velocity values were derived from the available literature. Based on the work of [Chopra \(1979\)](#), the tracheal mucus velocity was supposed to be 1.5 cm/min. Mucus velocity in each generation was 2/3 of the mucus velocity in the preceding higher order airway generation. Based on the ICRP66 data, the halftimes of the transport of the deposited attached radon progenies from bronchial airways to blood is 10 hours. This mechanism was also built into the model.

Figure 1 presents the velocity of the mucus as a function of generation number. In this study only the deposition of ^{214}Pb and the clearance of ^{214}Pb and ^{214}Bi isotopes were simulated, where ^{214}Bi is the decay product of the primarily deposited ^{214}Pb isotope. The applied particle diameter is considered to be 200 nm which is the most frequent aerodynamic diameter in the number distribution of the environment aerosols ([Haninger, 1997](#)). The unattached fraction of ^{214}Pb is negligible ([Marsh et al. 2008](#)). Regarding attached radon progenies the number distribution is the relevant because usually zero or one radon progeny attaches to an aerosol particle. The ^{214}Pb and ^{214}Bi radioisotopes decay and result in ^{214}Po , which is alpha active with a very short half-life. Finally, the ratio of the up cleared and primarily deposited activity densities has been calculated in each airway generation at the above mentioned four breathing patterns. The main input data of the clearance model are the deposition data, the velocity-distribution of mucus, the airway lengths and the half-lives of radon progenies. The

average lengths and the surfaces of the bronchial airways (Table 1) were taken from the newest version of stochastic lung model (Balásházy et al. 2009).

Table 1. The average lengths and total surface areas of the airways in airway generations 1-20 based on the newest version of the stochastic lung model.

Generation number	Length (cm)	Surface (cm ²)	Generation number	Length (cm)	Surface (cm ²)
1		68.88	11		277.6
2		22.35	12		358.5
3		21.21	13		459.3
4		28.85	14		581.1
5		43.36	15		726.8
6		56.4	16		931.5
7		80.28	17		1144
8		117.5	18		1301
9		159.2	19		1408
10		215.7	20		1446

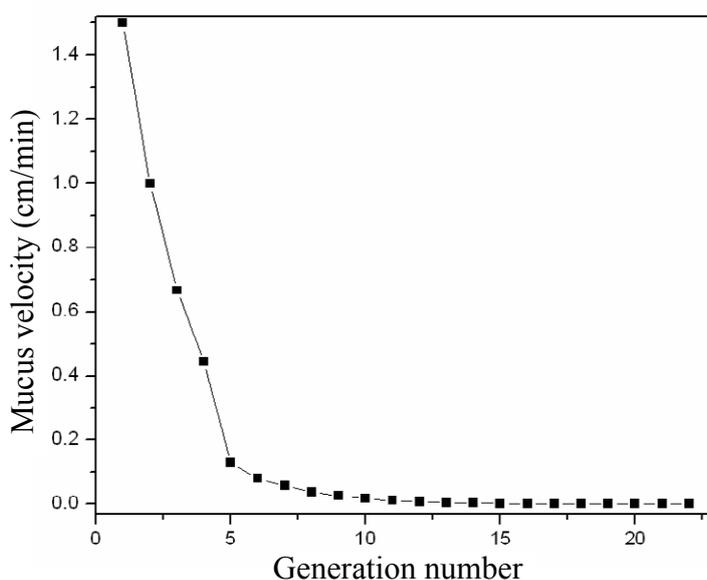


Fig. 1. Mucus velocity as a function of airway generation number.

Results

Figures 2–5 summarise the results of the surface decay density distribution computations. The upper panels refer to the primary deposition, while the lower ones depict the decay density distribution of the up clearing ²¹⁴Pb and ²¹⁴Bi isotopes at sleeping, sitting, light exercise and heavy exercise breathing conditions, respectively. The number of selected inhaled particles was always 10⁵ at the computation of the deposition fraction distributions.

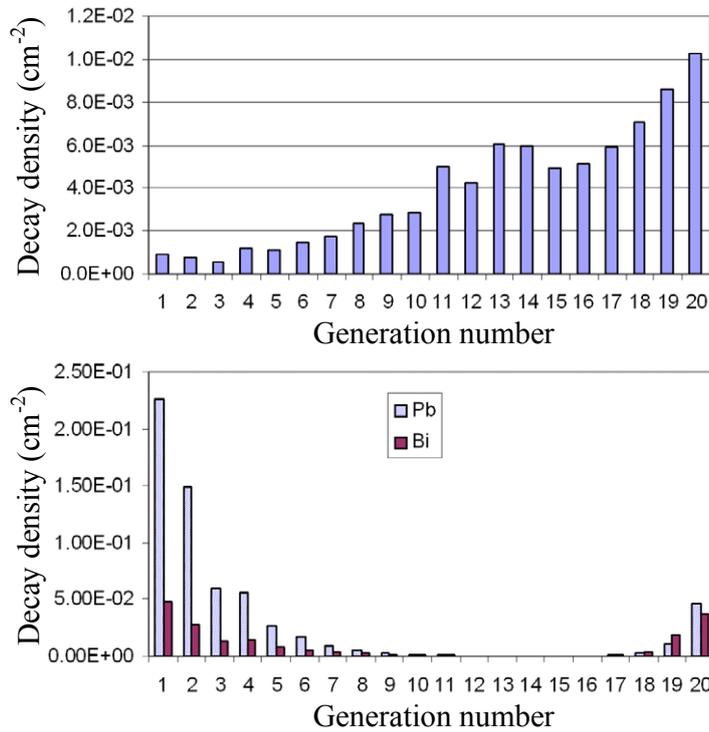


Fig. 2. Decay densities as a function of airway generation number in case of the primarily deposited (upper panel) and up cleared (bottom panel) radon progenies during sleeping.

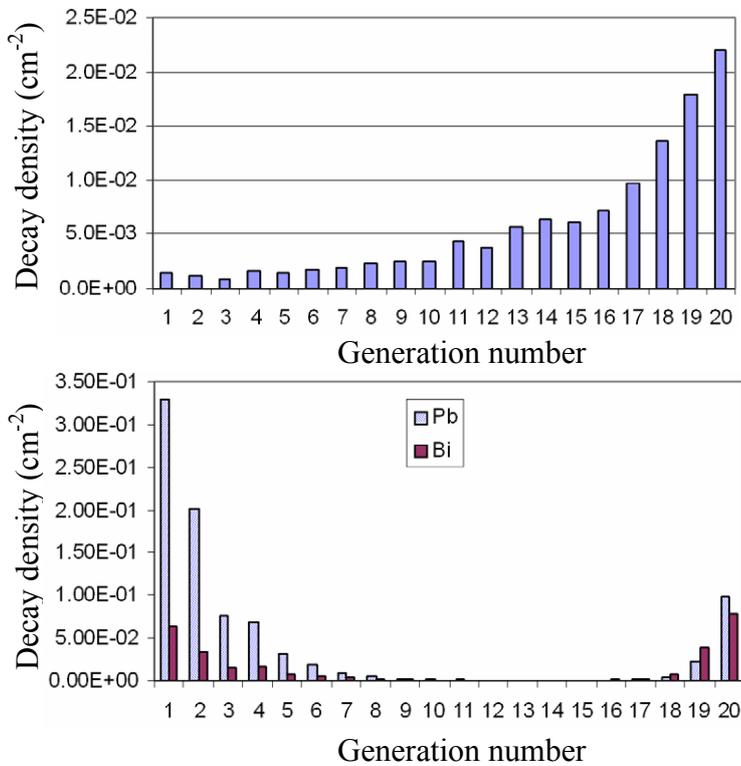


Fig. 3. Decay densities as a function of airway generation number in case of the primarily deposited (upper panel) and up cleared (bottom panel) radon progenies during sitting.

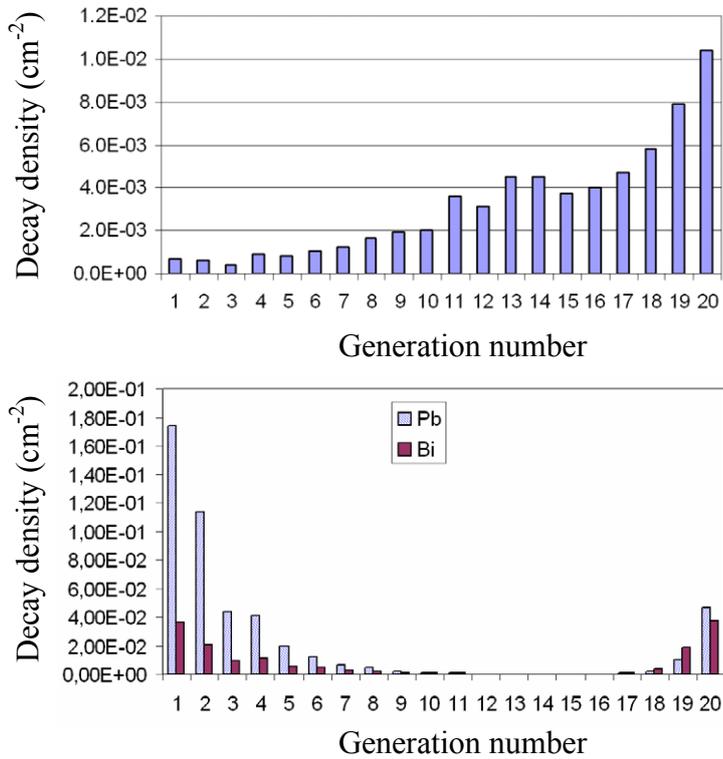


Fig. 4. Decay densities as a function of airway generation number in case of primarily deposited (upper panel) and up cleared (bottom panel) radon progenies during light physical exercise.

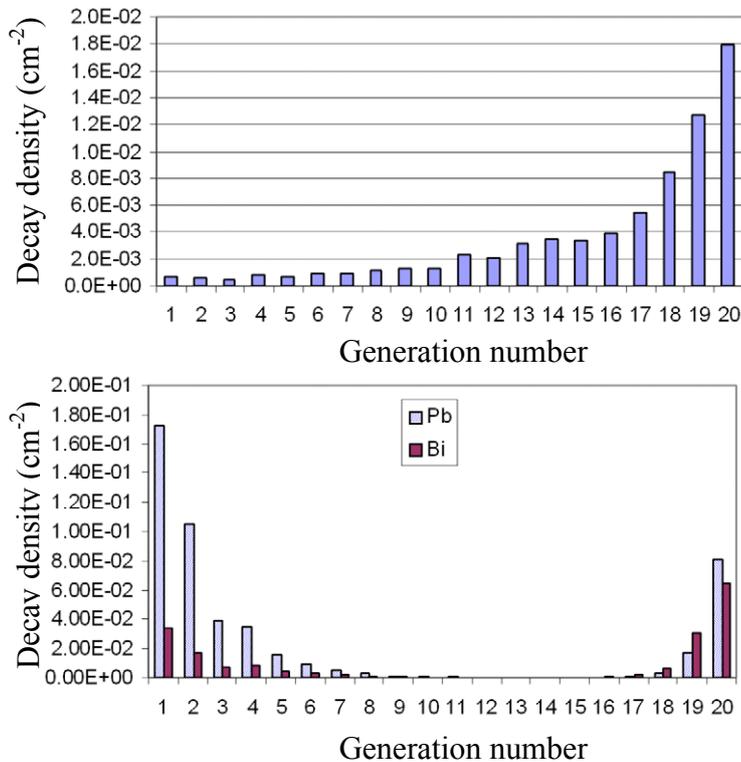


Fig. 5. Decay densities as a function of airway generation number in case of primarily deposited (upper panel) and up cleared (bottom panel) radon progenies during heavy physical exercise.

The figures demonstrate that the decay density due to the primary deposition increases with the increase of the generation number for each type of physical activity.

The decay density originating from the up cleared ^{214}Pb and ^{214}Bi isotopes is significant in the first few generations and slightly in the peripheral regions. This tendency holds for all the studied physical activities. The cumulated decay density, provided by the primary deposition and the up clearing fraction, is the highest in the first few generations, that is, in the large bronchi where most of the radon induced preneoplastic and neoplastic lesions were found. Comparing the relative contributions of the primarily deposited and up cleared isotopes it can be stated that in the most exposed region (large bronchi) the up cleared fraction is determinant. This aspect is usually not considered in current computational dosimetry and risk modelling. Present computations may provide useful input for such models and thus contribute to a quantitatively better estimation of radiation exposures and the related health consequences. Since only about 1 % of the total number of radon progenies is not attached to the aerosols in the mine environment and 5-6 % in homes (BEIR VI, 1999), in the current approach the unattached fraction has been neglected.

Conclusions

Based on the present results, in the central airways, the radiation burden of the deeply deposited and up clearing radon progenies can be up to two orders of magnitude higher than the burden of the primarily deposited fraction in this airways. Physical activity, although affects the deposition and the related clearance fractions, does not seem to influence the above tendency. The results demonstrate that one of the reasons of the site specific radon induced lung cancer may be the dose contributions of the deeply deposited and up clearing radon progenies.

In our next publication we will compute the deposition and alpha burdens of all the short lived radon progenies (unattached: ^{218}Po ; attached: ^{218}Po , ^{214}Pb , ^{214}Bi).

Acknowledgements

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References

- Balásházy I, Horváth A, Sárkány Z, Farkas Á, Hofmann W. Simulation and minimisation of airway deposition of airborne bacteria. *Inhalation Toxicology* 2009; 21: 1021-1029.
- BEIR VI Report: Health effects of exposure to radon. Washington D.C.: National Academy Press 1999.
- Chopra S K. Measurement of tracheal mucociliary transport velocity in human smokers versus nonsmokers. *American Review of Respiratory Diseases* 1979; 119: 205.
- Haninger T. Size distributions of radon progeny and their influence on lung dose. *Radon and Thoron in the Human Environment, Proceedings of the 7th Tohwa University International Symposium*, Editors: Katase, A. and Shima, M., Publisher: World Scientific Singapore, New Jersey, London, Hong Kong 1997.
- ICRP66 Human Respiratory Tract Model for Radiological Protection, Publication 66, *Annals of ICRP London, UK, Pergamon Press* 1994.

Koblinger L, Hofmann W. Monte Carlo Modeling of aerosol deposition in human lungs. Part I: Simulation of particle transport in a stochastic lung structure. *Journal of Aerosol Science* 1990; 32: 817-832.

Marsh J.W., Bessa Y, Birchall A, Blanchardon E, Hofmann W, Nosske D, Tomasek L. Dosimetric models used in the Lapha-Risk project to quantify exposure of uranium miners to radon gas and its progeny. *Radiation Protection Dosimetry* 2008; 130, 1, 101-106.

Reducing the risk to military personnel from radon gas

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Abstract

Radon is attributable to approximately 1500 deaths a year in the UK alone. It is a naturally occurring radioactive gas that derives from uranium found in rocks and soils, and is therefore a natural environmental hazard. Employers have a legal obligation to assess the radon health risk for all their employees. Recent improvements in the UK radon data set and developing work on the risk of radon gas has made this a priority issue for the UK Ministry of Defence (MOD). The Defence Science and Technology Laboratory (Dstl) were given the challenging task of developing a strategy to address this issue and to implement a monitoring protocol to cover the whole of the MOD estate (thousands of locations) throughout the UK and overseas. The development of this involved:

- Working with and/or obtaining information from the Health Protection Agency and the Health and Safety Executive.
- Utilising the most up-to-date guidance from the Building Research Establishment (BRE) and academia to understand the most appropriate and effective remediation techniques.

The radon monitoring program is now well under way covering thousands of workplaces, with the aim of protecting the health of military personnel now and in to the future. A number of examples are given, including the unusual example of 'working' in caves, where radon levels may be extremely high. A three year research project has been undertaken assessing the radon doses to military personnel in caves in the North Pennines currently used for adventure training activities. The findings from this work not only aid in protecting the personnel directly involved, but also have the potential to inform risks in future caving activities. The data set collected will be invaluable for future theatres of operation and also potential litigation work. Most importantly, the remediation work undertaken will reduce the health risk to MOD employees across the UK and overseas.

An assessment of radon exposure to CR-39 alpha track detectors during postal transit in Ireland

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Abstract

In many countries, including Ireland, radon measurements are carried out by sending radon detectors to and from customers through the standard postal system. In Ireland, radon detectors are left in place for at least 3 months before the customer returns them by post. The detectors used are CR-39 alpha track detectors and they are sent in standard A5 envelopes with no radon-proof membranes or seals. To date, this has been done on the premiss that the level of radon detected during postal transit was insignificant compared with the much longer period in situ in the customers' premises. This study investigates the contribution made by levels of radon in the Irish postal system to detectors in transit. Thirty one volunteers, located throughout the country were identified for participation in the project. Practically every county in Ireland was represented. Two CR-39 detectors were sent to each volunteer in standard issue envelopes. On receipt of the envelopes, the volunteers immediately posted them back using a similar envelope. Detectors posted close to or during weekends are likely to be in the postal system the longest. For this reason the Radiological Protection Institute of Ireland always issues detectors before Friday. However, there is no control over when customers return them. Detectors were posted to volunteers on a Thursday afternoon to ensure the transit time coincided with at least one weekend. Results from this study conclude that there is no significant radon exposure to Cr-39 alpha track detectors during normal postal transit in Ireland.

Introduction

Radon-222 commonly referred to as radon, is a naturally occurring radioactive gas, formed by the radioactive decay of radium-226, a component of the uranium-238 decay series. Uranium is present in soils and rock. Radon is the largest contributor to the annual radiation dose received by the Irish public, accounting for approximately 60% of all radiation exposure in Ireland (Colgan *et al.*, 2008). Radon has been classified as a class 1 carcinogen by the International Agency for Research on Cancer (IARC 1988, 2001). Inhaling radon and its progeny can lead to lung cancer. It is estimated that in Ireland 150-200 people a year die from radon induced lung cancer (RPII & NCRI, 2005).

Ireland's relatively high radon concentrations were identified during the National Radon Survey (NRS) which was carried out between 1992 and 1999 (Fennell *et al.*, 2002). An average indoor radon concentration of 89 Bq/m³ was calculated for Ireland, based on measurements made in 11,319 randomly selected homes over a 12 month period. A recent survey by the World Health Organisation (WHO) found this national average to be the eighth highest in the world (WHO, 2009).

Current radon measurement practice in the Radiological Protection Institute of Ireland (RPII) is to use CR-39 alpha track detectors over an exposure period of at least three months in conjunction with the application of a seasonal correction factor (Colgan *et al.*, 2008; RPII, 2008). Normal practice is to send two detectors with each measurement pack; one to be placed in a bedroom and one in a living area (RPII, 2008). These radon detectors are sent to and received from customers through the standard postal system. They are sent in standard A5 envelopes with no radon-proof membranes or seals.

The RPII has made a recommendation that radon measurements, and where necessary, remediation at the time of sale and/or purchase of buildings is an appropriate mechanism to reduce the collective dose from radon in Ireland. However, it recognises that it may not always be possible to complete a three month measurement during the conveyancing process. Hence the RPII has undertaken research on the use of shorter screening measurements for these circumstances (Rochford *et al.*, IRPA 2010). With a shorter measurement period a contribution from radon in the postal system could contribute to and influence the final result.

Thus, this research was undertaken to investigate the contribution made by levels of radon in the postal system to detectors in transit.

Material and methods

Thirty-one volunteers, located throughout the country participated in the project. Twenty three of the twenty six counties in Ireland were represented.

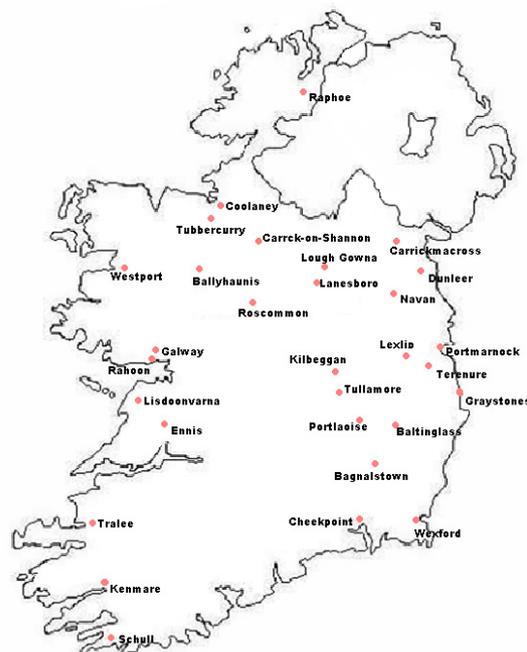


Fig. 1. Location of the volunteers for this study.

The detectors were issued and posted out in accordance with normal procedures. However, on this occasion on receipt of the detectors the volunteer was requested to return them immediately to RPII.

When posting detectors to its customers the RPII avoids weekend and public holidays so as to minimise the time the detectors are in transit. However, there is no control over when customers post back the detectors, which could include weekends. To simulate this, detectors were posted from RPII to volunteers on a Thursday afternoon to ensure maximum time in the postal system.

When the detectors were received at RPII they were subject to the normal practice and procedures in use in the laboratory.

The Radon Measurement Service is accredited by the Irish National Accreditation Board (INAB) to the International Organization for Standardisation and International Electrotechnical Commission (2005) standard ISO/IEC 17025. The scope of accreditation covers radon concentration measurement in air using passive CR-39 alpha track etch detectors for an exposure time of three to twelve months and a minimum detectable concentration of 10 Bq/m^3 .

Quality control procedures are carried out on all new CR-39 detectors received in the laboratory: 10% of the unexposed detectors are etched. The subsequent counting determines the background track density (tracks/cm^2). If the average background track density of detectors from a sheet (approximately 100 CR-39 detectors) is less than 50 tracks/cm^2 the sheet is released for use and if this is greater than 50 tracks/cm^2 the sheet is discarded. The average track density for a number of detector sheets accepted for use in the RPII is presented in figure 2. In addition, 5% of the new detectors are exposed in a secondary standard radon chamber. The radon source maintains a radon concentration of 3000 Bq m^{-3} . This is continuously monitored by an ATMOS 12dpx, which is calibrated annually by the manufacturer using a working standard that is traceable to the National Institute of Standards and Technology (NIST), USA.

Detectors are chemically etched in 6.25 M sodium hydroxide at 75°C for 8 hours, resulting in uniform tracks ranging from 240 to 340 mm^2 . Following the chemical etch, the detectors are measured using the laboratory's Image Analysis System (Quantimet).

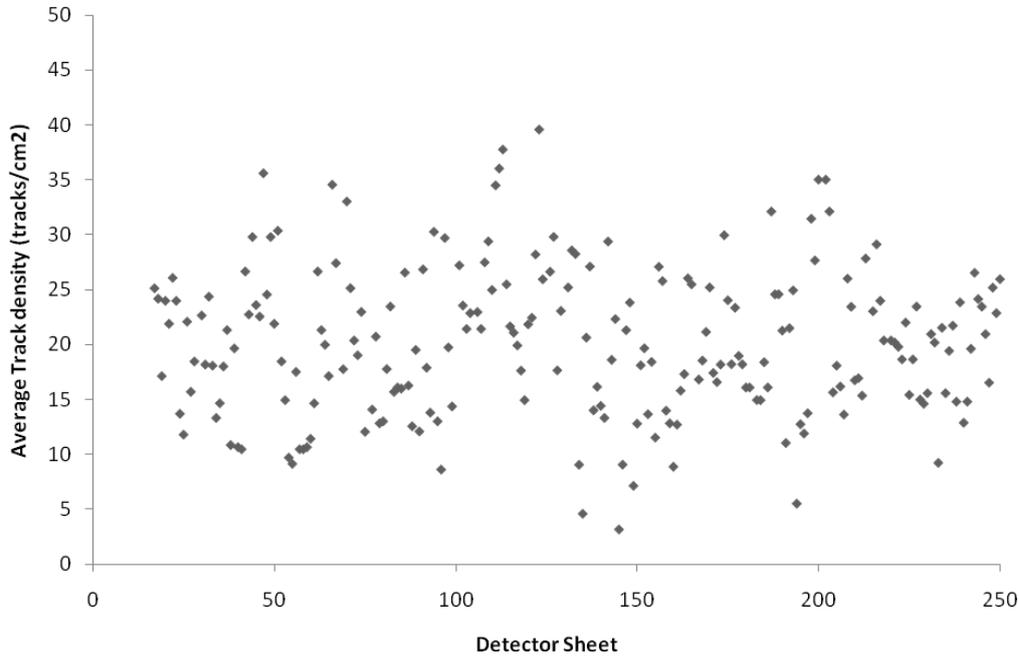


Fig. 2. Average track density of many detectors used by RPII.

Results

It is evident from the data presented in figure 2 that there is considerable variability in background tracks among detectors. The average track density in the set of sheets illustrated in this figure range from 3 to 40 with an average of 21 tracks/cm².

The average track density for the two detectors received from each volunteer was calculated and is presented in figure 3.

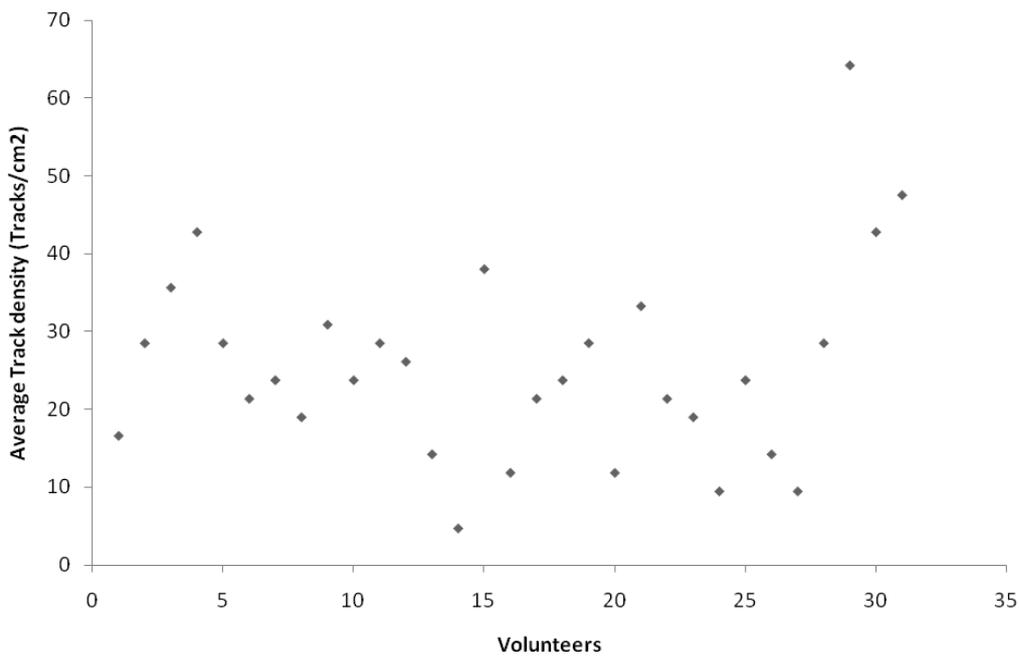


Fig. 3. Average track density of the two detectors.

With the exception of one set of detectors, the average track density for the detectors returned by the volunteers is below 50 tracks/cm², the upper limit for background track density at RPII. The range of values is between 5 and 64 tracks/cm².

The highest average track density, 64 tracks/cm², is from a volunteer address in a county in the west of Ireland. These detectors were in the postal system for six days. This, however, was not the longest transit time.

Two other addresses from this county were also included in this study. One of these recorded the lowest average track density at 5 tracks/cm². A similar transit time was recorded for the third detector set from this county which recorded a track density of 29 tracks/cm².

The shortest time between detector dispatch and return to RPII for detectors in this study was four days and the longest was seven days. The average time spent in the postal system being five days.

Comparing figures 2 and 3 it can be concluded that there is no significant difference between the detector background track density accepted at RPII and the track density on detectors after a transit time of four to seven days in the postal system.

Conclusions

This study was undertaken to investigate the contribution made by levels of radon in the Irish postal system to detectors in transit.

The result of this study involving thirty one volunteer addresses across the country demonstrates that there is insignificant radon exposure to Cr-39 alpha track detectors during normal postal transit in Ireland.

References

- Colgan P. A, Organo C, Hone C. and Fenton D., Radiation doses received by the Irish population. Radiological Protection Institute of Ireland. 2001
- Fennell S. G., Mackin G. M., Madden J. S., McGarry A. T., Duffy J. T., O'Colmain M., Colgan P. A, and Pollard D. Radon in dwellings, the Irish national radon survey. Radiological Protection Institute of Ireland. 2002
- International Agency for Research on Cancer: Man-made mineral fibres and radon. Monographs on the evaluation of carcinogenic risks to humans, 1988. Vol. 43.
- International Agency for Research on Cancer: monographs on the evaluation of carcinogenic risks to humans. 2001 Vol. 43.
- Irish National Accreditation Board: Directory of accredited organisations, 2008.
- Rochford H. and Fenton D., A comparison of one and three month radon measurements. IRPA 2010.
- Radiological Protection Institute of Ireland., measurement protocol for the determination of the annual average radon gas concentration in domestic dwellings. 2008.
- RPII and National Cancer Registry of Ireland: health risks due to exposure to radon in homes in Ireland- the implications of recently published data Dublin 2005 Radiological Protection Institute of Ireland.
- World Health Organisation: Handbook on Indoor Radon: A Public Health Perspective. WHO, Geneva 2009.

Radon areal distribution in Campania region (Italy) inferred from a geostatistic analysis

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Abstract

The territory of Campania region is one the most rich of Radon of Italy and presents prone areas of indoor radon because of the characteristics of the subsoil and of the building materials of local origin which is prevalently volcanic. The national survey on indoor radon classifies this region with a mean concentration higher of 30% than national mean value, but other regional surveys on selected building underline the presence of numerous sites where indoor radon levels are very high. In last fifteen years, our work-group has investigated radon levels within dwellings, schools and workplaces. The principal aim of the present work is to summarize the results of about 700 measurements by using a geostatistic approach which has allowed the realization of a Radon distribution map of the region. Each result is the mean value of an entire year and has been performed by the SSNTDs with LR115 films. Data have been normalized respect to the building material and floor location and, then, located on the map. The lognormal distribution of data has allowed the application of geostatistic techniques using spatial interpolators that not require an uniform distribution of data. The analysis has been performed by the Arcview software which allow the selection of the best variogram and furnishes also the map of the variance of results. Different maps have been extracted from different normalization of data. The maps well describe the real situation according to the experimental results.

Radon mapping strategy in the Republic of Moldova

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Abstract

Radon is a chemically inert radioactive gas. It is formed by the natural radioactive decay of uranium in rock, soil, and water. Naturally existing, low levels of uranium occur widely in Earth's crust. Radon is responsible for the majority of the mean public exposure to ionizing radiations. Constant exposure to high concentration of radon gas may cause lung cancer. Radon gas from natural sources can accumulate in buildings, especially in confined areas such as basements. The radon concentrations in a building are dependent on the concentration of radium in subjacent ground and surrounding soil, the geological bed rock, the radioactivity of building materials, the ventilation conditions, the meteorological conditions and human activities, also. The results of radon concentrations monitoring in the air samples which have been collected in different buildings placed on the territory of the Republic of Moldova during the period of time since 1991 till 2008 years are given in the paper. Investigations have related, that the ^{222}Rn concentrations (92,0...179,1 Bq/m³) in most cases do not exceed a maximum permissible level. The establishment of ^{222}Rn concentrations in the air samples collected from Cricova storage of wine undergrounds, Chisinau underground galleries, and Milestii Mici, some mines from Orhei, traced out the values of concentrations (200...1800 Bq/m³) which exceeded the maximum permissible level. Only 2,1% among all investigated houses in territory of Republic of Moldova exceeds the level of 200/Bq/m³ for radon concentration. The results require the need of radon concentrations monitoring carrying out in dynamics, with the subsequent elaboration of the radon concentrations maps [1].

Reference

Bahnarel I., CoreÅŃchi L., Thomas Streil et. al. Evaluation of exposure risk to radon in the conditions of Republic of Moldova // Scientific Journal of the Academy of sciencis of Moldova Republic, 2007, nr. 4, p. 317–325.

Radon survey in a village close to a former uranium mine (S-W Hungary)

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Abstract

The studied former uranium mine is located at the village of Kovagoszolos (S-Hungary). In the area Permian sandstone layers were found to be rich in uranium for mining, which lasted for 40 years. Kovagoszolos has ~350 family houses. At different distances from the surface projection of a mining tunnel radon concentration was measured in 120 houses with passive detector. The average value of the radon concentration is 483 Bq/m³. Significantly higher radon concentrations (average 667 Bq/m³) were measured in houses within 150 m from the surface projection of the mining tunnel, compared with the houses further than the 300 m belt (average 291 Bq/m³). Nine houses were selected for detailed study: short term indoor radon concentration measurement (RAD 7, AlphaGuard); physical (²²⁶Ra content, radon exhalation) and geochemical study on collected soil samples from house gardens. From the nine studied houses, in four particular ones the radon concentration was above the recommended level. The radium content in all cases was higher than the world average value. In the studied soil samples the finest fraction is dominated, potential radon source minerals were considered as Fe-oxides and hydroxides. Among the four chosen houses in one house an extrem radon anomaly was recognized. The indoor radon concentration was measured for one month (by active and passive detectors). Outdoor the gamma dose rate, soil gas radon concentration, radon exhalation and air radon concentration were also determined in the surrounded area of the house. In the center of detected radon anomaly (an area 5 m in diameter) the radon concentration of the outdoor air was 1660 Bq/m³, the gamma dose rate on the soil surface 380 nGy/h, the radon exhalation 20167 mBq/m²s and the soil gas radon concentration was > 2000 kBq/m³. Based on these results, it is clear that the local geology plays as important role in the development of a radon anomaly as the distance from the surface projection of the mining tunnel.

Radon survey based on home stored CDs/DVDs

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Abstract

This work presents results from a pilot radon survey based on retrospective measurements by CDs/DVDs. A short description of the CD method for retrospective measurements of integrated radon concentrations is given. The results of the survey are presented, demonstrating that the method allows measurements representative for the risk assessment with uncertainty better than 20 %. The survey includes private homes and public buildings. A large percent of the measurements were organized remotely using disks sent by mail, which clearly demonstrates the serious potential of the method for large-scale radon surveys.

Introduction

At present radon (^{222}Rn) is considered the second most important cause for lung cancer after smoking (WHO, 2009). When the contemporary risk from radon is assessed, it is necessary to reconstruct the historical exposure of the subjects. This goal is targeted by the retrospective methods. The majority of them are based on measurements of the long-lived radon progeny $^{210}\text{Pb}/^{210}\text{Po}$ implanted in hard surfaces (Samuelsson, 1988) or trapped in spongy materials (Oberstedt and Vanmarcke, 1996). The first approach gives results that are highly dependent on the complex behaviour of the short-lived radon progenies in the air, while the second involves elaborate and costly radiochemical procedures. A principally different approach for retrospective measurement of radon by compact disks (CDs) was proposed (Pressyanov et al. 1999, 2001). Since then substantial experimental and theoretical work has been devoted to tests of the CD method (Pressyanov 2009, 2010; Pressyanov et al. 2001, 2003, 2004). The aim of this work is to present results from a pilot study organized in Bulgaria that demonstrates the practical potential of the method for large-scale radon surveys.

Description of the CD method

The CD method is based on the remarkable ability of the material from which CDs and DVDs are made to absorb ^{222}Rn . This material is the same type of polycarbonate from which some track-etch detectors for alpha particles (Makrofol[®], Lexan[®]) are produced. The basic idea of the method is to combine the absorption ability and the track-etch properties of the material of the disks. When a disk is exposed to air, ^{222}Rn from the air is absorbed in the polycarbonate (Fig 1.). The alpha particles emitted by the absorbed ^{222}Rn and its short-lived progenies form latent tracks inside the disk. The number of

those tracks is proportional to the activity concentration of ^{222}Rn in the air, integrated over the exposure time. However, near the surface, tracks are also formed by ^{222}Rn progenies existent in the air or plated-out on the disk's surface. In such way, a “noise” signal is formed, which is hard to correlate to the activity concentration of ^{222}Rn (due to the complex behaviour of radon progenies in the air). To avoid the “noise” signal, tracks are developed at depths greater than $79\ \mu\text{m}$ below the disk surface. This depth is enough to ensure that no tracks are formed by progenies of ^{222}Rn (and ^{220}Rn) plated-out on the surface or present in the air (Pressyanov et al. 2000).

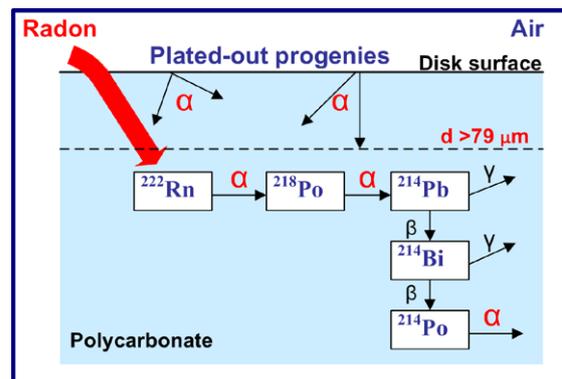


Fig. 1. Principle of the CD method - radon is absorbed in the polycarbonate and the tracks at $d \geq 79\ \mu\text{m}$ are only due to the absorbed ^{222}Rn and its progenies.

At a depth greater than $79\ \mu\text{m}$ below the disk surface the net track density n_0 (number of tracks per unit area) is only due to radon absorbed in the polycarbonate and is proportional to the activity concentration of radon in the air A_V , integrated over the exposure time T_{exp} :

$$n_0 = CF \int_0^{T_{exp}} A_V dt \quad (1)$$

where CF is a calibration factor. Experimental studies (Pressyanov 2010; Pressyanov et al. 2000, 2003, 2004) have shown that for a given depth of etching the following factors have negligible influence on CF :

- ^{222}Rn progenies in the air or plated-out on the disk surface;
- ^{220}Rn and its progenies;
- ^{210}Po , generated inside the polycarbonate by absorbed radon for reasonable exposure times;
- fading and aging of the polycarbonate material;
- storage of the disks in enclosed (but not hermetic) space, like jewel cases or cabinets;
- cigarette smoke and dust;
- atmospheric pressure in the range $57 - 148\ \text{kPa}$;
- humidity in the range $0 - 100\% \text{ RH}$.

In addition, theoretical estimates indicate that no effect on the track density could be expected from the laser light used to write and read data from the disks (Pressyanov 2010).

The only factor known so far to have significant influence on the calibration factor is the ambient temperature. However, as shown in (Pressyanov et al. 2003), a correction for the ambient temperature could be made after the exposure. If such a correction is not applied, the expected bias of the result is within 12% for etching at 80 μm . It is estimated for the interval $10 \div 30^{\circ}\text{C}$ and for reference temperature of 20°C (Pressyanov 2010). Considering that the average room temperature varies in an even narrower interval, the bias for disks exposed indoors should be even smaller.

The applicable range of the method for 10 years exposure time is from a few $\text{Bq}\cdot\text{m}^{-3}$ to over $20\text{ kBq}\cdot\text{m}^{-3}$ (Mitev et al. 2010; Pressyanov et al. 2003, 2008). The upper range is reached by etching at higher depths, where the track density is smaller. On the other hand, a disk exposed as shortly as one year might give statistically significant signal above $30\text{ Bq}\cdot\text{m}^{-3}$. The method is applicable for the whole range of activity concentrations of ^{222}Rn indoors that are of practical interest.

Principle steps of the CD method

Exposure

It is assumed that the exposure continues from the day the disk is obtained by its owner till the day the disk is processed in the laboratory. Any tracks formed before the owner obtains the disk are considered “background”. To estimate an average value for the background track density in CDs and DVDs a large number of new disks were etched. They were bought from different places and were of different brands. The individual background track densities varied from 2 to $40\text{ tr}\cdot\text{cm}^{-2}$. The average background track density was estimated at $6,3\text{ tr}\cdot\text{cm}^{-2}$ with standard deviation $2,3\text{ tr}\cdot\text{cm}^{-2}$.

In order to make retrospective measurements which are representative for the risk from exposure to radon, the analysed disks have to be more than 5 years old. Our experience shows, that in most households disks which are at least 10 years old and whose age could be determined with accuracy better than 1 year are found. However, in case “old” disks are not available, disks that are less than 5 years old are analysed. Such disks could also detect an existing radon problem, but would have limited value for estimates of the long-term past exposure.

Gathering disks

A major advantage of the CD method over other methods for retrospective radon measurements is the fact that no visit to the studied homes is necessary. Disks could be sent by mail, which allows large-scale surveys to be organized very efficiently.

Calibration

Another advantageous feature of the method is the possibility for *a posteriori* calibration. This means that the individual *CF* of each disk could be determined after it is taken for analysis (i.e. after the exposure). To do this two pieces are cut from the disk (usually two quarters). One of them is processed right away and the “original” track density in the disk *n* is found. The other piece is additionally exposed to known activity concentration of radon. Then *CF* is determined as:

$$CF = \frac{n_C - n}{I_V} = \frac{\Delta n}{I_V} \quad (2)$$

where n_C is the track density in the additionally exposed piece and I_V is the integrated activity concentration to which it was exposed. Note that n and n_C should be determined for the same depth.

In our laboratory the calibration is performed using the set-up shown in Fig 2. (including 50 L hermetic box, certified ^{226}Ra source and AlphaGuard[®] radon monitor). At initial activity concentration of 2 MBq.m^{-3} 10 hours of exposure are enough to provide an increase in the track density of over 400 tr.cm^{-2} . After the exposure, the disks are left to degass in radon-free atmosphere for about 4 weeks, so that all absorbed radon could decay or desorb. Further the two pieces are processed together in an identical way.

Any bias due to difference in the properties of the disks is avoided by *a posteriori* calibration. Our experience shows that even disks of the same brand might have somewhat different *CFs*. The average *CF* determined for 34 disks is $0,020 \pm 0,03 \text{ cm}^{-2}/\text{kBq.h.m}^{-3}$. The biggest difference we have observed between the individual *CF* of a disk and this value is -45% . That is an argument in favour of the *a posteriori* calibration of each studied disk. The procedure increases the time needed to obtain the final result, but is quite simple and could be applied simultaneously on many disks.

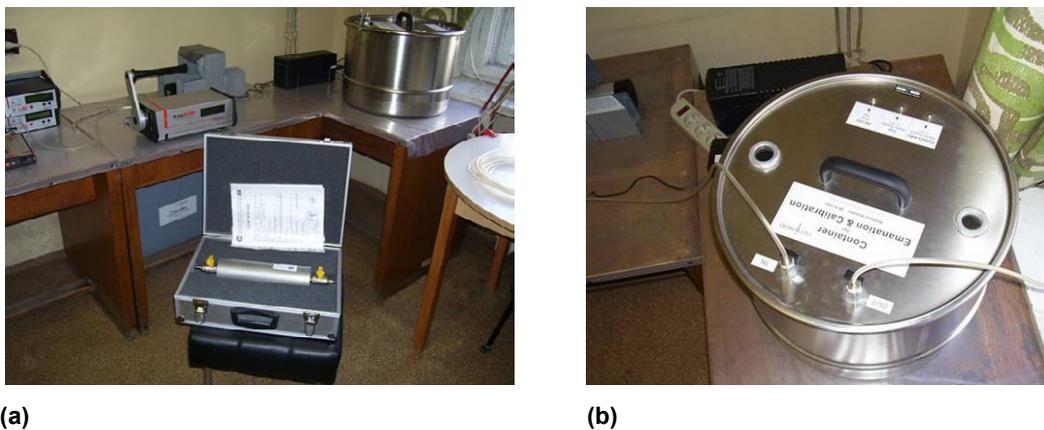


Fig. 2. Set-up used for calibration of CDs. a) Traceability is provided by a certified ^{226}Ra source and AlphaGuard[®] radon monitor. (b) The exposure is carried out in 50 L hermetic box.

Pre-etching and electrochemical etching

A surface layer is removed from each disk, so that the tracks at a certain depth below the surface ($d \geq 79 \mu\text{m}$) could be developed. This is done by chemical pre-etching (CPE) using an aqueous solution of 52% KOH (m/v) and 40% methanol (m/v) at 30°C . At this regime the bulk-etch velocity is about $1 \mu\text{m.min}^{-1}$. The depth of the removed layer is determined by measuring the disk thickness before and after the CPE by micrometer.

The tracks at the studied depth are revealed by electrochemical etching (ECE). The ECE process is performed at effective electric field of 3.0 kV mm^{-1} with frequency of 6 kHz . The temperature is 25°C . The etching solution is a mixture of ethanol with

6N KOH solution with 1:4 volume ratio (Vanmarcke and Janssens 1986). The process is preceded by a 30 min pre-etching with the same solution. After this the electric field is applied for 3 hours. The equipment available in our laboratory (shown in Fig. 3.) allows us to process about 30 disk quarters daily.

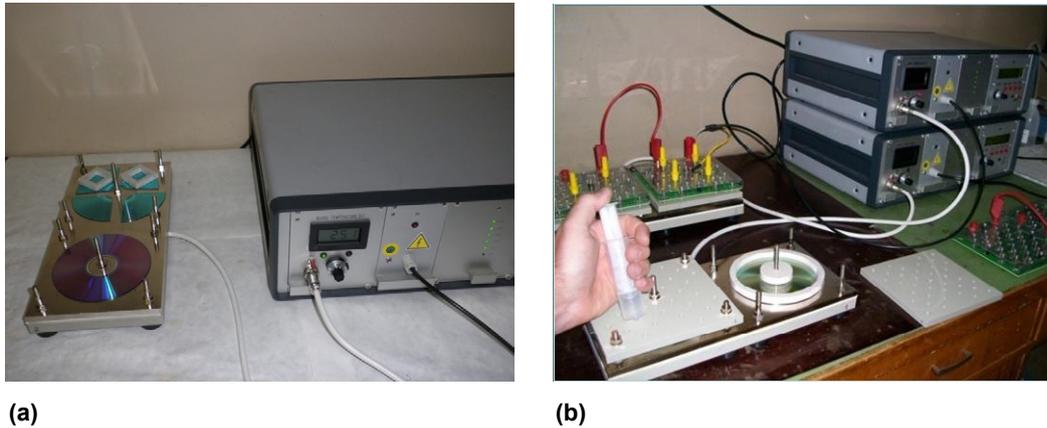


Fig. 3. Set-up used for CPE and ECE. (a) Disks prepared for etching. (b) Injecting the etching solution (front) and ECE in progress (back).

Track counting

The tracks are counted automatically after the disk is scanned by a commercial computer scanner (Tsankov et al. 2005) as shown in Fig.4(a). An example of a scanned image is shown in Fig. 4(b). A computer program (DGTrack) developed specifically for counting ECE tracks in CDs/DVDs is used to process the image (Mitev et al. 2010). The program has the ability to discard artefacts (like scratches that are common in used disks) and to separate overlapping tracks (as can be seen in Fig.4(c)). Scanning and counting 30 disks by DGTrack takes up to 60 minutes and most of this time is consumed by scanning (Mitev et al. 2010).

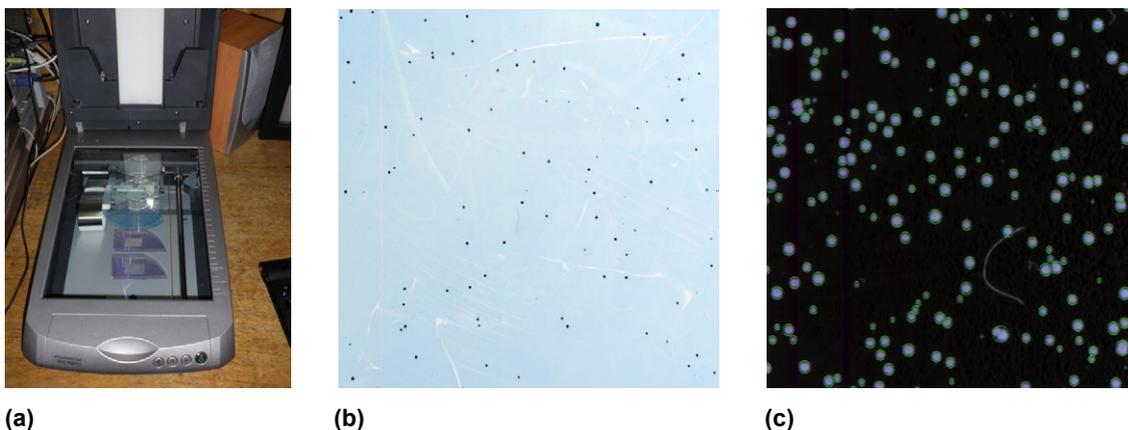


Fig. 4. (a) Scanning CD/DVD pieces for automatic counting of tracks. (b) Scanned image of the etched area of a CD. (c) ECE tracks in a CD counted by DGTrack (Mitev et al. 2010).

Estimating radon activity concentration

After the track density at a certain depth in the disk n is determined along with the corresponding CF , the average radon activity concentration for the period for which the disk was stored is found as:

$$A_V = \frac{n_0}{CF \cdot T_{exp}} = \frac{n - n_b}{n_C - n} \frac{I_V}{T_{exp}} \quad (3)$$

where T_{exp} is the length of this period (i.e., the age of the disk) and n_b is the background track density. The relative uncertainty of A_V , $\delta(A_V)$ is given by:

$$\delta(A_V) = \sqrt{\delta^2(stat) + \delta^2(I_V) + \delta^2(T_{exp}) + \delta^2(temp) + \delta^2(d)} \quad (4)$$

where the first term accounts for the statistical uncertainty in the track densities, and $\delta(I_V)$ and $\delta(T_{exp})$ are the relative uncertainties of I_V and T_{exp} respectively. The term $\delta(temp)$ accounts for any difference between the temperature of exposure of the original disk and the temperature during the calibration exposure. The term $\delta(d)$ accounts for the uncertainty in the depths of etching – this uncertainty might mask small differences in the depths at which the two pieces are etched. The last two terms in Eq(4) are evaluated theoretically, using a model given in (Pressyanov 2009). The typical and extreme values of the components of the uncertainty of A_V are shown in Table 1.

As it could be seen, in most cases the average radon activity concentration could be determined with uncertainty better than 20%. Higher uncertainty is usually due to the high relative uncertainty of the exposure time when one or two year-old disks are used.

Table 1. Typical and maximum values of the components in the relative uncertainty of radon activity concentration determined by retrospective measurements with CDs/DVDs.

Relative uncertainty	Typical, %	Maximum, %	Notes
$\delta(stat)$	5	10	-
$\delta(I_V)$	5	10	-
$\delta(T_{exp})$	10	50	Maximum – for short exposure times
$\delta(temp)$	12	33	For $T = 10 \div 30^0$ C (Typical at 80 μ m and Maximum at 120 μ m)
$\delta(d)$	5	10	(Typical at depth uncertainty ± 3 μ m and Maximum at ± 5 μ m)
Total ($\delta(A_V)$)	18	62	-

Results

A blind test of the method was performed in 2009 in the frames of an international intercomparison of passive radon detectors organised by the Health Protection Agency (HPA), UK. Compact disks were exposed at HPA and were sent to us by mail. A good agreement between the referent values and the results obtained by the CD method was found within the stated uncertainties. The results confirmed that the method could detect elevated radon levels even for short exposure times.

A pilot survey started in Bulgaria aiming to test the potential of the method for large-scale measurements. Around 200 disks were collected from 88 buildings. The disks were provided by their owners and varied in brands and age (from 1 to 15 years). The regions from which disks were collected include the cities Sofia and Varna, the town of Eleshnitsa and the region of the town of Bouchovo. In the last two regions uranium mining and milling had been in progress in the past and they are considered areas with high radon risk. The distribution of the activity concentrations in the studied buildings in these regions are shown in Fig.5(a). Although the number of buildings is small, it is clear that in many of them radon poses a problem. For comparison, the distribution of the activity concentrations in the studied buildings situated in Sofia, Varna and some other locations is presented in Fig.5(b). The obtained average is close to the average reported by UNSCEAR (UNSCEAR 2000). The averages and the medians for the studied buildings in the 3 regions, from which most of the disks were collected, are given in Table 3. The 95% confidence interval (CI) for the median was determined using non-parametric statistical analysis (Conover 1980). Moreover, it should be noted that CDs were taken from some of the homes in Eleshnitsa in which prospective measurements had been made in the past. As shown in (Pressyanov et al. 2010) the results obtained by CDs correlate very well with those obtained by the independent past measurements.

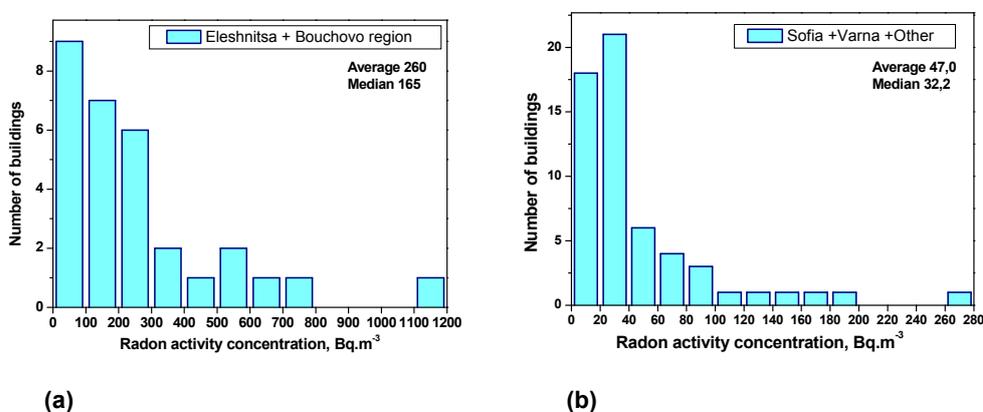


Fig. 5. Distribution of the activity concentration of radon obtained by measurements with CDs/DVDs in buildings in (a) risk areas (Eleshnitsa and in the region of Bouchovo); (b) areas considered “normal” (Sofia, Varna and some other locations).

Table 2. Values of the average and median of the activity concentrations of radon in buildings in three towns in Bulgaria obtained by measurements with CDs/DVDs.

Area	Number of buildings	Radon activity concentration , Bq.m ⁻³	
		Average	Median (95% CI)
Sofia	24	41,1	29,5 (19,0; 38,7)
Varna	17	38,5	17,3 (13,8; 29,7)
Eleshnitsa	22	166,1	123,4 (78,4; 210,0)

Most of the disks used in the survey (75) had been stored in homes, while the rest of them had been stored in different public buildings – four schools, a kindergarten, a hotel and several workplaces. Elevated radon concentrations were found in the kindergarten (about $500 \text{ Bq}\cdot\text{m}^{-3}$), which had since been successfully remediated by an active suction system. An interesting result was obtained in one of the other buildings (Fig.6). The analysis of a 3,5 year-old disk (CD1) lead to an estimate for the radon activity concentration about two times higher than the analysis of a 1,9 year-old disk (CD2). It turned out that before the second disk was bought, passive mitigation of the building had been installed. Subtracting the integrated activity concentration estimated by CD2 from the one estimated by CD1 allowed us to determine the average radon activity concentration for the period before the remediation (Fig.6). In this way, using CDs we determined a reduction factor of $3,7 \pm 1,4$ (at the level of 1σ). For comparison, conventional measurements showed about 3 times reduction in radon concentrations after the remediation. The example illustrates the ability of the CD method to roughly detect substantial changes in radon concentrations. In addition, the same approach could be used to exclude the last few years, which do not contribute to the present risk. This application of the CD method is useful for case-control studies and will be explored further.

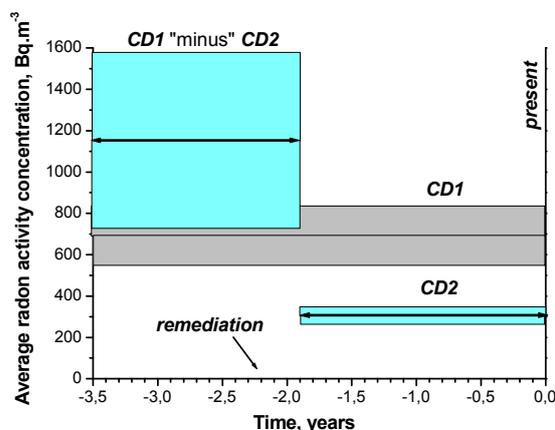


Fig. 6. Estimate of the average radon concentration for a past period by using two disks of different age. Remediation of the building has been made before CD2 was bought. The filled regions mark the estimated concentrations $\pm 1\sigma$.

Conclusion

The conducted survey, however small, demonstrates that the CD method:

- allows precise retrospective measurement of the activity concentration of ^{222}Rn with uncertainty potentially better than 20 %;
- allows individual calibration of each disk after the exposure;
- could be widely applied – CDs and DVDs are available in homes, work places, schools, etc.;
- could provide results representative for risk estimation – in many households disks as old as $10 \div 15$ years are available;

- pinpoints buildings with radon problem even with disks less than one year-old;
- could detect significant changes in the activity concentration of ^{222}Rn in the past by etching disks of different age;
- allows to monitor the individual exposure of the occupants even when they change residencies often;
- allows to organise measuring campaigns remotely by asking the participants to send disks by mail;
- is fast, simple and inexpensive.

The above features of the CD method make it appropriate for large-scale radon surveys. The method gives results that are representative for the risk from exposure to radon and could prove useful in case-control studies.

Acknowledgements

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References

- Conover W. Practical nonparametric statistics. Second edition. New York; John Wiley and Sons; 1980.
- Mitev K, Madzhunkov Y, Gerganov G, Dimitrova I, Georgiev S. Automatic counting of electrochemically etched tracks in compact disks. Application to retrospective measurements of Rn-222. IEEE Transactions on Nuclear Science 2010; 57(1): 300—308.
- Oberstedt S, Vanmarcke H. Volume traps – a new retrospective radon monitor. Health Physics 1996; 70(2): 222—226.
- Pressyanov D, Van Deynse A, Buysse J, Poffijn A, Meesen G. Polycarbonates: a new retrospective radon monitor. In: Proceedings of the IRPA Regional Congress on Radiation Protection in Central Europe. 1999 Aug 23—27; Fontenay-aux-Roses, France. p.716—722.
- Pressyanov D, Buysse J, Poffijn A, Meesen G, Van Deynse A. Polycarbonates: a long-term highly sensitive radon monitor. Nuclear Instruments and Methods in Physics Research A 2000; 447: 619—621.
- Pressyanov D, Buysse J, Van Deynse A, Poffijn A, Meesen G. Indoor radon detected by compact discs. Nuclear Instruments and Methods in Physics Research A 2001; 457: 665—666.
- Pressyanov D, Buysse J, Poffijn A, Meesen G, Van Deynse A. The compact disk as radon detector – a laboratory study of the method. Health Physics 2003; 84: 642—651.
- Pressyanov D, Buysse J, Poffijn A, Van Deynse A, Meesen G. Integrated measurements of ^{222}Rn by absorption in Makrofol. Nuclear Instruments and Methods in Physics Research A 2004; 516: 203—208.

- Pressyanov D, Dimitrova I, Georgiev S, Mitev K. Measurement of ^{222}Rn by absorption in polycarbonates – research and practice. In: Proceedings of the 18th AARST International Radon Symposium. 2008 Sep 14—17; Las Vegas, USA. p.1—10.
- Pressyanov D. Modeling a ^{222}Rn measurement technique based on absorption in polycarbonates and track-etch counting. *Health Physics* 2009; 97(6): 604—612.
- Pressyanov D. Nuclear tracks in polycarbonates with high radon absorption ability: Opportunities for measuring ^{222}Rn . In: Nuclear track detectors: Design, methods and applications. Nova Science Publishers, Inc., 2010; in press (ISBN: 978-1-60876-826-4).
- Pressyanov D, Mitev K, Georgiev S, Dimitrova I. Radon mapping by retrospective measurements – an approach based on CDs/DVDs. *Journal of Environmental Radioactivity* 2010; in press.
- Samuelsson C. Retrospective determination of radon in houses. *Nature* 1988; 334: 338—340.
- Tsankov L, Pressyanov D, Mitev K, Georgiev S, Dimitrova I. Automatic counting of chemically etched tracks by means of a computer scanner. *Radiation Measurements* 2005; 39: 557—559.
- UNSCEAR, Sources and Effects of Ionizing Radiation. UNSCEAR 2000 Report to the General Assembly, with Scientific Annexes. vol. I, Sources. New York: U. N. Publications; 2000.
- Vanmarcke H, Janssens. Study of the properties of electrochemically etched alpha-tracks in polycarbonate foil used in a radon diffusion chamber. *Nuclear Tracks* 1986; 12: 689—692.
- World Health Organization. WHO Handbook on Indoor Radon. Geneva: WHO Press; 2009.

Radon measurement method with passive alpha track detector at STUK, Finland

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Abstract

In Finland, Radiation and Nuclear Safety Authority (STUK) has performed approximately 5 000 – 20 000 indoor radon measurements per year. The detector material is polycarbonate and the holder model is STUK's own. After at least a two-month measurement in the heating period, the polycarbonate films are electrochemically etched in order to see the alpha tracks. Tracks are calculated with image processing and analysis system. Research and Environmental Surveillance of STUK is an accredited testing laboratory T167 (EN ISO/IEC 17025) by the decision of the Finnish Accreditation Service (FINAS). Airborne radon concentration is one of the accredited fields of testing performed at STUK and verified by FINAS. STUK's Health Risks and Radon safety laboratory also makes comparison measurements every second year with primary standard of Physikalisch-Technische Bundesanstalt (PTB), the national metrology institute laboratory in Germany. STUK's Health Risks and Radon Safety laboratory sends its reference measuring device to PTB for calibration. This is to conserve the measurement standard at STUK.

Introduction

The first passive radon detector that STUK used was STUK's own making. It was an open Kodak LR-115 detector, used from 1980 to 1984 (Mäkeläinen, 1984). In 1984 STUK started to use closed passive radon detector. The detector holder was made from clear plastic and the detector was a 300 - μm thick Makrofol polycarbonate film. The other side of the detector was clear and the other side was matt (Mäkeläinen, 1986). In 1989 the detector holder material was replaced with an electric conductive (carbon fibre reinforcement) ABS plastic and 250- μm thick polycarbonate was used as the detector.

Material and methods

The present day passive detector is used for dwellings and workplaces. The detector holder is STUK's own design, closed and with a filter, 17 mm high and 45 mm in diameter. It is made from ABS plastic including 10% carbon fibre. There are six holes in the holder cover, and below the cover there is a paper filter disc, Whatman / Schleicher & Shuell 589/3, diameter 45 mm. STUK's detector is shown in Figure 1.



Figure 1. STUK's detector.

The detector is made of 250 - μm thick polycarbonate sheet, Bayer Makrofol DE 1-1 CC. Both sides of the detector are clear. STUK gets the film directly from factory in 610 x 915 mm sheets, clear cover plastic on one side and green cover plastic on the other side. Finnish company die-cuts the Makrofol to keep the clear cover plastic as one piece and the green one will be removed just before packing it into the detector holder. Cover plastic prevents the detectors from scratching. The background was three tracks per cm^2 for the new detector and today it is five tracks per cm^2 . STUK performs control tests for background in every three months. Roughly one out of 5 000 detectors breaks down because of high voltage. Also the track density can vary in one or two per 5 000 detectors so that they must be rejected.

In the detector holder there is a 19- μm thick aluminium-metallized sheet of polyester, Hostaphan RNK 19. The surface resistance for the aluminium coating is 2 ohm/m^2 , and the thickness of the aluminium coating is less than 0,05 μm . Inside the holder steel spring keeps the parts in their places. The detector holders, detectors and questionnaires are identified using bar code labels. The bar code type Interleaved 2/5 is suitable for small detectors like in our case.

The pre-etching time is 1 h 12 min and the electrochemical etching time is 2 h 22 min. Etching temperature is 36 $^{\circ}\text{C}$, frequency 2 kHz and field 28.8 kV/cm. The etching solution is potassium hydroxide, KOH and ethanol. For the KOH solution we take 385 ml saturated potassium hydroxide and 620 ml distilled water, and compound it with

ethanol 1:1. On the other side of the detector, we use sodium chloride solution, 61 g NaOH in 1 l water, as a conductive liquid. Control unit takes care from etching times. Fluke 87 True RMS Multimeter stores ranges of voltage, average, maximum and minimum. Etching chambers in constant temperature cabinet are shown in picture 2.

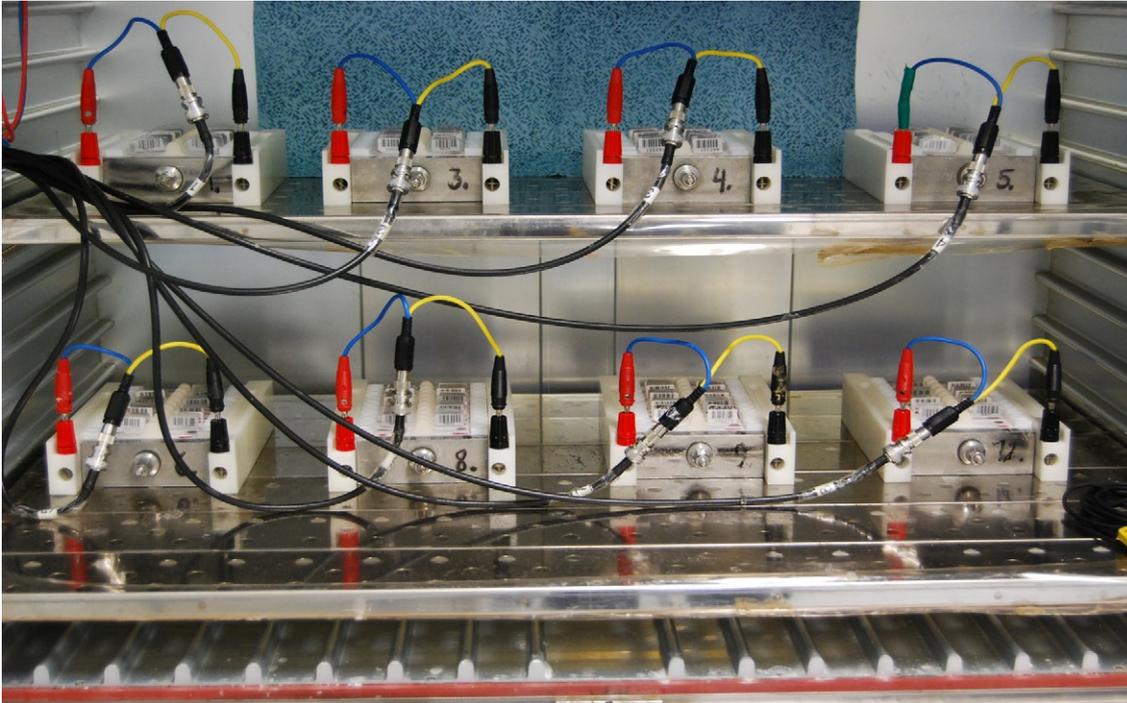


Figure 2. Etching chambers in constant temperature cabinet.

Track counting is made with Leica image analyze system. The software is Qwin, the microscope Mz6 and the camera DC 300. The counting area used is 1.52 cm². We take one picture from the detector and the program will divide it into 16 sectors for calculation. If the amount of tracks differs significantly in more than three sectors, the system rejects the detector for hand control. STUK makes every other month verification to the counting system by re-counting the same test detectors.

The main testing system is to use test detectors. 300 - 600 test detectors are exposed to the same radon concentration. At least every twentieth detector is a test detector and they will go through every stage daily.

Laboratory information system RAMI includes the customer register and the measurement register. RAMI takes care of result calculations, result letters and invoices.

Research and Environmental Surveillance of STUK is an accredited testing laboratory T167 (EN ISO/IEC 17025) by the decision of the Finnish Accreditation Service (FINAS). Airborne radon concentration is one of the accredited fields of testing performed at STUK and verified by FINAS. STUK participates in intercomparisons of passive radon detectors. STUK's Health Risks and Radon Safety laboratory also makes comparison measurements every second year with primary standard of Physikalisch-Technische Bundesanstalt (PTB), the national metrology institute laboratory in Germany. STUK sends its reference measuring device, Alpha Guard, to PTB for calibration. This is to conserve the secondary measurement standard at STUK.

In Finland, Radiation and Nuclear Safety Authority has performed approximately 5 000 – 20 000 indoor radon measurements per year. Amount of annual radon measurements is shown in figure 3.

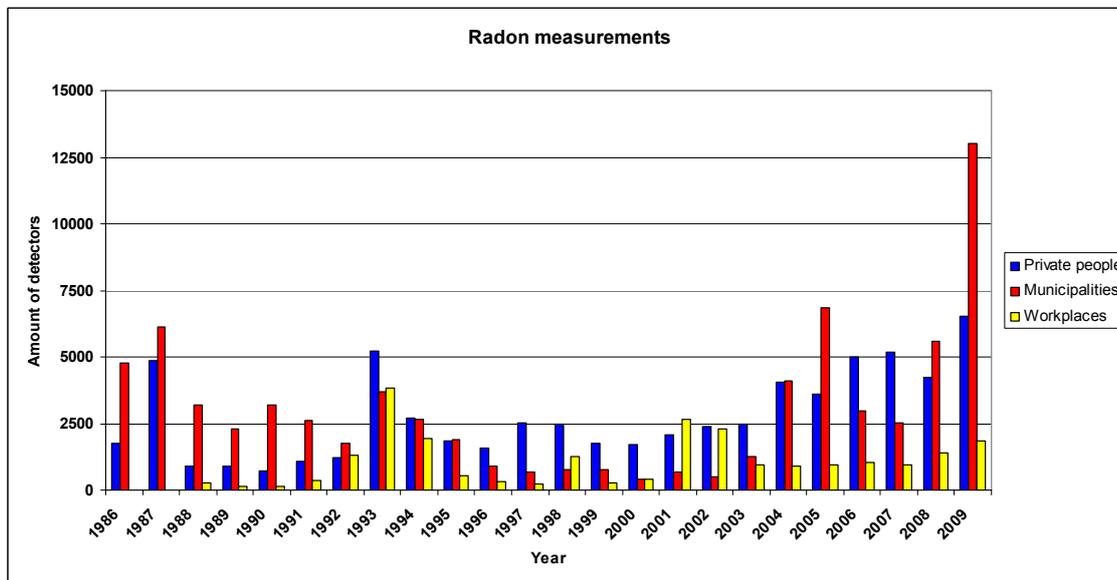


Figure 3. Amount of annual radon measurements in Finland.

References

- Makeläinen I. Calibration of bare LR-115 film for radon measurements in dwellings. *Radiation Protection Dosimetry* 1984; 7 (1-4): 195-197.
- Mäkeläinen Ilona. Experiences with track etch detectors for radon measurements. *Nuclear Tracks* 1986; 12 (1-6): 717-720.

Results obtained in the measurement of Rn-222 with the Romanian standard system

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Abstract

This paper presents the following results: (i) Realization of the metallic radon standard system; (ii) Quantitative extraction of radon from the radium source; (iii) Absolute standardization by liquid scintillation counting and relative measurements of radon activity, by using the HPGe gamma-ray spectrometry method and the reentrant ionization chamber. The final purpose of the work is to calibrate adequately the secondary standard systems, for using them in the measurement of the working standards, glass vials containing radon gas standard, in order to assure the traceability. A method for modeling the radon transport in various matrices was also elaborated, with reference to the simulation of the radon detectors containing active charcoal. It will be validated experimentally, with radon gas standards.

Introduction

The necessity to create a primary Romanian ²²²Rn standard system and the general concept of such a system to be established at IFIN-HH, Radionuclide Metrology Laboratory were presented at IRPA 12 Congress by Sahagia et al. (Sahagia et al. 2008). A preliminary variant of a glass circuit was realized and used for the extraction of radon. It contains a vacuum system for the circulation and recovery of radon and a Pylon solid source of ²²⁶Ra, <http://www.pylonelectronics.com/pylonradioactive.php>, type RN-1025-250, flow-through, with the activity: $A_{\text{Ra-226}} = (259 \pm 10) \text{ kBq}$, on 21 August 2008, traceable to the NIST, USA. The method for absolute standardization of ²²²Rn in equilibrium with its daughters by liquid scintillation counting (LSC) was first used by a common French-Romanian team at the Laboratoire National Henri Becquerel (LNHB), France, such as presented by Cassette et al. (Cassette et al. 2006). The method was developed at IFIN-HH, with some original aspects, referring to the correction for the decay of the very short half life daughter ²¹⁴Po during the extendable type dead time

of the LS counter. The results obtained in the absolute standardization of radon were published by Sahagia et al. (Sahagia et al. 2009a)

This paper presents the following results: (i) Realization of the final metallic system, provided with all the necessary control gauges and the preparation of sources by the quantitative extraction of radon from the radium source. (ii) Absolute standardization by LSC and relative measurements of radon activity, by using the HPGe gamma-ray spectrometry method and the CENTRONIC IG12/20A ionization chamber. The final purpose of the work will be to calibrate adequately these secondary standard systems for using them in the measurement of the working standards, glass vials containing gas radon, prepared with the radon facility. These standards will be used for the calibration of equipments of various laboratories involved in radon measurement. A method for modeling of the radon transport in various matrices was also elaborated. One part of it refers to the simulation of the radon detectors containing active charcoal, a particular case of a purely diffusive transport in a medium with constant saturation. It will be validated experimentally, with radon gas standards produced with the standard radon system.

Material and methods

1. Presentation of the system and the preparation of sources

The new variant of the system was constructed from stainless steel and contains all the necessary gauges for the control of the pressure inside the circuit. It allows the extraction of large activities of radon from the Pylon source. At the same time it can be used in several modes of work, as it contains two ways of access to the circuit: (i) the concomitant extraction in two recipients; (ii) the extraction of radon in a single recipient and the transfer into another. Both these types of operation were intended to prepare the final (iii) mode, consisting of the sequential extraction and quantitative transfer from a recipient to another, in order to establish the traceability chain. This mode of operation is treated in an internal IFIN-HH Report (Report, 2009). Photograph 1 presents the two variants of installations



Fig. 1 (a) Glass system.



Fig.1(b) Metallic system.

Several sources were prepared in glass ampoules or vials, in both modes of work, (i) and (ii). The pair of sources 9 - 10 were prepared in the manner (i), and the pairs 13-14, 15-16 and 17-18 were prepared in the manner (ii). The sources 9,13,15 and 17

contained the radon as gas, while the sources 10, 14, 16 and 18 were prepared by adsorption/ dissolving of radon in liquid scintillator (LS) type OPTIFLUOR O, a Perkin Elmer product. The recovery of radon in the recipients was done at the 77 K temperature, by using Dewar vessels with liquid nitrogen. The pressure in the metallic variant of system was fully controlled and allowed for the preparation of high activity sources by the recovery of the main part of radon exhaled by the Pylon source. Figure 2 represents both types of radon ampoules, flame sealed.



Fig.2. Flame sealed ampoules: left – LS; right - gas.

All the operations were performed in a radionuclide fume cupboard, coupled to the ventilation circuit. The radon concentration in the laboratory was permanently measured with a monitor, Radon Scout, SARAD GmbH, Germany product, coupled to a personal computer. Figure 3 shows the registrations for a 24 h period of the radon concentration in the laboratory, during the preparation of sources.

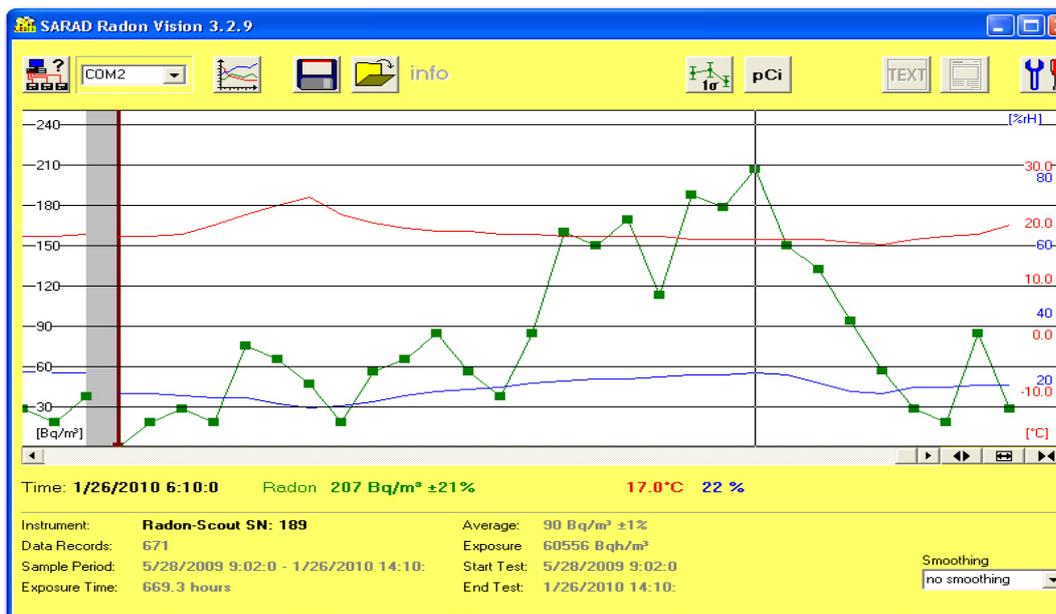


Fig. 3. Radon concentration in the laboratory.

Such as it can be seen from the figure, the maximum concentration values are registered during the night time, when the laboratory ventilation is not working; the marked, 210 Bq/m^3 , is at 6 h in the morning. During the working time the values are less than 90 Bq/m^3 , showing that no contamination occurs.

2. The measurement of activity

The measurements were performed by the absolute LSC method with the ampoules prepared in LS, and relatively, by the gamma-ray spectrometry using a high resolution HPGe system and by the measurement in a CENTRONIC IG12/20A well type ionization chamber, with all types of recipients.

2.1. Measurement by the LSC method

The method was described in the above cited papers. The method consists basically from the measurement of the whole sequence of short lived nuclides of the ^{222}Rn decay chain in a LS counter. The main correction is due to the disintegration of ^{214}Po during the dead time of the LS counter. The formula for the calculation of the ^{222}Rn from the counting rate R_0 is:

$$R_0 = 5.0242 \cdot A_{\text{Rn222}} \quad (1)$$

In relation (1), R_0 represents the corrected counting rate for the ^{214}Po decay. The approximate relation for this correction is:

$$R = R_0 \left[1 - 0.0008576 \tau \left(1 + \frac{\tau}{2} (\rho - \lambda) \right) \right] \quad (2)$$

In this relation, R is the registered counting rate, corrected for background; τ is the fixed dead time of the counter, in μs , $\lambda = 0.00427 (\mu\text{s})^{-1}$ is the decay constant of ^{214}Po and ρ is the true counting rate.

A method based on the precise determination of the fixed counter dead time $\tau = (40.07 \pm 0.06) \mu\text{s}$ and the repetition of measurements for several days, with the extrapolation to the source preparation time was applied, such as described by Sahagia et al. (Sahagia et al. 2009a). The extrapolation is correct, and the data are correctly used, when the linear extrapolation equation is accomplished:

$$[R_0] = [R_0]_0 2^{-\frac{t}{T_{1/2}}} \quad \text{or} \quad \log[R_0] = \log[R_0]_0 - \frac{\log 2}{T_{1/2}} t \quad (3)$$

$[R_0]_0$ is the extrapolated counting rate, corresponding to the source preparation time, and $T_{1/2} = (3.8232 \pm 0.0008) \text{ d}$ is the half life of ^{222}Rn according to Monographie BIPM-5. (Bé et al. 2008). Contrary to the previous measurements, when low ^{222}Rn activities were extracted from the Pylon source (a maximum 1572 Bq at the preparation time), in this case higher activities were extracted and had to be measured. It was necessary to wait for longer periods the decay of radon, in order to be measured. As the extrapolation was extended on longer time intervals, more measurements and checks of the correct extrapolations were necessary.

2.2 The measurement by gamma-ray spectrometry

The measurements were performed with gas and LS recipients. A gamma-ray spectrometer, provided with a high efficiency HPGe detector was used. The sources were measured at a distance of 44.2 cm from the detector surface, in order to diminish

the influence of the recipient geometry. The measurements were made on the two main photopeaks: 352 keV (Pb-214) and 609 keV (Bi-214). The emission intensities for the two quanta, $I, (\gamma s^{-1})/Bq$ were respectively: 0.3560(7) and 0.4549(19) (according to Bé et al 2008). Various models for calculation of efficiency, leaving from point source approximation and the GESPECOR programme (GESPECOR, 2007) were used. More details are given in the Internal Report IFIN-HH, 2009.

2.3 Measurements with the ionization chamber

The laboratory disposes of a well type ionization chamber type CENTRONIC IG12/20A, provided with an electrometer type Keithley 6517A, which was calibrated for a number of 18 different radionuclides. The results were validated during our participation in key and supplementary comparisons, Sahagia et al. (Sahagia et al. 2009b). The calibration factors were expressed in terms of the ratio between the ionization current and the activity of the measured sources. The measurements were performed with both types of recipients by registering the obtained ionization current. In the case of the gas ampoules, the measurements based on the HPGe were taken as reference. In the case of the LS ampoules, both methods of activity measurement, LSC and HPGe, were used. The measured activities were considered as the arithmetic mean of the two photopeaks' results.

3. Modelling methods

A conceptual and mathematical model describing the migration of the radon generated from the radium existing in the soil was elaborated. The experience gained in various modeling situations, such as presented by Toro et al. (Tora et al. 2008) was used. The radon transport is produced first of all due to the diffusion which occurs as a consequence of the radon concentration difference between the two phases: gas and liquid. Leakage of the transport fluids, air and water, drives to an advective - dispersive transport. The description of this biphasic emanation process is complicated also by the physic-chemical properties of the porous medium; more equations must be written both for the transport and leakage, coupled by the degree of saturation and physic-chemical processes. The modelling consists in several types of activities: (i) Definition of a conceptual model, containing the work hypotheses; (ii) Elaboration of a mathematical model, containing the sets of equations which describe the physical processes; (iii) Elaboration of the numerical model for solving the equations. A particular case of the model application is the simulation of the transport of radon inside the detectors containing active charcoal, a pure diffusive transport in the medium with a constant saturation. The calculation results follow to be compared with those experimentally obtained with the use of radon gas standard vials.

Results

The radon prepared sources activity measurement results, obtained by using the three methods, are presented in Tables 1, 2 and 3.

1. Measurement of activity by the LSC method

A number of 4 LS ampoules were measured and the results, in terms of total decay chain activity $[R_0]_0$, radon activity, $[A_{Rn-222}]_0$ on the source preparation time and the optimum calculated half life, $T_{1/2}$, are presented in Table 1.

Table 1. LSC measurement results.

Amp. no	Time from the preparation date, d / no of points	$Y_0 = A_0 + B_0 t$, $\tau = 40.07\mu s$
10	(20.8403 – 28.9062)/ 5	$Y_0 = (5.7411 \pm 0.0074) - (0.07793 \pm 0.00028) t$ $[R_0]_0 = (550\ 883 \pm 9\ 475) \text{ Bq}$; $T_{1/2} = (3.8628 \pm 0.0138) \text{ d}$ $[A_{Rn222}]_0 = (109\ 646 \pm 1\ 886) \text{ Bq}$, $k=1$
14	(8.8125 - 14.8611)/ 5	$Y_0 = (5.0762 \pm 0.0087) - (0.07868 \pm 0.00014) t$ $[R_0]_0 = (119\ 182 \pm 2\ 395) \text{ Bq}$; $T_{1/2} = (3.814\ 8 \pm 0.036) \text{ d}$ $[A_{Rn222}]_0 = (23\ 721 \pm 477) \text{ Bq}$, $k=1$
16	(19.0556 - 26.0208)/ 2	$Y_0 = (5.7725 \pm 0.0066) - (0.07868 \pm 0.00014) t$ $[R_0]_0 = (592\ 243 \pm 8\ 943) \text{ Bq}$; $T_{1/2} = (3.8274 \pm 0.036) \text{ d}$ $A_{Rn222} = (117\ 878 \pm 1\ 780) \text{ Bq}$, $k=1$
18	(12.9410 – 30.000)/ 3	$Y_0 = (5.4486 \pm 0.0053) - (0.07855 \pm 0.00068) t$ $[R_0]_0 = (280\ 931 \pm 3\ 425) \text{ Bq}$; $T_{1/2} = (3.8232 \pm 0.033) \text{ d}$ $[A_{Rn222}]_0 = (55\ 916 \pm 671) \text{ Bq}$, $k=1$

2. Measurement of activity by the HPGe gamma-ray spectrometry

A number of 2 gas and 2 LS ampoules were measured and the results are presented in Table 2.

Table 2. Results of measurement by the HPGe Gamma-ray spectrometry.

Recipient No./ Measurement	Photo peak,	$N\gamma$, s^{-1} , on reference time	ϵ , $s^{-1}/(\gamma s^{-1})$ /model	Activity on reference time , Bq	A_{Bi}/A_{Pb}	^{222}Rn , activity, Bq, on reference time
1	2	3	4	5	6	7
9/ horizontal	352 keV	13.231 ± 0.071	0.000364/point	^{214}Pb :102100	1.126	101547 ± 2132
	609 keV	10.459 ± 0.061	0.000200/point	^{214}Bi : 114952		113915 ± 2392
13/ horizontal	352 keV	24.98 ± 0.135	0.000368/point	^{214}Pb :190675	1.052	189657 ± 3983
	609 keV	19.810 ± 0.114	0.000217/point	^{214}Bi :200682		198906 ± 4177
10/ horizontal	352 keV	12.263 ± 0.066	0.000364/point	^{214}Pb : 94630	1.166	94117 ± 1946
	609 keV	10.036 ± 0.058	0.000200/point	^{214}Bi : 110313		109318 ± 2296
10/ vertical	352 keV	10.872 ± 0.059	0.000275 GESPECOR	^{214}Pb :111052	1.012	110450 ± 1767
	609 keV	8.897 ± 0.052	0.000174 GESPECOR	^{214}Bi :112403		111389 ± 1782
14/ vertical	352 keV	2.330 ± 0.023	0.000275 GESPECOR	^{214}Pb : 23800	1.0033	23671 ± 426
	609 keV	1.890 ± 0.019	0.000174 GESPECOR	^{214}Bi : 23878		23663 ± 426

2. Measurement of activity by the ionization chamber

Two gas and four LS sources were measured. The results are presented in Tables 3 and 4.

Table 3. Measurement of gas ampoules with the ionisation chamber.

Amp no.	I, pA, on the reference time	Photopeak energy	Rn-222 Activity, MBq, HPGe Determined, Table 2	F, pA/MBq, HPGe based
1	2	3	4	5
9	5.831 ± 0.044	352 609	0.10155 ± 0.0021 0.11392 ± 0.0024	57.42 ± 1.28 51.18 ± 1.13
13	10.877 ± 0.083	352 609	0.18966 ± 0.0040 0.19891 ± 0.0042	57.34 ± 1.26 54.68 ± 1.20

Table 4. Measurement of the LS sources with the ionization chamber.

Amp no	I, pA, on reference time	Activity, MBq, LSC determined, Table 1	F, pA/MBq, LSC	Activity, MBq, HPGe determined, Table 2	F, pA/MBq, HPGe	Difference Col (6 - 4)/ Col 4
1	2	3	4	5	6	
10	5.617± 0.039	0.10965 ± 0.00189	51.23± 0.94	0.11092 ± 0.00177	50.64± 0.88	-1.15%
14	1.145± 0.034	0.023721 ± 0.000477	48.26± 1.74	0.02367 ± 0.00043	48.38± 1.69	+0.25%
16	5.963± 0.042	0.11788 ± 0.00178	50.59± 0.86	-	-	-
18	2.814± 0.028	0.055916 ± 0.000671	50.33± 0.81	-	-	-
		Weighted mean values and standard deviations :	50.49±0.65		50.17±1.13	-0.63%

Discussion

The measurement results, such as presented in Tables 1, 2, 3 and 4 reveal the followings.

Regarding the absolute, liquid scintillation method, it is the primary method, to be taken into account for the realisation of a primary radon standard. The LSC method assured a good precision of standardization, combined standard uncertainty situated between 1% and 2%, even in the case of these high activity sources. The calculated radon half life values from the extrapolation procedure are in agreement with the theoretical value $T_{1/2} = (3.8232 \pm 0.0008)$ d.

Regarding the HPGe gamma-ray spectrometry, Table 2 results, one may comment. The theoretical ratio of the ^{214}Pb and ^{214}Bi activities is $A_{\text{Bi}} / A_{\text{Pb}} = 1.00363$. The determined ratio values, column 6, is much higher for the point source approximations in efficiency calculation; the ^{222}Rn activity values, column 7, differ significantly from a photopeak to another and consequently the model is not adequate for efficiency evaluation. The GESPECOR variant applicable only to the LS sources is much better, as the values agree and also they agree with the values measured absolutely by the LSC (sources 10 and 14). This program is not applicable to the gas recipients, maybe because the volume distribution of the ^{214}Pb and ^{214}Bi inside these sources is not

known. The conclusion is that the only possibility to determine the activity of gaseous sources is to achieve a quantitative transfer of radon from the gas to LS recipients, to measure them by the LSC method and to establish the traceability chain.

Table 3 and Table 4, ionization chamber measurement results discussion. The calibration factors obtained with 2 gas ampoules, leaving from the gamma-ray spectrometry measurements are not consistent in terms of their combined standard uncertainties. On the contrary, for a number of 4 different LS sources the calibration factors agree, once as individual results with reference to the LSC method, and twice as compared with those determined taking as reference the activity measured by the HPGe gamma ray spectrometry method, based on the use of the GESPECOR program for efficiency calculation. This result has the same conclusion, that the main problem is to develop the method for the transmission of activity unit from the LSC method to the gaseous sources, in order to assure the traceability chain.

Conclusions

- The radon system was used to prepare recipients containing radon extracted from a radium source, both as gas and dissolved in liquid scintillator.
- The activity of all radon recipients was measured by various methods: the LS ampoules were measured absolutely by the LSC method; all recipients, gas and LS, were measured relatively by using the gamma-ray spectrometry and the reentrant ionization chamber.
- The comparison of results revealed that in the case of the LS ampoules a model for gamma-ray spectrometry efficiency calculation is adequate, such as the agreement of results demonstrated, while for the gas recipients no model can be used.
- The general conclusion is that a traceability scheme for the transfer of activity unit from primary to secondary standards is needed.

Acknowledgement

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References

- Bé M –M, Chisté V, Dulieu C, Browne E, Chechev V, Kuzmenko N, Kondev F, Luca A, Galán M, Pearce A, Huang X. Table of Radionuclides (Vol.4 – A=133 to 252), Monographie BIPM-5, Ed. Bureau International des Poids et Mesures, Pavillon de Breteuil, F-92310 Sèvres, France, 2008, pages 79, 97 and 143.
- Cassette P, Sahagia M, Grigorescu E L, Lepy M C, Picolo J L. Standardization of ²²²Rn by LSC and comparison with α - and γ -spectrometry. Appl. Radiat. Isot. 2006; 64: 1465-1470.
- GESPECOR version 4.2: Manual, CID Media GmbH, 2007, 63579 Freigericht / Bernbach, Germany
- Internal Research Report IFIN-HH, 2009

- Sahagia M, Stanga D, Wätjen A C, Luca A, Toro L, Varlam C, Cassette P. Concept for a primary Romanian radon standard. IRPA12 Congress, Buenos Aires, 2008. Proc. <http://www.irpa12.org.ar/index.php>. Topic III 4.4. NORM & radon issues in buildings. Pdf.2398
- Sahagia M, Stanga D, Wätjen A C, Luca A, Cassette P, Ivan C. Antohe A. The Rn-222 Standard System established at IFIN-HH, Romania. Appl. Radiat. Isotopes (2009a),doi:10.1016/j.apradiso.2009.11.060, available online 3 December 2009
- Sahagia M, Wätjen A C, Luca A, Ivan C. IFIN-HH ionization chamber calibration and its validation; electrometric system improvement. Appl.Radiat.Isotopes(2009b), doi:10.1016/j.apradiso.2009.11.009, available online 13 November 2009
- Toro L, Gheorghe R, Gheorghe D. Modelling the distribution of Rn-222 concentration in a multi level, general purpose building . IRPA12 Congress, Buenos Aires, 2008. Proc. <http://www.irpa12.org.ar/index.php>. Topic III 4.4. NORM & radon issues in buildings. Pdf. 0902

Estimating lung cancer risk due to radon exposure in the radon-prone areas of Belgium

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Abstract

Radon exposure in Belgium is particularly pronounced in the southern part of the country, characterized by a sub-surface composed of highly deformed and fractured (black) shale, schist and quartzite of the Ardenne massif. A national indoor radon measurement campaign (1995-2000) showed that all of the high radon risk areas (where more than 5% of the measured buildings exceed the current Belgian action-level of 400 Bq/m³) were situated within the Ardenne massif, affecting a population of about 380 thousand. For this reason, detailed information, measurement and prevention campaigns have been organized for the local population and municipal authorities. Whereas the national average indoor radon concentration is about 50 Bq/m³, this average increases to about 130 Bq/m³ in the high risk areas. Here, 13% of the houses exceed the action level, affecting more than 50 000 people, and 4% of the houses exceed 800 Bq/m³, affecting more than 15 000 people. In 33% of the dwellings, the design level for new buildings (200 Bq/m³) is exceeded. According to the risk estimates from international epidemiological studies, about 18% of the occurring lung-cancers in the high risk areas (~43 cases on 240 per year) would be due to radon exposure. About 38% of the radon-induced lung-cancers (LC) would occur in the population exposed to more than 400 Bq/m³ (about 30 lung-cancers per year). Comparison of these theoretical values with actual LC statistics of the Belgian Cancer Registry shows a good match between the total number of annual LC in the high risk areas (239 calculated to 240 observed in the period 2004-2005). The correlation between LC incidence rate and average radon concentration however is obscured by the high number of influencing factors (migration, age-distribution, life-habits,...) and the relatively limited population and LC incidence rate. Radon campaigns aim at stimulating house owners and building responsables to mitigate the radon affected buildings and to apply preventive measures in new buildings. In the high risk areas, preventive reduction of radon exposure to below 200 Bq/m³ should lead to a reduction of the LC incidence rate with 7%.

Introduction

For the general population, radon is usually the most prevailing source of radiation exposure in the indoor environment (ICRP 60, 1990). The link between radon and lung cancer has been first recognised through miner cohort epidemiological studies (BEIR

IV, 1988; BEIR VI, 1998; UNSCEAR 2000). More recent case-control studies highlight the linear no-threshold relation between lung cancer risk and indoor radon-concentration in dwellings (Darby et al., 2005). In order to efficiently manage the radon exposure, most European countries have adopted a radon action plan, setting out the criteria, strategies and practical aspects of radon controlling activities. The Belgian radiation protection regulation (ARBIS, 2001) foresees the control of radon exposure in workplaces and in dwellings in radon prone areas. A national radon measurement campaign during the 1990's highlighted the occurrence of radon prone areas (defined at that time as municipalities where more than 1% of the dwellings exceed the action level of 400 Bq/m³) in the southern part of the country (Poffijn and Vanmarcke, 1990; Zhu et al., 1998). Ongoing indoor radon measurements led to the classification of the territory into radon regions (Fig. 1) on a national scale and into radon classes on a local scale (Fig. 4). Within the radon prone areas, a specific region shows a high risk of having high indoor radon concentrations. This is the high risk area (HRA, Radon region 2 on figure 1), where more than 5% of dwellings exceed the action level. It is characterised by the occurrence of highly deformed metamorphic rocks of Lower Palaeozoic age. The HRA affects a population of about 380 thousand. If the national action level would be brought to 200 Bq/m³, the population living in the HRA would increase to more than 1.1 million. The measurement campaigns also allowed assessing the radon exposure of the Belgian population (Table 1).

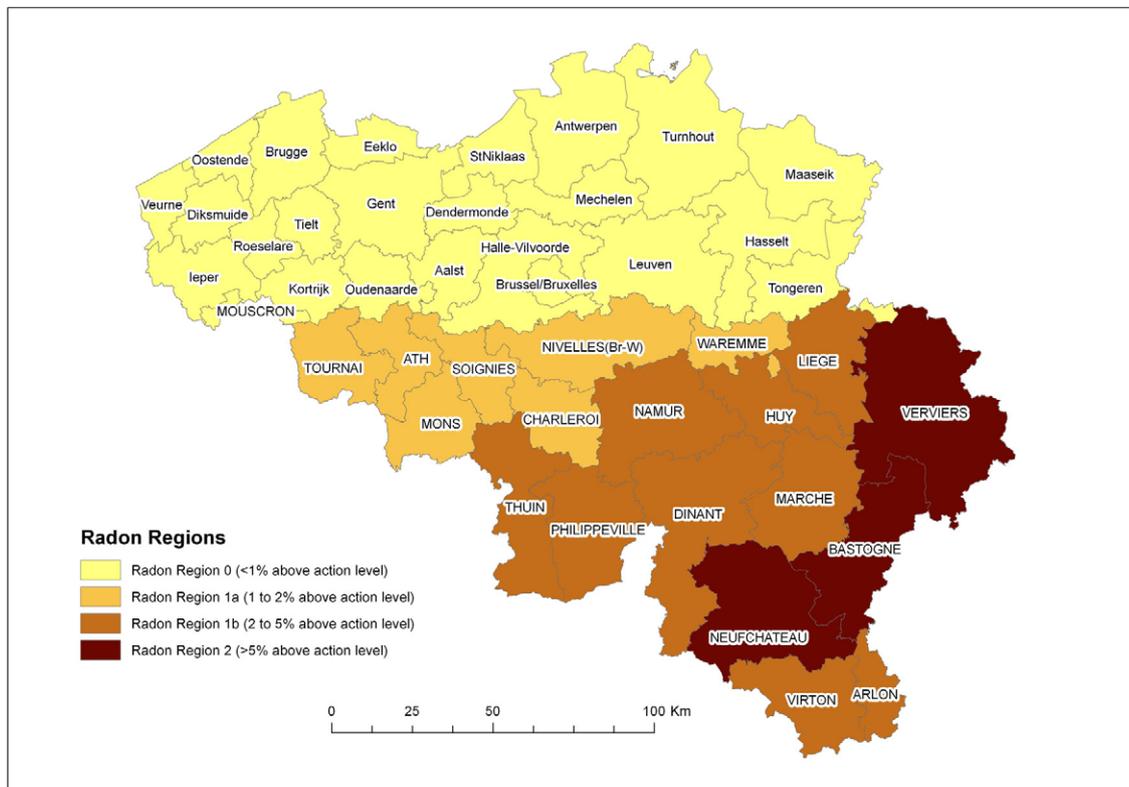


Fig. 1. Radon distribution per district.

Table 1. Statistics for the indoor exposure of the Belgian population. GM: Geometric mean. GSD geometric standard deviation. Radon concentrations are in Bq/m³.

	Population	dwelling	Median	GM	GSD	Max	% >100	% >200	% >400	% >800
Belgium	10584534	5043023	52	59	1.7	4204	11.0	2.2	0.4	0.1
Wallonia	3435879	1570265	69	84	2.0	4204	25.0	4.4	1.3	0.3
Flanders	6117440	2928158	38	44	1.2	70	5.0	0.8	0.0	0.0
Brussels	1031215	544601	38	44	1.2	120	5.0	0.8	0.0	0.0
HRA	376568	166000	127	137	2.5	5500	43.0	33.0	13.1	4.3

Material and methods

The Belgian Cancer Registry contains LC incidence data on a municipal scale starting from the year 2004. The most recent data concern 2005. These data show the variability in LC incidence rate between men and women as well as some regional variation. Table 2 shows the annual LC incidence rate for the period 2004-2005 in Belgium. For this period, about 7000 LC per year have been registered.

Table 2. Observed annual LC incidence rate in Belgium in the period 2004-2005.

Region	population	men	women	total
Belgium	10584534	5361.5	1539.5	6901.0
Wallonia	3435879	1744.0	521.5	2265.5
Flanders	6117440	3213.5	844.0	4057.5
Brussels	1031215	404.0	174.0	578.0
HRA	376568	180.0	61.0	241.0

Table 3. Observed annual LC incidence rate in the HRA in the period 2004-2005.

District	men	women	total
Verviers	127.5	46.5	174.0
Bastogne	21.5	6.0	27.5
Neufchâteau	31.0	8.5	39.5
Total	180	61	241

The linear increase without threshold of the relative risk with indoor radon concentration has been estimated in various recent studies (Baysson et al., 2004; Darby et al., 2005). In this paper, the value of 16% increase of relative risk per trench of 100 Bq/m³ has been used following Darby et al., 2005. This leads to the estimation of LC incidence rate based on the average (GM) radon concentration for each region (Table 4). The obtained values show a good correlation between the observed values (table 2) and calculated LC occurrence. This estimation uses a smoker population of 1/3, which is justified taking into account the importance of the long term exposure of the population.

Table 4. Estimated annual LC incidence rate in Belgium for smokers (S) and non-smokers (NS). Lifetime LC risk (0.16% increase per Bq/m³)* expressed per thousand. Lifetime =70 y.

	LC risk NS (promille)	LC risk S (Promille)	LC NS	LC S	total	Without radon	due to radon
Belgium	4.487	110.534	452	5571	6023	5504	520 (9%)
Wallonia	4.651	114.574	152	1875	2027	1787	240 (12%)
Flanders	4.389	108.110	256	3149	3405	3181	224 (7%)
Brussels	4.389	108.110	42	521	563	536	38 (7%)
HRA	4.999	123.139	18	221	239	196	43 (18%)
No radon*	4.100	101.000					

*After Darby et al.. 2005

A more refined estimate of LC occurrence can be obtained taking into account the variability of the radon exposure within the HRA. This estimate gives a slightly higher LC incidence rate.

Table 5. Estimated annual LC incidence rate in the HRA for smokers (S) and non-smokers (NS).

Exposed to (Bq/m ³)	Ref used (Bq/m ³)	Population in the HRA	annual LC					
			NS	S	total	without radon	due to radon	
>800	800	18828		2	20	22	10	12 (56%)
400 to 800	400	30125		2	24	25	16	10 (39%)
200 to 400	200	86611		4	54	59	45	14 (24%)
<200	100	241004		11	133	144	124	20 (14%)
total		376568		19	232	250	194	56 (23%)

Results

The number of calculated LC (Table 4) corresponds well to the number of observed LC (Table 2). On the national level this would mean that about 8% of the LC incidence rate would be due to radon. whereas this incidence rate due to radon increases to 18% in the HRA. The calculated incidence rate within the HRA depends largely on the exposure class, where for the highest (lifetime) exposures of more than 800 Bq/m³ 56% of the LC incidence rate could be attributed to radon.

When looking at the scatter plot of lung cancer incidence rate and radon concentration per district, no statistical correlation can be observed. For the data per municipality, the LC incidence rates for the observed period are so low that no correlation whatsoever can be observed. When looking at the (age standardised) LC incidence rate among women, however, a vague trend can be observed (Fig. 2).

Figure 3 shows the age standardised LC incidence rate among women per district. This figure shows that the HRA contain some of the highest incidence rates in the country, except for one district (District *Marche*) with very low LC incidence rates.

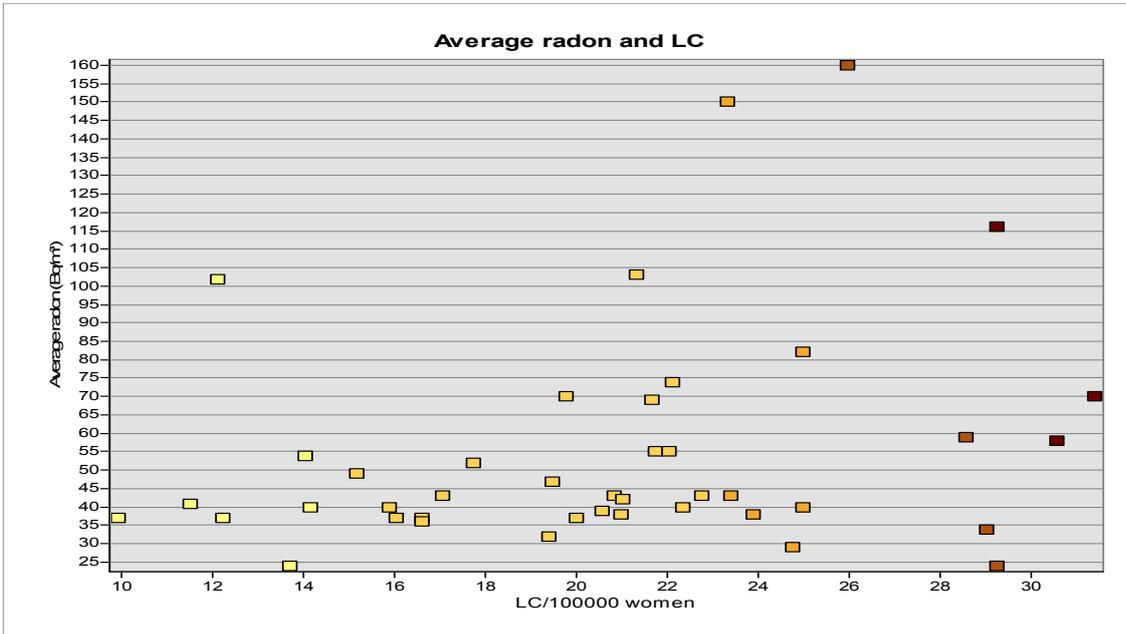


Fig. 2. Scatter plot of the average (GM) radon concentration per district versus LC incidence rate among women.

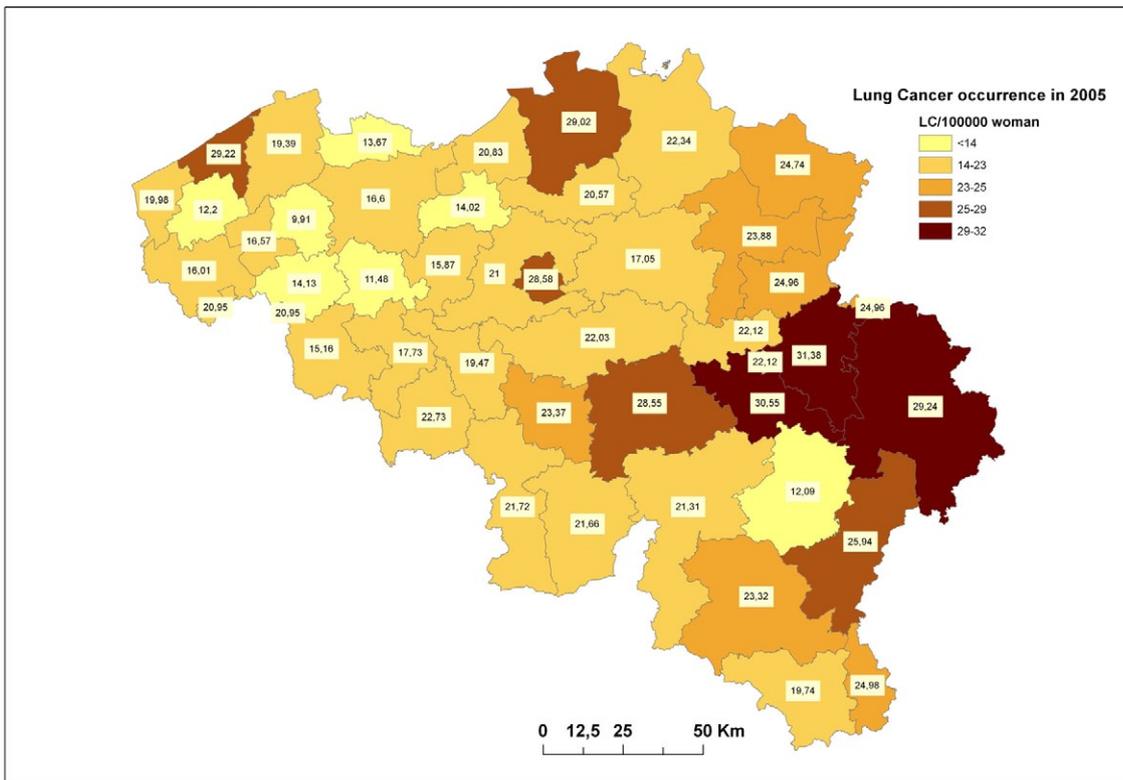


Fig. 3. Distribution of age standardised LC incidence rate among women per district.

Figure 4 shows the radon distribution per municipality on the Belgian territory. This figure shows that, in the case of the district 'Marche', partly covered by the HRA, only 4 municipalities, representing only 22% (12368) of the population of the total district (53123) actually are within the HRA.

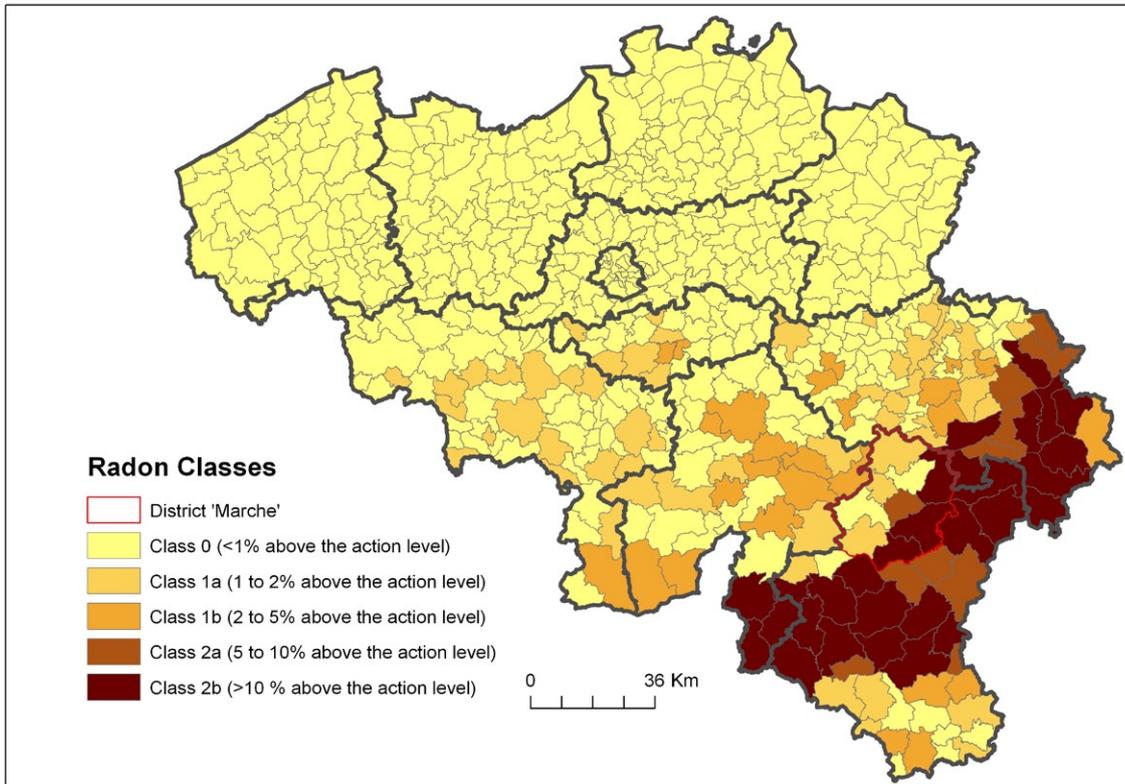


Fig. 4. Radon distribution per municipality.

Discussion

The LC incidence for 2004-2005 contained in the National Cancer Registry correlates well with the data calculated from the radon risk studies. Comparing the observed number of lung cancers to the calculated number of lung cancers, there is a better match for the high risk areas than for the other areas. Part of the explanation could be that much more radon measurements have been made in the HRA than in the less affected regions, improving the accuracy of the calculated LC incidence values.

A slight trend can be observed when looking at the distribution of radon on the territory and LC incidence rate for women per district. A remarkable deviation from this general trend (district 'Marche' on fig. 4) could be due to the discrepancy between the district boundaries and the HRA limits. Refining the resolution of the LC incidence rate data to the municipality scale, however, leads to too few cases to allow statistical correlation. A possible trend in the LC incidence rate data among men, from the other hand, seems not at all suggested by the data. Smoking habits and occupational exposures might be a reason for this.

Conclusions

A reoccurring question among the population in the high risk areas concerns the link between regional variations in LC incidence rate and increased indoor radon concentrations in their region. The current preliminary study investigates the risk estimates based on the recently published international epidemiological studies of radon and LC, applied to the high radon risk areas in Belgium, and compares them to the observed number of LC in this region as available from the Belgian Cancer Registry. Although the Belgian Cancer Register contains until today only data for the years 2004-2005, some preliminary conclusions can be drawn from the present analysis.

LC incidence rate correlates well with LC estimates taking into account radon, based on the most recent international epidemiological studies (Baysson et al., 2004; Darby et al., 2005). For areas with a better estimation of radon concentration distribution, the fit between the observed and calculated LC incidence rate is better. This confirms the quality of the used epidemiological studies and their ability to estimate the influence of radon on the general LC incidence rate and hence to allow a risk reduction policy based on the epidemiological findings.

This preliminary study indicates that the correlation between the regional variation of LC incidence and the regional variation in radon concentration is statistically weak and remains until now unproven. This is partly due to the very low number of cases, and due to the high uncertainty about other influencing factors, such as smoking/living habits and migration of inhabitants. Once the Cancer Registry data set will be extended and contain the LC incidence rate data of most recent years, a statistical study could possibly reveal this correlation, as is suggested by the weak trend already observed for LC incidence rate among women.

References

- 90/143/EURATOM. 1990. Recommendations of the Commission. of 21 Februari 1990. relative to the protection of the population against the dangers resulting from indoor radon exposure. Official Journal of the European Communities L 080 du 27/03/1990. p. 0026 – 0028.
- ARBIS. 2001. Règlement général de la protection de la population. des travailleurs et de l'environnement contre le danger des rayonnements ionisants (RGPRI). Arrêté royal du 20 juillet 2001. Moniteur belge. 30/08/2001. p. 28909-29368.
- Baysson H., Tirmarche M., Tymen G., Gouva S., Caillaud D., Artus J-C., Vergnenegre A., Ducloy F. and Laurier D. Indoor radon and lung cancer in France. *Epidemiology* 2004; v. 15: 709-716.
- BEIR IV. 1988. Health risks of radon and other initially deposited alpha-emitters. US National Research Council Report. National Academy Press. Washington DC.
- BEIR VI. 1998. Health effects of the exposure to radon. US National Research Council Report. National Academy Press. Washington DC.
- Darby S. et al. Radon in homes and risk of lung cancer: collaborative analysis of individual data from 13 European case-control studies. *British Medical Journal* 2005; v. 330: 223-227.
- ICRP 60. 1990. Recommendations of the International Commission on Radiological Protection. International Commission on Radiological Protection. Publication 60. Oxford. UK. Pergamon Press. 1991. 215 p.

- Poffijn A. and Vanmarcke H. The Indoor Radon Problem in Belgium. In: Indoor Air Quality and Ventilation. 1990; Selper Ltd. pp. 339-345.
- UNSCEAR 2000. Sources and Effects of Ionising Radiation. Rapport to the General Assembly. United Nations.
- Zhu H.C., Charlet J.M. and Tondeur F. Geological Controls to the Indoor Radon Distribution in Southern Belgium. The Science of the Total Environment 1998; v. 220. no. 2-3: 195-214.

Estimation of seasonal correction factors – a new model for indoor radon levels in Irish homes

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Abstract

Indoor radon concentrations have been shown to vary considerably with season. Many countries account for this by applying a correction factor to radon measurements of less than one year. To date, Irish radon measurement services have used correction factors based on data collected during a UK national survey of radon in 2000 homes in the 1980s. In the absence of similar data for Ireland at the time, these were considered suitable for use due to the similarities between the climate, house types and lifestyles in both countries. In order to better estimate the long term radon concentration in Irish homes from measurement results, a dataset comprising measurements from 5640 Irish homes was analysed and used to derive a set of correction factors specifically for Ireland. These were generated by means of Fourier decomposition analysis and the new correction factors compared, using 95% confidence intervals, to those derived in the UK using the same analysis and to those currently in use in Ireland. In both cases, differences were found between 10 of the 12 monthly seasonal correction factors. The results of this analysis will be given along with an overview of the methods used.

Introduction

1.1. Background

Radon is a naturally occurring radioactive gas which originates from the decay of uranium present in rocks and soils. When radon surfaces in the open air, it is quickly diluted to harmless concentrations, but when it enters an enclosed space, such as a house or any other building, it can sometimes accumulate to relatively high concentrations.

In air, radon decays quickly to produce radioactive particles that, when inhaled, are deposited in the airways and in the lungs. These result in a radiation dose which, over a long period of time, may lead to lung cancer. Exposure to radon in homes is linked to between 150 and 200 lung cancer deaths each year in Ireland. This represents 10 to 15% of all cases of lung cancer in Ireland and it is the second most significant cause of lung cancer after smoking (RPII and NCRI 2005).

Indoor radon concentrations can vary significantly due to a large number of factors which include the local geology, soil permeability, building and lifestyle characteristics and climate (Gunby et al 1993). Ireland's relatively high indoor radon concentrations were established during the National Radon Survey which was carried out between 1992 and 1999 by the Radiological Protection Institute of Ireland (RPII 2002). An average radon concentration of 89 Bq/m³ was calculated for Ireland, based on the 11,319 homes measured during this survey. This national average has been shown in a recent survey by the World Health Organisation to be the eighth highest concentration in the world (WHO 2009). Since 1989 the Radiological Protection Institute of Ireland (RPII) has worked to raise awareness of this issue and provides a measurement service to encourage home-owners to measure and, where necessary, remediate their homes.

To measure indoor radon concentrations the RPII use a passive alpha track-etch detector which consists of a two-part polypropylene holder and a CR-39 (polyallyl diglycol carbonate) detection element (RPII 1992). The annual average radon gas concentration for a home is determined using two detectors; the first is placed in the main living area and the second placed in the main bedroom for at least three months. This three month measurement is then converted to an annual average radon concentration by applying a seasonal correction factor. The seasonally adjusted annual average radon concentration for the home may then be compared with the National Reference Level of 200 Bq/m³.

1.2. Seasonal correction factors

The temperature difference between indoors and outdoors combined with the effect of wind on a building result in a lower atmospheric pressure indoors relative to that in the ground. This results in a pressure-driven flow of radon from the ground into the building, once an entry route exists (Wrixon et al 1988). Consequently, external changes in temperature between seasons can result in significant variation in indoor radon concentrations. For this reason it is important to apply seasonal correction factors to radon measurements of less than one year. In Ireland, the seasonal correction factor applied to any three month measurement is the mean of the three individual monthly correction factors for the measurement period (RPII 1994). These were derived from data collated for the UK national survey by Wrixon et al (1988). As mentioned in Organo and Murphy (2007), the suitability of these Irish factors has not been assessed until now, as it was assumed that the seasonal characteristics of both the UK and Ireland are similar.

The use of seasonal correction factors is a complex issue and has been much debated in the literature. Miles (2001) has shown that, for homes of "atypical" construction, factors such as wind speed and direction may have more influence on radon levels than the external temperature. He pointed out that a significant minority of homes (maybe 10 to 20% in the UK) have no substantial seasonal variation or followed a different seasonal pattern to that for typical homes. However, he showed that for a "typical" home, i.e., a home that responds to the weather in a manner typical to many Northern European homes, the application of seasonal correction factors improved the accuracy of estimates of the annual average radon concentration. Denman et al (2007)

agreed that such correction factors improve the accuracy of predictions of long-term risks for measurements of at least three months.

It has been shown that one of the most significant effects on indoor radon concentrations is rock type (Gunby et al 1993) and that the type of geology can impact on seasonal variation. For example, it has been shown that radon-rich sedimentary geologies show a high degree of seasonal variation, while radon-rich igneous geologies result in relatively constant radon concentrations (Groves-Kirkby et al 2009). Consequently, a number of studies advise against the use of a single seasonal correction factor for a wide range of geologies. Pinel et al (1995) initially raised concern regarding this while more recently, Gillmore et al (2005) also advised caution in applying a single set of seasonal correction factors to regions with complex geologies. Pinel et al's study calculated correction factors using a series of measurements made in southwest England. However, despite the very different geology in this part of the country and different time-scales over which the measurements were made, the correction factors derived agreed closely with the original correction factors based on nationwide data (Wrixon et al 1988).

Due to this concern regarding the application of general seasonal correction factors to specific regions, a number of studies have derived regional seasonal correction factors. A study by Denman et al (2004) in an area with uniform geology showed that the seasonal variation observed did not match the "average" seasonal correction factors derived by the National Radiological Protection Board (NRPB) for use across the UK (Wrixon et al 1988). This study was carried out on a small sample size (34 homes) and over a limited geographical area and consequently, it is not surprising that the correction factors differ from those derived by the NRPB. The UK Childhood Cancer Study Investigators (2000) also derived region specific seasonal correction factors and concluded that the use of these improved the accuracy of their data. However, other studies have derived regional seasonal correction factors and found either that there was no statistical difference between these correction factors and the "average" correction factors (Grainger et al 2000) or that the differences were minor (Baysson et al 2003).

On balance, it is clear that the use of seasonal correction factors will result in a better estimate of the long term indoor radon concentration. On this basis, a collaborative study was carried out between the RPII and the School of Mathematical Sciences at University College Dublin to derive seasonal correction factors specifically for Ireland.

Material and methods

The statistical methodology used to estimate seasonal correction factors for Ireland is based on that described in Pinel et al. (1995). This makes use of the lognormality of background-corrected indoor radon concentrations and describes the data using Fourier decomposition. The data is transformed appropriately and a linearization is used to maintain approximately normal errors for least squares regression. The Fourier parameters are estimated by least squares regression and used to compute the appropriate seasonal correction factors.

This methodology results in two equations. The first is used to calculate “three month seasonal correction factors” which may be applied to correct radon measurements of three months (equation 1):

$$\hat{f}_i = \frac{3 \sum_{k=1}^{12} \hat{m}_k}{12 \sum_{k=i-1}^{i+1} \hat{m}_k} \quad (1)$$

The second equation is used to calculate “one month seasonal correction factors” and may also be applied to a radon measurements of greater than three months. The mean of the individual monthly correction factors for the measurement period is calculated and applied to the radon result.

$$\hat{f}_i^{(1)} = \frac{\sum_{k=1}^{12} \hat{m}_k}{12 \hat{m}_i} \quad (2)$$

Application of this method to 5,640 background-corrected, lognormally distributed data from the RPII’s home measurement database results in two sets of seasonal correction factors for use with future radon measurements in Irish homes. This statistical methodology is described in full detail by Burke et al. (2010).

Results

3.1. Comparison with UK factors

Table 1 reports the three-month seasonal correction factors (equation 1) calculated for Ireland using the Fourier decomposition analysis alongside the factors calculated by Pinel et al. (1995) for the UK using the same analysis. It should be noted that the convention adopted in reporting the seasonal correction factors means that the UK factors reported below are in fact the reciprocals of those presented by Pinel et al.

A simulation study was carried out – simulating 10,000 datasets, each consisting of monthly data with 1,000 observations in each of the twelve months. This allowed the calculation of the empirical 95% confidence intervals for the Irish factors.

Table 1. New Irish seasonal correction factors compared to UK factors.

Measurement Month (i)	New Irish Factors	New Irish Factors: Standard Error	New Irish Factors: 95% Confidence Interval	UK factors (Pinel et al, 1995)
1	1.14*	0.00627	(1.12, 1.17)	1.35
2	1.14*	0.00633	(1.12, 1.17)	1.27
3	1.10	0.00502	(1.08, 1.13)	1.10
4	1.04*	0.00220	(1.02, 1.07)	0.91
5	0.97*	0.00217	(0.94, 0.99)	0.75
6	0.89*	0.00728	(0.87, 0.92)	0.65
7	0.86*	0.01106	(0.83, 0.88)	0.64
8	0.86*	0.01123	(0.83, 0.88)	0.74
9	0.89	0.00769	(0.87, 0.92)	0.89
10	0.96*	0.00259	(0.93, 0.99)	1.09
11	1.04*	0.00189	(1.01, 1.06)	1.25
12	1.10*	0.00485	(1.08, 1.13)	1.35

Note:

Correction factors apply to a three month period, centred on measurement month i

A significant difference between factors is indicated with *

The standard errors were calculated using the Delta method (Pawitan 2001)

It is clear that all of the factors are significantly different with the exception of the factors associated with the third and ninth months (March and September). These months correspond to the time points close to where the graph of the two sets of factors intersect (Figure 1).

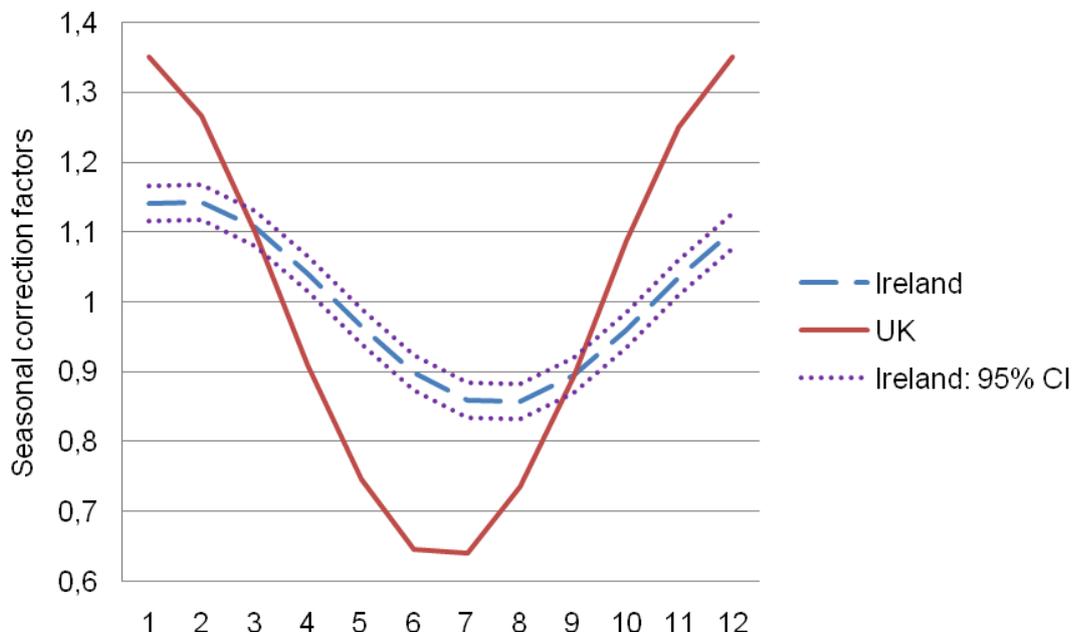


Fig. 1. Comparison of new Irish seasonal correction factors with UK factors for months 1 - 12

3.2. Comparison with seasonal correction factors currently used in Ireland

The seasonal correction factors currently in use in Ireland (RPII 1994) are one month factors based on the Wrixon et al. moving average analysis of UK data. The seasonal correction factor that is presently applied to any three month measurement is the mean of the three individual one month seasonal correction factors for the measurement period. These are given in Table 2 where they are compared with the one month seasonal correction factors that have been calculated in this study using equation (2).

The Irish seasonal correction factors calculated in this study are significantly different from the current factors in ten of the twelve months (Table 2). The two sets of factors associated with measurement months 4 and 10 (April and October) are not found to be significantly different (Figure 2).

Ideally, in order to fully validate the newly calculated seasonal correction factors, we would compare seasonally corrected observations to true annual measurements for each dwelling. Unfortunately, since this was not a designed experiment, we do not have access to both short term and corresponding annual measurements on a house-to-house basis and this validation analysis cannot be done. However, we can provide some evidence to support the robustness of the new Irish seasonal correction factors. In particular, we have examined the year-to-year variation of the factors by analysing data from two three-year subgroups (1999-2001 and 2003-2005) and found that the pattern of the seasonal correction factors remains stable across the years.

To illustrate the application of these factors in practise, an example may be useful for the reader. Consider a January measurement of 130 Bq/m^3 . The RPII estimate the total measurement uncertainty to be 27% (Hanley et al 2008). The 95% confidence interval on the measurement is therefore (94.9 Bq/m^3 , 165.1 Bq/m^3). The January factor (1.16) with corresponding 95% confidence interval (1.14, 1.20) is then applied to each end of the measurement confidence interval (94.9 Bq/m^3 , 165.1 Bq/m^3). This allows us to create a 95% confidence interval for the seasonally adjusted value (108.19 Bq/m^3 , 198.12 Bq/m^3).

Table 2. Comparison of new and current seasonal correction factors for Ireland.

Measurement Month	New Irish Factors	New Irish Factors: 95% Confidence Interval	Current Irish Factors
1	1.16*	(1.14, 1.20)	1.35
2	1.16*	(1.14, 1.20)	1.30
3	1.12*	(1.10, 1.16)	1.20
4	1.05	(1.02, 1.08)	1.05
5	0.96*	(0.93, 0.99)	0.90
6	0.89*	(0.85, 0.91)	0.75
7	0.85*	(0.80, 0.86)	0.60
8	0.84*	(0.80, 0.86)	0.65
9	0.88*	(0.85, 0.90)	0.80
10	0.96	(0.92, 0.98)	0.95
11	1.04*	(1.01, 1.07)	1.10
12	1.11*	(1.10, 1.15)	1.20

Note:

Correction factors apply to a one month period

A significant difference between factors is indicated with *

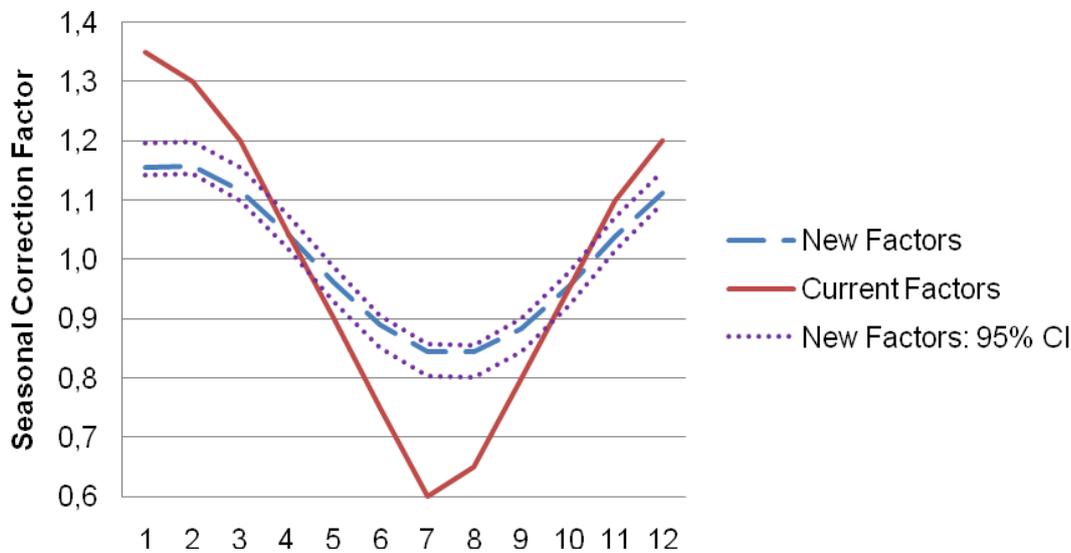


Fig. 2. Comparison of new and current one-month seasonal correction factors for Ireland for months 1 to 12.

Discussion

The “three month” correction factors have been generated from three-month data so ideally, if all measurements were exactly three months duration, these correction factors would be applied to future radon measurements. However, in reality, many measurements exceed three months, making use of “three month” correction factors impractical. In this paper we also have estimated a set of “one month” correction factors. For measurement periods differing from three months, the use of the mean of the individual one month correction factors for the measurement period is more practical and flexible. Use of these factors has shown that there is negligible difference in the correction factor that is applied, whichever set of correction factors are chosen.

Both the “one month” and the “three month” correction factors differ from the equivalent factors derived by Pinel et al. and Wrixon et al. There may be a number of reasons for this observed difference. It has been shown that monthly mean radon concentrations correlate strongly with the monthly mean outdoor temperature during the measurements (Miles 1998). Overall, there are larger extremes of temperature in the UK, most likely due to the climate moderating influence of the Atlantic Ocean on Ireland. This may account for some of the observed differences in seasonal correction factors. As discussed earlier, seasonal variation in indoor radon concentrations may also be affected by other external factors such as local geology, the structure of the dwelling or climate and may vary from year to year. In addition, it may not be appropriate to apply correction factors for measurements of less than three months, to homes of atypical construction or those built on unusual geology. Analysis, to investigate the effects that these external factors may have on the seasonal correction factors derived, is currently ongoing in University College Dublin.

Conclusions

The main aim of this paper was to produce, for the first time, a set of seasonal correction factors for indoor radon levels in Ireland derived from Irish data. Prior to this the factors used in Ireland were based on UK data.

The new set of seasonal correction factors for Ireland is calculated using a Fourier decomposition procedure recommended by Pinel et al. (1995) as an improvement on the Wrixon et al. (1998) procedure. The new seasonal correction factors for Ireland are statistically significantly different from the current factors in use in Ireland and the UK.

As discussed, we are aware that there are other external factors that influence the seasonality of radon emissions. However, the set of factors reported here is that which best summarizes the position for a typical Irish home and their use will provide a better estimate of long-term radon concentrations in Irish homes.

References

- Baysson H, Billon S, Laurier D, Rogel A, Tirmarche, M. Seasonal correction factors for estimating radon exposure in dwellings in France. *Radiation Protection Dosimetry* 2003; 104(3): 245–252.
- Burke O, Long S, Murphy P, Organo C, Fenton D, Colgan P.A. Estimation of seasonal correction factors through Fourier decomposition analysis – a new model for indoor radon levels in Irish homes. *Journal of Radiological Protection*, *In Press*.
- Denman A R, Crockett R G M, Groves-Kirkby C J, Phillips P S, Woolridge A C. Reliability of integrating radon gas measurements in the domestic environment – an inter-comparison between one-week, one-month and three-month sampling. In: *Proceedings of the 11th International Congress of the International Radiation Protection Association*. 2004 May 23-28; Madrid, Spain. ISBN 84-98078-05-2.
- Denman A R, Crockett R G M, Groves-Kirkby C J, Phillips P S, Gillmore G K, Woolridge A C. The value of seasonal correction factors in assessing the health risk from domestic radon – a case study in Northamptonshire. *UK Environment International* 2007; (33): 34–44.
- Gillmore G K, Phillips P S, Denman A R. The effects of geology and the impact of seasonal correction factors on indoor radon levels: a case study approach. *Journal of Environmental Radioactivity* 2005; (84): 469–479.
- Grainger P, Shalla S H, Preece A W, Goodfellow S A. Home radon levels and seasonal correction factors for the Isle of Man. *Physics in Medicine and Biology* 2000; (45): 2247–2252.
- Groves-Kirkby C J, Denman A R, Phillips P S, Crockett R G M, Sinclair J M. Seasonal variation in European radon measurements. *Geophysical Research Abstracts* 2009; (11); EGU2009-4351-1.
- Gunby J A, Darby S C, Miles J C H, Green B M R, Cox D R. Factors affecting indoor radon concentrations in the United Kingdom. *Health Physics* 1993; 64(1): 2–12.
- Hanley O, Gutiérrez-Villanueva J L, Curriuan L, Pollard D. Assessment of the uncertainties in the Radiological Protection Institute of Ireland (RPII) radon measurements service. *Journal of Environmental Radioactivity* 2008; (99): 1578–1582.
- Miles, J C H. Mapping radon-prone areas by lognormal modeling of house radon data. *Health Physics* 1998; (74): 370–378.

- Miles J C H. Temporal variation of radon levels in houses and implications for radon measurement strategies. *Radiation Protection Dosimetry* 2001; 93 (4): 369–375.
- Organo C, Murphy P. The Castleisland Radon Survey - follow-up to the discovery of a house with extremely high radon concentrations in County Kerry (SW Ireland). *Journal of Radiological Protection* 2007; (27): 275–285.
- Pawitan Y. In *All Likelihood: Statistical modeling and inference using likelihood*. New York: Oxford University Press; 2001.
- Pinel J, Fearn T, Darby S C, Miles J C H. Seasonal correction factors for indoor radon measurements in the United Kingdom. *Radiation Protection Dosimetry* 1995; 58(2); 127–132.
- Radiological Protection Institute of Ireland. *Radon in Dwellings in Selected Areas of Ireland*. Dublin: Radiological Protection Institute of Ireland; 1994.
- Radiological Protection Institute of Ireland. *Radon in Dwellings, the Irish National Radon Survey*. Dublin: Radiological Protection Institute of Ireland; 2002.
- RPII and NCRI. *Health Risks due to Exposure to Radon in Homes in Ireland - the Implications of Recently Published Data Joint Statement by the Radiological Protection Institute of Ireland and National Cancer Registry of Ireland*. Dublin: Radiological Protection Institute of Ireland; 2005.
- The UK Childhood Cancer Study Investigators. The United Kingdom childhood cancer study: objectives, materials and methods. *British Journal of Cancer* 2000; 82(5); 1073–1102.
- World Health Organisation. *WHO Handbook on Indoor Radon – A Public Health Perspective*. Geneva: World Health Organisation; 2009.
- Wrixon, A D, Green, B M R, Lomas, P R, Miles, J C H, Cliff, K D, Francis, E A Driscoll, C M H, James, A C, O’Riordan, M C. *Natural Radiation Exposure in UK Dwellings NRPB-R190*. London: HMSO; 1988.

Upgrade of the NIRS radon chamber – generation of aerosol-attached radon progeny

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Abstract

A condensation monodisperse aerosol generator has been used in NIRS radon-aerosol chamber; aerosol particles are generated by the evaporation–condensation method and supplied into the chamber through the sampling port. Carnauba wax is used as the aerosol material. This study describes the generation and measurement techniques for radon and its progeny, in order to make available an accurate calibration facility for radon concentration and to allow investigations covering fundamental questions of physics with regard to the behavior of radon and its progeny as a function of the environmental parameters. Furthermore, we try to control the monodisperse aerosol with a differential mobility analyzer.

The study of behaviour of radon and its decay products in the low layer of the troposphere

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Abstract

Radon and its decay products are often used like tracers of dynamic processes in the atmosphere. They are used to study climatic phenomena and to produce climatic models scores of the time.

The source of radon in the atmosphere is the bedrock. The transport of radon from soil could be characterized by radon flux; UNSCEAR (2000) presents the estimation of the worldwide average of radon flux $0.016 \text{ Bq}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$. The value of radon flux in one place isn't in the time constant - it is influenced by three fundamental parameters: the concentration of radon in bedrock, the soil moisture and permeability of soil. Methods of determination of radon flux are very sensitive on interpretation of gained results in the dependence on the atmospheric condition for individual measurement.

The concentration of radon and its decay products isn't in the low layers of the atmosphere constant - it is strongly influenced by dynamics of the atmosphere. The main factors which influence the concentration of decay products are dry and wet depositions. Generally it is possible to observe differences between concentrations in the day and in the night and in cold and warm parts of the year. The mean concentration of radon outdoor are about $10 \text{ Bq}\cdot\text{m}^{-3}$ according to UNSCEAR (2000).

The research in this area was supported by project of SUJ 200402, investigation of a vertical and horizontal distribution of radon and its decay products in the atmosphere was realized among others.

Dose

Only a minority of mankind could be characterized as workers of category A (B) and a negligible number of workers is employed in waterworks and other NORM workplaces; therefore, we take into account the remaining men and women.

It is estimated [1], that the inhalation of radon decay products (RnDP) represents an essential part of human irradiation (dose).

The "radon" influence greatly differs for individual states. Our detectors for radon measurement were applied in Kuwait and the concentrations were many times lower than European results. Values in ships cruising to the South Pole were also one one-hundredth of the values measured in Central Europe.

Not only do thousands of kilometers or miles play a role, an Austrian village Umhausen is split due to different geological structures in two radon levels.

Czech Masiff

A very small country in Central Europe, the Czech Republic – CZ, “suffers” due to an influence of tectonic processes ending 5.10^6 years ago. Many years after (1985) it was organized representative research led to a mean of indoor EER (energy equivalent radon concentration connected with RnDP) of $55 \text{ Bq}\cdot\text{m}^{-3}$. It could be transformed to a year’s average of radon concentration of $140 \text{ Bq}\cdot\text{m}^{-3}$; probably the largest mean in the world.

The method of this estimation was very simple – an application of a solid state nuclear track detector (SSNTD): Kodak LR115 in this wave “bare” without the diffusion chamber. The choice of application in dwellings was governed by electricity consumers list.

The Task

The question:

When values of radon in dwellings are so high in Central Europe, what happens to the concentration outside? The indoor concentration is influenced not only by bad insulation of houses, but mostly by intensive radon flux from the Earth’s surface.

(It has been published that radon concentration outdoor in Masiff Central in France is sometimes more than $1000 \text{ Bq}\cdot\text{m}^{-3}$!)

Therefore, this is one of the reasons why the Czech State Office for Nuclear Safety (SONS) supported our outdoor measurement (the project SUJ 200402).

For this reason we developed methods for the estimation of instantaneous values of EER (“grab sampling” – called BUHS), pseudocontinuous measurement (TS96), and integral month mean estimation (STANTOM).

The output – distance

The results of measurement were interesting in some cases:

The distribution of instantaneous EER was estimated in heights of 0.3 m to 20 m as homogenous (measurement on a crane, on a view-tower). After the application of SSNTD, the radon concentration is seen as decreasing - see results after SSNTD application in diffusion chambers in heights of up to 40 m.

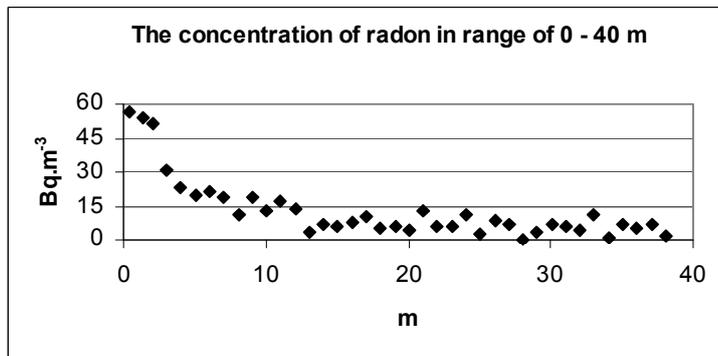


Fig.1. The concentration of radon in range of 0 – 40 m.

The distribution in the dimension of thousands of kilometers does not differ fundamentally – in Braunschweig (western Germany), the morning values were lower to compared to values in our country (the other points), but not dramatically:

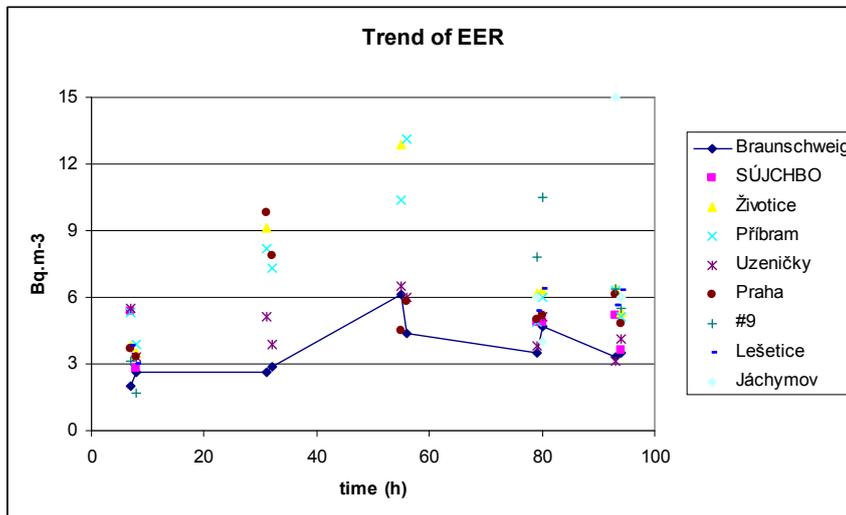


Fig.2. The trend of EER.

We didn't have an opportunity to measure in the Bering strait as our Japanese colleagues, but by chance we measured in Indianapolis (USA), on the coast of Finland and in central Romania. In most cases, the values and tendencies were similar. Of course, in the coastal regions the concentrations were lower due to negligible radon flux from the sea's surface. This hypothesis was supported by a more frequent number of measurements realized by the Dutch, when the influence of wind direction was seen as very important. The North Sea as well as other bodies of water are surely a big anti-source of radon.

We realized measurements around some radon sources or around absent source: old dump tailings originated in the Marie-Sklodowska era and ended up in the 1950s; the largest Czech lake; sludge beds near a reproducing plant. In these cases, no influences of radon sources or their absence were observed. Surprisingly, the mixing of air is probably a prevailing process. There is only one exceptional case – the neighborhood of active uranium mine exhaust, where radon (EER) is higher.

The output – time

Time (which is not always money) plays a role. The daily trend has been published many times. Only in the case of valleys (e.g. in Spain [2]), the tendencies are not typical. In all the cases of our location, there were only two systems observed:

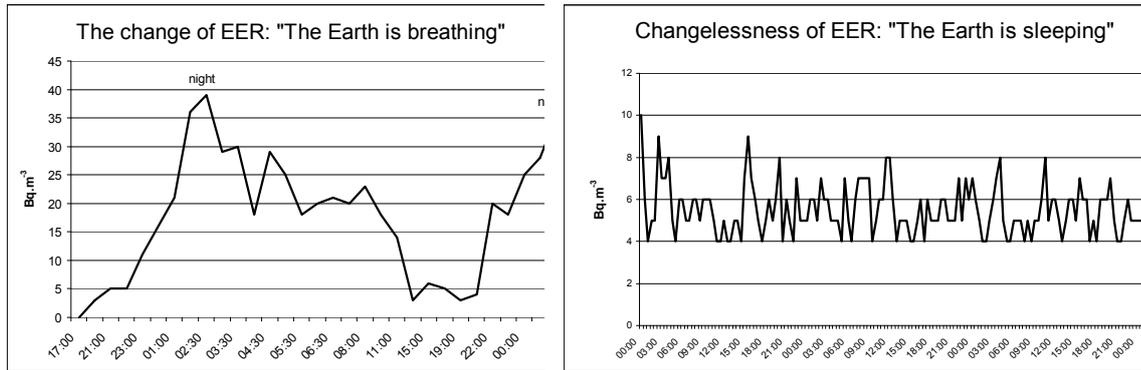


Fig.3 Different behavior of the Earth.

Appendix 1

Other radionuclide concentrations were measured, but the accuracy here is not sufficient for estimations with sufficient uncertainty:

- Concentration of thoron (^{220}Rn) daughter products is less than $0,3 \text{ Bq}\cdot\text{m}^{-3}$
- Concentration of long-lived alpha-emitting radionuclides. The mean result published by the State Institute for Radiation Protection – SURO [3] after a huge volume sampling is $0.5 \text{ mBq}\cdot\text{m}^{-3}$, and our results are lower - $0,2 \text{ mBq}\cdot\text{m}^{-3}$.

Preliminary results of F (ratio of EER and radon concentration) show to values near to 0.3. The ratio of RnDP unattached to aerosol to total RnDP is approximately 0,1.

Appendix 2

There were about 200 000 miners employed in the uranium industry and the registration of their lung cancer incidence and their intake was relatively accurate. This is a reason for including Czech data into metastudies

The described differences between parts of our country also allow us to realise epidemiological studies between inhabitants.

Appendix 3

In 1985 the Organization for Economic Cooperation and Development organized a world-wide comparison to define reference laboratories [4]. As far as we know, more of them do not yet exist (the Australian ARL Yallambie is the only one). One can see again some international intercomparison tendencies. One of them [5] showed us that our measurement could be compared to most results of European laboratories.

Appendix 4 – opinion

Theories exist that radon outdoor is possible to estimated after gamma dose measurement. Our experiences showed us that the correlations between measurable units (gamma dose - radium concentration – radon in soil – radon flux – radon outdoor – EER outdoor) are very weak. These hypotheses were supported by many field measurements.

Appendix 5 – time spent indoors

In our country only 0.03 of inhabitants are involved in agriculture and forestry.

Are there countries around the world where the whole population does not stare at the TV most of evening? After our sociological mini-research, the time spent outdoors in the CZ is 0.07 - lower than the global mean published by ICRP.

The problematic question is the duration of stay in cars and trucks. After commented research, an individual spends 0.05 in vehicles. Of course, due to air-condition, the EER is reduced by factor 2.

Conclusion

It is not surprising, that the intake (and therefore the contribution to dose) for an inhabitant outdoor is not very important.

Taking into account the usual transformation $6 \text{ nSv/ (Bq}\cdot\text{h}\cdot\text{m}^{-3})$ – [6], the dose for inhabitants being indoor is 3 mSv per year and for being outdoors only 0.015 mSv per year. The facts of lower radon concentration of an afternoon were included into the calculation and other sources were not impacted.

Another important fraction of the effective dose is of course the photon irradiation - 1 mSv per year is a rough estimation of this part of the effective dose. We did not see any essential difference between the situation outside and inside buildings.

References

- [1] UNSCEAR (2000): Sources and Effects of Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation Report to the General Assembly with Scientific United Nations, New York, NY.
- [2] D.Arnold, A.Vargas, X.Ortega: Analysis of outdoor radon progeny concentration measured at the Spanish radioactive aerosol automatic monitoring network. Appl. Rad. and Isot., Vol.67 (5), 2009, pp. 833-838
- [3] Kovář, P.: Report on Radiation situation in the Czech Republic in 2008. Bezpečnost jaderné energie, 17 (55), 2009, No. 9/10, p.257
- [4] International Intercalibration and Intercomparison of radon, thoron and daughters measuring equipment. Part I. Radon Measurement. 1985
- [5] Comparison of calibration facilities for radon activity concentration. Euromet Project 657. Final Report – 2005-02-01
- [6] Protection against Radon at Home and at Work. ICRP Publication 65, 1993