16ENV10 MetroRADON

Deliverable D3

Report on indoor and geogenic radon surveys in Europe, including their strategies, the methodologies employed, inconsistencies in the results, and potential methodologies to harmonise data and reduce inconsistencies

European Commission, Joint Research Centre, Ispra, Italy (JRC)

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Introduction

This document, titled "Report on indoor and geogenic radon surveys in Europe, including their strategies, the methodologies employed, inconsistencies in the results, and potential methodologies to harmonise data and reduce inconsistencies" represents the deliverable D3 of the MetroRADON project.

It reports the results of the Activities developed in Task 3.1 and Task 3.2 of Work Package 3 – WP3: Comparison and harmonisation of radon measurement methodologies in Europe of the EURAMET 16ENV10 MetroRADON project. The report is structured as:

- Introduction on WP3
- Brief summary of each Activity of Task 3.1
- Brief summary of each Activity of Task 3.2
- Annexes reporting the full results for each Activity.

Work Package 3 – WP3

One of the specific objectives of MetroRADON project is to compare existing radon measurement procedures in different European countries and to reduce inconsistency of the indoor radon measurements across the Europe. This objective is addressed within WP3 - "Comparison and harmonisation of radon measurement methodologies in Europe".

WP3 aims to:

- collect and analyse meta-information from radon surveys and existing radon databases in European countries;
- evaluate if the data and methodologies are comparable;
- identify how they could be harmonised in the event of methodical inconsistency.

Work Package 3 is divided into four Tasks:

3.1 Overview and analysis of indoor radon surveys in Europe
The aim of this Task is to analyse and evaluate indoor radon surveys in order (i) to identify the rationale and methodologies used, (ii) to identify the extent and possible sources of inconsistencies in the results of indoor radon surveys and (iii) to propose approaches to reduce inconsistencies and improve harmonisation of indoor radon data.

3.2 Overview and analysis of geogenic radon surveys in Europe
The aim of this Task is to analyse and evaluate geogenic radon surveys in order (i) to identify the rationale and methodologies used, (ii) to identify the extent and possible sources of inconsistencies in the results of outdoor geogenic radon surveys and (iii) to propose approaches to reduce inconsistencies and improve harmonisation of geogenic radon data, in analogy to indoor radon in Task 3.1.

3.3 Intercomparisons of indoor radon and geogenic radon measurements under field conditions
The aim of this Task is to organise an intercomparison of indoor radon measurements and geogenic radon measurements (including radon exhalation rate) under field conditions in order to identify physical reasons for

possible inconsistencies, particularly related to sampling and measurement techniques. Three different comparisons will be performed: (i) indoor radon gas (passive and continuous monitoring devices), (ii) radon exhalation from soil and (iii) radon concentration in soil gas.

3.4 Development of options for harmonisation of indoor and geogenic radon data including practical examples

Based on the results for Tasks 3.1, 3.2 and 3.3 the aim of this Task is to develop options for harmonisation of indoor and geogenic radon data, where appropriate using practical examples.

Task 3.1, "Overview and analysis of indoor radon surveys in Europe"

This Task aimed to analyse and evaluate indoor radon surveys in order to:

- identify the rationale and methodologies used,
- identify the extent and possible sources of inconsistencies in the results of indoor radon surveys
- propose approaches to reduce inconsistencies and improve harmonisation of indoor radon data.

There are differences in radon surveys both between countries and within countries (e.g. due to surveys performed in different periods of the year, short-term and long-term measurements or surveys serving different objectives). A radon survey does not merely consist of measurements, although correct measurement methodology is a prerequisite. Instead, a survey is a chain of conceptual and experimental steps from the survey design (corresponding to a given survey policy) through sampling, measurements to evaluation and interpretation of results. Each step has its particular quality assurance (QA) features. Methodologies can be equivalent in terms of QA compliance, yet their results may be inconsistent due to different preliminary boundary conditions. Moreover, a survey has objectives which are related to the needs and possibilities of society and its design and implementation is subject to these.

5 activities were set up to address the goals of this task. The actions and results are summarised in the following. Detailed results are discussed in the Annexes.

Activity 3.1.1.

"VINS, AGES and JRC will undertake a literature review of existing indoor radon surveys in Europe, regarding different steps of the "survey chain" e.g. from the survey design (corresponding to a given survey policy) hrough sampling, measurements to evaluation and interpretation that results in an output. Sources of information will include journals, reports and conference contributions."

The first Activity of the Task of the 3.1 is Activity 3.1.1 aiming to undertake a literature review of existing indoor radon surveys in Europe, regarding different steps of the "survey chain" e.g. from the survey design (corresponding to a given survey policy) through sampling, measurements to evaluation and interpretation that results in an output. VINS, AGES and JRC have undertaken a literature review using available sources of information including scientific journals, reports, conference proceedings and presentations.

One of the outcomes of this activity was a JRC Technical Report: Literature review of Indoor radon surveys in Europe: *G. Pantelić, et al., Literature review of Indoor radon surveys in Europe, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97643-8(online), doi 10.2760/977726 (online), JRC114370*, reported in **Annex 1**. The report contains data available in literature for 45 countries. For each country some of the most important details regarding radon surveys were included in the report, such as: survey goal, sampling strategy, sampling procedure, measurement technique, evaluation of single measurements, survey period, time of year, single measurement duration, number and type of locations, evaluation, interpretation of results, quality assurance and thoron measurements.

The findings of the literature survey where published in a peer reviewed paper: *G. Pantelić* et al*., Qualitative overview of indoor radon surveys in Europe, Journal of Environmental Radioactivity 204, (2019), 163-174, doi: 10.1016/j.jenvrad.2019.04.010,* reported in **Annex 2**. The focus of the overview article was on data that were not included in previous overviews of surveys. Special attention is given to the qualitative and conceptual description of surveys such as types of surveys and their representativeness, sampling strategies and measurement techniques, applied corrections, interpretation of survey results and how/if present thoron was considered.

According to the literature overview, national surveys were conducted in 22 EU countries: Austria, Croatia, Czech Republic, Denmark, Estonia, Finland, France, Greece, Hungary, Ireland, Italy, Lithuania, Luxembourg, Malta, Netherlands, Poland, Portugal, Slovakia, Slovenia, Spain, Sweden and United Kingdom. Only regional surveys were identified in 6 EU countries: Belgium, Bulgaria, Cyprus, Germany, Latvia, and Romania. Outside the EU, national surveys were conducted in Azerbaijan, Belarus, Iceland, Macedonia, Montenegro, Russia, Serbia, Switzerland, Ukraine and Norway. Only regional surveys were identified for Albania, Armenia, Bosnia and Herzegovina, Georgia, Kazakhstan, Moldova, and Turkey.

The number of measurement locations in the surveys covered in this paper differs by four orders of magnitude. The minimum number of locations was selected in Malta's national survey – 85. At the other end of the spectrum, radon measurements from more than 500'000 locations are available in UK. There are at least five countries besides UK with more than 50'000 measurement locations – Russia, Czech Republic, Switzerland, Finland and Norway. Density of the measurement locations per million inhabitants and per 1 000 km^2 is highest in the case of Switzerland, Finland, UK and Czech Republic.

A very important aspect of the qualitative analysis of the indoor radon surveys was the discussion on representativeness, since a truly representative indoor radon survey is difficult to achieve. It is necessary to have a complete list of dwellings and to have random sampling of locations from that list. Any deviation from pure random sampling can cause biases. The general impression from the reviewed literature is that only a few authors gave attention to details about survey design and its representativeness. For performing a representative survey, it is not sufficient only to have random, unbiased sampling of dwellings, but also to have appropriate measurement techniques and appropriate measuring locations. If the goal is to have a representative survey, it should also be part of the survey to test at the end, to what extend representativeness was reached (e.g. by comparison to national census data) which unfortunately in most of the surveys is not done yet.

The overview of reviewed surveys has shown large diversity of used measurement techniques (Fig 1.)

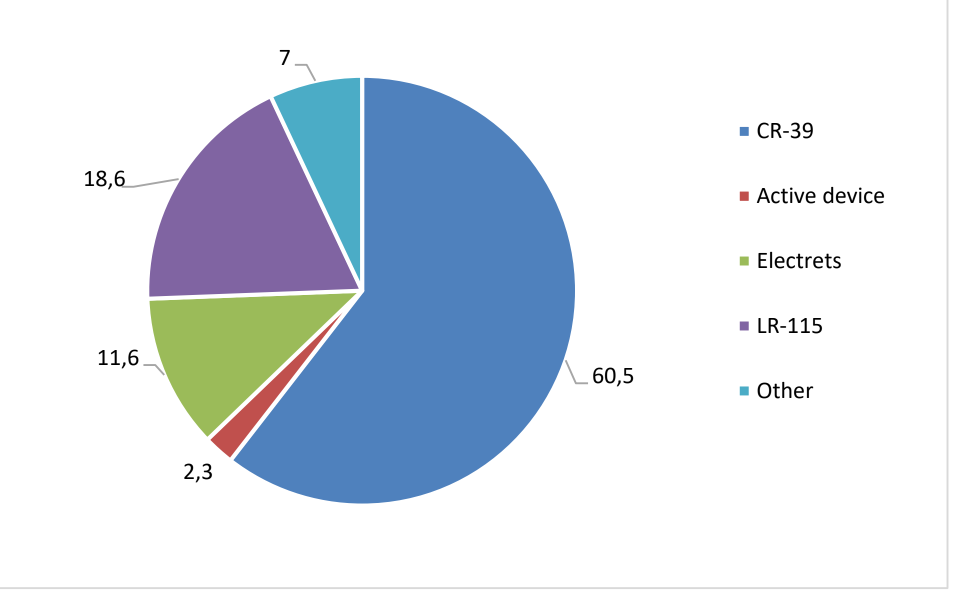

Figure 1. Overview of used techniques for radon surveys

Measurement times are mainly given by the selected measuring technique. For indoor radon measurements by highly sensitive active portable monitors (in Cyprus), the instruments were adjusted to record the data every two hours over a 24 h period. Passive alpha track detectors were exposed for mostly 2-3 months, but also for a one-year periods. Electret detectors were used with times of exposure from minimum 3 weeks, 3 months, up to one year. Due to the method specificity, measurements with charcoal canisters lasted for a few days, mostly three to four days.

Whole year measurements were performed in at least twelve European countries. In most cases, a single detector was exposed for approximately one year, but there were other combinations: two detectors were deployed in six consecutive months periods or four detectors in three consecutive months periods in at least ten surveys, measurements were performed only during winter or during the heating season. This period of year was often selected in Scandinavian and Baltic countries. Other surveys were performed at least partly outside the heating season, or the time of year was not specified in the literature source at all. Radon concentration variability in periods longer than one year was widely neglected, with a few exceptions.

Although different exposure periods were covered by different surveys, information on correction of estimated indoor radon concentration using seasonal factors were generally missing. Correction factor values were mainly taken from literature in some countries, like Albania and Austria the correction factors were obtained by studying the variations in indoor radon concentration observed in summer and winter seasons with respect to the entire year in randomly selected dwellings located in different geographical regions. The most detailed approach was used in Czech Republic where the seasonal corrections were calculated on the basis of the data containing 3 000 weekly measurements in 24 dwellings.

By design, there are various kinds of radon diffusion chambers. Some of them have a non-negligible sensitivity to thoron that is of the same order to the sensitivity to radon. This is especially true for older devices. Relative sensitivity to thoron, assuming that sensitivity is the same for typical radon detectors, is 0.78 for KfK detectors, 0.68 for RadTrak, 0.05 for SSI/NRPB detectors. Since, there are regions with higher thoron than radon concentration, it is also important to consider whether thoron was measured or not. In more than 70 % of surveyed papers, thoron was not mentioned.

The literature survey has shown that indoor radon surveys were performed in most European countries and in many cases the surveys covered the whole country. Methodologies used in the surveys were very diverse, to such extent that it is impossible to find two completely same methodologies. This diversity makes comparison between different surveys difficult and likewise makes it difficult to compile the data to produce a European radon map. Many sources omit some critical information on survey design, which makes it hard to evaluate the methodology or to replicate it. It was found that only in a few papers from the literature survey, authors have paid attention to the representativeness of the performed survey.

More details of the Activity 3.1.1 can be found in **Annex 1** (JRC technical report on Literature review of Indoor radon surveys in Europe) and **Annex 2** (peer review paper: Qualitative overview of indoor radon surveys in Europe)

Activity 3.1.2.

"Based on the information identified in A3.1.1 as missing from the literature, JRC and AGES will prepare questionnaires on policy making, planning and technical details related to indoor radon surveys in order to collect the missing information, and to obtain information about how the countries intend to transpose the EU-BSS into national law. JRC has close links with organisations in Europe involved in radon surveys and will therefore distribute the questionnaires to competent institutions in European countries. For practical reasons, the questionnaires in A3.1.2 may be combined or distributed together with the questionnaires in A3.2.2."

One of the specific objects of MetroRADON project is to compare existing radon measurement procedures in different European countries and use the results to improve the consistency of indoor radon measurements across Europe. For this purpose, based on the information identified in A3.1.1, a questionnaire was developed by JRC, AGES and BfS to collect information on indoor radon surveys in order to:

a) identify the rationale and methodologies used;

b) identify the extent and possible sources of inconsistencies in the results of indoor radon surveys;

c) propose approaches for reducing inconsistencies and improve harmonisation of indoor radon data;

Moreover, some information has been collected about how EU Member States intend to transpose (or have transposed) the latest Basic Safety Standards Directive (Council Directive 2013/59/Euratom) into national law.

The questionnaire has been addressed to all European institutions working in this field (not only national authorities but also regional administrations, universities, research centres). They have been invited to complete a separate questionnaire for each survey.

Apart from the details about respondent, the focus of the questionnaire was on three main topics:

- characteristics of indoor radon survey – design;
- measurements methods;
- data management, statistical treatment, aggregate and mapping.

The questionnaire could provide an answer to the question whether existing indoor radon measurement procedures (including rationale, design, measurement methods, data analysis, etc.) in different surveys are comparable in Europe.

Activity 3.1.3

"BfS and JRC will analyse the information collected in A3.1.1 and A3.1.2 on indoor radon surveys, and will identify and describe differences and possible inconsistencies. The impact and relevance of inconsistencies on stakeholders (the public, regulatory authorities, etc.) will be assessed. If relevant inconsistencies are identified, then it is likely that there will be a repercussion on the country or region involved in the survey, even if QA compliance is given. This may trigger need for "top-down" harmonisation of existing data. In this Activity, the rationale and techniques for harmonisation will be assessed, whilst further elaboration including case studies, where applicable, will be the subject of Task 3.4."

Between December 2017 and July 2018, a total of 56 questionnaire forms on indoor radon surveys were completed and returned by universities, research institutions and competent authorities on national and regional surveys from 24 European countries. **Annex 3 (**Report *"Results of analysis of MetroRADON questionnaire data on indoor radon surveys"*) results from the analysis of replies (performed by JRC, ISS and INAIL) to the questionnaire are presented, highlighting similarities and differences on radon survey methodologies across Europe.

Then BfS and JRC have analysed the information collected in A3.1.1 and A3.1.2 on indoor radon surveys, and have identified and described differences and inconsistencies.

Out of 56 respondents to the questionnaire, the dominant role of respondents was "Specialist/Experts" (19) and "Researchers" (11). Although 87 % of the institutions returning the questionnaire have indicated that more than one survey has been performed in their country (20 countries), only seven institutions from four countries have reported detailed information about all surveys. The majority of countries reported between two and five surveys, while the highest number of surveys performed in a country was 28. It is indicated that 81 % of the performed surveys have already been finished, 17 % are on-going, and only one survey is at the stage of planning, as of mid-2018. The average duration considering all surveys is five years (as arithmetic mean) and the median value is two years. Most of the surveys (46 %) have been indicated as nation-wide and 33 % as federal/regional. However, it is worth noting that at least one national survey was performed in 21 countries. It was indicated in more than 60 % of the questionnaires, that the survey had more than one purpose. The main purposes of the survey were quite homogeneously selected between the following options: "a first idea of the radon situation", "mean radon concentration of population", "mapping" and "identification of radon priority areas". About 50 % of all 56 surveys were reported to have more than one strategy covering almost equally all strategies: population, random, geological, administrative units, grid cells, etc. Although 75 % of the surveys were performed in dwellings, other locations were considered as well, such as: schools, kindergartens, caves, etc. The preferred location of the detectors was ground floor (65 %) while at 25 % of surveys there was no preferred measurement locations. A questionnaire was included in 89 % of the surveys, with the most dominant questions regarding the house type and building materials, followed by questions on heating system and ventilation habits.

A very important part of the questionnaire was about representativeness and to what extent obtained results are unbiased estimates of the targeted true value. It is interesting to notice that more than 60 % of surveys have targeted representativeness.

In almost 70 % of surveys, only one measurement method was used. The dominant type of detectors were solid state nuclear track detectors (around 82 %). In particular, the detector most frequently used was CR-39 (57 %). In Figure 2, an overview of detectors used in the surveys, according to questionnaires is presented.

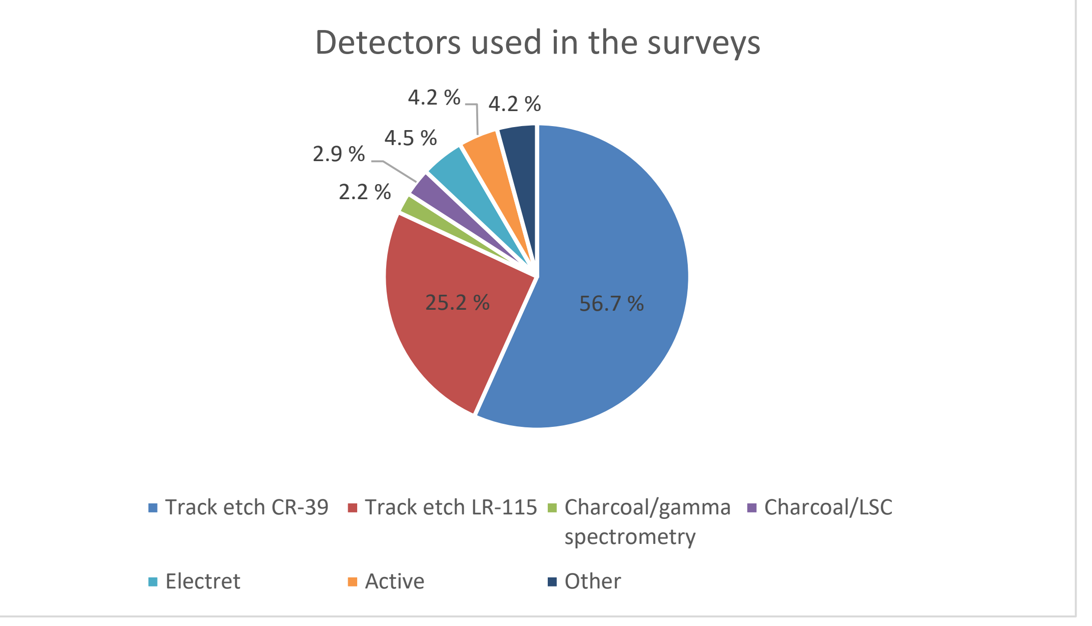

Figure 2. Overview of detectors used in the surveys

Since different types of detectors require different exposure times, detectors were deployed from two days (for charcoal canisters) up to one year for some SSNTD and electret detectors. The largest duration of exposure was 16 months for some SSNTD. In 44 % of surveys, detectors have covered a whole year of exposure. In some surveys, measurements were performed in each season, although the surveys in which the measurements were performed during the winter season were more frequent. Due to different exposure time, from survey to survey, the question was asked whether seasonal corrections were applied and how. However, in most cases, the answer was either that no corrections were applied or the question was not answered. The majority (80 %) did not answer the question how seasonal corrections were applied. Other questions have included inquiry regarding the sensitivity of detectors to thoron, data analysis, etc. More detailed analysis is given in **Annex 3**.

The questionnaire could provide an answer to the question whether existing indoor radon measurement procedures (include rationale, design, measurement methods, data analysis etc.) in different surveys are comparable in Europe. From the answers given by the respondents, it can be roughly concluded that European indoor radon surveys are:

- not comparable for the characteristics of indoor radon survey – design;
- comparable for the measurement's methods;
- too high uncertainty in the answers to say if comparable or not for data management, statistical treatment, aggregate and mapping

Activity 3.1.4.

"SUBG will analyse existing information and data related to the method of retrospective indoor radon measurements using CDs/DVDs and will evaluate the applicability of this approach for indoor radon surveys. The method employs CDs/DVDs as radon detectors (from the available stock stored indoors) and provides long term (> 1 year) retrospective indoor radon concentration results. The method covers the entire range of radon concentrations that can be found indoors and is suitable for identification of buildings with elevated radon concentrations, epidemiology and radon mapping. A very recent development is the possibility to evaluate the impact of the energy-efficiency house retrofit on indoor radon by analysis of 2 CDs/DVDs of different ages."

In this Activity, SUBG has analysed existing information and data related to the method of retrospective indoor radon measurements using CDs/DVDs and has evaluated the applicability of this approach for indoor radon surveys.

The method employs CDs/DVDs as radon detectors (from the available stock stored indoors) and provides long term (> 1 year) retrospective indoor radon concentration results.

Numerous existing references that cover the period from 1999 to 2017 and are related to MetroRADON Tasks are given in **Annex 4.** They reveal the methodology of the CD/DVD method and their different usages. The main directions of usage of the CD/DVD method can be summarized as:

- retrospective dosimetry of radon and thoron (incl. for the purposes of radon mapping);
- identification of radon prone areas and buildings with radon problems (annual average ^{222}Rn > 300 Bq m^{-3});
- retrospective evaluation of the effect of building retrofits on radon levels;
- measurements in working places (incl. mines);

Within the laboratory infrastructure it is possible to calibrate detectors using standard or a posteriori calibration under the conditions that are close to real exposition. The method is traceable to the reference STAR (Systems for Test Atmospheres with Radon) laboratory.

The work regarding the verification of the reliability and quality of the CD/DVD method for ^{222}Rn is based on the long-term exposure that is on-going at UC. Four sets of ten CDs and ten DVDs each were placed at the exposure site (where ^{222}Rn levels are continuously followed). This work is discussed in detail in WP4 and will not be discussed in this report.

The uncertainty of the method is very small and the probability for a false alarm is 5 % with one-year old disks and even lower for older disks, assuming that the disk is correctly dated.

In the era of constantly increasing awareness for energy saving, houses have been improved with respect to energy efficiency (e.g.: changing old windows with tighter new ones). With the CD/DVD method it is possible to retrospectively study the effect of building reconstruction on radon levels using two CD/DVD detectors with different ages as shown in Figure 3.

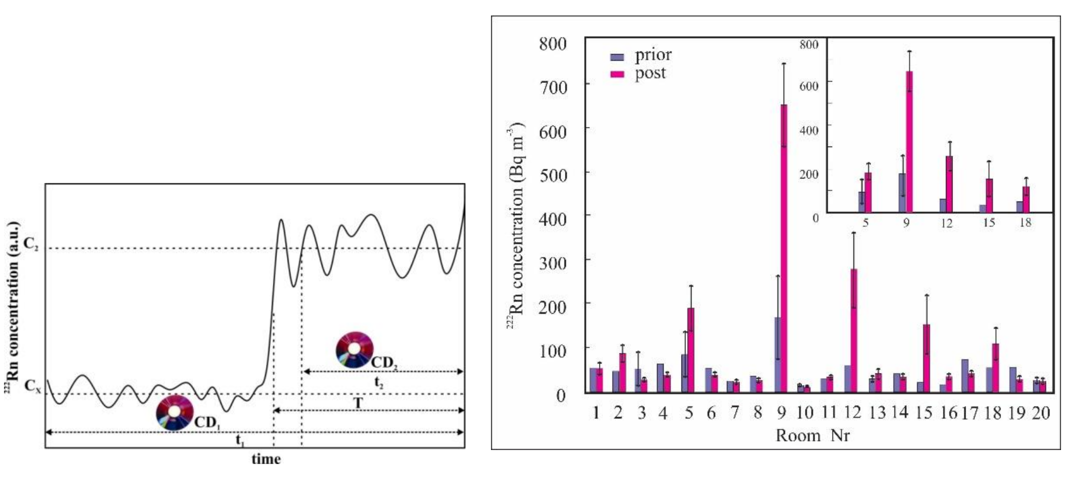

Figure 3. Concept of the CD/DVD method (left) and results of radon measurements in rooms before and after the energy efficiency reconstruction (right).

Previously collected data have shown that in 35 % of the rooms a statistically significant increase (95 % level) of ^{222}Rn concentrations was observed after the energy efficiency reconstruction.

More details about CD/DVD method can be found in the report given in **Annex 5**.

Activity 3.1.5.

"Based on information from A3.1.1-A3.1.4, VINS, AGES, BfS and JRC will compile a report about indoor radon surveys in Europe including their strategies, the methodologies employed, inconsistencies in the results, potential methodologies to harmonise data and reduce inconsistencies and approaches to assist member states to implement the EU-BSS (mapping, providing information about radon exposure to the public, preventive measures, building codes etc.)."

A report on Activity 3.1.5 Regarding Indoor Radon Surveys in Europe has been prepared. The section "*Task 3.1, "Overview and analysis of indoor radon surveys in Europe"* of the present document mainly reports the contents of the report. Below you find the conclusion reported in the report.

Conclusions:

Conclusions from both literature overview and questionnaires on performed indoor radon surveys in Europe are that the overall design of surveys is quite diverse and that it is difficult to find two completely same approaches to a surveys. Often, some of the critical information regarding the design are missing and make it hard to evaluate the survey.

Looking into details, the key question would be to what extent existing indoor radon surveys performed in Europe are different and could they be comparable? By looking at 3 main aspects of the survey: design, measurement methods and data analysis, it can be summarised that: a) designs of surveys performed in Europe are not comparable; b) measurement methods are comparable between surveys; c) data management, statistical analysis and mapping are for some aspects comparable for others not.

The most critical part of the surveys was estimation of representativeness. While literature overview has shown that only in a few surveys representativeness was considered to some extent, according to the answers to the questionnaire, the representativeness was targeted in more than 60 % of surveys. However, answers to more specific questions regarding the representativeness, e.g. how it was achieved and estimated, lead to the conclusion that some inconsistencies exist and need to be further investigated.

In order to provide harmonization of radon data across Europe, it is important to have a representative survey, and it should be a part of the survey to test whether representativeness was reached or not. This can be done by comparison with national census data, for example. Unfortunately, in the large majority of surveys, this is not done. So, if feasible, it is necessary for the harmonisation of data that representativeness is checked. In this way, if representativeness was not reached, sources of biases should be identified, helping to make appropriate corrections. For example, weighting factors could be applied in the case of oversampling in some kind of buildings.

For performing a representative survey, it is not sufficient only to have random, unbiased sampling of dwellings, but also appropriate measurement techniques should be used, regarding e.g. duration of measurement and measuring location. According to the questionnaire, 44 % of surveys were not performed during the whole year, and seasonal corrections were not applied in all of them. Therefore, another important aspect in harmonisation is to apply seasonal corrections. This is a very delicate question since seasonal variation of radon could differ within a country from region to region due to different factors, such as climate, living habits, or building construction.

Furthermore, a non-negligible effect of reported indoor radon concentrations could be due to thoron influence. Although a large percentage of participants knew about the interference of thoron they did not check for thoron presence. Therefore, interference of thoron to the reported indoor radon concentration should be estimated where missing and in case where found necessary, radon concentrations should be corrected.

These questions regarding the harmonisation will be further assessed in Task 3.4.

Task 3.2 - "Overview and analysis of geogenic radon surveys in Europe"

Task 3.2 - "Overview and analysis of geogenic radon surveys in Europe" aims to analyse and evaluate geogenic radon surveys in order to

- identify the rationale and methodologies used;
- identify the extent and possible sources of inconsistencies in the results of outdoor geogenic radon surveys;
- propose approaches to reduce inconsistencies and improve harmonisation of geogenic radon data, in analogy to indoor radon in Task 3.1.

Quantities physically related to geogenic radon (such as uranium concentration in rocks and soils, radon gas exhaled from soil and soil permeability, radon exhalation rate, terrestrial gamma dose rate, geological information and standardised indoor data) are used to estimate the geogenic radon potential and in consequence develop maps of geogenic radon. Its concept is to show "what the earth delivers" in terms of radon, which is the geogenic baseline, which – given anthropogenic factors of building type and the behaviour of inhabitants – leads to a certain level of indoor radon concentration. Hereafter the term "radon exhalation" will be used in the broad sense of "what the earth delivers", hence also taking into account the radon concentration in soil gas.

Geogenic radon maps may serve as base for defining radon priority areas (see WP4), for example by applying thresholds or certain qualitative criteria. The methodology for surveying geogenic radon quantities is different from indoor radon and is therefore treated in a separate task.

Activity 3.2.1
"BFKH, VINS, AGES and BfS will undertake a literature review of existing geogenic radon surveys in Europe, regarding different steps of the "survey chain" e.g. from the survey design (corresponding to a given survey policy) through sampling, measurements to evaluation and interpretation that results in an output, in analogy to A3.1.1. Sources of information will include journals, reports and conference contributions."

BFKH has undertaken a literature review of existing geogenic radon surveys in Europe, regarding different steps of the "survey chain" e.g. from the survey design (corresponding to a given survey policy) through sampling, measurements to evaluation and interpretation of the results in an output. Sources of information include scientific journals, reports and conference contributions.

The results of the literature review have been summarized in a report by Szücs et al. (2018) in **Annex 6**. The report shows the diversity of measurement methodology in several aspects:

- definition and estimation of the Geogenic Radon Potential (GRP); this concerns the actual definition and covariates and proxies used to estimate it;
- sampling design: depth, spatial scheme, areal coverage;
- sampling and measurement methodology: instrumentation;
- evaluation and displaying the results as maps: post maps, class maps, interpolated maps.

Activity 3.2.2
"Based on the information identified in A3.2.1 as missing from the literature, JRC and BFKH will prepare questionnaires on policy making, planning and technical details related to geogenic radon surveys in order to collect the missing information, and to obtain information about how the countries intend to transpose the EU-BSS into national law. JRC has close links with organisations in Europe involved in radon surveys and will therefore distribute the questionnaires to competent institutions in European countries. For practical reasons, the questionnaires in A3.2.2 may be combined or distributed together with the questionnaires in A3.1.2."

One of the specific objectives of WP3 is to compare existing radon measurement procedures in different European countries and use the results to optimise the consistency of indoor radon measurements across Europe. For this purpose, a questionnaire was developed by JRC, AGES and BfS and was sent to all European countries. The scope of this questionnaire is to collect information to analyse and evaluate geogenic radon surveys in order to:

- identify the rationale and methodologies used in Europe;
- identify the extent and possible sources of inconsistencies in the results of outdoor geogenic radon surveys;
- propose approaches to reduce inconsistencies and improve harmonisation of geogenic radon data.

The questionnaire has been addressed to all European institutions working in this field (not only national authorities but also regional administrations, universities, research centres). They have been invited to complete a separate questionnaire for each survey.

The questionnaire intended to collect information about surveys of geogenic radon; this includes Rn concentrations in soil gas and water, radon exhalation from the ground, concerning Rn proper, and for covariates (predictors, proxies) of geogenic Rn: U concentration in the ground, airborne gamma ray surveys and ambient dose rate surveys. Basic information was wanted about methodology (sample acquisition and measurement) and spatial design, next to rather administrative questions.

In **Annex 7** the questionnaire is reported.

Activity 3.2.3
"UC and IRSN will review the existing ISO standards (in particular ISO 11665-7 and ISO 11665-11) on the methodology of radon exhalation measurement (radon concentration in soil gas and surface exhalation rate) in order to assess whether and how appropriate the methodologies in these standards are for use in the project (particularly in Task 3.3 and Task 3.4)."

In Activity 3.2.3, UC and IRSN evaluated the existing ISO standards EN ISO 11665-7:2012 and ISO 11665-11:2016 on the methodology of the radon exhalation measurement and of radon concentration in soil gas measurement, in order to assess whether and how appropriate the methodologies in these standards are for use in the MetroRADON project particularly in Tasks 3.3 and 3.4.

The results of this Activity are reported in **Annex 8.**

Summarising, UC and IRSN agreed that the two ISO standards 11665-7 and 11665-11 are well related to the MetroRADON project. The work of Task 3.3 might provide some relevant data to evaluate the methods and to give some elements for further revision of the standards. One comment on the EN ISO 11665-7 could be sent to the ISO group: to give another example for the measurement of a radon exhalation rate above 5 mBq m^{-2} s^{-1} (Annex B, B.5 Example) in order to be in the scope of the standard. The result of the current example is lower than the limit value given in the scope of the standard.

Activity 3.2.4 and Activity 3.2.5

"BfS and JRC will analyse the information collected in A3.2.1 and A3.2.2 on geogenic radon surveys and will identify and describe differences and possible inconsistencies. The impact and relevance of inconsistencies on stakeholders (the public, regulatory authorities, etc.) will be assessed. If relevant inconsistencies are identified, then it is likely that there will be a repercussion on the country or region involved in the survey, even if QA compliance is given. This may trigger the need for "top-down" harmonisation of existing data. In this Activity, the rationale and techniques for harmonisation will be assessed, whilst further elaboration including case studies, where applicable, will be the subject of Task 3.4."

"Based on information from A3.2.1-A3.2.4, BfS, VINS, AGES and JRC will compile a report about geogenic radon surveys in Europe including their strategies, methodologies employed, inconsistencies in the results, potential methodologies to harmonise data and reduce inconsistencies, the potential to use radon surveys to develop geogenic radon map (Article 103, EU-BSS) and approaches to assist member states to implement the EU-BSS (mapping, providing information about radon exposure to the public, preventive measures etc.)."

A report as stated in Activity 3.2.5 has been prepared and is reported in **Annex 9**. Below you find a summary of this report and the main conclusions.

Geogenic radon questionnaire:

Between December 2017 and July 2018, a total of 50 questionnaire forms on geogenic radon surveys were completed and returned by universities, research institutions and competent authorities on national and regional surveys from 19 European countries. This includes Austria, Belgium, Bulgaria, Croatia, Czech Republic, Finland, Germany, Italy, Lithuania, Netherlands, Norway, Portugal, Romania, Serbia, Spain, Sweden, Switzerland, GB and Ukraine. From several countries, more than one institution responded. A summary is shown in Table 1.

Table 1: Contributors to the questionnaire on geogenic surveys. The figures denote the number of participating institutions in that country. Status (around Sept. 2018): fin – finished; on – ongoing; (not) pl. – (not) planned. If no number is given: only one institute responded in that country. "fin.+pl.", etc. – one survey finished, another planned by the same institution.

ISO code	Soil Radon	Radon exhalation	Radon in water	Geochem-istry	Aero-gamma	ADR
AT	fin.	not pl.	fin.+pl.	fin.		fin.
BE	2 fin., 1 on.	not pl.	1 fin., 2 on.	1 fin, 2 not pl.	2 fin.	2 fin., 1 on.
BG	pl.	not pl.	on.	not pl.	not pl.	not pl.
CH	not pl.	not pl.	not pl.	not pl.	not pl.	not pl.
CZ	1 fin., 2 on.	2 fin.	fin.	fin.	not pl.	fin.
DE	2 fin.	1 fin., 1 not pl	1 not pl.	2 not pl.	1 not pl.	1 fin.
ES	on.+plan.					
FI	fin.	fin.	fin.	fin.	not pl.	fin.
GB	not pl.	not pl.	not pl.	not pl.	not pl.	fin.
HR	on.	not pl.	fin.+on.			
IT	1 fin., 2 on., 1 not pl.	1 fin., 1 pl., 1 not pl.	3 on., 1 pl.	3 on, 1 not pl.	2 on., 1 not pl.	3 on., 1 pl.
LT	on	not pl.	on.	fin.		on.
NL	not pl.		fin.	not pl.	not pl.	fin.
NO	1 fin., 1 not pl		2 fin., 1 on.		1 on.	1 on.
PT	on.	on	on	on	not pl.	fin.
RO	fin.+on.	pl.	fin.+on.	pl.	not pl.	fin.
RS	on.	on.	on.	on.	on	on.
SE	fin.	not pl.	on.	on.	on.	on.
UA	on.	on.	pl.	on.	on.	on.

Soil radon and permeability

Table 2 summarizes the replies about the sampling designs of soil radon measurements. The most common sampling depth appears to be 80 cm, followed by 100 cm (see figure 4)

Table 2: Sampling designs for measuring radon in soil gas. number - number of individual bore holes per sample location; statistic - evaluation of the individual results.

country	geometry	number	statistic
AT	triangle around or line across defined meas. point; size=?	3	AM, max
BE	rand at point (=?) in 1x1km² grid square	2-3	max
BG	construction site in RPA (legal); square sampling grid	10	AM, max, min
CZ	construction site, regular grid (legal)	typically 15	3.quartile
DE	triangle, 5 m side	3	max
ES	lithostrat. unit within 10x10km² grid cell	2	AM, Med
IT-1	"study area", rand. or square scheme	5	AM,GM
IT-2	triangle (size=?)	3	AM,max
LT	diagonal of 10x10m² square	3	AM
NO	Triangle (size=?) of ADR meas. points; within triangle 2 points separated 50cm	2	AM
PT	Geological outcrop or building site; acc. gamma survey or transect across faults	3 to about 1 per 4m²	Med
RO	10x10km² grid cells, rnd within	3	AM,GM,min,max,CV
SE	2 points <15m apart; rnd where possible	2	all data
UA	1 km², square scheme	30	AM,max

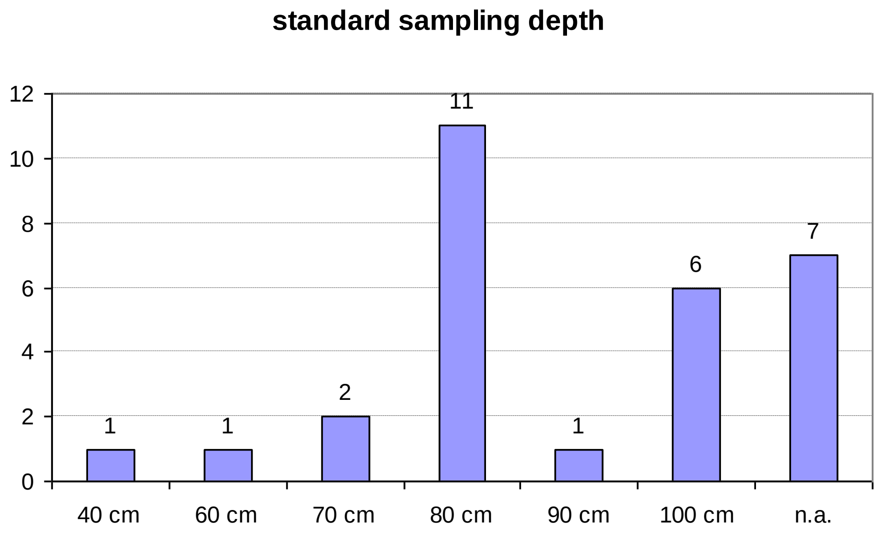

Figure 4. Standard sampling depths for soil radon measurement

About permeability 54 % of respondents that reported geogenic radon surveys also measured permeability parallel to all or parts of the soil radon measurements.

About the sampling point, we can summarize that when reporting soil radon values, attention should be given to indicating for which area a value is thought representative. More precisely, the uncertainty of the reported value should be estimated with respect to a hypothetical mean over a target area, in addition to the measurement uncertainty.

Radon surface exhalation

Most questionnaire participants use the closed box method (some correcting for the finite box size) and analyse the slope and/or the saturation value of radon concentration per time function. One institute uses the method of excess/depleted-^{210}Pb in upper soil layers. Also, in one case, track etch detectors 10 cm above surface were used for long-term exhalation assessment on waste piles. Two participants indicated the use of electrets and two of Si semiconductors.

Radon in water

Many of the institutions that participated in the questionnaire indicated that they measure radon in water. Motivation is mostly legal obligation (ensuring safety of drinking water), scientific interest (not specified - possibly hydrological tracer studies) and support for radon studies (may coincide with tracer studies).

Some use it as complement to assess geogenic radon. Sampled media are drinking and tap water, butalso ground water and spring water. A few also measure surface and thermal waters.

Ambient Dose Rate

Ambient dose rate (ADR) is easy to measure, but achieving comparability of ADR, acquired with different protocols, is not. This concerns the geometrical setup of the measurement system, i.e. its position relative to the environment, which it is supposed to characterize, and the way how data are evaluated. The reason why ADR is considered relevant in geogenic radon study is as proxy to geogenic radon.

Many of the institutions which responded to the questionnaire, also performed ADR surveys. Institutions from 13 countries replied that they performed surveys. In 5 countries, 100 % coverage was achieved, and >80 % in two more countries. Interestingly, the most cited motive for performing ADR surveys is scientific interest, followed by emergency preparedness. ADR is being surveyed and continuously monitored by networks of probes in most European countries. In the questionnaire, the questions about geometry, measurement height and percent conformity were motivated by checking whether participants would find these problems relevant for operating their detectors and for interpretation of results.

Geochemical surveys

Uranium concentration in the ground, or more precisely, the concentration of its progeny ^{226}Ra, is the source of geogenic radon. As motivation for performing geochemical surveys, scientific interest was indicated in the first place, followed by support for radon and geogenic radon potential (GRP) studies.

Conclusions

Relatively much information is available on the status of geogenic radon surveys in European countries, as well as about methodology.

On the other hand, not many countries have performed geogenic radon surveys; therefore, European coverage is poor. Again, on the other hand, surveys and data sets about quantities,which can serve as predictors (U concentration) or proxies (ADR) of the GRP, are available in many countries..

So far, the data have been exploited for generating European wide geogenic radon map only in experimental trials. As expounded in WP4, section 4.3.4, current work seems more focused on developing a geogenic radon hazard index (GRHI) which relies on Europe wide available data bases (such as for geology and geochemistry), rather than on assembling regional un-harmonized datasets. However, this discussion is ongoing.

Regarding methodical harmonization of geogenic quantities, a few issues have been identified. The problems can be solved, but in some cases require further experiments and partly development of procedures for harmonization.

List of Annexes:

- **Annex 1:** G Pantelic et al., Literature review of Indoor radon surveys in Europe, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97643-8(online), doi 10.2760/977726 (online), JRC114370, JRC Technical Report

- **Annex 2:** G. Pantelić et al., Qualitative overview of indoor radon surveys in Europe, Journal of Environmental Radioactivity 204, (2019), 163-174, doi: 10.1016/j.jenvrad.2019.04.010

- **Annex 3:** Report: Results of analysis of MetroRADON questionnaire data on indoor radon surveys

- **Annex 4:** List of references regarding CD/DVD method

- **Annex 5:** Report on Activity A.3.1.4

- **Annex 6:** Report on Activity A3.2.1

- **Annex 7:** Geogenic radon questionnaire, A3.2.2

- **Annex 8:** Report on Activity A3.2.3

- **Annex 9:** Report on Activity A3.2.4 –A3.2.5

Corrigendum

Page 85 of the Annex 1, G Pantelic et al., Literature review of Indoor radon surveys in Europe, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97643-8(online), doi 10.2760/977726 (online), JRC114370, JRC Technical Report.

Change

47 Conclusions
TO BE COMPLETED.

To the following

Conclusions

The report contains data available in literature for 45 countries. For each country some of the most important details regarding radon surveys were included in the report, such as: survey goal, sampling strategy, sampling procedure, measurement technique, evaluation of single measurements, survey period, time of year, single measurement duration, number and type of locations, evaluation, interpretation of results, quality assurance and thoron measurements.

Annex 1

G Pantelic et al, Literature review of Indoor radon surveys in Europe, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97643-8(online), doi 10.2760/977726 (online), JRC114370, JRC Technical Report

European Commission

JRC TECHNICAL REPORTS

Literature review of Indoor radon surveys in Europe

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VUKANAC I, NIKOLIĆ JK, CINELLI G,
GRUBER V

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Contents

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Abstract

Natural radioactivity is the main source of population exposure to ionising radiation. Radon and its progenies contribute with more than 50% to annual effective dose received from all sources of ionising radiation (UNSCEAR, 2000) and has been identified as a second leading cause of lung cancer after smoking (WHO, 2009).

The aim of this report, under the MetroRadon project, is to provide a literature review of existing indoor Rn surveys in Europe. Different steps of the "survey chain", e.g. from survey design through sampling, measurements to evaluation and interpretation, that yield an output have been explored.

Journal papers and papers in international and national conference proceedings were reviewed, resulting in data collected from 45 countries. The information contained in the report should serve as an input to propose approaches to reduce inconsistencies and improve harmonization of indoor radon data.

1 Introduction

Natural radioactivity is the main source of population exposure to ionising radiation. Radon and its progenies contribute with more than 50% to annual effective dose received from all sources of ionising radiation (UNSCEAR, 2000).

Radon is a radioactive noble gas, with no stable isotopes. Three naturally occurring isotopes ^{222}Rn, ^{220}Rn and ^{219}Rn originate from the decay chain of three primordial decay series ^{238}U, ^{232}Th and ^{235}U, respectively. The relative importance of Rn isotopes with respect to the population exposure, increases with an increase of their half-lives and their relative abundance and thus the most abundant and long-lived one, ^{222}Rn ($T_{1/2}$=3.82 days) is the most important. In the regions with high $^{232}Th/^{232}U$ ratios, ^{220}Rn (also known as thoron) whose half-life is short-lived ($T_{1/2}$=55.6 s) compared to the half-life of ^{222}Rn, cannot be ignored.

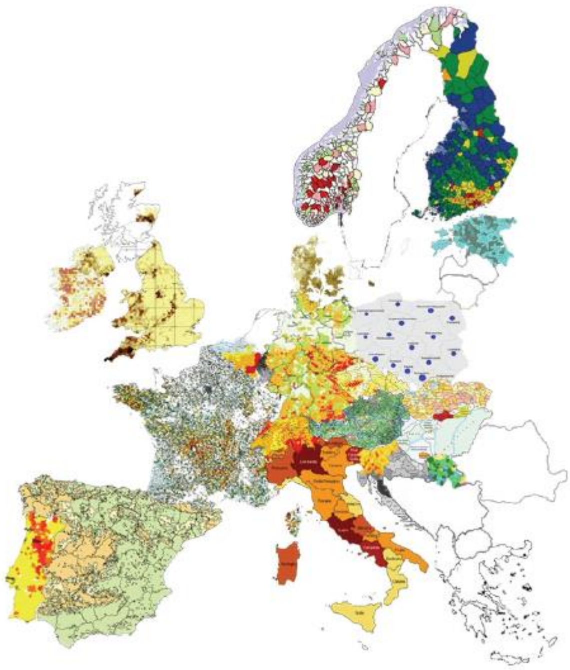
First written documents related to the radon problem dated from XVI century when Paracelsius reported about high mortality of solver miners in Saxony and Bohemia and at the end of XIX century, those deaths were attributed to lung cancer. It took 50 years from the discovery of radon in 1901, to identify radon progenies as major cause of lung cancer.

Based on the epidemiological studies performed in Europe, Asia and America, radon has been identified as a second leading cause of lung cancer after smoking, being responsible between 3-14% of all lung cancers (WHO, 2009).

The exposure of members of the public or of workers to indoor radon is now explicitly taken up in the scope of Council Directive 2013/59/Euratom (Article 2 (2d)) (European Union, 2013). Based on this, the Directive introduces, for the first time, legally binding requirements on protection from exposure to radon.

A first overview of indoor radon surveys in Europe has been performed in 2005 by Dubois (2005). The map shown in Figure 1.1, reported in the document, reflects the strong heterogeneity of indoor radon surveys, mapping strategies, reference levels etc.

Figure 1.1. Overview of indoor radon maps in Europe from 2005

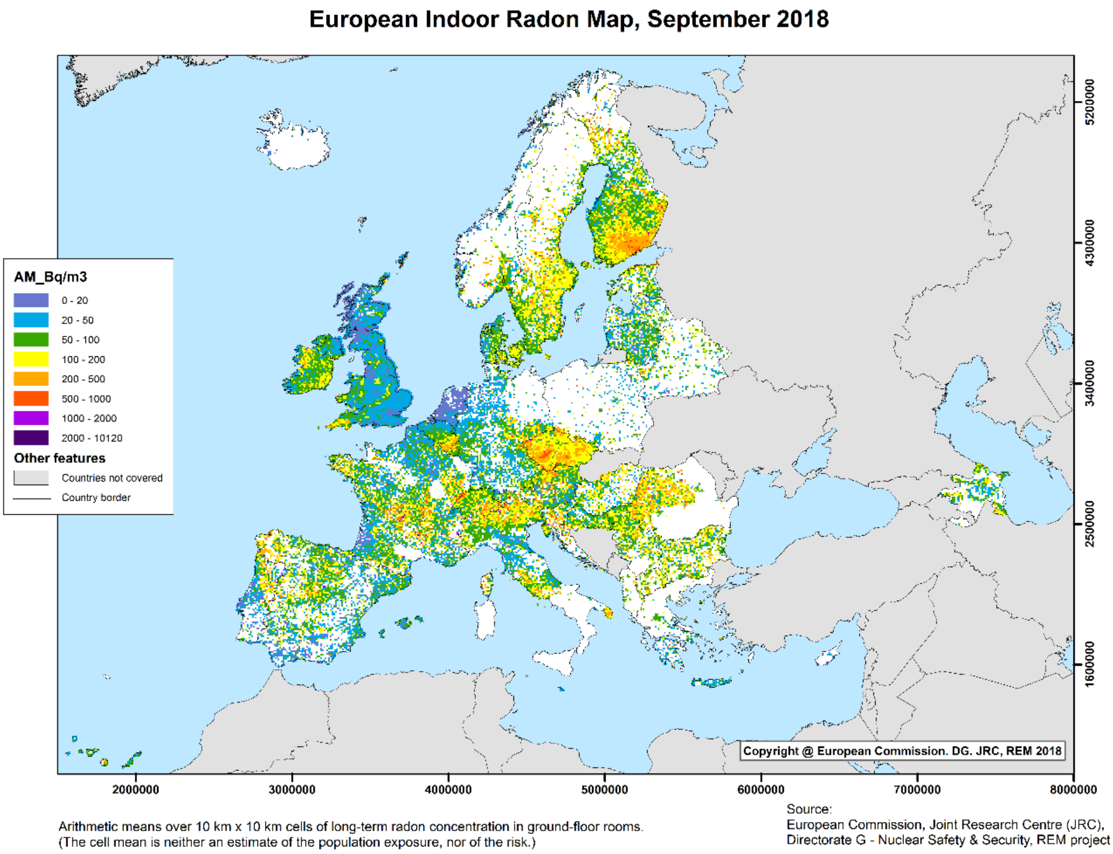


Source: Dubois, 2005.

Already a huge effort has been taken with this respect by the Joint Research Centre of the European Commission, by collecting Rn data from different countries and integrating them in a homogeneous way to produce a European Indoor Radon Map using 10 km x 10 km grid cells (Dubois, 2010). Last update of map has been done in September 2018 (Figure 1.2).

The European indoor radon map is part of the European Atlas of Natural Radiation (EANR), a collection of maps displaying the levels of natural radioactivity from different sources. The digital version of the EANR is available on line at https://remon.jrc.ec.europa.eu/ (Cinelli et al., 2018) and the publication is foreseen in 2019.

Figure 1.2. Arithmetic mean over 10 km × 10 km cells of long-term radon concentration in ground-floor rooms of 35 European countries. Latest update, September 2018



Thirteen years after Dubois (2005) the MetroRADON partners have been working to update information about indoor radon surveys in Europe.

The aim of this report, under the Activity of A 3.1.1 of the MetroRadon project, is to provide a literature review of existing indoor Rn surveys in Europe, regarding different steps of the "survey chain" e.g. from the survey design (corresponding to a given survey policy) through sampling, measurements to evaluation and interpretation that results in an output. Journal papers and papers in international and national conference proceedings were reviewed.

For each country some of the most important details regarding Rn survey were included in the report, such as: Survey goal, Sampling strategy, Sampling procedure, Measurement technique, Evaluation of single measurements, Survey period, Time of year, Single measurement duration, Number and type of locations, Evaluation, Interpretation of results, Quality assurance, Thoron measurements.

Finally, the report contains data available in the literature for 45 countries, and should serve as an input to propose approaches to reduce inconsistencies and improve harmonization of indoor radon data.

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UNSCEAR (2000) United Nations Scientific Committee on the Effects of Atomic Radiation Report, Annex B: Exposure due to Natural Radiation Sources. Vol. 1, United Nations, New York.

WHO (2009) WHO Handbook on Indoor Radon. World Health Organisation, WHO, Geneva.

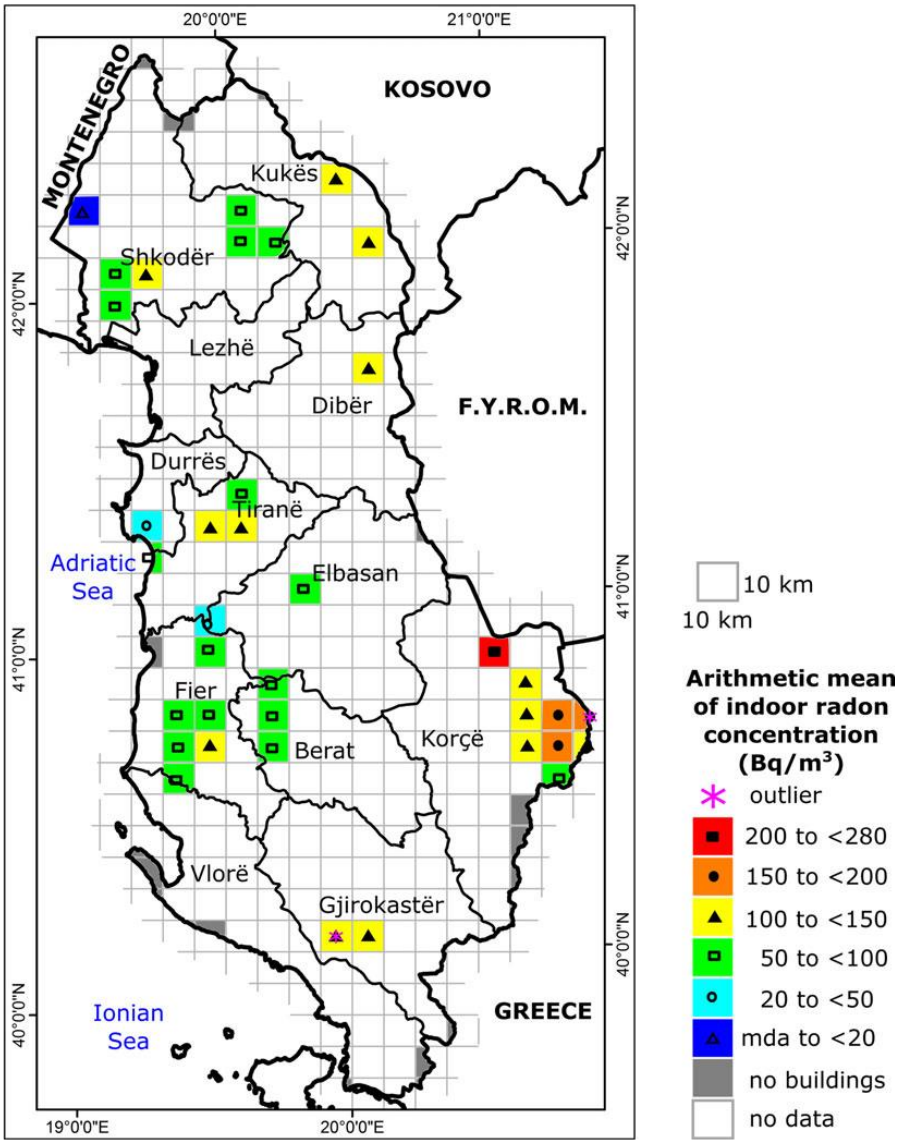
2 Albania

A national survey was conducted between 2009 and 2014. This survey aims to gather operational information by investigating the indoor radon concentrations in the dwellings of the most populated cities located in 10 of the 12 regions of Albania. The first stage of the national indoor radon survey includes the design of a regular grid with 345 cells of 10 x 10 km resolution that covers the whole territory of the Republic of Albania.

The indoor radon concentrations are measured by passive detectors based on SSNTD Radtrak, consisting of track etch detectors made of CR 39 plastic films contained in an antistatic holder (NRPB/SSI type). Detectors are placed in the inhabited rooms of the dwelling at approximately between 1 and 2 m height from the floor and as far as possible from windows and doors in order to avoid air currents. Each detector is exposed for 3 months during summer and winter seasons. For quality control purposes, duplicate detectors were placed in randomly selected dwellings. In order to obtain an estimate of the annual average, the carried out measurements are corrected for seasonal variations. The correction factors are obtained by studying the variations in indoor radon concentration observed in summer and winter seasons with respect to the entire year in randomly selected dwellings located in different geographical regions (Bode Tushe et al., 2016).

The indoor radon survey is conducted from 2009 to 2014, in 10 regions (18 districts) of Albania, where 247 dwellings. The distribution of indoor radon concentrations ranges between 14 and 1238 Bq/m^3, with an arithmetic mean (120±67) Bq/m^3. It was observed that the indoor radon concentrations follow a lognormal distribution. The population-weighted average indoor radon concentration was calculated to be 101 Bq/m^3 (Bode Tushe, 2016).

Figure 2.1. The arithmetic mean of indoor radon concentrations (Bq/m^3) over a 10x10 km cells grid.



Source: data obtained from the survey 2009 to 2014 (Bode Tushe, 2016).

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Bode Tushe, K. et al., (2016) First Step Towards the Geographical Distribution of Indoor Radon in Dwellings in Albania, Radiation Protection Dosimetry, Volume 172, Issue 4, 1 Pages 488–495.

3 Armenia

Some measurements were performed before 1991. Apart from that measurements, "Radon program" in Armenia is "just starting" as quoted by (Haroyan, 2017).

Within this project, in total 800 alpha track detectors from "GAMADATA" Sweden company were deployed in 2010 and 2011.

In 147 measurements, radon concentration was found to be larger than 200 Bq/m^3.

Figure 3.1. Map of regions of Armenia.

Source: Haroyan, 2017.

Table 3.1. Number of deployed detectors in each region of Armenia.

Region	I step	II step	Total
Yerevan	59	62	121
Armavir	31	19	50
Ararat	25	20	45
Kotayq	37	37	74
Aragacotn	37	32	69
Shirak	25	31	56
Tavush	30	32	62
Gexarqunik	38	44	82
Syuniq	41	34	75
Lori	43	51	94
Vayoc Dzor	27	30	57

Source: Haroyan, 2017.

References

Karen Haroyan, 2017, National Radon Programme and Radon Action Plan, Presentation, RER/9/136-1701370, Yerevan, Armenia, 23 - 27 October, 2017.

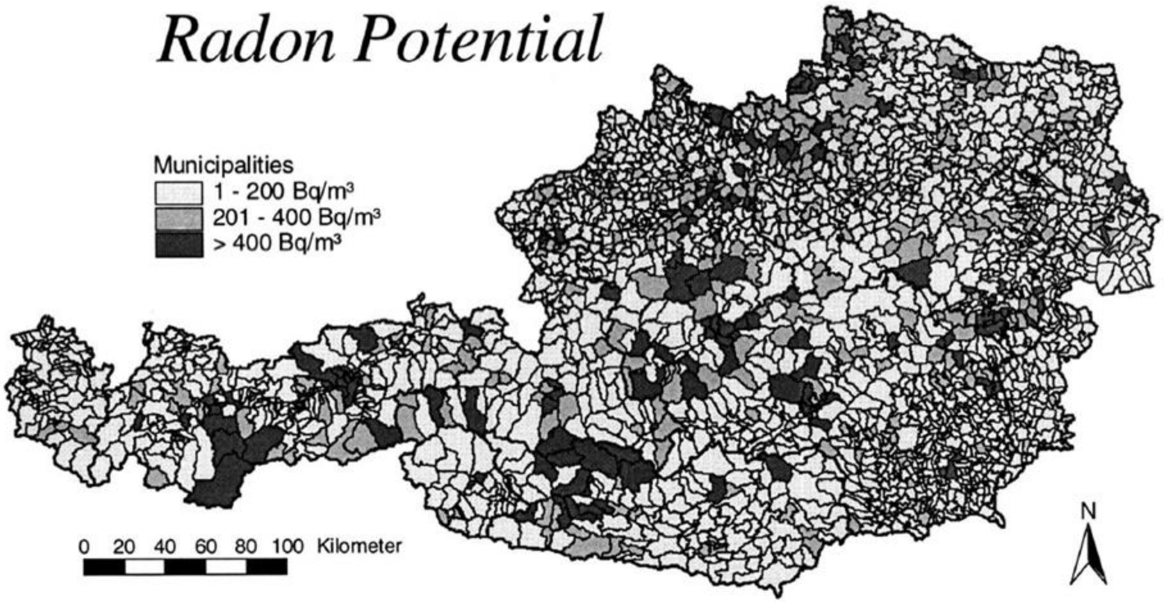
4 Austria

Survey on national scale was performed between 1992 and 2001. Survey goal was to find areas with enhanced indoor radon concentrations and to define areas with elevated risk. Dwellings were selected by random sampling. In total, 40000 measurements were performed in 16000 ground floor rooms. Usual procedure was to place 2 detectors in most frequently used room, 1 to 2 meters from the floor, away from doors and windows. Questionnaires were also distributed with the detectors. Three detector types were used: electret E-Perm detectors, track detectors KFK and charcoal detectors with liquid scintillation counting, Pico-Rad. One single detector type was used in each municipality. Measurements were usually performed in autumn or spring and seasonal correction factors were applied (Friedmann, 2005).

Descriptive statistics and log normality checks were used to evaluate the data. Based on the data, mean radon potential map was constructed (expected radon concentration in standard situation) and mean radon concentration map. Municipalities were divided in three categories – municipalities with mean concentration above 400 Bq/m^3, between 200 Bq/m^3 and 400 Bq/m^3, and below 200 Bq/m^3 (Friedmann, 2005).

The quality of the measurements was checked by intercalibration, intercomparisons, parallel measurements and other QA/QC programs. Thoron measurements were performed in selected locations. Thoron concentration thus measured was negligible (Friedmann, 2005).

Figure 4.1. Radon potential map.



Source: Friedmann, 2005.

References

Friedmann H., (2005), Final Results of the Austrian Radon Project, Health Physics 89, 4, pp. 1-10.

5 Azerbaijan

Indoor radon survey in Azerbaijan was performed in 2010. Since ultimately, data had to be integrated in the European Indoor Radon Map, Institute of Geology and Geophysics got support from the Swiss National Science Foundation of around 2500 radon detectors of the Gammadata–Landauer type.

Radon detectors were placed randomly in 2404 houses in different regions of the country, mainly in residential but in some cases in industrial buildings. Detectors were exposed in the period from November till December 2010 and did not exceed 2 months since cold season in Azerbaijan is short.

Each detector was accompanied with a questionnaire that besides general data (det ID, dates of exposure, etc) contained also information about floor, type and material of the measured building, etc.

Uncertainty of the measurement was considered. The level of uncertainty for each single dosemeter is around 15%, according to the supplier, Gammadata–Landauer and our laboratory, with another 1% error resulting from problems in transport.

The obtained data were processed using purely statistical methods.

Measured radon concentrations varied considerably: from almost radon-free houses to around 1100 Bqm^{-3}. Out of the 2404 measured houses, 169 were above 200 Bqm^{-3} and 418 remained between 100 and 200 Bqm^{-3}.

The frequency distribution of the measured radon concentrations: log-normal character with a median of 58 Bqm^{-3} and a mean of 84 Bqm^{-3}.

Geological aspects as well as distribution of radon concentrations in buildings with respect to the floor level and building materials were analysed. In Figure 5.1, a spatial indoor radon distribution in Azerbaijan is presented.

Figure 5.1. Spatial indoor radon distributions in Azerbaijan.

Source: Hoffmann, 2016.

References

M. Hoffmann et al., 2016 First Map of Residential Indoor Radon Measurements in Azerbaijan. Rad. Prot. Dosim. pp 1-8, doi:10.1093/rpd/ncw284.

6 Belarus

According to the reference (Yaroshevich et al., 2012), the national survey was conducted with main purpose to monitor radon. Radon monitoring was performed in a period 2004 – 2012 in all region of Belarus and in town of Minsk. 3444 locations (exploited dwellings, industrial and public buildings)) in all administrative regions (6) in Belarus were covered by this campaign. A new concept and a research radon program in Belarus for the period up to 2013 are developed. Sampling strategy was based on geological characterization of different regions and population density. Measurements were carried out with solid state track detectors, LR-115 type 2, DOSIRAD (France). Detector were exposed for 1,5 up to 3 months. Evaluation of a single measurement was performed by chemical etching in a NaOH solution (1.22 g/cm^3) at 50 °C for 170 min. Subsequently the tracks on the etched film were counted manually with a microscope (200×).

Evaluation of results contained arithmetic and geometric mean calculation, comparison between different regions and calculation of annual effective dose. Correction for thoron was included. Annual mean indoor EEVA values vary from 31 Bq/m^3 to 76 Bq/m^3, the average annual population doses – over the range of 2.0 – 4.8 mSv/year. The highest percentage of dwellings where Rn concentration exceeded 200 Bq/m^3 was in Grodno region (4.5 %), the lowest one (0.6 %) – in Birest region. (Yaroshevich et al., 2012)

In reference (Vasilyeva, 2015) results of measurements of radon in Republic of Belarus in 2015 are given. For 4078 new buildings, radon concentration was more than 100 Bq/m^3 in one building, and in 424 existing buildings radon concentration was between 100 Bq/m^3 and 200 Bq/m^3 in 8 buildings (in other were less) in Gomel, Grodno and Mogilev region. Descriptive statistic of measurements of radon in Belarus in 2004 – 2013 period (average equilibrium equivalent concentration – EEC, maximum EEC and percentage of measurement results that exceeded 200 Bq/m^3 are given, also.

Table 6.1. Results of measurements of radon indoors in Republic of Belarus in 2004-2013 years (scientific data).

Region	Average equilibrium equivalent concentration (EEC), Bq/m^3	Maximum equilibrium equivalent concentration (EEC), Bq/m^3	Value exceeding equilibrium equivalent concentration (EEC) (%) >200 Bq/m^3
Brest region	31	220	0,6
Vitebsk region	76	515	2,2
Gomel region	35	507	0,7
Grodno region	66	808	4,5
Minsk	74	1052	5,3
Minsk region	84	1052	6,1
Mogilev region	57	313	1,4
All regions	57	1052	2,5

Source: Vasilyeva, 2015.

References

Yaroshevich et al., (2012), Indoor Radon And Radon Component Of Population Radiation Doses In Different Areas Of Belarus, Минск, Белорускаја Наука, 56, No. 6, pp. 92.

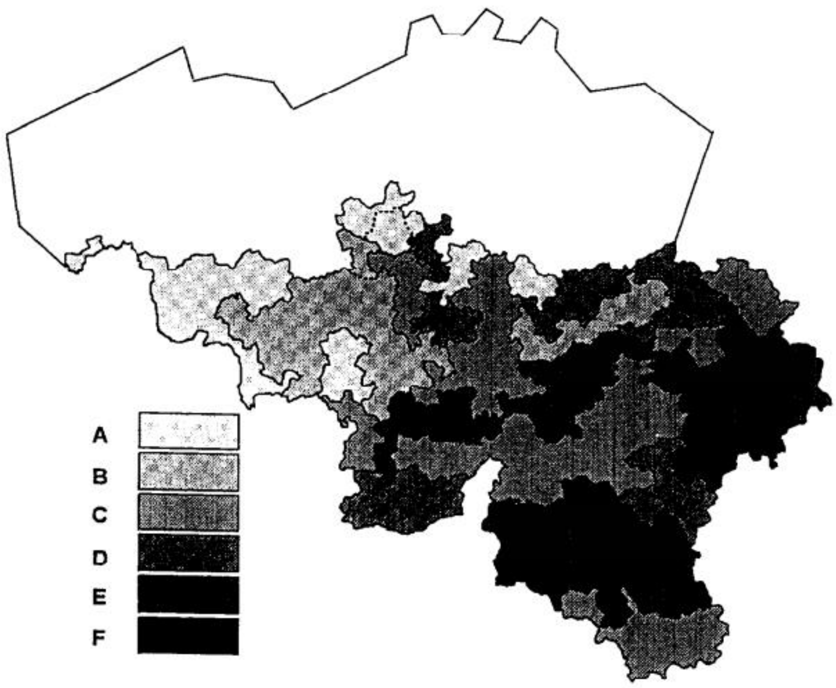
Power Point Presentation, Measurements of radon in workplaces in Republic of Belarus, Marina Vasilyeva, Ministry of Health, 2015.

7 Belgium

Indoor radon measurements in Belgium are described in 5 papers. Surveys described in these papers are regional, covering the region of Waloon (1 papers), Vise (1 paper) and southern Belgium (3 papers).

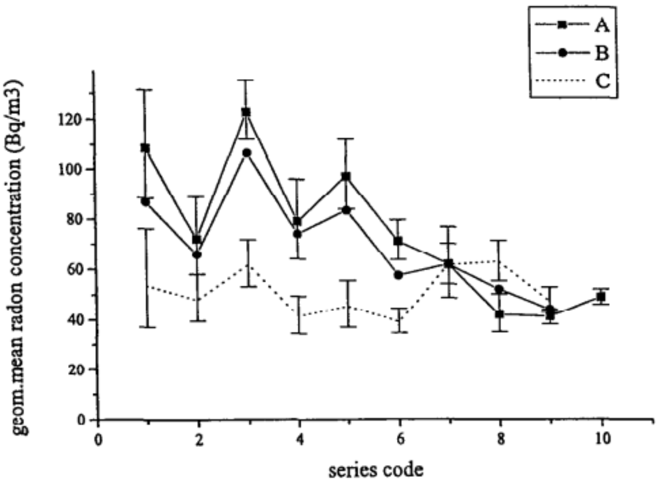
The goal of two papers Tondeur et al., 1996, and Zhu et al., 1998, covering the region of southern Belgium in the period from 1988 to 1995, was the development of indoor radon map of Southern Belgium and study of the correlations between geological features and indoor Rn concentrations. The sampling sites were chosen based on the local structure and composition of the rocks and on the movement of underground waters. Activated charcoal canisters with diffusion barriers were exposed for 3-4 days in semi-confined conditions (closed windows, no permanent opening of the doors) during the whole year. Total of 3404 dwellings were investigated. The results of radon measurements are taken from the database and statistical correlations between indoor Rn concentration and the geological environment of homes are calculated. Map presentation of the results is given in Figure 7.1, taken from Tondeur et al 1996. Also, the geometrical mean indoor concentration was calculated for each geological series. A significant variability associated with geology was observed. Although the most acute radon problems are found in Belgium on the old geological stages, less frequent butstill significant indoor air concentrations are found on Cenozoic formations. Indoor Rn on the ground floors and in the cellars from 83 homes shows a logarithmic linear correlation coefficient of +0.68 which is significant at the 99% confidence level. If ground floors, which are indirectly above a cellar or a basement were distinguished from those directly above a cellar or a basement, then an improved correlation was observed (Table 7.1 taken from Zhu et al, 1998, and Figure 7.2, taken from Tondeur et al., 1996).

Figure 7.1. Map of indoor radon in southern Belgium. The different areas are indicated by six grey levels, according to the geometrical mean indoor radon concentration: A (<30 Bq/m^3); B (30-45 Bq/m^3); C (45-70 Bq/m^3); D (70-100 Bq/m^3); E (100-150 Bq/m^3) and F (>150 Bq/m^3).



Source: Tondeur et al., 1996.

Figure 7.2. Geometrical mean indoor radon concentration for the different geological series.



Source: Tondeur et al., 1996.

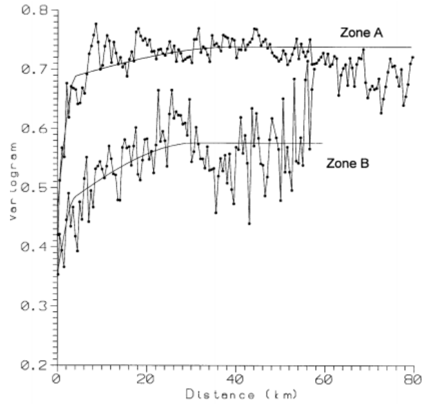
Table 7.1. Statistics on Rn values in homes in Southern Belgium.

	Second floors	First floors	Cellars
Geometric mean (Bq m^{-3})	44	65	215
Geometric standard deviation	3.8	3.2	5.1
Arithmetic mean (Bq m^{-3})	109	149	874
Total nb. of samples	170	1339	236
Range of values (Bq m^{-3})	1–1720	1–6300	1–25 000
Distribution	Lognormal	Lognormal	Lognormal

Source: Zhu et al., 1998.

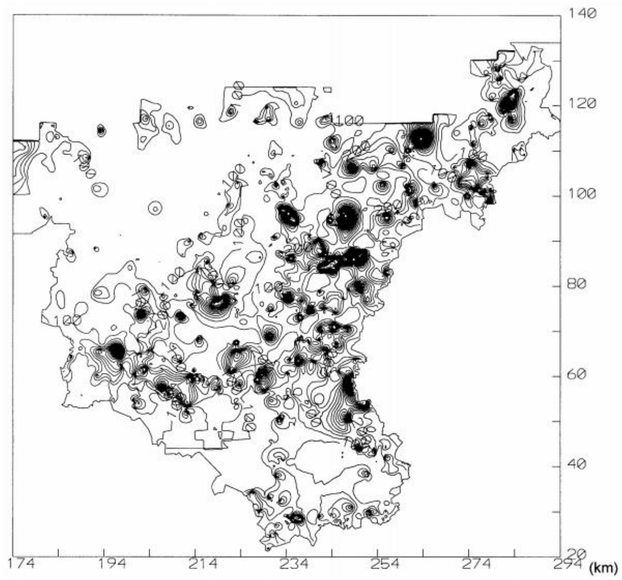
The goal of the third paper covering the southern Belgium region Zhu et al., 2001, was to evaluate the relationships between various spatial datasets, with the goal of producing radon risk maps in digital form. The dataset covering dwellings in southern Belgium were chosen from the national survey from winter of 2001, from 2198 dwellings and the study region was divided into 2 stationary zones (zone A and zone B). The mean logarithmic variograms are shown in Figure 7.3, below. High, medium and low risk areas were determined. All the results were represented in a digitalized map. A radon risk map which integrates a variety of data available, including geological maps, radon map, measured houses and administrative boundaries can simplify any subsequent administrative action and should be useful in design of future surveys. It also allows linking of the radon values to geological environments. This map is represented on Figure 7.4, below.

Figure 7.3. The mean logarithmic variograms for zone A and zone B.



Source: Zhu et al., 2001.

Figure 7.4. Kriged contour map of indoor Rn concentrations. Contour interval is 50 Bq/m^3.



Source: Zhu et al., 2001.

The paper Poffijn *et al.*, 1994, covers the measurements in approximately 8000 dwellings in the region of Vise during several years up to 1994 with the goal to obtain a detailed radon map with clear indication of risk areas and mitigation. Based upon the available information some 160 houses (2% of the building stock) are expected to have real radon problems (>400 Bq/m^3) and 24 of these problem houses have been localized. Three of the most contaminated houses (>3000 Bq/m^3 in the living areas) have been studied in detail for mitigation purposes.

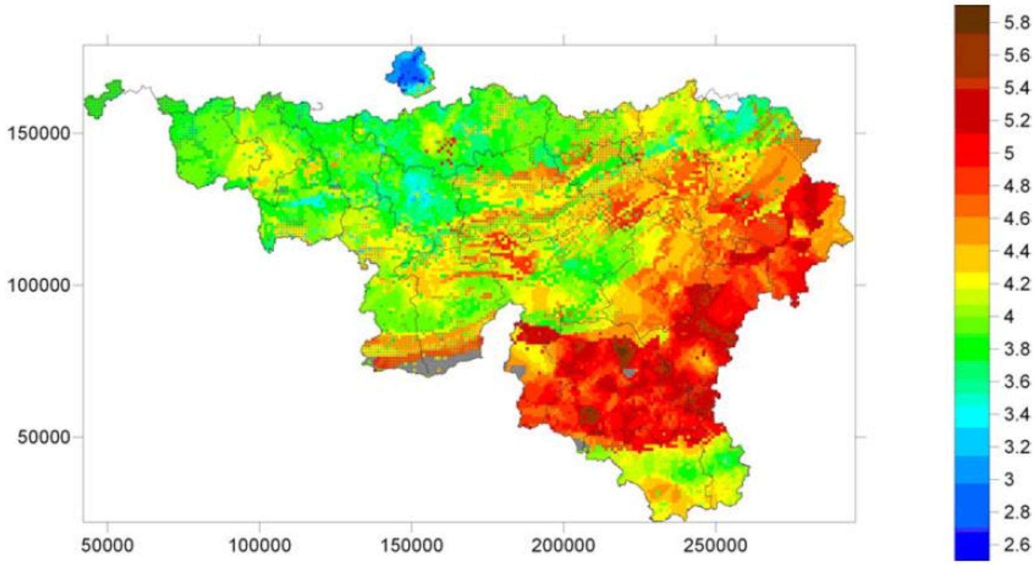
In the paper G. Cinelli *et al* 2011, the goal was producing a radon risk map for Walloon region. The map displays the predicted percentage of dwellings thathave a radon concentration above the action level. The two data sets used have been collected by the federal agency for nuclear control (FANC) and by the Institut Superieur Industriel de Bruxelles (ISIB) covering the survey periods from 1990-2000 and 1995-2004. Charcoal canisters exposed on ground floors of the dwellings for 3-4 days in all seasons except summer and track-etch Makrofol detectors exposed for 3 months. Total of 12500 dwellings were investigated and geometrical mean of the data from two datasets. T-test was performed in order to establish that the datasets are compatible. Variograms have been studied separately for each geological group. In general, the variograms show a low local correlation, and for the most part a constant model is consistent with data. The map has been constructed separately for each geological unit. Map of the logarithmic mean based on the geology and indoor radon measurements, the map of the logarithmic mean in the areas covered by loess and the map of the proportion of the distribution above 400 Bq/m^3 is made. These maps are shown in Figures 7.5, 7.6 and 7.7, below. Also, the data used for creating these maps are presented in the Table 7.2 below.

Table 7.2. Number of data, logarithmic means and standard deviations for each geological group.

	Num FANC	Num ISIB	LM FANC	LM ISIB	LSD FANC	LSD ISIB
Devillian	5	171	3.87	3.94	0.81	0.94
Revinian	78	204	4.65	4.71	1.06	1.36
Salmian	222	72	4.57	4.73	0.79	0.95
Ordivician	18	83	4.12	4.39	0.46	1.15
Silurian	35	49	4.58	3.59	1.01	1.21
Gedinnian	652	69	4.92	4.99	0.90	1.34
Siegenian	2,312	314	4.92	4.88	0.88	1.25
Emsian	143	59	4.69	4.31	0.89	0.98
Couvinian	155	84	4.57	4.37	0.91	1.16
Givetian	77	73	4.36	4.39	0.66	1.01
Frasnian	158	71	4.09	4.17	0.59	0.92
Famennian	275	162	4.17	4.20	0.74	1.11
Tournaisian	83	99	4.18	3.95	0.88	1.13
Visean	116	175	4.39	4.16	0.82	1.29
Namurian	63	76	4.11	4.05	0.79	1.08
Westphalian	111	217	3.92	3.88	0.68	0.87
Permian	24	14	3.79	5.04	0.58	1.19
Trias-Jurassic	373	78	4.14	4.09	0.67	0.65
Cretaceous	148	147	3.78	3.91	0.68	0.94
Eocene	197	730	3.87	3.66	0.61	0.94
Oligocene-Miocene-Pliocene	29	19	4.26	4.26	0.54	0.84
Loess + ale	1,225	809	4.27	3.88	0.76	0.85
Alluvian alm	832	383	4.54	3.68	0.96	0.96

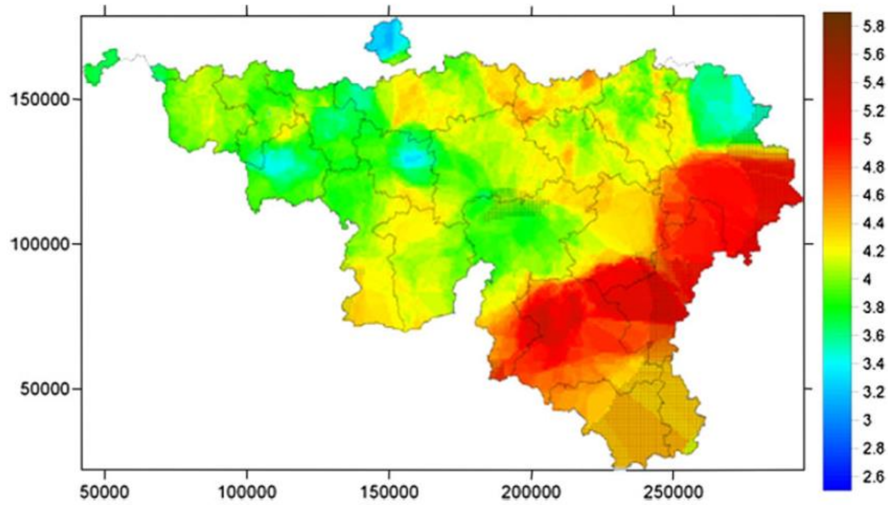
Source: G. Cinelli et al., 2011.

Figure 7.5. Map of the logarithmic mean based on geology and indoor radon measurements.



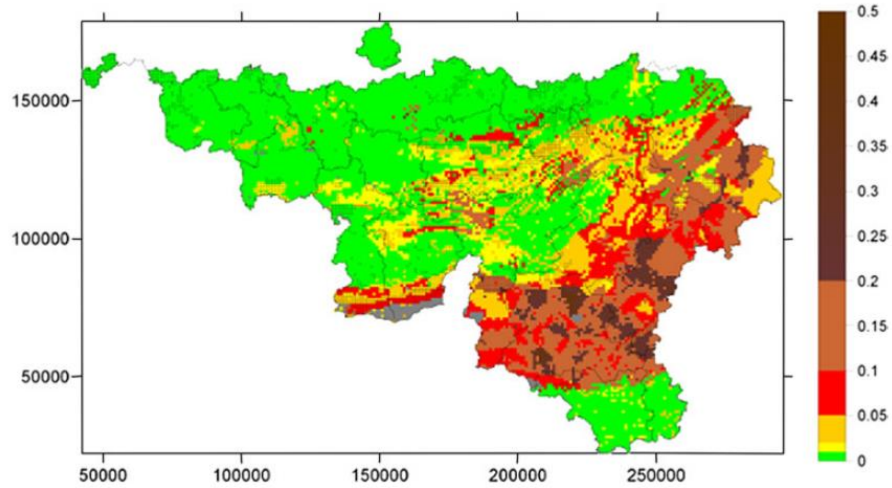
Source: G. Cinelli et al., 2011.

Figure 7.6. Map of the geometrical mean on loess cover.



Source: G. Cinelli et al., 2011.

Figure 7.7. Map of the proportion of the distribution above 400 Bq/m^3 based on geology and indoor radon measurements.



Source: G. Cinelli et al., 2011.

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Zhu, H. -C., J. M. Charlet and F. Tondeur (1998). Geological controls to the indoor radon distribution in southern Belgium. The Science of the Total Environment, 220(2-3): 195-214.

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Poffijn, A., Eggermont, G., Hallez, S. and Cohilis, P. (1994). Radon in Belgium: Mapping and Mitigation in the Affected Area of Visé. RadiationProtection Dosimetry, 56(1-4): 77-80 Abstract only.

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8 Bosnia and Herzegovina

In Bosnia and Herzegovina only local surveys of indoor radon concentrations were conducted.

A radon survey has been carried out in Bihać municipality in 2006 (100 measurements) and Tuzla city in 2010 (48 measurements). Measurements have been made using CR-39, diffusion chamber. The duration of measurement varies from 3 month in Bihać to 4 month in Tuzla. The arithmetic mean of indoor radon concentration was 82.1 Bq/m^3 in Bihać municipality and 27.9 Bq/m^3 in Tuzla city (IAEA-TECDOC-1810, 2017).

From May 2011 to April 2012 the first investigation on indoor radon, thoron and their decay products concentration in 25 primary schools of Banja Luka, capital city of Republic Srpska was performed. The measurements have been carried out using 3 types of commercially available nuclear track detectors, named: long-term radon monitor for radon concentration measurements, radon-thoron discriminative monitor (RADUET) for thoron concentration measurements, while equilibrium equivalent radon concentration and equilibrium equivalent thoron concentrations measured by Direct Radon Progeny Sensors/Direct Thoron Progeny Sensors. In each school the detectors were deployed at 10 cm distance from the wall. The obtained geometric mean concentrations were 99 Bq/m^3 and 51 Bq/m^3 for radon and thoron gases respectively as well as for equilibrium equivalent radon concentration and equilibrium equivalent thoron concentrations were 11.2 Bq/m^3 and 0.4 Bq/m^3, respectively (Ćurguz, 2015).

References

IAEA-TECDOC-1810. Status of Rasdon related Activities in member States Participating in technical Cooperation Projects in Europe, IAEA, Vienna, 2017.

Ćurguz, Z. et al. (2015). Long-Term Measurements of Radon, Thoron and Their Airborne Progeny in 25 Schools in Republic of Srpska, Journal of Environmental Radioactivity,148, 2015, 163-169.

9 Bulgaria

Reference (Ivanova et al., 2013) describes results of a pilot survey in four Bulgarian districts: Sofia city, Sofia, Plovdiv and Varna. Survey goal was to obtain first systematic data and to investigate variability of indoor radon concentration in selected districts. The districts were chosen to meet the diverse topography of a country with a large population.100 detectors were deployed per district. Survey took place from October 2011 to May 2012, and single measurement duration was six months. During the survey, 373 dwellings were investigated. One detector in the most frequently used room was deployed, at least 1 m above the floor and away from windows and doors. The detector consists of a CR-39 chip with active area of 1.4 cm^2 placed in a cylindrical diffusion chamber.

Evaluation of the results included descriptive statistics, and log-normality was checked by Kolmogorov–Smirnov test, Mann–Whitney and Kruskall-Wallis tests for differentiation of regions.

Average radon concentration in rural and urban municipality in 4 districts. The measured values show considerable spatial variability. The indoor radon concentration varied from region to region.

It was found that indoor radon concentration varied between 20 and 3560 Bq/m^3 with median value of 90 Bq/m^3. The fractions of dwellings in four districts: Sofia city, Sofia districts, Plovdiv and Varna above the reference levels of 300 Bq/m^3 were3, 9, 14 and 5%, respectively. Each data set does not follow a log–normal distribution at a significance level of 95%. The results of the analysis of the variance showed statistically significant differences among the indoor radon concentrations for the regions between urban and rural municipalities as well for the building with and without basement. These results may be utilized to set up the methodology for a more systematic survey in Bulgaria.

Table 9.1. Descriptive statistics of indoor radon concentrations in 373 dwellings.

	Indoor radon concentration				
	Plovdiv district	Sofia city	Sofia district	Varna district	All regions
No. of dwellings	91	88	96	98	373
Minimum (Bq m^{-3})	30	20	30	20	20
Median (Bq m^{-3})	100	70	100	70	90
Maximum (Bq m^{-3})	3560	410	800	650	3560
AM (Bq m^{-3})	280	96	151	107	158
SD (Bq m^{-3})	568	72	141	102	304
SE (Bq m^{-3})	60	8	14	10	16
GM (Bq m^{-3})	137	78	111	80	99
GSD	2.62	1.85	2.14	2.09	2.25
Percentage of dwellings above 300 Bq m^{-3}	14.3	3.4	9.4	5.1	8.0

Source: Ivanova et al., 2013.

References

Ivanova, K., Stojanovska, Z., Badulin, V. and Bistra Kunovska (2013). Pilot Survey of Indoor Radon in the Dwellings of Bulgaria. Radiation protection Dosimetry, 157 (4), 594-599.

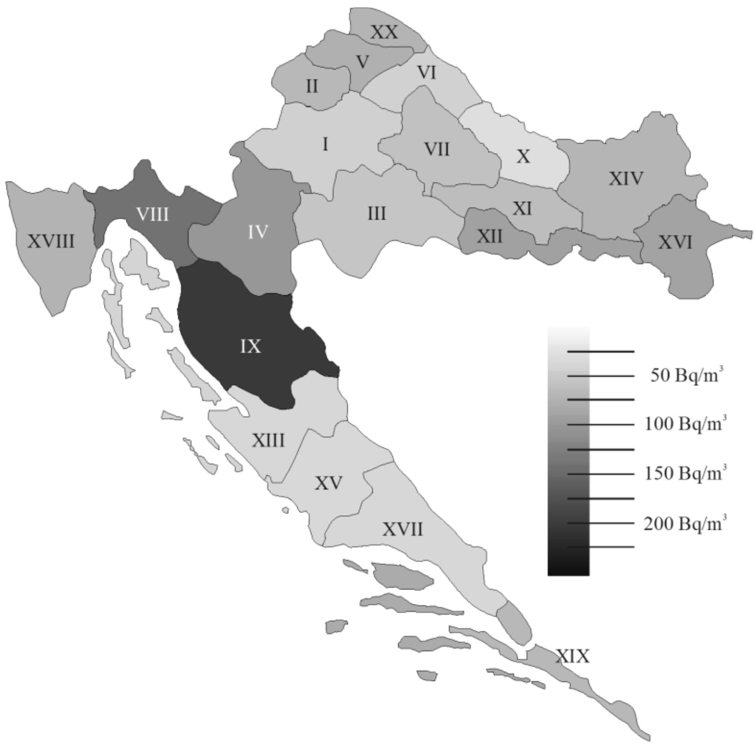
10 Croatia

National survey of indoor radon concentration was performed by a random sampling of 782 dwellings in Croatia from October 2003 to spring 2005.

Continuous measurements of radon and its alpha emitter progeny in the air were performed by means of the passive track etching method with strippable LR-115 SS, film, type II (Kodak-Pathe, France). The cylindrical plastic vessel of detector, with the diameter and length of 11 and 7 cm, respectively, was covered with a paper filter of 0.078 kg/m^2 surface density, inside, on the bottom of the vessel, a LR-115 film of 2×3 cm^2 was fixed that presented the diffusion detector. Outside, on the cylindrical shell of the vessel, another film was fixed, that presented the open detector. The measurement method with two detectors (diffusion and open) enabled determination of the equilibrium factor for radon and its progeny in air (Radolić, 2006).

Random phone numbers was chosen proportionally to the number of inhabitants of the county (in twenty counties) and one detector is sent by mail with short instruction for 12-month exposure. Radon concentrations were measured for one year and arithmetic and geometric means of 68 Bq/m^3 and 50 Bq/m^3 were obtained, respectively. The arithmetic means of radon concentrations on 20 counties were from 33 Bq/m^3 to 198 Bq/m^3. The percentage of dwellings with radon concentrations above 200 Bq/m^3 and 400 Bq/m^3 was 5.4% and 1.8%, respectively. The average annual effective dose of the indoor radon was estimated as 2.2 mSv. The statistical test, applied on the empirical and theoretical frequencies, did not show that the empiricalfrequency distribution for the radon in dwellings of Croatia belonged to the log-normal distribution (Radolić, 2006).

Figure 10.1. Annual indoor radon concentrations of the Croatian counties.



Source: Radolić, 2006.

References

Radolić, V., (2006) National Survey of Indoor Radon Levels in Croatia, J. Radioanal. Nucl. Ch., 269, 87-90.

11 Cyprus

Goal of the survey was to systematically register the indoor ^{222}Rn concentration in Cypriot buildings and dwellings. Part of the work was to compare results with the previous work and another part to investigate a region of Pano Polemidia where a number of cases of leukemia were reported.

Within the paper, it is slightly discussed geology of Cyprus: types of rocks and existence of faults; typical Cypriot houses and climate; and high ventilation rate underlined.

In addition to this project was measurement of the terrestrial gamma radiation.

The measurements were carried out over 9 months (beginning of September 2001 to end of May 2002).

For radon measurements a high–sensitivity modern portable detectors "RADIM3" were used. Besides, an additional sensors to measure ventilation coefficient, the pressure, the temperature and the humidity were used. Measurement was corrected for the humidity.

In total 84 buildings and dwellings were selected in 37 different villages and towns in Cyprus.

Sampling was random by contacting the house owners by telephone. Drought–free areas in the houses were selected such as basement, in order to obtain maximum radon concentrations. The detectors were placed at a height of approximately 1 *meter*. Sampling interval was adjusted from 0.5-24h, but usually it was 4h, over the 48h of operation.

Information on quality assurance was provided. Calibration over the whole dynamical range of the instrument is made by the manufacturer. Accuracy of the calibration was verified in the State Metrological Institute of the Czech Republic. Verification was achieved by comparing the results of measurement of ^{222}Rn concentrations provided by the Radim3 instrument and a reference instrument using a secondary ATMOS standard. Obtained overall uncertainty of the calibration was ±10%.

In the analysis only arithmetic mean, standard deviation and min and max values were reported. Rn concentrations ranged from 6.2 to 102.8 $Bq\ m^{-3}$, with an overall arithmetic mean value of (19.3 ±14.7) $Bq\ m^{-3}$. Overview of obtained radon concentrations in the main regions in Cyprus is given in Table 11.1.

Table 11.1. Radon concentrations in the main regions of Cyprus.

A/A	Region	Samples	^{222}Rn Concentration [$Bq\ m^{-3}$]			
			A.M.	S.D.	Min	Max
1	Ammochostos	4	11.9	3.8	2.0	19.3
2	Larnaka	3	17.3	2.1	9.8	25.1
3	Lemesos	8	29.6	30.3	1.7	183.5
4	Lefkosia	53	19.4	13.1	1.1	111.0
5	Lemesos forest area	3	13.9	5.0	5.3	27.9
6	Pano Polemidia	4	20.2	12.2	0.9	48.2
7	Pafos	2	10.7	3.0	1.1	44.5
8	Larnaka centre	2	8.6	2.0	6.3	12.7
9	Lemesos centre	1	23.5	4.8	6.3	93.0
10	Lefkosia centre	3	19.4	19.6	3.4	55.7
11	Pafos centre	1	15.7	4.0	2.9	66.9

Source: Anastasiou, 2003.

References

Anastasiou T. et al., 2003. Indoor radon (^{222}Rn) concentration measurements in Cyprus using high–sensitivity portable detectors, J Environ Radioact. 68(2):159-69.

12 Czech Republic

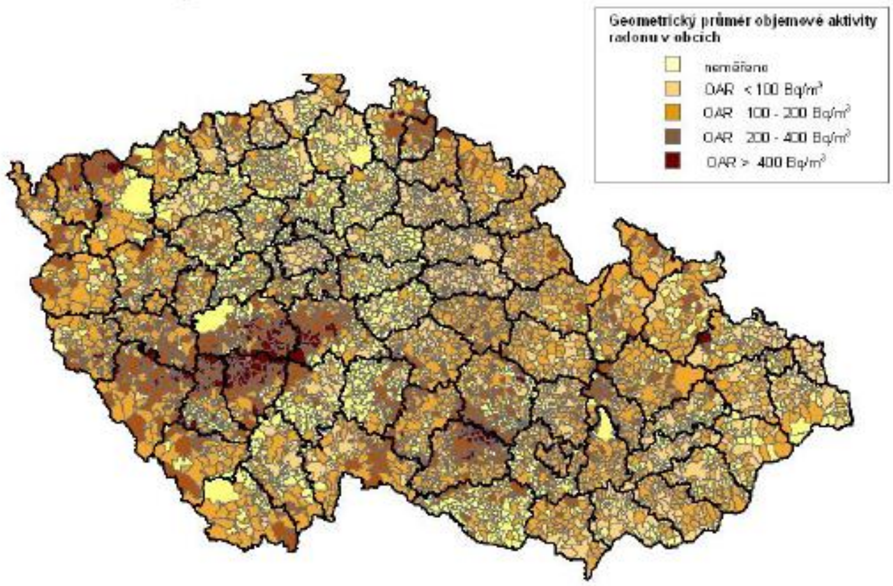
According to the references (Dubois, 2005; Hulka, 2014), the national radon survey has been continuously conducted since 1984.

The general survey goal was/is to create radon database and radon mapping. During that period more than 150000 dwellings were investigated, and two detectors were used per dwelling, mainly in living rooms. Firstly, dwellings were selected randomly, and random selection was followed by targeted survey in regions with higher radon concentrations. Track-etch SSNDs Kodak LR 115 detector placed in diffusion chamber were used for the search with an exposure period of one full year. This approach eliminates the season variations and detectors can be placed continuously during the year. Thus, duration of an single measurement was 365 days (Hulka, 2014).

Based on 305000 measurements in total, arithmetic and geometric mean were calculated. Estimated mean annual radon levels in Czech dwellings was 140 Bq/m^3, while 10-15% of measured radon concentration in dwellings were above 200 and below 400 Bq/m^3 and 2-3 % exceeded 400 Bq/m^3. Local averages were calculated at the municipal level (Dubois, 2005).

Metrology of radon and radon daughters is ensured by national Authorized Metrological Centre. Its calibration is verified and compared internationally. Centre provides certification for used equipment (Thomas et al., 2002).

Figure 12.1. Indoor radon concentrations levels (geometric mean) shown an municipality level (180000 dwelling included).



Source: Hulka, 2014.

References

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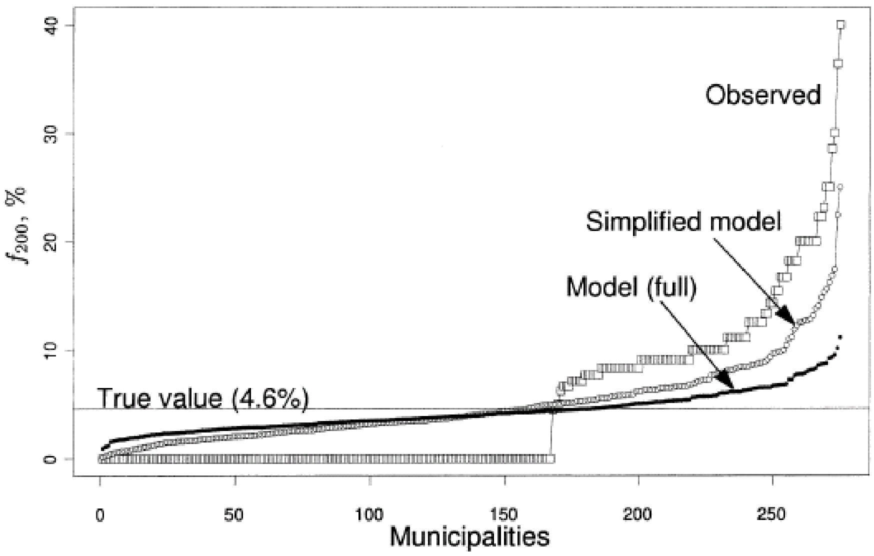
Power Point Presentation, 30 years of experience of Czech radon program, Jirí Hulka, SÚRO - National Radiation Protection Institute, Prague, Czech Republic, Latin American Symposium on Radon and II Symposium on Radon in Brazil, Pocos de Caidas, May 2014.

13 Denmark

Indoor radon measurements in Denmark are described in 2 papers, both describing the results of the national survey, conducted from 1995-1996 and from 1990-2000.

In the first paper, Andersen et al. (2001), the goal was obtaining the statistical model for the prediction of the fraction of houses in each municipality with an annual average radon concentration above 200 Bq/m^3. Alpha track detectors CR-39 were placed in randomly selected single homes (3019 dwellings in all 275 municipalities in the period of 1995-1996). It is assumed that within each municipality,the transformed radon concentration is normallydistributed with a true mean and a true standard deviation. Then estimators were calculated and the final result represents the estimation of number of houses with Rn concentration above 200Bq/m^3. Bayesian statistics, a transformation of the data to normality and on analytical unbiased estimators of the quantities of interest was used for evaluation of the results. Even though model assumptions such as those concerning normality and homogeneous variance may not be perfect, the model does not seem to be strongly biased: on-the-average, the model accounts well for data at the levelof individual counties and for Denmark as a whole. The results of the model prediction and observed values are presented in Figure 13.1, below.

Figure 13.1. Test with synthetic data: Comparison between model estimates ($f_{200,m}$) and observed values for f_{200} in 275 municipalities when true fraction above 200 Bq/m^3 is 4.6%. The curve labeled *simplified model* corresponds to the situation without the Bayesian correction.



Source: Andersen et al., 2001.

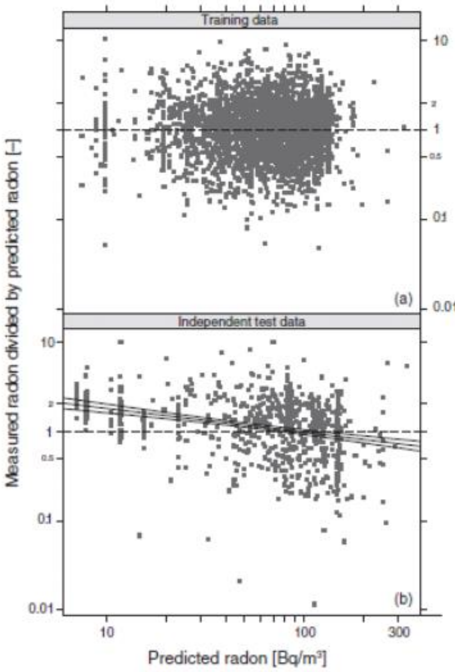
In the second paper, Andersen et al., 2007, a linear regression model has been developed for the prediction of indoor ^{222}Rn in Danish houses, connecting this measurement to the geological data. Track detectors CR-39 were placed in 3120 randomly selected single family houses as a part of previously conducted national survey and regression model with 9 predictors and 59 independent coefficients was obtained. The various tests showed that the model is correct on the average and can predict radon concentrations in the individual houses with an uncertainty of a factor of 2. The model appears to be best at predicting low concentrations. The results used for fitting the model are given in Table 13.1 and the ratio between measured and predicted radon values are depicted in Figure 13.2, below.

Table 13.1. Summary statistics for the radon measurement data (living room concentrations) used to fit and test the model.

	N	AM	ASD	GM	GSD	f_{200}	f_{400}	Min	%-quantiles (Bq m^{-3})					Max
									2.5	25	50	75	97.5	
Training data; 2001 national survey														
Apartments	91	18	19	12	2.4	0	0	0.5	2.5	7.5	12	18	82	100
Single-family houses	3025	94	84	67	2.4	9	1.2	1.8	11	39	71	120	310	790
All	3116	91	83	64	2.5	8.7	1.2	0.5	8.6	37	68	120	310	790
Test data (all)														
Apartments	148	20	12	18	1.5	0	0	8	10	13	18	22	45	118
Single-family houses	610	120	130	88	2.4	15	2.6	1	16	50	97	160	410	1800
All	758	100	120	64	2.8	12	2.1	1	10	29	75	140	350	1800
1. Test data; 1987 national survey														
Apartments	148	20	12	18	1.5	0	0	8	10	13	18	22	45	120
2. Test data; Hvalsø														
Single-family houses	65	120	69	94	2.1	12	0	11	23	56	110	170	250	290
3. Test data; Radon-95														
Single-family houses	270	160	170	110	2.4	20	4.8	0.3	18	75	120	180	430	1800
4. Test data; Risø homeowner measurements														
Single-family houses	275	96	82	68	2.5	10	1.1	1	11	40	75	130	280	620

Source: Andersen et al., 2007.

Figure 13.2. Ratio of measured and predicted radon concentrations for a) the training data (N=3116) and b) the independent test data (N=758). The $\log_e$ - transformed value of this ratio equals to the model residuals. The standard deviation of the residuals is approximately $\log_e(2)\approx 0.7$ for the training data and 0.80 for the independent test data. The mean of the residuals for the independent test data is 0.13 ($\log_e$ - scale) which means that the average measurement – prediction ratio is 1.14 (i.e. on the average, the measurements were 14% higher than predicted by the model). The solid line in b) is a regression line (R^2 = 0.10) which suggests that the measurement errors are not completely independent of the predicted radon concentration. A 95% confidence interval of the regression line is included in the figure.



Source: Andersen et al., 2007.

References

Andersen, C. E., Ulbak, K., Damkjær, A., Kirkegaard, P. and Gravesen, P. (2001). Mapping indoor radon-222 in Denmark: design and test of the statistical model used in the second nationwide survey, The Science of The Total Environment, 272(1-3): 231-241.

Andersen, C. E. et al., (2007) Prediction of ^{222}Rn in Danish Dwellings Using Geology and House Construction information Radiation Protection Dosimetry 123 (1), 83–94.

14 Georgia

The survey of indoor radon concentration was conducted from 2007 to 2011 in 2000 dwellings in West Georgia (IAEA-TecDoc-1810, 2017).

For radon measurements in the home alpha track detectors were used to provide integrated mean radon concentration normally placed for a period from 6 to 12 months. Criteria to select dwellings were geographically and geologically based. Measurements were conducted in West Georgia. Measured radon concentrations were from 5 Bq/m^3 to 245Bq/m^3 (IAEA-TecDoc-1810, 2017).

Also electrets ion chambers available with different sensitivities for a few days measurements or for measurements over month were used (IAEA TC Project RER/9/127, 2014).

References

IAEA TC Project RER/9/127. Establishing Enhanced Approaches to the Control of Public Exposure to Radon, Presentation, 22.04.2014, Vienna, Austria.

IAEA-TECDOC-1810. Status Of Radon Related Activities in Member States Participating in Technical Cooperation Projects in Europe, Iaea, Vienna, 2017.

15 Greece

Results of national survey of indoor radon concentration in Greece are described in reference (Nikolopoulos D. et al., 2002). Survey was conducted from 1995 to 1998 during whole year, with a main goal to determine the percentage of houses with indoor radon concentration exceed certain reference levels, radon distribution in Greece indoors, and to estimate average risk to the population due to radon exposure. During this survey, 1277 dwellings were investigated. One detector was deployed per 1000 dwellings; trained personnel selected the buildings irrespective of the floor. Detector was placed 1 meter above ground in a bedroom by trained personnel and questionnaire was filled. MPD radon dosimeters consisted of a cylindrical nonconductive plastic cup of 5 cm height and 1.5 cm radius were used. The cover had a 3 mm hole on the center and a filter that prevented radon daughters from entering. Radon was detected by a 2×2 cm CR-39 nuclear track detector placed at the bottom of the cup. The overall uncertainty of radon measurement in the 95% confidence interval was below 10 %. Single measurement duration was 12 months.

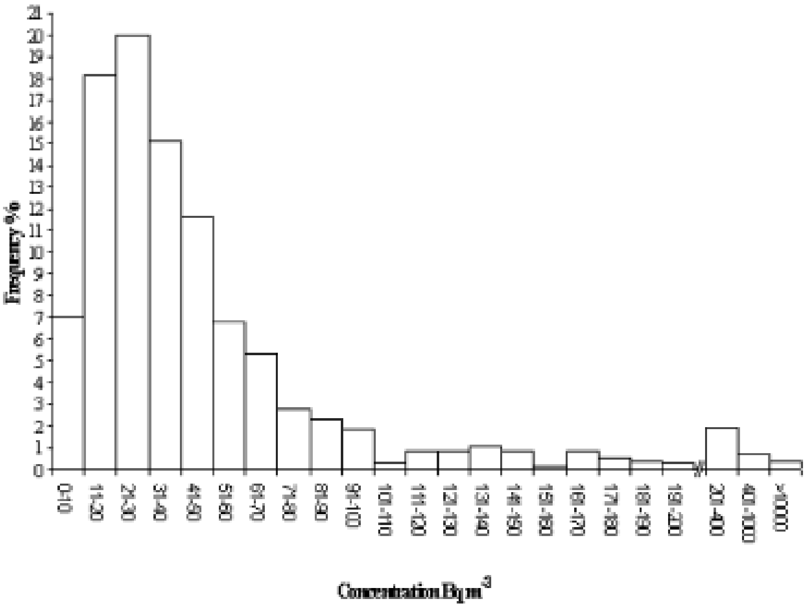
Figure 15.1. Sampling locations, locations where elevated radon concentrations occurred and "radon prone" areas in Greece.

Source: Nikolopoulos D. et al., 2002.

Evaluation of the results included descriptive statistic and tests for lognormality. Descriptive statistic was performed for each prefecture, and percentage of houses with indoor radon concentration over 200 Bq/m^3 was determined. Used detectors were calibrated and tested in the University of Athens.

Residential radon concentration ranged between 200 and 400 Bq/m^3 in 22 dwellings (1.9%), between 400 and 1000 Bq/m^3 in eight (0.7%) dwellings, and above 1000 Bq/m^3 in four (0.4%) dwellings. In the full data set, arithmetic mean was found to be equal to 55 Bq/m^3 and the geometric mean equal to 44.0 Bq/m^3 with a geometric standard deviation of 2.4 Bq/m^3. In only a small percentage (1.1%) of dwellings in Greece did the measured radon concentrations exceed the European Commission (1990) action level (400 Bq/m^3).

Figure 15.2. Frequency distribution histogram of radon concentrations in Greek dwellings (1227 samples).



Source: Nikolopoulos D. et al., 2002.

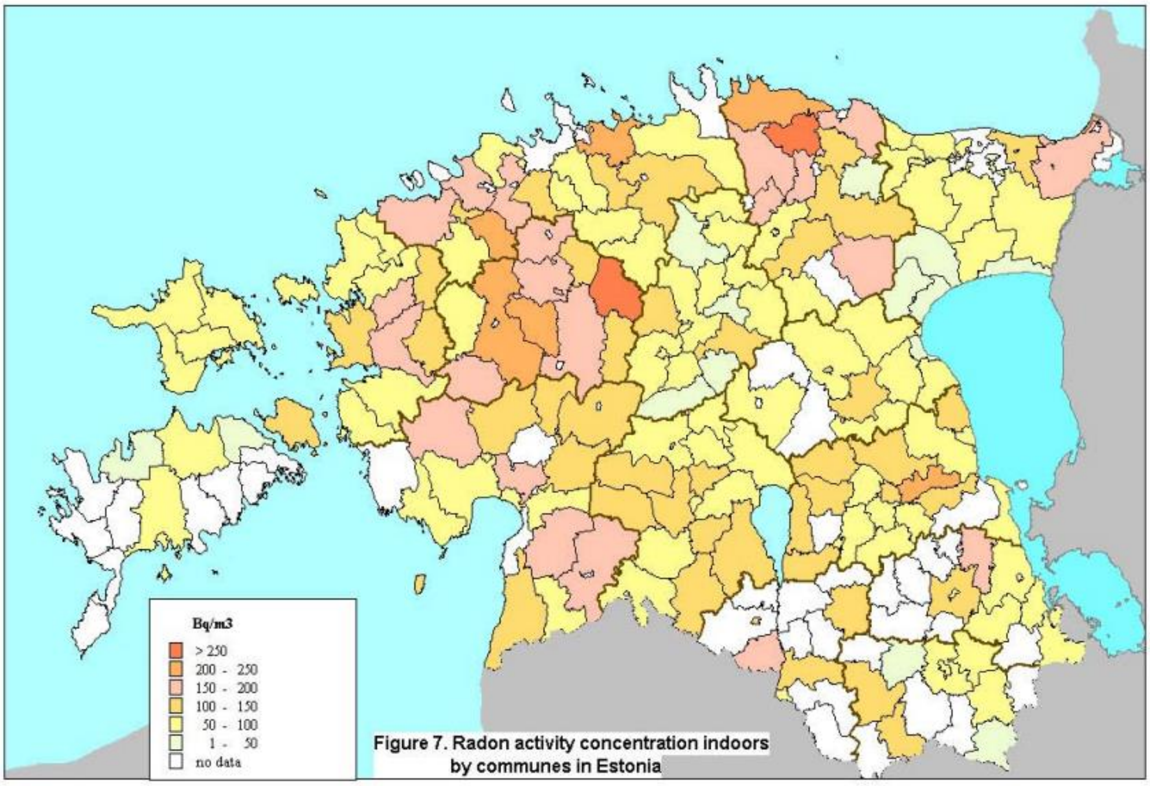
References

Nikolopoulos D. et al., (2002), Radon Survey in Greece - risk assessment, Journal of Environmental Radioactivity 63, 173-186.

16 Estonia

The results of the national survey in Estonia are described in Pahapill et al., 2003. The goal of this survey was to estimate the countrywide radon situation for calculation of the public health risk due to indoor radon and to provide a basis for work on protective measures. The survey was focused on the geographical distribution of indoor radon, measurements in 550 dwellings randomly selected from the 617,400 dwellings. The detectors were exposed during two or three month in the winter heating season. Two detectors were placed in each dwelling, usually, one in a bedroom and one in the living room during the heating season of 1998-1999, 1999-2000 and 2000-2001. Descriptive statistics was used to evaluate the measurement results. The indoor radon concentrations (arithmetic mean and maximum values shown by county, type of dwelling and number of residents living in these dwellings) were calculated. The mean annual effective dose to the whole of the Estonian population was also obtained and the results are presented in the Table 16.1 below. Radon map of Estonia by communes is represented in Figure 16.1 below.

Figure 16.1. Radon activity concentration indoors by communes in Estonia.



Source: Pahapill et al., 2003.

Table 16.1. Indoor radon concentrations in dwellings measured in the national Radon Survey, 1998-2001. Arithmetic mean (Am), maximum values (Max), of indoor radon levels and distribution

of indoor radon activity concentrations (%) are shown. The distributions of data in five activity concentration intervals are shown (%).

COUNTY	No. of dwellings	Indoor radon-222 concentration, Bqm^{-3}		Distribution of indoor radon-222 concentrations (Bqm^{-3}), %				
		Am.	Max.	<100	101-200	201-400	401-800	>800
Harjumaa	41	115	475	57	27	15	1	-
Hiiumaa	10	80	127	87	13	-	-	-
Ida-Virumaa	66	68	317	82	13	5	-	-
Jõgevamaa	31	76	255	74	22	4	-	-
Järvamaa	26	63	137	81	19	-	-	-
Läänemaa	30	86	174	75	25	-	-	-
Lääne-Virumaa	73	130	1,044	64	18	16	-	2
Põlvamaa	22	72	290	89	7	4	-	-
Pärnumaa	35	103	197	56	44	-	-	-
Raplamaa	33	203	558	12	52	25	10	-
Saaremaa	24	66	321	82	10	8	-	-
Tartumaa	39	100	260	61	35	4	-	-
Valgamaa	17	115	272	56	35	9	-	-
Viljandimaa	39	93	220	66	30	4	-	-
Võrumaa	29	66	227	86	11	3	-	-

Source: Pahapill et al., 2003.

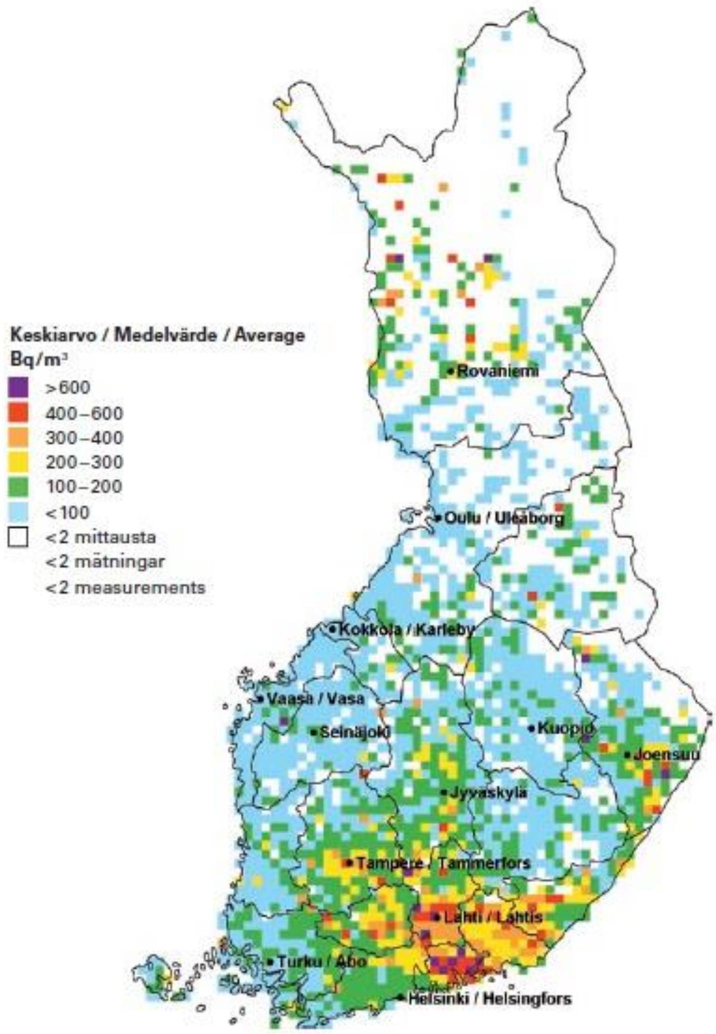
References

Pahapill, L., Rulkov, A., Rajamäe, R., Akerblom, G., (2003) Radon in Estonian Dwellings.

17 Finland

A study on national scale is still ongoing, since 1986. The goal of the study is to identify radon prone areas, defined as areas where concentrations over 400 Bq/m^3 are possible. Measurements were performed in more than 100000 residential objects, with more measurements performed in the identified radon prone areas. Measurements are usually performed in the winter period, between November and April, lasting between 2 months and 1 year. Alpha track detectors were used and the measurements were corrected for the outdoor temperature and wind speed. Based on the results, radon map was created with number of houses over 400, 800 and 1000 Bq/m^3 (Weltner et al., 2002; Valmari et al., 2010).

Figure 17.1. Radon concentration in Finish houses.



Source: Valmari et al, 2010.

References

Weltner A. et al., (2002). Radon Mapping Strategy in Finland, International Congress Series 1225, 63-69.

Valmari T. et al., (2010) Radon Atlas of Finland STUK-A245 / ELOKUU 2010, STUK Radiation and nuclear safety authority, ISBN 978-952-478-538-9.

18 France

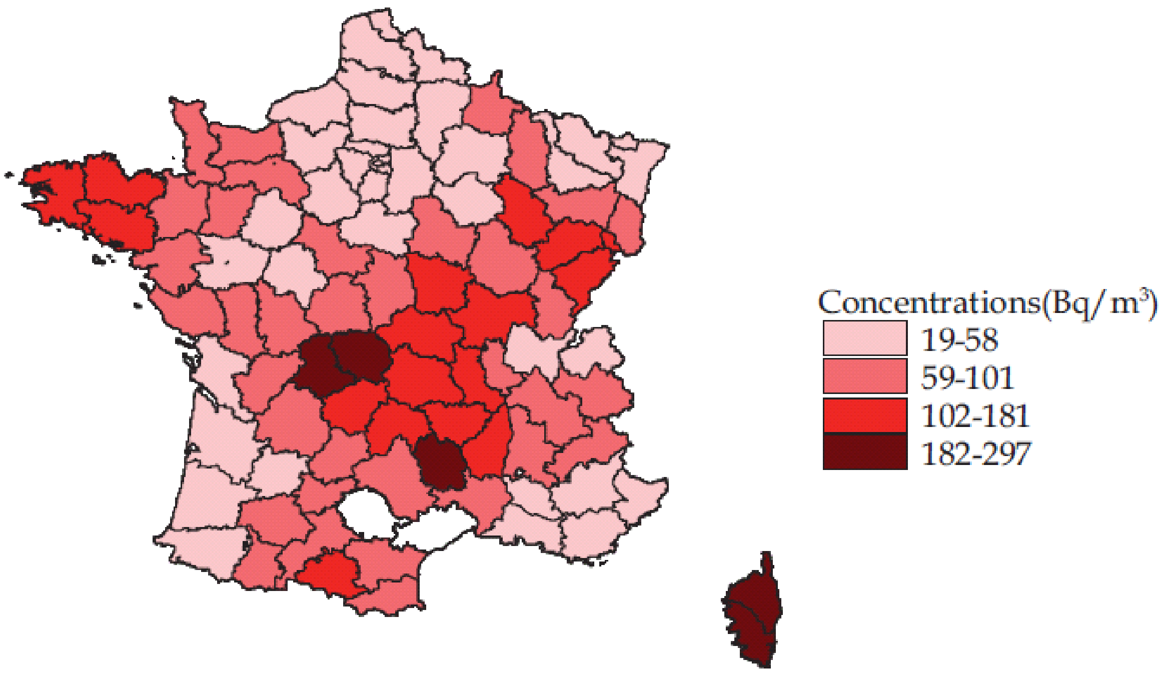
The indoor radon survey was conducted in the period from 1983-2002. The main objectives of the survey were to identify radon priority area, to estimate the percentage of dwelling above the action levels and to investigate factors influencing radon concentration. In total 12261 measurements were performed in 10098 local communities (ref: INSLR).

Bare LR115 detectors were deployed for two months, in one room per dwelling. Correction of seasonal variations was applied (Baysson, 2003). The questionnaire was enclosed with detector with question regarding building characteristics, living habits, etc.

Obtained results followed log-normal distribution, with arithmetic mean of 89 Bq/m^3 (standard deviation 162 Bq/m^3), median value of 55 Bq/m^3 and geometric mean of 53 Bq/m^3 with a GSD = 2 (Billon, 2005).

In the report it was not mentioned if thoron was measured, but since bare LR115 detectors were used they were certainly influenced by the thoron.

Figure 18.1. Distribution of indoor radon concentrations in France (ref: INSLR)



Source: INSERM (2008).

References

Baysson, H., Billon, S., Laurier, D., Rogel, A. And Tirmarche, M. (2003) Seasonal Correction Factors For EstimatingRadon Exposure In Dwellings In France, Radiation Protection Dosimetry 104 (3), 245–252.

Billon S. et al. (2005) French population exposure to radon, terrestrial gamma and cosmic rays. Radiation Protection Dosimetry 113 (3), 314-320.

INSERM (Institut national de la santé et de la recherche médicale Cancer et environnement), 2008. Chapter 55: Données d'exposition aux rayonnements ionisants (report in French)
http://www.ipubli.inserm.fr/bitstream/handle/10608/102/?sequence=72

19 Germany

In the paper by H. Schimer and A. Wicke 1985, a large scale radon survey has been carried out in the Federal Republic of Germany. In approximately 6000 arbitrarily selected dwellings in the Federal Republic of Germany, the mean radon concentration was measured for at least 3 months using the Karlsruhe type nuclear track dosimeter. The main results are presented in the Table 19.1 below.

Table 19.1. Radiation exposure of the lung from Rn and its short-lived daughter products and annual contribution to the effective dose equivalent.

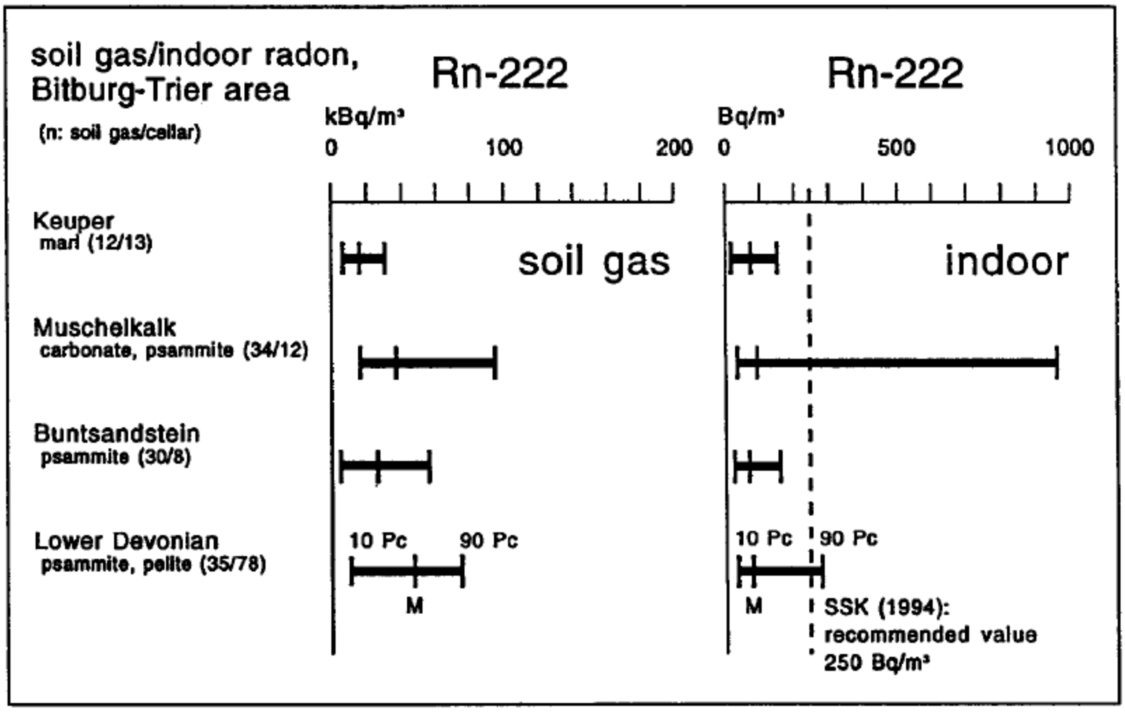
	Radon 222-concentration (Bq/m³)	Annual effective dose of different lung regions (mSv)		Annual contribution to the effective dose equivalent (mSv)
		Trachea & bronchial tree	Pulmonary region	
Median value	40	14	2	0.8
Mean value	49	18	2	1.2
10% exceeding	80	29	3	1.9

Source: Schimer and Wicke, 1985.

In the paper by Kemski et al. 2004, 6000 houses over nine federal states were investigated, with two detectors per building, one in basement one in living room. In the eastern part of the Germany the radon activity concentration in buildings were significantly higher than in the western part due to the differences in the building and construction type of the houses. The paper is in German, so for the present moment, it is not suitable for extracting data.

In paper Kemski et al. 1996, in an on-going research project of the German Federal Ministry for the Environment, Conservation and Reactor Safety, radon-prone areas in Germany have been defined and these results were used in the paper in order to produce a radon prone region map. The aim was to generalize and to extrapolate the results of the test areas to other regions of Germany with comparable geological situations as far as possible. Measurements were conducted from September to December 1994. An indoor radon survey was done in the Bitburg-Trier area in about 130 buildings, where solid-state nuclear track detectors were exposed over a period of 3 months. The first results show in cellars median values generally below 100 Bq/m^3; varying between 65 and 97 Bq/m^3 (Figure 19.1). On the ground floor, the median values of all units are between 41 and 58 Bq/m^3.The data are in agreement with the gross average median values of 52 Bq/m^3 (cellars), respectively, 43 Bq/m^3 (living rooms), for western Germany.

Figure 19.1. Soil gas and indoor radon concentrations in the main stratigraphic units in Bitburg-Trier area; median values and percentiles.



Source: Kemski et al., 1996.

References

Schimer, H. and Wicke, A. (1985). Results from a Survey of Indoor Radon Exposures in the Federal Republic of Germany, The Science of the Total Environment, 45, 307-310.

Kemski, J., Klingel, R., Stegemann, R. (2004): Validierung der regionalen Verteilungen der Radon konzentration in Häusern mittels Radonmessungen unter Berücksichtigung der Bauweise (Abschlussberichtzum orschungsvorhaben St. Sch. 4271).- Schriftenreihe Reaktorsicherheit und Strahlenschutz, BMU-2004-641.

Kemski, J., Klingel, R., and Siehl, A., (1996). Classification and Mapping Of Radon Affected Areas In Germany Environment International, 22 (1), S789-S798.

20 Hungary

A study on national scale was conducted to identify radon prone areas. The study was conducted between 1994 and 2004 in 15277 first floor rooms and 325 upper floor rooms in dwellings. Detectors were distributed by teachers to volunteers. Three measurements were performed in each room in spring, autumn and winter and each measurement lasted 2-3 months. The annual mean was calculated as average for 4 seasons, where the summer concentration was estimated based on the previous studies. CR-39 detectors in plastic cylinders were used. After the exposure, they were etched in 20% NaOH for 4 hours at the temperature 92 °C and counted by image analyzing code (Hamori, 2006).

The data was evaluated by log normality test and Kolmogorov test. The evaluation showed that the whole dataset didn't follow log normal distribution. After defining strata, datasets within each stratum were following log normal distribution. Percentage of dwellings over 4 levels of concentration (150, 200, 400 and 600 Bq/m^3) was determined for each stratum, as well as the mean value (Hamori, 2006).

Table 20.1. Estimated percentage of first-floor dwellings above the given radon levels in Hungarian villages by regions.

Geography	Strata	Number of		Estimated percentage of dwellings above[a]	
		All dwellings	Measured dwellings	150 Bq m^{-3} (%)	600 Bq m^{-3} (%)
Plain	Great Hungarian Plain	670 712	1859	17.8	0.1
Plain	Mezőföld	88 777	313	24.8	0.1
Plain	Little Hungarian Plain	88 442	471	22.9	0.2
Hills	Vas-Zala Hills	81 679	357	7.5	<0.1
Hills	Hilly Region of N. Hun.	35 427	746	24.7	0.2
Hills	The Trans-Danubian H.	137 946	1007	26.1	0.4
Limestone	Vértes-Dunazug M.	76 756	1205	16.2	0.1
Limestone	Bakony Mountain	75 027	393	21.3	0.2
Limestone	Bükk Mountain	15 012	351	36.4	0.6
Granite	Mórágy Hills	1589	779	46.9	1.6
Granite	Velence Hills	6116	665	36.8	2.3
Limestone	Mecsek Mountain	15 405	154	43.1	3.1
Volc.-l.stone	Börzsöny-Cserhát	50 360	1003	51.4	3.4
Volcanic	Mátra Mountain	20 916	1262	50.7	4.6
Warp	Sajó-Hernád-Valley (−*X*)	53 371	903	39.8	1.3
Warp	Village *X*	298	153	78.0	6.9

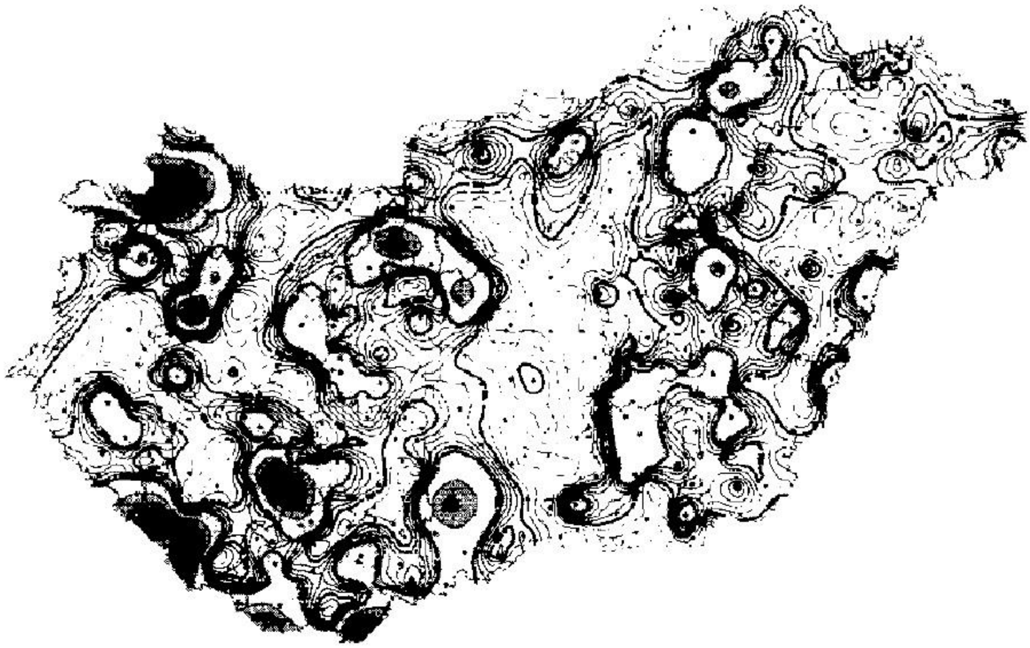
[a] One hundred percent is the total number of first-floor dwellings in the given region.

Source: Hamori, 2006.

System was calibrated at NPRB, UK. The detector also measured thoron, but it is not possible to estimate the thoron contribution to measured total radon concentration (Hamori, 2006).

Another national survey was organized between December 1993 and December 1994. The measurements were performed with E-Perm electrets for 12 months. The country was divided in 10 km by 10 km squares and one dwelling was selected from each square, giving the total of 998 dwellings. The results were evaluated by performing log normality test and by descriptive statistics. Arithmetic, geometric and weighted means were calculated and annual effective dose was estimated. System was calibrated in Swedish radiation protection institute. Thoron was not measured (Nikl, 1996).

Figure 20.1. Contour map of indoor radon concentrations in ground contact dwellings in Hungary.



Source: Nikl, 1996.

References

Hámori K., Tóth E., Pál L., Köteles G., Minda M., (2006). Evaluation of Indoor Radon Measurements in Hungary, Journal of Environmental Radioactivity 88, 189-198.

Nikl I., (1996) Radon Concentration and Absorbed Dose Rate in Hungarian Dwellings, Radiation Protection Dosimetry, 67, 225−228.

21 Iceland

Previous measurements were performed for the geological/geophysical research, such as prediction of earthquakes. No large surveys performed previously.

The first radon survey was made in 18 basements in 1982, with an average of 11 Bq/m^3 and highest of 26 Bq/m^3 (Ennow K.R. and Magnússon S.M, 1982).

Another survey, performed in 2003 with liquid scintillator, encompassed 51 houses in the area Reykjavík. The results obtained from the 12h measurements show radon level with a mean of 4.7 Bq/m^3 and median 2.8 Bq/m^3 (Jónsson et al., 2003).

National Rn survey performed in 2012-2013, aiming to contribute to European Indoor Radon Map (Jonsson, 2016), with the following characteristics.

Detectors: 500 PADC/CR-39 detector chip from Radosys (Hungary).

Exposure: 12 months, LLD: 7 Bq/m^3; uncertainty under 15% for 12 months exposure at 150 Bq/m^3.

Sampling obtained via volunteers being selected by website and phone.

Detectors were sent to 278 homes (retrieved 250); 31 kindergartens and 40 swimming pools (retrieved 31 and 19, respectively).

Detectors were placed on the lowest floor and in an inhabited room. Survey included 0.2% of homes. Detectors were exposed for 9-13 months. Covered most of the inhabited areas.

The mean obtained radon level was 13 Bq/m^3 and the median 9 Bq/m^3. Only 5% of the results are over 40 Bq/m^3 and the highest measurement was 79 Bq/m^3. In kindergarten the mean radon level is 11 Bq/m^3 and the median 6 Bq/m^3 while for public swimming pools the mean radon level is 6 Bq/m^3 and the median 5 Bq/m^3.

In addition continuous Rn measurement based on liquid scintillation was performed in one indoor and one outdoor location. Radon was monitored for a bit more than 2 months, but no noticeable diurnal, week variations could be observed, while measurement was short in order to observe seasonal variations.

It is concluded that radon is not a health problem in Iceland.

References

Ennow, K.R., Magnússon, S.M. (1982) Natural Radiation in Iceland and the Faroe Islands. Statens Institut for strålehygiejne Denmark.

Jónsson, G., Theódorsson, P. (2003) Radon í andrúmslofti íbúða á Íslandi. Report to the Icelandic, Student Innovation Fund.

Jónsson, G., Halldórsson, Ó., Theodórsson, P., Magnússon, S.M., Karlsson, R.K. (2016) Indoor and outdoor radon levels in Iceland. https://gr.is/wp-content/uploads/2016/09/Indoor-and-outdoor-radon-levels-in-Iceland_NSFS_Final_FINAL_version.pdf. Last access 12/11/2018.

22 Ireland

A national survey was conducted between 1992 and 1999, with the goal to determine geographical radon distribution in Ireland. Random sampling was performed from each 10 km x 10 km square. A total of 12649 measurements were performed out of which 11319 were valid. Detectors were exposed for approximately 12 months, 2 in each dwelling (main living area and main bedroom). Mean value is calculated based on the assumption of equal occupancy. CR-39 detectors were used. After exposure, they were etched with 6.25 M NaOH for 8 hours at 75 °C. Questionnaires were issued with the detectors (Fennell et al, 2002).

Data was evaluated by performing log normality test and by descriptive statistics. Radon map was produced with 10 km squares grid. Percentage of dwellings with over 200 Bq/m^3 was determined for each square. Squares with more than 10% were designated as high radon areas. National average and population weighted national average concentrations were determined. Regular quality checks were performed during the survey (Fennell et al, 2002).

National survey was conducted in 2015 in order to confirm previous findings and to measure average national concentration. Sampling was stratified, based on the previously determined radon risk. Measurements were performed in 649 dwellings. Detectors were exposed for approximately 3 months (September – November), 2 in each dwelling (main living area and main bedroom). Mean value is calculated based on the assumption of equal occupancy. CR-39 detectors were used. After exposure, they were etched with 6.25 M NaOH for 1 hour at 98 °C. Questionnaires were issued with the detectors (Dowdall et al, 2017).

Data was evaluated by identification of outliers, log normality tests, tests for bias due to measurement duration. National average concentration was weighted according to previous findings. Measurements were performed by an accredited laboratory (Dowdall et al, 2017).

Table 22.1. Comparison of 2002 NRS and 2015 national average indoor radon concentration survey key metrics.

	2002	2015
Number of homes measured	11,319	649
No. of homes >200 Bq m^{-3}	9%	8%
Minimum concentration measured (less 6 Bq m^{-3} background subtraction) (Bq m^{-3}) after subtraction of background?	8	5
Maximum concentration measured (Bq m^{-3})	1924	1001
Arithmetic mean (Bq m^{-3})	89	77
Geometric mean (Bq m^{-3})	57	51
Geometric standard deviation (Bq m^{-3})	2.4	2.4

Source: Dowdall et al, 2017.

Table 22.2. Summary of survey results for each county in Ireland.

County	No. of Dwellings Measured	No. >200 Bq/m^3 (% of dwellings measured)	Mean (Bq/m^3)	Max (Bq/m^3)
Carlow	194	30 (15%)	123	1562
Cavan	180	5 (3%)	67	780
Clare	742	66 (9%)	88	1489
Cork	1211	71 (6%)	76	1502
Donegal	487	18 (4%)	69	512
Dublin	155	6 (4%)	73	260
Galway	1213	181 (15%)	112	1881
Kerry	932	52 (6%)	70	1924
Kildare	480	29 (6%)	90	1114
Kilkenny	181	16 (9%)	100	717
Laois	334	17 (5%)	83	565
Leitrim	145	6 (5%)	60	433
Limerick	524	41 (8%)	77	1102
Longford	132	8 (6%)	75	450
Louth	124	14 (11%)	112	751
Mayo	1184	152 (13%)	100	1214
Meath	233	18 (8%)	102	671
Monaghan	120	4 (3%)	68	365
Offaly	286	7 (2%)	68	495
Roscommon	235	17 (7%)	91	1387
Sligo	270	54 (20%)	145	969
Tipperary	852	63 (7%)	79	1318
Waterford	162	20 (12%)	119	1359
Westmeath	289	20 (7%)	91	699
Wexford	469	54 (12%)	99	1124
Wicklow	185	24 (13%)	131	1032

Source: Fennell, 2002.

References

Fennell, S.G. et al, (2002). Radon in Dwellings, the Irish National Radon Survey, RPII-02/1, Radiological Protection Institute of Ireland, Dublin, www.epa.ie/pubs/reports/radiation/radonindwellingstheirishnationalradonsurvey.html

Dowdall, A. et al, (2017). Update of Ireland's national average indoor radon concentration - Application of a new survey protocol, Journal of Environmental Radioactivity 169-170, 1-8.

23 Italy

A national study was performed in order to evaluate novel radon mapping strategy by using Telecom infrastructure. The study was conducted between 2004 and 2007, while the paper reported only the first year results. Underground inspection rooms were used for this purpose, as well as Telecom buildings. The buildings were selected in such way to be similar to normal buildings and also having in mind geographical distribution within each of the 20 Italian regions. A total of 1438 inspection rooms were selected and 1414 Telecom buildings. One CR-39 detector was positioned in each inspection room for 12 months, while 1 detector was positioned in two rooms in each Telecom buildings for the same period. In 10 – 15% of cases, additional detector was positioned for quality control purposes. Concentrations are averaged for each building (Carelli et al, 2009).

The results were evaluated by descriptive statistics and by excluding the results from rooms directly connected to underground pipelines. Average concentrations for each of the 20 regions were calculated. All the equipment used has traceable calibrations and QA/QC procedures are in place (Carelli et al, 2009).

Table 23.1. Detectors summary results of the first year of measurements in Telecom buildings.

Region	Detectors	Radon concentration (Bq/m^3)							
	N	Min	Max	Average	Median	SD	SE	GM	GSD[a]
Abruzzo	133	7	2031	69	19	219	19	49.7	5.9
Basilicata	21	5	2458	200	22	551	120	34.4	5.2
Calabria	210	2	3303	60	16	244	17	20.9	3.0
Campania	281	6	8823	356	96	782	47	105.3	4.7
Emilia-Romagna	483	4	735	33	14	69	3	17.3	2.4
Friuli-Venezia Giulia	75	3	1938	88	18	252	29	24.4	3.9
Lazio	552	8	5941	171	47	483	21	59.6	3.3
Liguria	91	4	214	18	9	29	3	10.9	2.3
Lombardia	669	4	3610	135	40	303	12	51.4	3.4
Marche	77	5	1720	50	11	208	24	16.0	2.7
Molise	30	3	589	40	15	107	20	16.9	2.8
Piemonte	409	2	2204	89	31	192	9	38.7	3.1
Puglia	195	5	1941	120	39	256	18	46.4	3.5
Sardegna	263	5	681	46	21	75	5	26.4	2.5
Sicilia	563	4	1520	65	22	148	6	27.6	3.1
Toscana	269	3	830	58	20	119	7	25.1	3.1
Trentino-Alto Adige	147	7	3207	196	62	401	33	77.3	3.5
Umbria	112	5	807	37	17	91	9	19.2	2.5
Val D'Aosta	17	8	755	139	21	227	55	48.1	4.3
Veneto	140	5	1711	126	43	252	21	50.4	3.4
Italy	4737	2	8823	109	27	327	5	35.5	3.6

SD = standard deviation; SE = standard error; GM = geometrical mean; GSD = geometrical SD.
[a] Dimensionless.

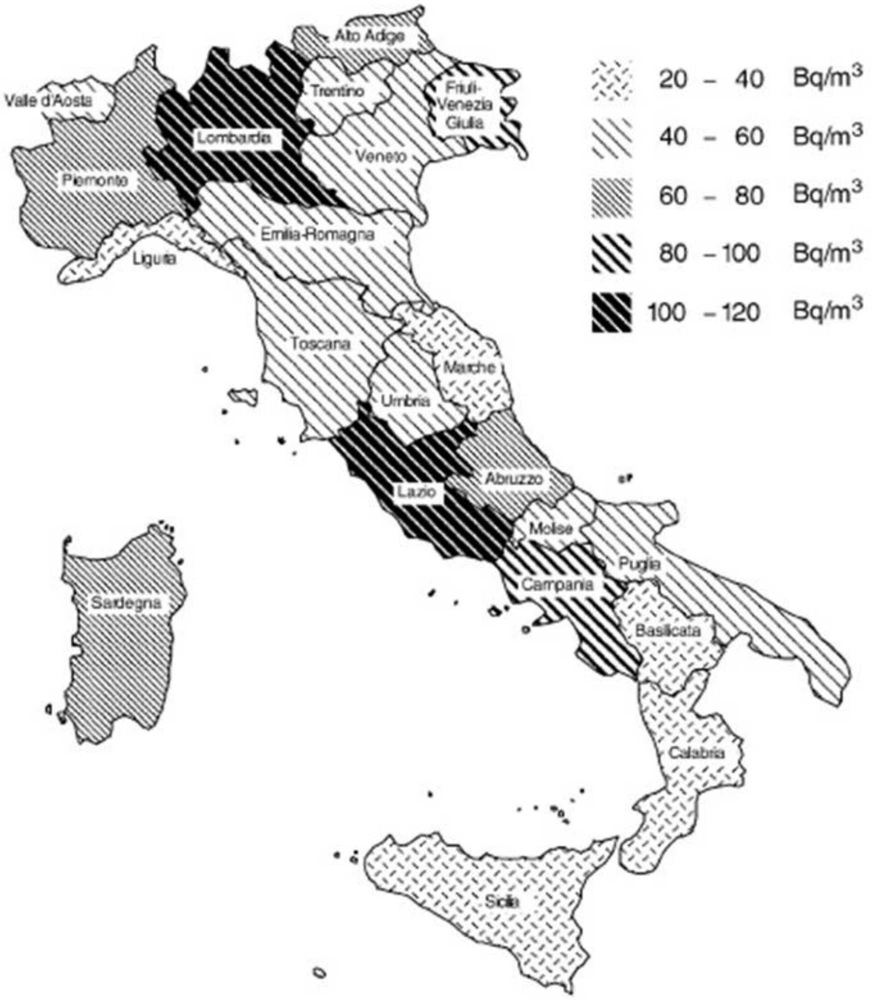
Source: Carelli et al, 2009.

Another national study was conducted between 1989 and 1998 in all 21 Italian regions for the purpose of estimating the national distribution of radon levels in dwellings. Measurements sites were selected by simple random sampling in cities over 100000 inhabitants and cluster sampling in smaller cities. A total of 5631 validated measurements were performed. Median floor for large cities was 2nd floor and for the small cities 1st floor (Bochicchio et al, 2005).

Ad hoc SSNTD detector with KODAK LR115-II was used, made by Dosirad. Spark counting was used for track counting. Thoron was blocked from entering detectors. Detectors were exposed for two consecutive periods of 6 months (spring-summer and autumn-winter). If one period was missing, seasonal correction factors were applied (Bochicchio et al, 2005).

Results were evaluated by descriptive statistics and log-normality tests. Calibration at NPRB UK was performed and several intercomparisons were performed between regional laboratories. Population weighted national average, and percentage of houses over 150, 200, 400 and 600 Bq/m^3 were calculated for national level and for each region. Radon map was also produced (Bochicchio et al, 2005).

Figure 23.1. Map of the average annual radon concentration levels in all the 21 Italian regions.



Source: Bochicchio et al, 2005.

References

Carelli, V. et al, (2009) A National Survey on Radon Concentration in Underground Inspection Rooms and in Buildings of a Telephone Company: Methods and First Results, Radiation Measurements 44, 1058-1063.

Bochicchio, F. et al, (2005). Annual Average and Seasonal Variations of Residential Radon Concentration for all the Italian Regions, Radiation Measurements 40, 686-694.

24 Kazakhstan

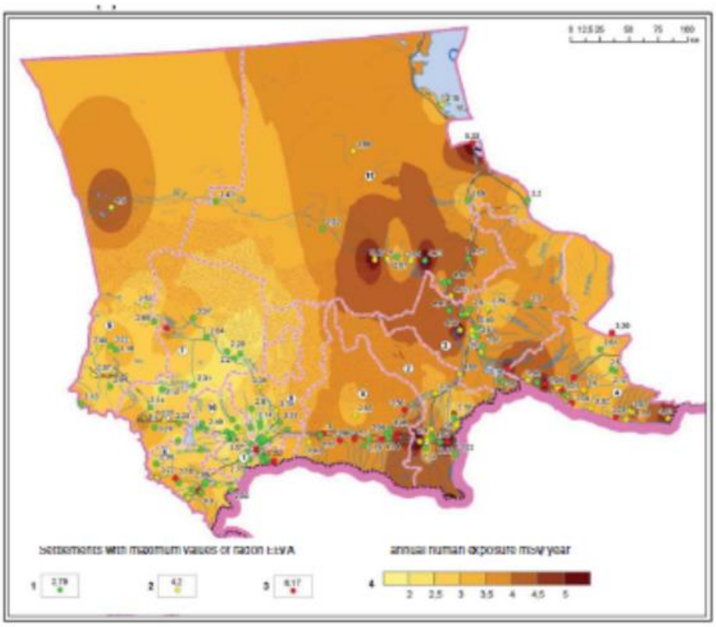
Paper (Fyodorov et al., 2014) describes complex radiation studies that were carried out on territory of Zhambyl oblast in 2011-2013. The territory is situated in the main part of Balkhash uranium ore province, including 12 uranium deposits, more than 20 ore occurrences, which to a greater extent determined the radiation situation in the area. In addition, dozens of areas of radioactive contamination of various origins in the region were identified, also contributing to the formation of high levels of radiation risk.

The main goals of these studies were radiological surveying of the settlements, estimation of radon concentration in soil, water, agricultural products, evaluation of indoor radon concentration and radon concentration in drinking water sources, and estimation of public doses.

Taking into account studies of previous years in Zhambyl oblast, a radiation survey of 316 villages and 4 towns (Taraz, Shu, Karatau and Zhanatas) was made. Analysis of natural and geological features allowed selecting of 4 landscapes-radiogeochemical blocks with various structural tectonic and radiation-geochemical characteristics. Different levels of public exposures were identified 10 areas with high radiation intensity, which occupy about 15% of the territory.

In the result of the radon hazardous assessment it was found that the 26.2% of surveyed villages were exceeding the regulation limit (200 Bq/m^3) of radon concentration.

Figure 24.1. Map of the total radiation dose Zhambyloblast.
Legend: Settlement with maximum values of radon EEVA: 1- to 100 Bq/m^3, 2- from 100 to 200 Bq/m^3, 3- 200 Bq/m^3 and above (upper value of the annual total dose, mSv/year), 4- the annual human exposure mSv/year.



Source: Fyodorov et al., 2014.

References

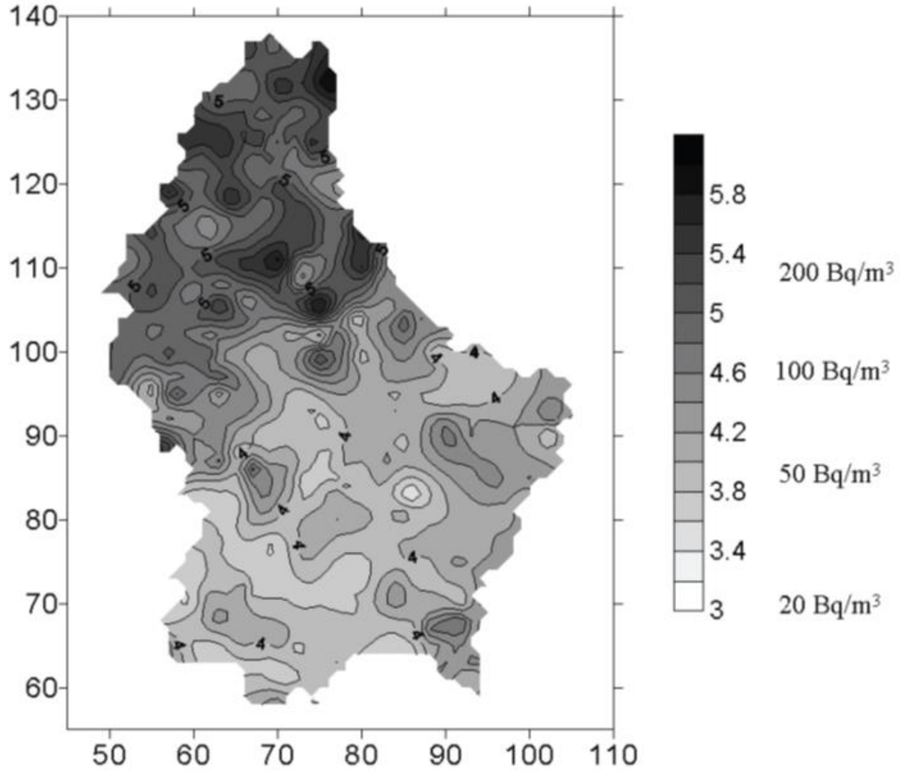
Fyodorov, G.V., Berkinbayev, G.D., Kayukov, P.G. (2014). Radiological atlas of Zhambyl oblast in Kazakhstan, Научные статьитом 7(4), 62-66.

25 Latvia

The survey of indoor radon concentration was conducted from 1993 to 1994 in 300 random selected dwellings in Latvia (Dubois, 2005).

A computer was used to find on the map of Latvia random points at a density proportional to the number of small houses in each region (approximately one point for 780 houses was chosen).They didnot generally know if at the place where the computer put a random point a house is located. Therefore, an additional two random points ineach district were chosen. The radon measurements were made with the E-PERM system, consisting of 60 standard 200 ml ionizing chambers, short term electrets of high sensitivity and 20 long term electrets. The average indoor radon concentration in detached houses is estimated as 68.5 Bq/m^3, but averages in different districts range from 20 Bq/m^3 to 120 Bq/m^3 (Dambis, 1994).

Figure 25.1. Map of annual mean radon concentration values.



Source: Dubois, 2005.

References

Dubois, G. (2005) An Overview of Radon Surveys in Europe, European Communities.

Dambis, M. (1994) Radon in Latvia's Dwellings, Radiation and Society: Comprehending Radiation Risk, Vol.2, IAEA Conference Paris, 24-28 october 1994, IAEA CN-54/31P, 379-382.

26 Lithuania

A national survey of indoor radon levels in Lithuania was performed between 1995 and 1998. The main objective of this survey was to evaluate the average of indoor radon concentrations in Lithuania and to determine whether there were significant variations with different areas (Morkunas and Akerblom, 1999).

Measurements have been carried out in 400 randomly selected detached houses. The duration of one measurement was at least 3 weeks. The levels in two commonly used rooms on the lowest level were measured using passive E-PERMTM electrets. As part of the quality assurance program the measuring system has been tested through intercomparisons. Measurements were carried out during the cold weather season, October 1st - 30 April 30th. Information on house construction and layout, including the age of the house, the building materials and whether there was a basement, the type of water supply, as well as the ambient gamma dose rate, were also recorded.

The results show that the arithmetic mean of indoor radon in the randomly selected detached houses is (55±4) Bq/m^3 (confidence level 95%) and the geometric mean is 22 Bq/m^3 (Morkunas and Akerblom, 1999). A separate set of measurements was performed in Birzai karst region. The arithmetic and geometric mean values in detached houses in this region are (98±16) Bq/m^3 and 50 Bq/m^3, respectively. Five regions (excluding the karst region) where the indoor radon concentrations are two or more times higher than the average concentrations in the rest of Lithuania have been found.

The source of indoor radon in Lithuania is the bedrock and the soils. The type and construction of house have significant influence on the indoor radon concentrations. The radon concentration in ground water is less than 30 Bql^{-1}. Application of the t-test indicates that there are no statistically significant differences between average values in winter and in summer. Statistically significant difference between concentrations in houses in the karst region and in randomly selected houses was found ($p<0.01$). The distribution of indoor radon concentrations in houses obeys the same lognormal shape.

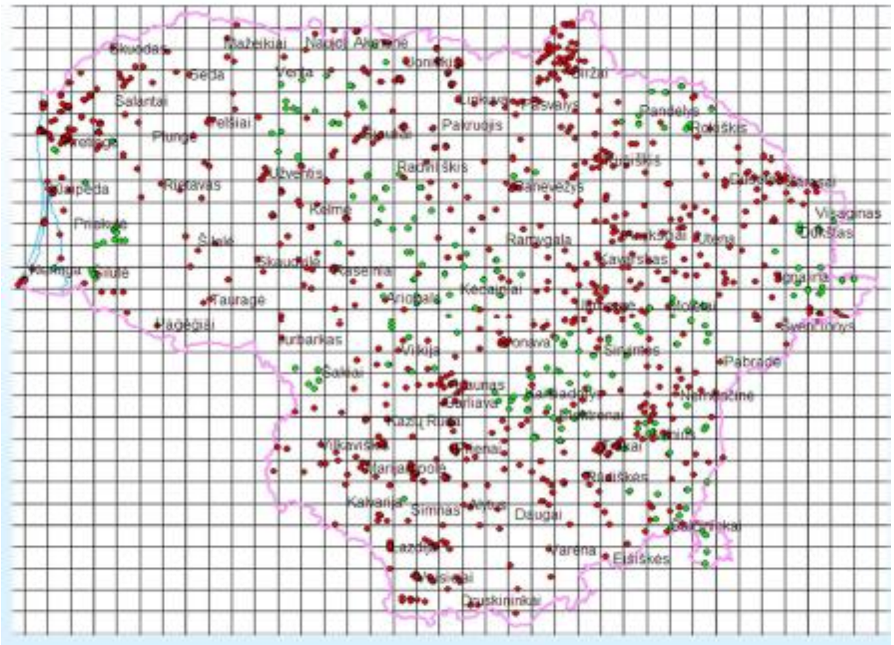
The annual effective doses as a result of indoor radon have been estimated and the average value for detached houses was 0.97 mSv (Morkunas and Akerblom, 1999).

According to reference (Ladygienė, 2015), a different range and purpose indoor radon surveys were performed or are going on starting year 1995, in Lithuania: National survey of indoor radon in 1995-1998; Survey in multi-storey houses and in workplaces in 2001-2004; Survey in region of higher radon risk in Northern part of Lithuania in 2001-2002; Survey in regions with higher conc. of indoor radon in 2002-2007; Children' and teenagers' institutions survey in 2002-2003 and 2014 year; Indoor radon mapping, data transference to EC JRC in 2007 till now; Geogenic radon potential map, starting in 2008.

Average indoor radon concentrations measured in 1995-1998 was 44 Bq/m^3 and exposure was up to 0,55 mSv per year. During year 2011-2015 measurements in the same 11 municipalities show increase of indoor radon up to 44 percent (due to saving energy measures and new dwellings constructed). Average indoor radon concentration (according to data of 2015, (Ladygienė, 2015)) is 79 Bq/m^3, this results in an annual 1.4 mSv for public exposure. In terms of the latest internationally recognized methodology, the average exposure for the population would reach up to 2.0 ± 0.4 mSv per year. This would represent more than 60 percent of public exposure from all sources of ionizing radiation received during the year.

In Figure 26.1 below, the map of indoor radon measurements in dwellings, approx. 3000 measurements, grid 10 x 10 km, is presented (Ladygienė, 2015).

Figure 26.1. Indoor radon measurements in dwellings, approx. 3000 measurements, grid 10 x 10 km, 1 dwelling.



Source: Ladygienė, 2015.

Future plans are to develop a new national radon action plan (to address long-term risks from radon exposures) which will be approved according to requirements of *Council Directive 2013/59/EURATOM of 5 December 2013* laying down basic safety standards for protection against the dangers arising from exposure to ionizing radiation and *IAEA GSR Part 3* during 2018 (Ladygienė, 2015).

References

Morkunas, G. and Akerblom, G. (1999). The Results Of The Lithuanian Radon Survey, Radon In The Living Environment, 19-23 April 1999, Athens, Greece.

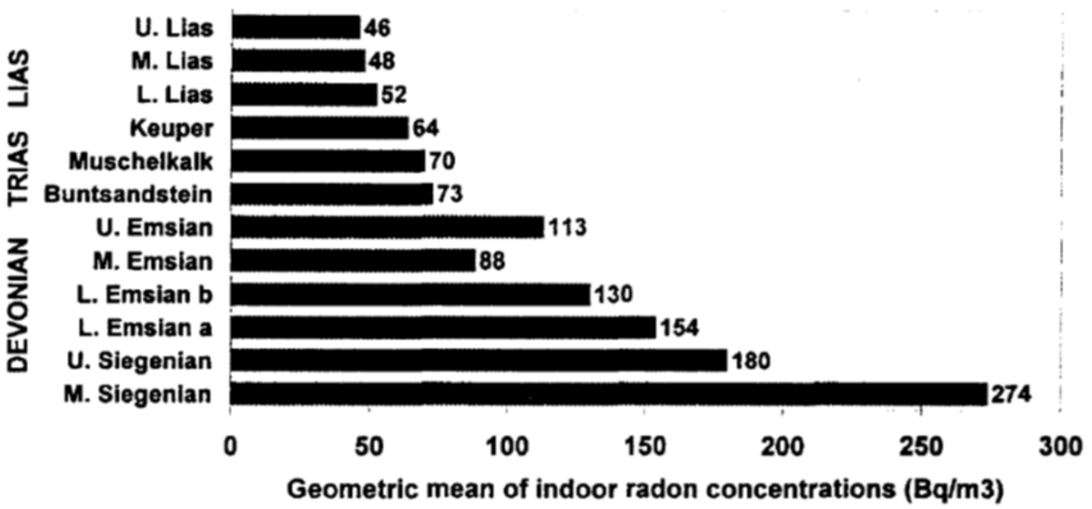
Ladygienė, R., Phd, Power Point Presentation, Current Indoor Radon Situation In Lithuania, Radiation Protection Centre, 2015.

27 Luxembourg

The survey of indoor radon concentration was conducted from 1993 to 2002 in 2619 random selected dwellings in Luxembourg. The average indoor radon concentration in houses is estimated as 115 Bq/m^3 (Dubois, 2005).

Since 1990 more than 5000 Solid State Nuclear Track detectors of the Karlsruhe type measurements in 3000 houses have been taken, 5% of the measurements carried out on request, 95% randomly distributed by the voluntary fire brigades. For the analysis, only single-family houses with at least one exposure period of over three months in the living area and with a complete questionnaire were retained. Descriptive statistics and lognormality checks were used to evaluate the data. Influence of lithology analyses, influence of the existence of a cellar, age and building characteristics were discussed. Higher indoor radon concentrations (geometric mean 150 Bq/m^3) are found in the North and lower ones (geometric mean 60 Bq/m^3) in the South (Kies, 1996).

Figure 27.1. Indoor radon concentrations measured in houses built on different geological stages.



Source: Kies, 1996.

References

Dubois, G. (2005) An Overview of Radon Surveys in Europe, European Communities.

Kies, A., Biell, A., and Eowlinston, L. (1996) Radon Survey in the Grand-Duchy of Luhembourg - Indoor Measurements Related to House Features, Soil, Geology, and Environment, Environment International, 22(l) 1, S805-S808.

28 Macedonia

The results of the national survey in FYR Macedonia are described in Stojanovska et al, 2012. The goal was to estimate the mean radon concentration, annual effective dose and radon distribution by investigating total of 437 dwellings, selected based on the population density. The RSKS and RADUET CR-39 etch track detectors were placed in most used rooms during the whole year from 2008-2009 (4 periods of 3 moths in each dwelling). Descriptive statistics, tests for lognormality and ANOVA tests were used to evaluate the results. The final result of the survey was the annual mean indoor radon concentrations for different statistical regions, presented in the Table 28.1 below. Based on these results, a radon map with descriptive statistic for each region was produced and is presented in Figure 28.1 below.

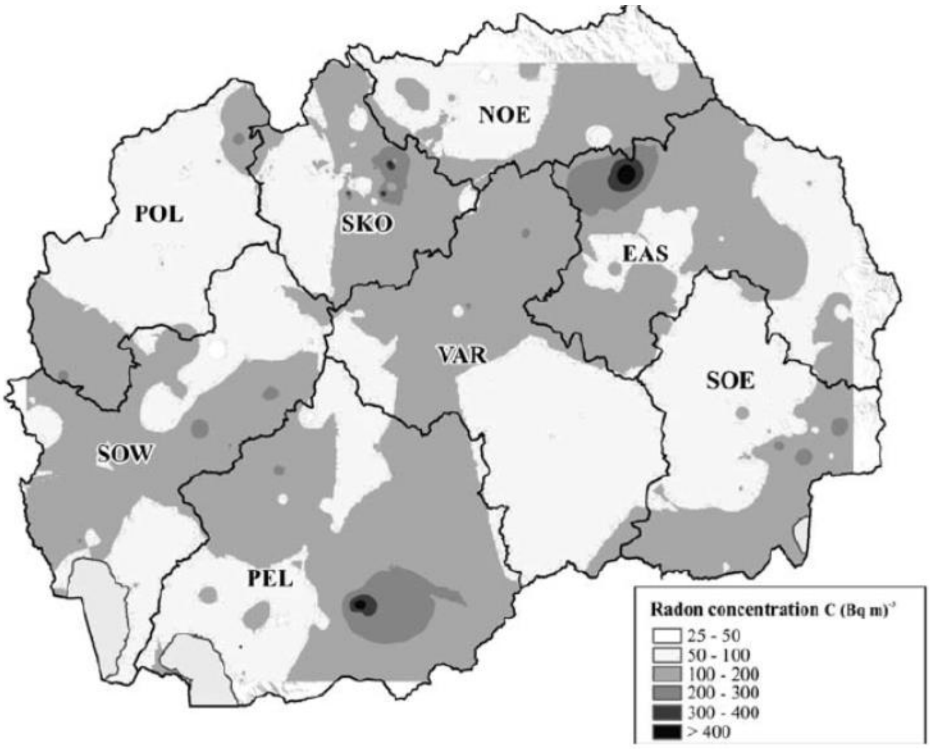
Table 28.1. The annual mean indoor radon concentration.

Statistical region	Code	Geotectonical zone	NM[a]	C (Bq m^{-3})				
				Max[b]	AM	SD[c]	GM	GSD[d]
Northeast	NOE	Serbo-Macedonian massif	43	300	91	58	78	1.7
Easter	EAS	Vardar zone	48	511	127	99	103	1.8
Southwest	SOW		47	245	94	52	81	1.8
Skopje	SKO	Vardar zone	124	502	105	83	83	1.9
Vardar	VAR		20	267	89	55	78	1.6
Polog	POL	Western-Macedonian zone	42	236	77	54	62	1.9
Southeast	SOE		48	307	104	70	88	1.8
Pelagonia	PEL	Western-Macedonian zone Pelagonian massif	65	720	127	120	99	1.9
All regions			437	720	105	84	84	1.9

[a]Number of measurements.
[b]Maximum.
[c]Standard deviation.
[d]Geometric standard deviation.

Source: Stojanovska et al, 2012.

Figure 28.1. Interpolated map of the studied area for the annual mean indoor radon concentration.



Source: Stojanovska et al, 2012.

References

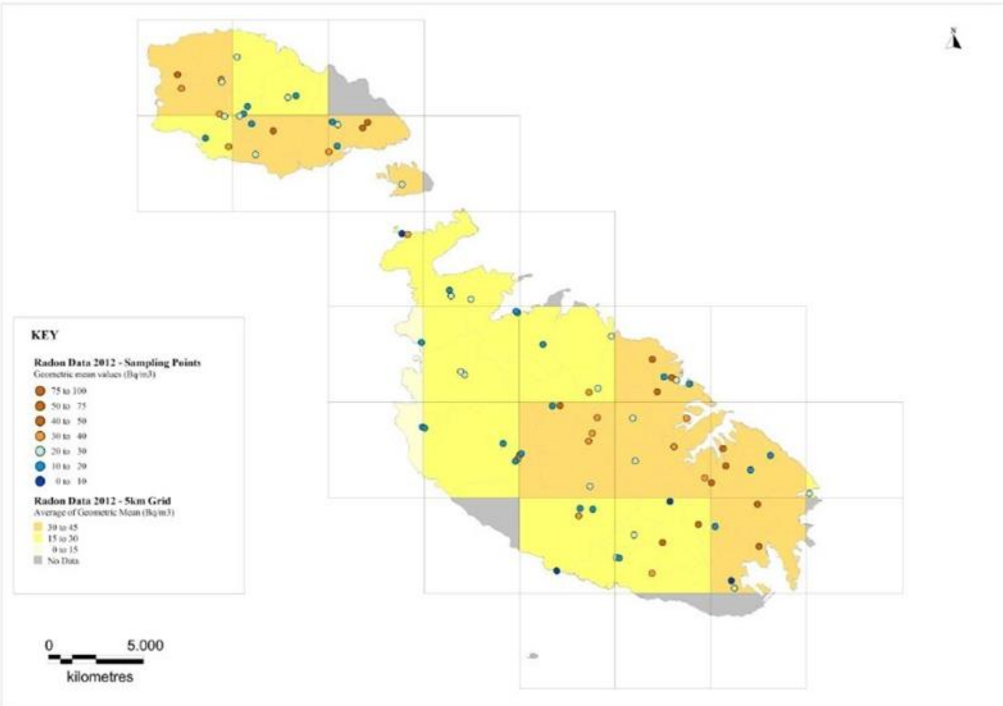
Stojanovska, Z. et al, (2012). Indoor Exposure of Population to Radon in the FYR of Macedonia, Radiation Protection Dosimetry 148 (2), 162–167.

29 Malta

A national survey was conducted between 2010 and 2011 in order to determine distribution of indoor radon gas concentration. The study was performed during the whole year, with two consecutive exposures at each selected building lasting 6 months. Five buildings (1 school, 1 public building and 3 private residences) were sampled from each of the 5 x 5 km grids – a total of 85 buildings. In each building, 2 Kodak LR115 film detectors were positioned in different ground floor rooms by trained personnel, near the head height (Baluci et al, 2013).

Results were evaluated by descriptive statistics and nearest neighbor analysis. All results were lower than 100 Bq/m^3. Method was validated by NPRB, UK (Baluci et al, 2013).

Figure 29.1. Map of indoor radon in Malta.



Source: Baluci et al, 2013.

References

Baluci, C. et al, (2013). National Mapping Survey of Indoor Radon Levels in the Maltese Islands, Malta Medical Journal 25(4), 33-39.

30 Moldova

The aim of the research was focused on the need for a National Radon Strategy and National Action Plan.

Investigation of radon concentration took place between 1991 and 2011.

An active device RTM1688-2 from SARAD company was used. It is not clear whether all measurements were performed by RTM1688-2.

Table 30.1 shows the range of radon concentrations measured in the period 1991-1999.

In 2007, 430 measurements were made in 61 rooms. At 421 measured places, Rn concentrations were below 100 Bq/m^3, 7 between 100 and 200 Bq/m^3 and two above 200 Bq/m^3.

In 2008, 280 indoor measurements were made in 39 areas. Only 2 locations exceeded the level of 200 Bq/m^3.

Table 30.1. Range of radon concentrations measured in the period 1991-1999.

Concentration, Bq/m^3	The years and the number of the measurement							
	1991	1992	1993	1994	1995	1997	1998	1999
15-30	25	71	20	9	14	-	4	4
31-50	15	21	9	5	8	-	2	5
51-70	-	-	4	-	7	3	1	2
71-90	-	-	-	-	5	1	3	1
91-120	-	-	1	-	4	-	1	1
121-141	-	-	4	-	2	-	3	1
201-300	-	-	1	-	2	-	1	-
313-400	-	-	1	-	2	-	1	-
411-500	-	-	-	-	4	-	-	-
516-600	-	-	-	-	1	-	-	-
625-700	-	-	-	-	2	-	-	-
1930	-	-	-	-	-	-	1	-

Source: Ursulean, 2013.

No other details were reported on these measurements.

References

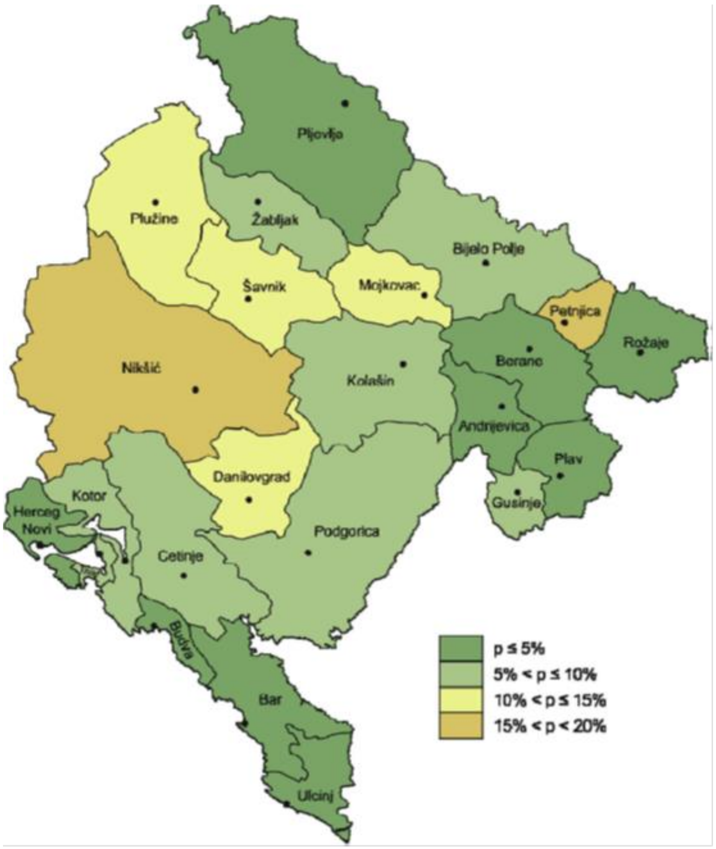
Ursulean, I., Coreţchi, L., Chiruţă, I., and Vîrlan, S. (2013) Estimation of indoor radon concentrations in the air of residential houses and mines in the republic of Moldova. Rom. Journ. Phys., Vol. 58, Supplement, S291–S297, Bucharest.

31 Montenegro

The first systematic indoor radon measurements on the Montenegrin Coast were carried out in the period 2002–2003, when 107 randomly selected homes in urban settlements (in each 500×500 m grid square one house was randomly selected and one dwelling in the house) were surveyed using CR-39 track-etch detectors, twice a year, each time for about 6 months. Dosimeter was regularly located in the living room or a bedroom on the ground floor or the first floor, in a place which is away from windows and doors, and about 1.5 m above the floor and 0.5 m away from the wall. In order to control the consistency and accuracy of dosimeter response, at each 10^{th} measuring location two dosimeters were placed together and, again at each 10^{th} (but the other) location, a passive radon monitoring device of the J. Stefan Institute, Ljubljana, Slovenia utilizing CR-39 detector, was placed beside authors dosimeter. None of the measured radon concentrations exceeded the action level of 400 Bq/m^3. The annual average radon concentrations were found to be lognormally distributed (GM = 25.5 Bq/m^3, GSD = 2.1) within the range from 3 to 202 Bq/m^3, with arithmetic mean of 31.8 Bq/m^3, and median of 25.1 Bq/m^3. The average effective dose due to exposure to radon in urban homes on the Montenegrin Coast is estimated to be 0.50 mSv y^{-1} (Antovic, 2007).

The first nationwide indoor radon survey in Montenegro started in 2002 and year-long radon measurements withCR-39 track-etch detectors, within the national grid of 5 km×5 km and local grids in urban areas of 0.5 km×0.5 km, were performed in homes in half of the country's territory. The survey continued in 2014 and measurements in the rest of the country were completed at the end of 2015. The 953 valid results, obtained in the national radon survey, give an average radon activity concentration in Montenegrin homes of 110 Bq/m^3. Assuming a log-normal distribution of the experimental results, geometric mean 58.3 Bq/m^3 is calculated. Normality tests show that the experimental data are not log-normal, and that they become closest to a log-normal distribution after subtracting from them radon concentration in the outdoor air of 7 Bq/m^3, which is theoretically calculated. Based on the results of radon survey, a new national radon reference level of 300 Bq/m^3 and an "urgent action level" of 1000 Bq/m^3 are suggested, with estimated fractions of the national dwelling stock above these levels of 7.4% and 0.8% respectively. Fractions of homes with radon concentrations above the suggested levels are also estimated for each of the 23 municipalities in Montenegro. The six municipalities which have more than 10% of homes with radon concentration above 300 Bq/m^3 are recommended as radon priority areas (Vukotic, 2018).

Figure 31.1. Radon map of Montenegro: percentage (p) of homes, in the municipalities, with radon activity concentrations above 300 Bq/m^3.



Source: Vukotic, 2018.

References

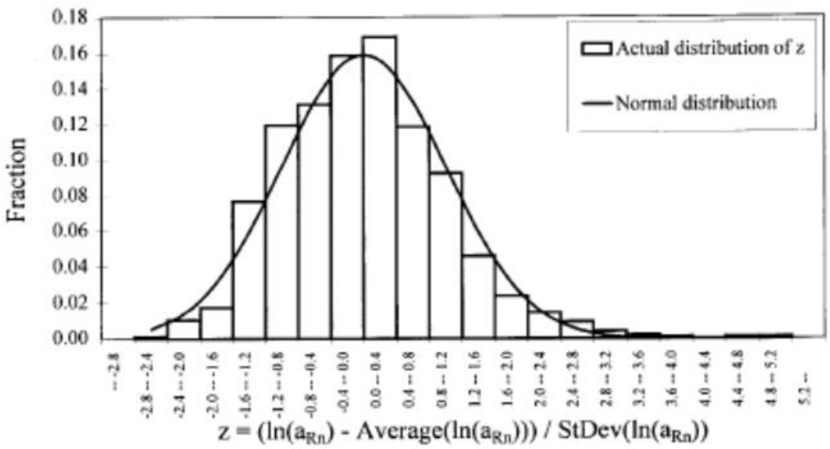
Antovic, N. et al., (2007). Indoor Radon Concentrations in Urban Settlements on the Montenegrin Coast. Radiation Measurements 42, 1573–1579.

Vukotic, P. et al., (2018). Radon Survey In Montenegro – A Base to Set National Radon Reference and "Urgent Action" Level, Journal of Environmental Radioactivity, doi: 10.1016/j.jenvrad.2018.02.009.

32 Netherlands

Two papers describe a national survey in Netherlands: Stoop et al (1998) and Lembrechts et al (1999). The goal of these investigations were to describe the trend in the average radon concentration by supplementing the first survey on dwellings built up to 1984 and to quantify the contributions of the most important sources of radon. The 1500 dwellings, built between 1985 and 1993, were randomly sampled from 52 municipalities. Track etch detectors from the 'Forschungszentrum Karlsruhe' (FzK) were placed in living rooms of 1500 selected houses during the period from 1995-1996. Lognormality tests were performed to evaluate the measurement results and it was concluded that 0.012% of new houses has a radon level above 200 Bq/m^3. The results of lognormality tests are shown in Figure 32.1, below, taken from (Stoop et al, 1998).

Figure 32.1. Test of lognormality of indoor radon concentration.



Source: Stoop, 1998.

References

Stoop, P., Glastra, P., Hiemstra, Y., De Vries, L., Lembrechts, J. (1998). Results of the second Dutch national survey on radon in dwellings, RIVM Report no. 610058006.

Lembrechts, J., Janssen, M., and Stoop, P. (1999). Ventilation and Radon Transport in Dutch Dwellings: Computer Modelling And Field Measurements, Radon in the Living Environment, 19-23 April 1999, Athens, Greece, 525-536.

33 Norway

Norway is among the countries with the highest indoor radon concentrations in the world mainly due to radium rich soil and bedrocks (such as alum shale and uranium rich granites) and highly permeable sediments (such as moraines and eskers).

Several large surveys were performed in Norwegian dwellings. The first one took place from 1984 till 1986. Detectors were deployed in 1600 dwellings in 79 municipalities. Measurements were performed using termoluminiscence detectors in charcoal and measurement lasted between 5 and 7 days. Two measurements per dwelling were deployed.

The second survey took place in the period 1987-89 covering 7500 dwellings. It used CR-39 detectors, one detector per dwelling. Number of dwellings per municipality was proportional to its population. Detectors were deployed for 6 months. Mean annual radon concentration was found to be between 55 and 65 Bq/m^3.

The measurements of the third survey were performed in the period 1991-1998 in 31 municipalities, using 5000 CR-39 detectors with one or two detectors placed in each dwelling for 2-3 months during the heating season. Mean annual radon concentration was found to be between 115 Bq/m^3.

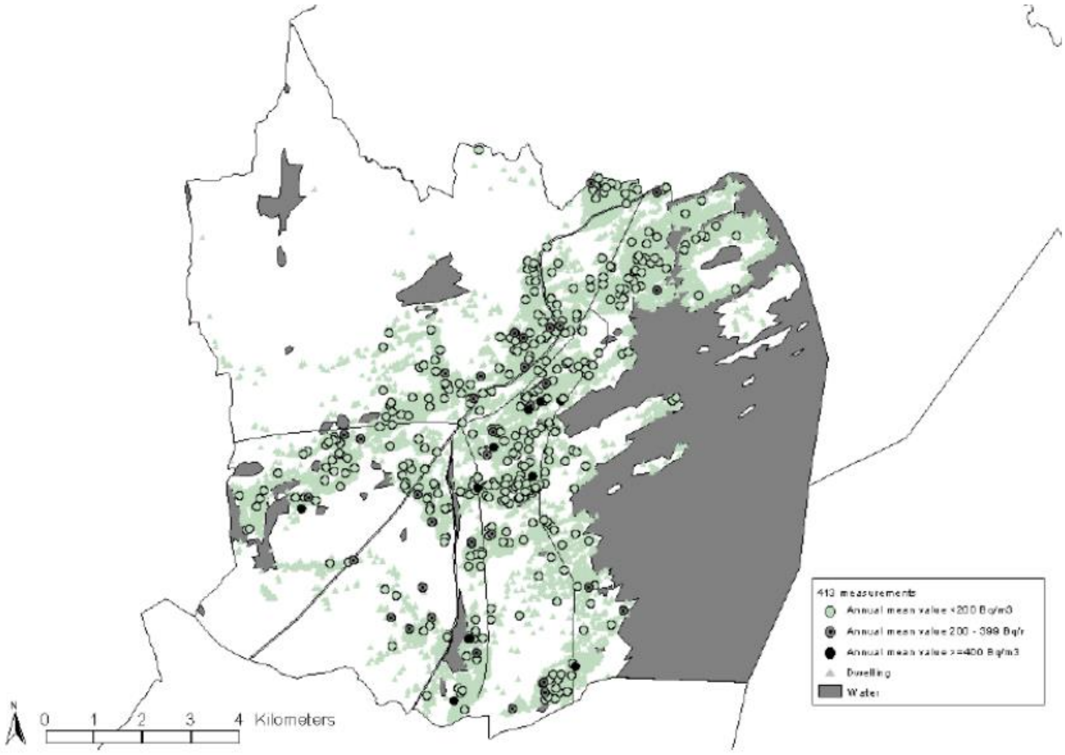
Next survey was conducted in the heating period of 2000/2001, with 29000 CR-39 detectors which were deployed one in each dwelling. Mean annual radon concentration was found to be between 89 Bq/m^3, with 9% and 3% of dwellings with radon concentrations higher than 200 and 400 Bq/m^3, respectively.

And finally, in the fifth survey, conducted in 2002/2003, 8400 dwellings in 44 municipalities were deployed. The detectors were exposed for 2 months in a heating season, with one detector for each dwelling. The primary objective was to identify radon priority areas. The highest value obtained was 18000 Bq/m^3. It was found that 18% and 7% of results exceed 200 Bq/m^3 and 400 Bq/m^3, compared to 9% and 3% for the whole country.

Also, around 20000 Rn measurements were performed by private companies and most of those results are not included in the surveys.

As a conclusion it is estimated that 9% of the dwellings has an annual mean radon concentration exceeding 200 Bq/m^3. However, there are regions where more than 50% of the results exceed the level of 200 Bq/m^3. In regions with only a few percentage points exceeding recommended level, no further surveys are recommended.

Figure 33.1. A point map of municipality in densely populated area.



Source: Jensen et al., 2004.

References

Jensen, C.L., Strand, T., Ramberg, G.B., Ruden, L., Ånestad, K. (2004). The Norwegian Radon Mapping and Remediation Program. In: Proceedings of the IRPA 11, Paper 6-61, 23-28 May 2004.

34 Poland

A national survey was carried out, starting from 1991. The duration of measurements was between 6 and 12 months. A total of 3305 measurement locations were selected geographically. CR-39 diffusion chamber was used (IAEA, 2017).

A national survey was conducted between 2008 and 2009 in order to perform comprehensive measurements of radon in the whole country. Before the survey, 13 geological regions were identified. In all 13 regions, a total of 129 building were selected. For each building, 12 monthly averages were calculated by placing 3 CR-39 detectors each month, and 4 quarterly averages by placing 3 detectors each quarter. Detectors were placed away from the doors, windows and ventilation and 1-2 m above the floor (Przylibski et al, 2011).

Data was evaluated by descriptive statistics and log-normality test. National mean radon concentration was calculated, as well as means, minimum and maximum value for each geological region. Intercomparison was performed in CLOR's calibration chamber (Przylibski et al, 2011).

Table 34.1. Selected statistical parameters describing the distribution of mean annual values of ^{222}Rn concentration [Bq/m^3] in the air of buildings located in the area of particular major tectonic units of Poland.

Tectonic unit	Number of data	Min.	Max.	Arith. mean	Std. dev.	Median	Geom. mean	Geom. St. dev.	Spread
		[Bq/m^3]							
Sudetes (*M*)	23	54	845	221	194	129	162	2.17	791
Sudetes (*Q*)	23	36	745	220	183	149	158	2.35	709
Fore-Sudetic monocline (*M*)	6	119	201	169	28	176	167	1.18	82
Fore-Sudetic monocline (*Q*)	6	131	212	179	27	184	177	1.16	81
Szczecin–Łódź–Miechów Synclinorium (*M*)	16	56	214	117	56	97	105	1.59	158
Szczecin–Łódź–Miechów Synclinorium (*Q*)	16	55	188	110	50	96	100	1.55	133
Mid-Polish Anticlinorium (*M*)	1	103							
Mid-Polish Anticlinorium (*Q*)	1	115							
Upper-Silesian Foredeep (*M*)	30	42	535	133	102	94	111	1.76	493
Upper-Silesian Foredeep (*Q*)	30	31	500	122	97	86	100	1.82	468
West-European Platform (*M*)	**76**	**42**	**845**	**159**	**133**	**110**	**127**	**1.87**	**803**
West-European Platform (*Q*)	**76**	**31**	**745**	**154**	**127**	**112**	**120**	**1.97**	**714**
Mazury-Podlasie Monocline (*M*)	26	90	556	249	117	226	224	1.59	466
Mazury-Podlasie Monocline (*Q*)	26	104	562	254	116	215	231	1.54	458
Pomeranian–Płock–Puławy Synclinorium (*M*)	7	53	255	117	83	80	98	1.78	202
Pomeranian–Płock–Puławy Synclinorium (*Q*)	7	64	253	120	81	75	101	1.72	189
East-European Craton (*M*)	**33**	**53**	**556**	**221**	**122**	**203**	**188**	**1.81**	**503**
East-European Craton (*Q*)	**33**	**64**	**562**	**225**	**122**	**202**	**194**	**1.76**	**498**
Carpathians (*M*)	5	77	161	114	36	118	110	1.33	84
Carpathians (*Q*)	5	72	117	94	18	88	93	1.19	45
Carpathian Foredeep (*M*)	15	83	257	156	44	151	151	1.31	173
Carpathian Foredeep (*Q*)	15	51	228	113	43	111	106	1.42	177
Carpathians and Carpathian foredeep (*M*)	**20**	**77**	**257**	**146**	**45**	**148**	**139**	**1.36**	**180**
Carpathians and Carpathian foredeep (*M*)	**20**	**51**	**228**	**108**	**39**	**103**	**102**	**1.38**	**179**
Poland (*M*)	**129**	**42**	**845**	**173**	**123**	**147**	**142**	**1.83**	**803**
Poland (*Q*)	**129**	**31**	**745**	**165**	**122**	**133**	**133**	**1.91**	**714**

Mean annual concentrations of ^{222}Rn activity calculated from monthly (*M*) and quarterly (*Q*) measurements.
Values in bold characterizes the main tectonic units of Poland and the country (Poland); values in normal style characterizes the tectonic units being the parts of the main units characterized in bold below them.

Source: Przylibski et al, 2011.

References

IAEA, IAEA-TECDOC-1810, (2017) Status of Radon RelatedActivities in Member StatesParticipating in TechnicalCooperation Projects in Europe, Vienna,ISBN 978–92–0–100617–2.

Przylibski, T.A. et al, Mean Annual ^{222}Rn Concentration in Homes Located in Different Geological Regions of Poland - First Approach to Whole Country Area, Journal of Environmental Radioactivity 102(8) (2011), pp. 735-741.

35 Portugal

The results of the national survey in Portugal, conducted from 1989-1990 are described in Faisca et al, 1992. The goal of the survey was to produce a radon map of the country. LR115 passive track detectors were distributed to the volunteer high school students, so there was no special sampling strategy. Total of 4200 dwellings were investigated by exposing the detectors for 3 months. Descriptive statistics is used to evaluate the measurement results and according to that, the radon map was produced.

References

Faisca, M.C., Teixeira, M.M.G.R., Bettencourt, A.O, Indoor Radon Concentrations in Portugal - A National Survey, Radiation Protection Dosimetry, Volume 45, Issue 1-4, 1 December 1992, pp. 465–467.

36 Romania

First two surveys performed in the periods from 1987-1990 and 1190-1994, covered in total around 460 dwelling. These surveys were performed with Makrofol detectors. Measurement sampling was 10 minutes, performed by filter sucking method. Sampling was performed in bedroom in any time of the season. The equilibrium equivalent concentration of 25 Bq/m^3 was reported from these measurements. (Iacob et al, 2005).

Based on the pilot study performed in Transylvania aiming to investigate relation between radon exposure and lung cancer risk, it was concluded that reported value of 49 Bq/m^3 was underestimated. Therefore, a more systematic research on population exposure to radon in Romania took place from year 2000.

The first map of residential indoor radon was build according to the recommendations of JRC, and it was based on the 10 years of research using CR-39 detectors from Radosys company (type RSK). Measurements have included 883 surveyed buildings in the Băița Ștei radon priority area and 864 in other regions of Romania. Measurements were performed following the HPA-NRPB Measurement Protocol in order to provide quality assurance and control of measurements. Detectors were exposed on the ground floor, at the height of 1-1.5 m from the floor at least 1m from the wall to avoid thoron and away from doors. Measurements lasted for a period of 3-12 months and seasonal correction were applied to obtain annual average mean, using correction factors proposed by Cosma (Cosma et al, 2009).

A large percentage of recovery (90%) was recorded. The influence of exposure outside the measurement point was negligible since storage time was less than 24h. Detailed questionnaire was provided: collect relevant information about factors relating to measurement site as characterisation of house, building materials, living habits etc. Accuracy of the measurement were checked periodically in a reference radon chamber and through international intercomparisons.

The lognormality of the distribution was checked by the D'Agostino–Pearson test.

Data were averaged over 10x10 km^2, except for RPA area of the Ștei - Băițaradon priority area where 1x1 km^2 grid was used. Geometric mean from all measurements was 121.8 Bq/m^3, with GSD=2.8, while it was 84 Bq/m^3 and 2.5 when excluding Ștei - Băița area.

Descriptive statistics of investigated regions is given in Table 36.1.

Table 36.1. Descriptive statistics of investigated regions in counties of Romania.

County	No. of surveyed dwellings	AM/Bq m^{-3}	SD/Bq m^{-3}	GM/Bq m^{-3}	GSD/Bq m^{-3}	Median/Bq m^{-3}	Max/Bq m^{-3}	CV/%	% (number) houses > 400/Bq m^{-3}
Alba	158	111	88	87.2	2.0	87	604	80	2 (3)
Bacău	15	119	62	103.5	1.8	116	237	52	–
Bihor	19	44	48	28.1	2.5	25	172	109	–
	883[a]	292	364	175.3	2.8	185	3653	125	21 (185)
Bistrița-Năsăud	136	125	127	90.2	2.3	99	897	101	4 (5)
Cluj	372	121	138	76.1	2.6	72	1050	114	5 (18)
Galați	12	53	22	48.8	1.5	55	104	42	–
Gorj	28	107	97	69.7	2.7	73	361	90	–
Maramureș	22	231	187	155.6	2.7	157	608	81	27 (6)
Mureș	28	232	154	180.4	2.2	230	696	67	11 (3)
Sibiu	46	95	69	76.0	2.0	74	361	73	–
Suceava	14	269	288	180.3	2.5	169	1140	107	21 (3)
Tulcea	14	205	134	171.2	1.9	158	507	65	7 (1)
Total	1747	210	287	121.8	2.8	123	3653	137	13 (224)
	864[b]	126	132	84.0	2.5	87	1140	105	5 (39)

AM, arithmetic mean; SD, standard deviation; GM, geometric mean; GSD, geometric standard deviation; CV, coefficient of variation.

[a] Ștei-Băița radon-prone area.

[b] Without Ștei-Băița radon-prone area.

Source: Cosma et al, 2013.

From 2013, there is an ongoing comprehensive survey of radon in homes, soil and water aiming to complete Romanian indoor radon map with 5000 additional Rn data.

This paper presents the results of radon measurements in homes, soil and water in 5 of 16 counties being analysed since 2013.

The same measurement protocol as described above was used. The average number of measuring location per cell was 4 ± 2, ranging from 4-15 depending on the population density except in the RPA of Ștei - Băița where 428 measurements per cell were made.

Lognormality of the distribution was tested by the Shapiro-Wilk test. The Spearman correlation coefficient was calculated in order to evaluate the relationship between the measured parameters. The comparison between samples was made with non-parametric Kruskal-Wallis test

A total of 1855 indoor radon measurements were carried out in 330 cells (see Table 36.2). The geometric mean of indoor radon measurements was 90 Bq/m^3, with a maximum value of 2592 Bq/m^3.

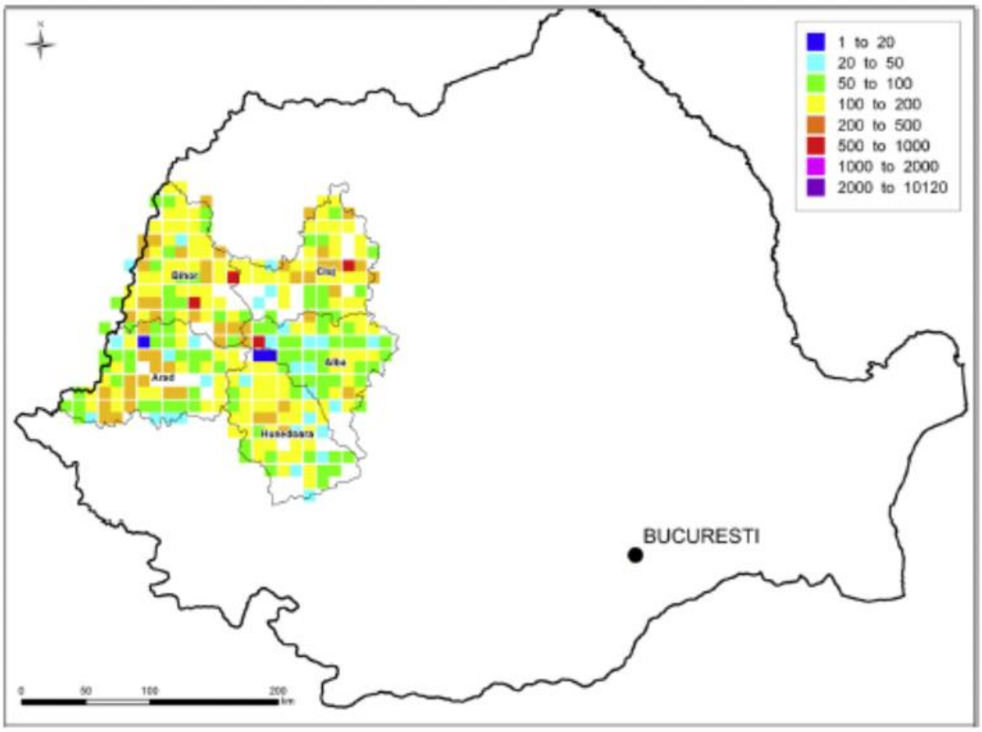
Table 36.2. Descriptive statistics of 5 counties of Romania.

County	No.	Min	Max	AM	SD	G.M	G.S.D.
Cluj	71	4.1	91.3	37.9	21.3	30.9	2.1
Alba	168	0.8	94.7	29.1	18.5	22.5	2.3
Arad	320	2.3	68.6	27.1	9.0	25.7	1.4
Hunedoara	287	8.5	169	36.0	10.1	32.7	1.5
Bihor	235	2.4	126	37.0	19.4	31.8	1.8
Total	**1081**	**0.8**	**169**	**32.6**	**17.2**	**28.4**	**1.8**

Source: Cucos et al, 2017.

In Figure 1, indoor map of average indoor radon concentrations measured at ground floors at 5 different Romanian counties. (Cucos et al, 2017).

Figure 36.1. Indoor map of average indoor radon concentrations measured at ground floors at 5 different Romanian counties.



Source: Cucos et al, 2017.

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Cosma, C., Szacsvai, K., Dinu, A., Ciorba, D., Dicu, T., Suciu, L., (2009). Preliminary integrated indoor radon measurements in Transylvania (Romania). Isot. Environ. Health Stud. 45 (3), 259-268.

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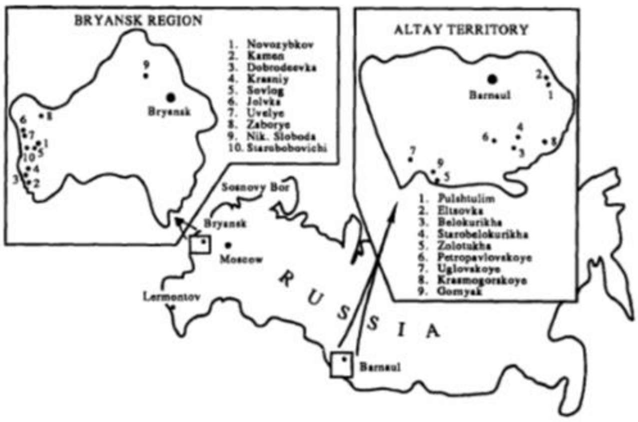
37 Russian Federation

Regional surveys that took place in four regions during the period from May to September 1993 are described in reference (Marenny et al, 1996). The main surveys goals were to estimate the collective doses and find the dwellings where the radon concentrations exceed the adopted level in Russian legislative.

Figure 37.1. Map of the Russia with the locations where the indoor and soil radon measurements were carried out.



Source: Marenny et al, 1996.

Sampling strategy was random and when possible, the buildings were selected so as to uniformly distribute the measurement points over the terrain of a given settlement. Measurement locations were predominantly on ground floors and, for comparison, in the cellars and on the upper floors of some buildings. About 1000 measurements of indoor radon concentration in dwellings and social buildings of investigated settlements were performed. Duration of a single measurement was 3 months for the track detectors and 5-8 days for the charcoal detectors.

During these surveys, passive and active methods were used. Indoor measurement chamber was 2.5 cm in diameter and 4.0 cm high with 22 microns thick polyethylene filter (CR-39 or CND). Visual microscopic method (200x) and the spark counting method were used to scan alpha tracks in the CR and CND detectors, respectively. The CR-39 detectors were etched for 3 h in 6N NaOH solution at 70 °C, and the cellulose nitrate detectors for 70 min in 6 N NaOH solution at 50 °C. Charcoal detectors were used also (Marenny et al, 1996).

The mean volume radon activity was calculated by multiplying the calibration factors by the measured track density, while the mean equilibrium equivalent radon concentrations were obtained by multiplying the resultant mean volume radon activities by an equilibrium factor, F = 0.5.

Results of radon indoor surveys in 83 regions in Russian federation are given in reference (Yarmoshenko et al, 2015). Survey period was from 2008 to 2013. Main survey goal was to estimate the arithmetic average indoor radon concentration. Sampling strategy was based on official annual reports - radiation measurements in 83 regions, those included more than 400000 indoor radon measurements, in all regions and for tree types of houses.

Table 37.1. The indoor mean EEC and mean annual EDE values.

Location	EEC, Bq m^{-3} Range	Mean	Median	EDE, mSv y^{-1} Range	Mean	Median
Altay Territory						
Pushtulim	23–218	93	96	1.4–13.3	5.7	5.7
Eltsovka	22–265	90	79	1.3–16.2	5.5	4.8
Belokurikha	22–577	80	52	1.3–31.5	4.8	3.2
Starobelokurikha	90–338	158	123	5.5–20.6	9.6	7.5
Zolotukha	44–170	93	76	2.7–10.4	5.7	4.6
Petropavlovskoye*	53–237	145	147	3.2–14.5	8.8	8.9
Uglovskoye	11–63	41	43	0.7–3.8	2.5	2.6
Krasnogorskoye	8–143	53	49	0.5–8.7	3.2	3.0
Gornyak	10–288	63	47	0.6–17.6	3.8	2.9
Bryansk region						
Novozybkov	29–111	67	67	1.8–6.8	4.1	4.1
Kamen	14–29	21	21	0.9–1.8	1.3	1.3
Dobrodeevka	10–92	28	20	0.6–5.6	1.7	1.2
Krasniy	12–69	22	16	0.7–4.2	1.3	1.0
Sovlog	16–26	21	21	1.0–1.6	1.3	1.3
Jalovka	14–48	27	28	0.9–3.0	1.6	1.7
Uvelye	30–82	57	58	1.8–5.0	3.5	3.5
Zaborye	23–56	35	32	1.4–3.4	2.1	2.0
Nik.Sloboda	8–85	38	40	0.5–5.2	2.3	2.4
Starobobovitchi	22–105	58	57	1.3–6.4	3.5	3.5
St Petersburg region						
Sosnovy Bor†	12–101	48	41	0.7–6.2	2.9	2.5
Lermontov (North Caucasus)	85–1554	549	369	5.2–95.0	33.5	22.5

*Charcoal measurements.
†The measurements were carried out during summer season of 1991.

Source: Marenny et al, 1996.

During performed surveys mostly short term radon measurements devices (grab sampling) were used. Only few laboratories were equipped with long term nuclear track detectors. Equilibrium factor 0.5 is used in Russia. Evaluation of the results were done using descriptive statistics, and test for lognormality.

Table 37.2. Parameters of the distributions of generated values of EEC of radon isotopes.

Type of building	Arithmetic mean, Bq/m^3	Geometric mean, Bq/m^3	GSD	Percentage above 300 Bq/m^3
Wooden houses	75	37	3.1	3.5%
One-storey brick and stone houses	59	32	3.0	2.1%
Multi-storey brick and stone houses[a]	46	24	3.0	1.1%
All types	48	25	3.1	1.3%

[a] Average over all floors.

Source: Yarmoshenko et al, 2015.

It is important to mention that legal restriction on indoor annual equivalent equilibrium concentration of radon isotopes in Russian legislation is calculated as ^{222}Rn EEC + 4.6 ^{220}Rn EEC, i.e. activity of thoron is not neglected.

References

Marenny, A.M. et al, (1996) Results of radon concentration measurements in some regions of Russia, Radiation Measurements, 26 (3), 43-48.

Yarmoshenko I. et al, (2015). Reconstruction of national distribution of indoor radon concentrations in Russia using results of regional indoor radon measurement programs, Journal of Environmental Radioactivity 150, 99-103.

38 Serbia

In Serbia there were several local and regional surveys of indoor radon concentrations. Some of those researches were conducted by individual efforts to identify regions with high indoor radon. Perennial survey in several regions of Serbia (former Yugoslavia, former Serbia and Montenegro) starting 1997 had a specific goal to estimated population exposure to natural radioactivity based on geochemical and integrative pattern research approach. This was the first identification and assessment of high areas of natural radiation in Serbia which provides insight into its regional characteristics, the interpretation of the results in terms of geological aspects, building types and human habits, the first introduction and field applicability of both (surface and volume trap) retro techniques in Serbia and assessment of doses and risks to the population in investigated high natural radiation rural communities. Several differently designed chambers for the CR-39 and polycarbonate detectors were used such as: SSI/NRPB detectors, the CR-39 detectors enclosed in small cylindrical (5 cm height, 3 cm diameter) diffusion chamber, passive discriminative Cr-39 Radopot and Raduet detectors, passive discriminative polycarbonate UFO detectors. Exposure periods were generally of about 3 months covering one season. Annual averages were obtained using either results of all the seasonal measurements, if available, or results of some periods corrected with seasonal factors. Annual averages were obtained using either results of all the seasonal measurements, if available, or results of some periods corrected with seasonal factors. In these surveys, indoor radon concentration of rural communities of Serbia and some part of Balkans were investigated. Obtained data followed lognormal distribution, strongly depending on the type of underlying rock and average radon levels range between 45 Bq/m^3 for limestone in Montenegro and 1560 Bq/m^3 for travertine in Niška Banja (Žunić, 2009). A radon priority area of Niška Banja was investigated in details by Žunić and collaborators. In one of those surveys the region of Gornja Stubla an area with high radon and thoron was identified (Žunić, 2010). Besides indoor radon concentrations in dwellings, radon concentrations in schools in rural parts of Serbia were investigated as well (Žunić, 2017).

In Vojvodina, the northern province of Serbia, radon was monitored from 1992 till 2003 by using charcoal canisters. In total 220 measurements were performed in Novi Sad, with maximal radon concentration of 503 Bq/m^3, minimal of 1,2 Bq/m^3 and geometric mean of 28.5 Bq/m^3 (Forkapić, 2007).

The first large survey in Serbia, was conducted in Vojvodina in the winter period from December 2002- March 2003. In total 968 measurements with CR-39 detectors were performed with 1 measurement per dwelling. Radon was measured in dwellings that were considered typical and thus the most representative in rural regions of 45 municipalities. A lognormal distribution was obtained with descriptive statistics given in Table 38.1.

Table 38.1. Descriptive statistics of the indoor radon measurements in Vojvodina covering the period December 2002 - March 2003.

Number of measurements	Measurements statistics (in Bq m^{-3} units)					
	Mean	Standard deviation	Geo. Mean	Standard deviation of Geo. Mean	Min.	Max.
968	144	120	104.2	2.3	2 measured at Ada	893 measured at Zrenjanin

Source: Forkapic, 2007.

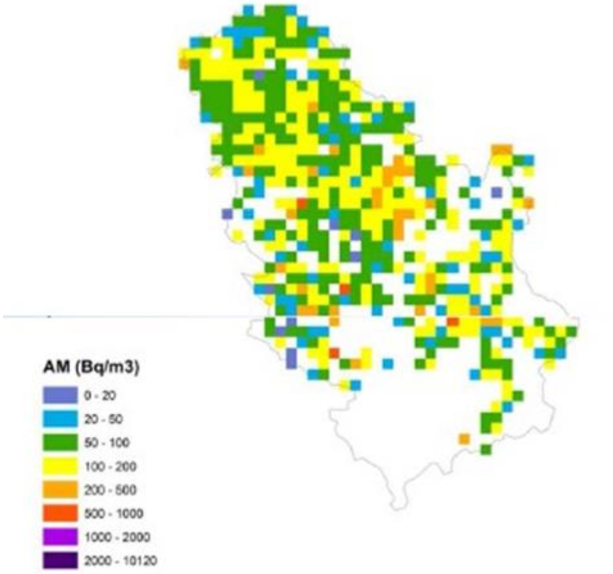
A radon map of Vojvodina, from the same survey, is presented in Figure 38.1.

Figure 38.1. Radon map of Vojvodina. Numbers given along the names of municipalities indicate geometric mean radon concentration in Bq/m^3.

Source: Forkapić, 2007.

Serbia started work on Radon action plan in 2014, with the first step of preparing, and performed the national indoor radon survey in Serbia, planned and conducted to be done in 2015 (Udovičić, 2016). Indoor radon survey was conducted in 2015 and 2016 using CR-39 detectors. The project was supported by IAEA through the national project: SRB/9/003 - Enhancing the Regulatory Infrastructure and Legislative System. During the realization of the national programme for indoor radon measurements several institutes involved in the project together with the Serbian Radiation Protection and Nuclear Safety Agency performed good communication strategy (first basic information leaflet on radon to accompany the measurement explaining the purpose of the measurement, internet site, public relation, public education, etc) which led to high survey efficiency (about 88 %), together with very hard field work. In total 6000 detectors have been distributed during October 2015 and exposed in houses and apartments for six months (till April 2016). Afterwards, 5300 detectors were collected and sent to an authorized laboratory (Landauer Nordic AB) to be processed. Measured indoor radon concentrations varied in a wide range: from 3 Bq/m^{3}to 4335 Bq/m^3. In 87 % measurement radon concentration was below 200 Bq/m^3, 10% between 200 and 400 Bq/m^3, 3% higher than 400 Bq/m^3 and 0.3 % higher than 1000 Bq/m^3. Average radon concentration was 105 Bq/m^3 (*IAEA SRB/9/006, 2018*). In selected dwellings additional detector was exposed for 1 year, and thus seasonal correction was obtained. Data were averaged over the 10 km x 10 km, and from March 2017 they are incorporated in the European Indoor Radon Map. Indoor radon map of Republic of Serbia is shown in Figure 38.2.

Figure 38.2. Indoor radon map of Republic of Serbia, January 2017.



*Source:*IAEA SRB/9/006 , 2018.

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Žunić, Z.S. et al.,(2009) Identification and assessment of elevated exposure to natural radiation in Balkan region (Serbia), Radioprotection 44(5): 919–925 (and reference therein).

Žunić, Z.S. et al., (2010) Collaborative investigations on thoron and radon in some rural communities of Balkans, Radiation Protection Dosimetry 141(4): 346–350 (and reference therein).

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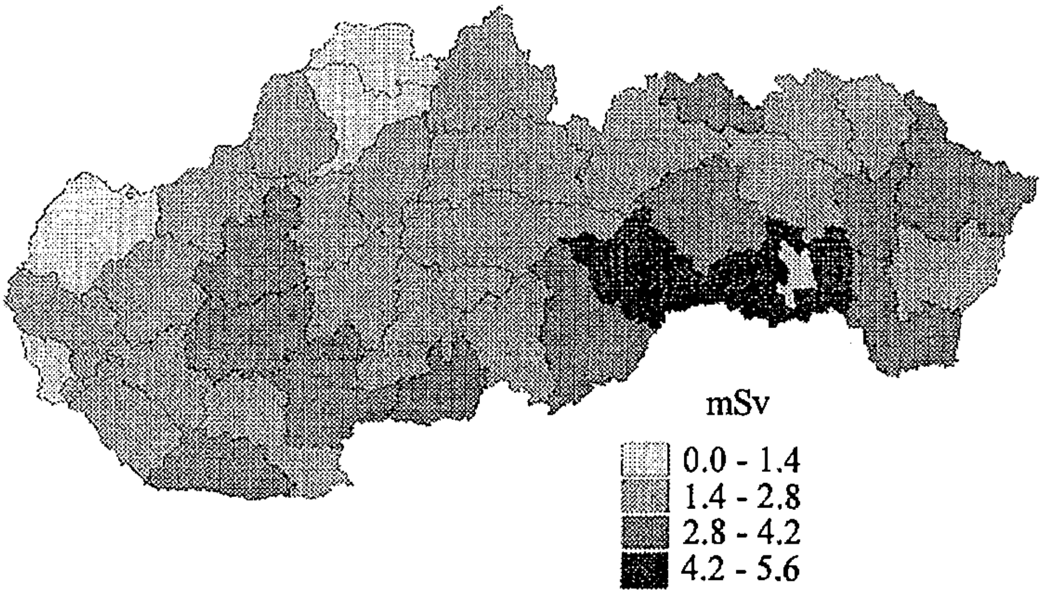
39 Slovakia

Three regional surveys were conducted in Slovakia in 2014, which effectively covered the whole country and thus qualifying it as a national survey. Three papers that present the results of these surveys are Vicanova et al. 1998, Vladár et al. 1996 and M. Mullerova et al. 2014. Descriptive statistics, population weighted, was used to evaluate the results in all three surveys. The annual average effective dose from indoor radon exposure is 2.1 mSv per inhabitant. The soil is marked as probably the main source of radon in Slovak dwellings.

Slovak National Radon Program started in order to investigate Radon concentrations and radiation load in dwellings (family and multifamily), schools, public buildings, spa buildings, caves and mines.6000 selected dwellings (minimum two detectors for every residence), 1,000 selected buildings of the kindergartens and elementary schools and 12 selected spa buildings were investigated and the results were published in Vicanova et al. 1998. The geometric mean (GM) was about 41±2.22 Bq/m^3 and 11% of dwellings (N=409) had a greater EEC of radon than the action level. The sample of family houses (N=2,363) has AM 125±135 Bq/m^3, GM 73±1.8 Bq/m^3 and the sample of multifamily houses (N= 1,294) has AM 22±24 Bq/m^3, GM 15± 1.46 Bq/m^3. The population-weighted AM of EEC for every district by different type of house was calculated, and then estimated this value for the whole of Slovakia obtaining a figure of 48 Bq/m^3.

The paper Vladár et al. 1996 was based on measurement of EEC in 1832 dwellings. Passive solid state nuclear track detectors (SSNTD type CR-39) were used to measure indoor radon concentrations. Detectors were placed in about 6,000 selected dwellings (minimum two detectors for every residence). The results were used to produce a map of annual average effective doses from indoor radon exposure, presented in the Figure 39.1 below. The distribution of indoor radon concentrations in Slovakia is presented in the Table 39.1 below.

Figure 39.1. Annual average effective doses from indoor radon exposure in districts of Slovakia.



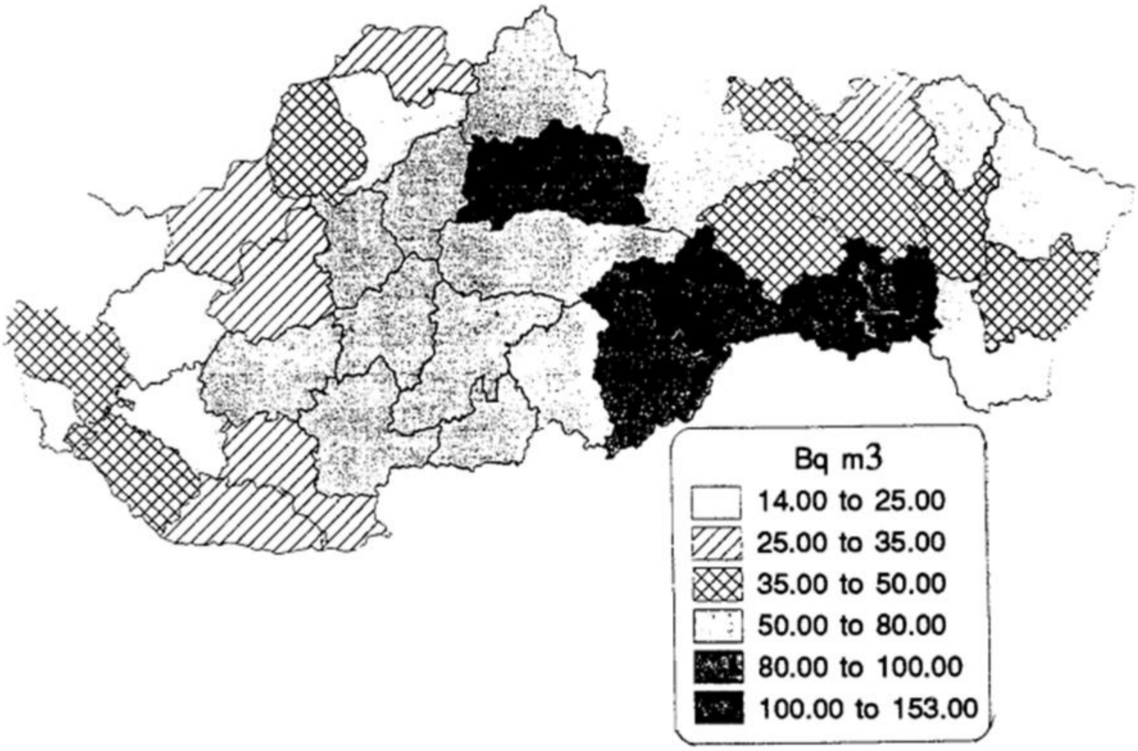
Source: Vicanova et al., 1998.

Table 39.1. Distribution of indoor radon concentrations in Slovakia.

EEC [Bq.m^{-3}]	Number of dwellings [%]	Remedial Actions
< 200	88.6	-
200 – 599	10.6	to 10 years
> 600	0.8	to 3 years

Source: Vicanova et al., 1998.

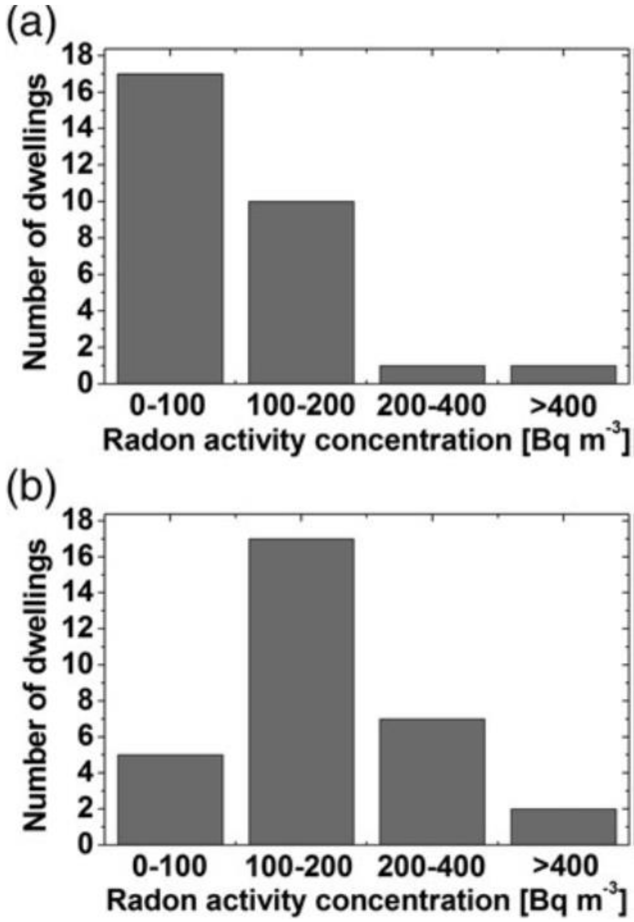
Figure 39.2. Equivalent radon concentration in Slovakia.



Source: Vladár et al., 1996.

The goal of the survey, published in Mullerova et al. 2014, which covered the region spanning through selected regions with possible higher than average concentrations, was harmonization of determination of the radiation dose due to indoor radon, improving radon and thoron map. Miners and tourist guides had personal dosimeters and the third publication was made on bases of measurements in 3,657 residences.

Figure 39.3. The frequency distribution of the radon activity concentration in two localities in Slovakia: Bratislava (a) and Mochovice (b).



Source: Mullerova et al., 2014.

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Mullerova, M. et al. (2014). Preliminary Results of Indoor Radon Survey in V4 Countries, Radiation Protection Dosimetry, 160(1-3):210-213.

40 Slovenia

The results of the national survey in Slovenia were published in Humar, M., et al. 1995. The survey was conducted during 1990-1992 in kindergartens, 1992-1994 in schools and 1993-1995 in dwellings. The goal was the construction of map of estimated annual mean radon concentration values in dwellings for EUR_RADON. Track-etch detectors were distributed to total of 730 kindergartens, 890 schools and 892 dwellings and exposed for 96 days. The annual mean values were derived using the relation Cmean = 0.7 Cwinter. Descriptive statistics was used to evaluate the results. The map shown hereafter was generated by interpolating the values on a grid with a resolution of 2 km × 2 km. The interpolation method is universal kriging with linear drift. The model chosen for the spatial correlation (variogram) was linear. All values were selected for estimating the value in each cell.

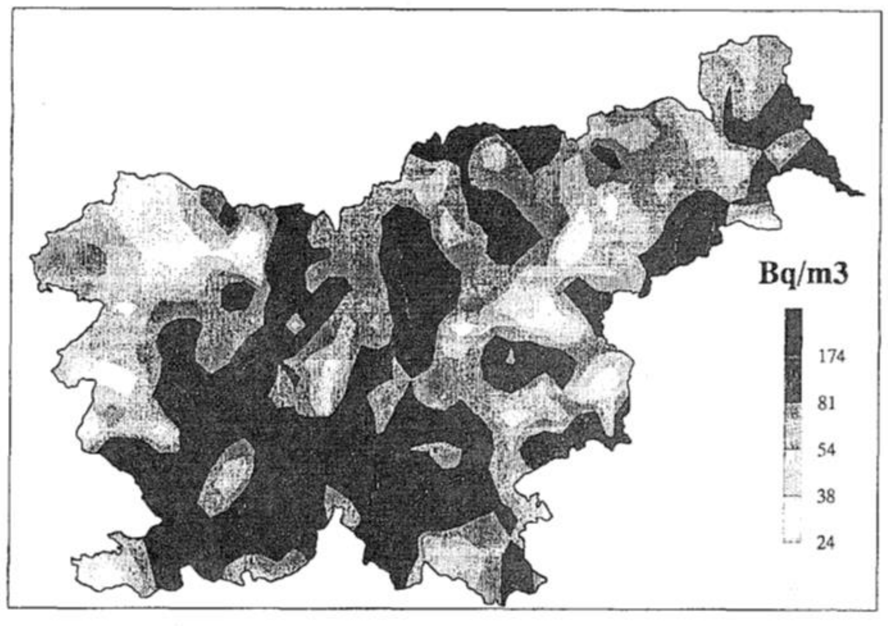
Also, the results of the national survey in Slovenia, conducted in 1993-1994, were published in Križman M. et al, 1995. The goal was to produce a radon map and identify radon prone areas. CR-39 etch track detectors were randomly distributed in 892 dwellings during the winter period. Results were corrected by multiplying with seasonal correction factor and descriptive statistic and tests for lognormality were performed. The results are summarized in Table 40.1 below. The map of the indoor radon measurement results is given in Figure 40.1 below.

Table 40.1. Summary statistics for radon-222 in dwellings in Slovenia.

No. of meas.dwell.	AM (Bq/m^3)	1 SD (Bq/m^3)	GM (Bq/m^3)	1 GSD (Bq/m^3)	Median (Bq/m^3)
892	**86.9**	110	**59.6**	2.23	**54.0**

Source: Križman M. et al, 1995.

Figure 40.1. Map of indoor radon in Slovenia (percentile values in Bq/m^3).



Source: Križman M. et al, 1995.

References

Humar, M. et al, (1995). Radon Concentrations in Living Environment of Slovenia (final report-in Slovene), Jožef Stefan Institute, Ljubljana, IJS-DP-7164, January 1995.

Križman, M. et al, (1996). A survey of Indoor Radon Concentrations in Dwellings in Slovenia, In: Proceedings of the IRPA Regional Congress, Portorose, September 4-8th, 1995 (Glavič-Cindro, D., ed.) J. Stefan Institute, Ljubljana, January 1996, pp. 66-70.

41 Spain

Extensive investigation of indoor radon in Spain was performed in several different surveys. There were numerous references, yet in this report, only the last one was used which summarize data from previous surveys.

The aim was to produce a radon map of the Spanish territory that shows the probability of finding areas with levels of radon indoors, and is related to the European legislation that has to be implemented in the member states before the end of 2018.

In total 9211 indoor radon measurements were performed since 1989 in a few sampling campaigns and all data ware included in the Spanish indoor radon map. In summary: 2117 data were performed in the period from 1989-2010, in the first campaign organised from 2010-2012 in total 5556 indoor Rn data were gathered, with additional 344 measurements in period from 2012-2012. An finally, in the second campaign organised from 2013 till 2014, data of 1194 measurements were performed.

Sampling strategy was based on several criteria: 1.surface criterion: at least one measurement per 10x10km grid; 2. population criterion: additional measurements for towns with population >50000 and similar, 3. MARNA criterion: considering geological factors i.e. considering 226Ra content in soil, and 4. Litostratigrafic criterion.

Random selection of location within the cell was chosen. Detectors were placed in ground-level buildings in the main room, height 1-2 m, on wardrobe separated from the walls, away from air flow and heat source.

With each detector, detailed questionnaire was enclosed regarding the building design, materials, living habits, etc.

Quality control and quality assurance was validated annually by the validation scheme designed by Public Health England. In addition, national and international comparisons were performed on a regular basis.

Data averaged in the grid consisting of 10x10 km^2 cells. Data confirmed lognormal distribution. Descriptive statistics are given in Table 41.1.

Table 41.1. Descriptive statistics of data used to produce the Spanish indoor radon map up-to-date.

Number of measurements	Arithmetic mean	Arithmetic standard deviation	Geometric mean	Geometric standard deviation	Median	Range
9211	95.0	270	56.6	2.6	54	10–15,400

Source: Fernandez, 2017.

The classification of data was carried out into four categories: <50, 50-100, 100-300 and > 300 Bq/m^3, in compliance with recommendations of the World Health Organization. Distribution of radon data according to the classification of data is given in Table 41.2.

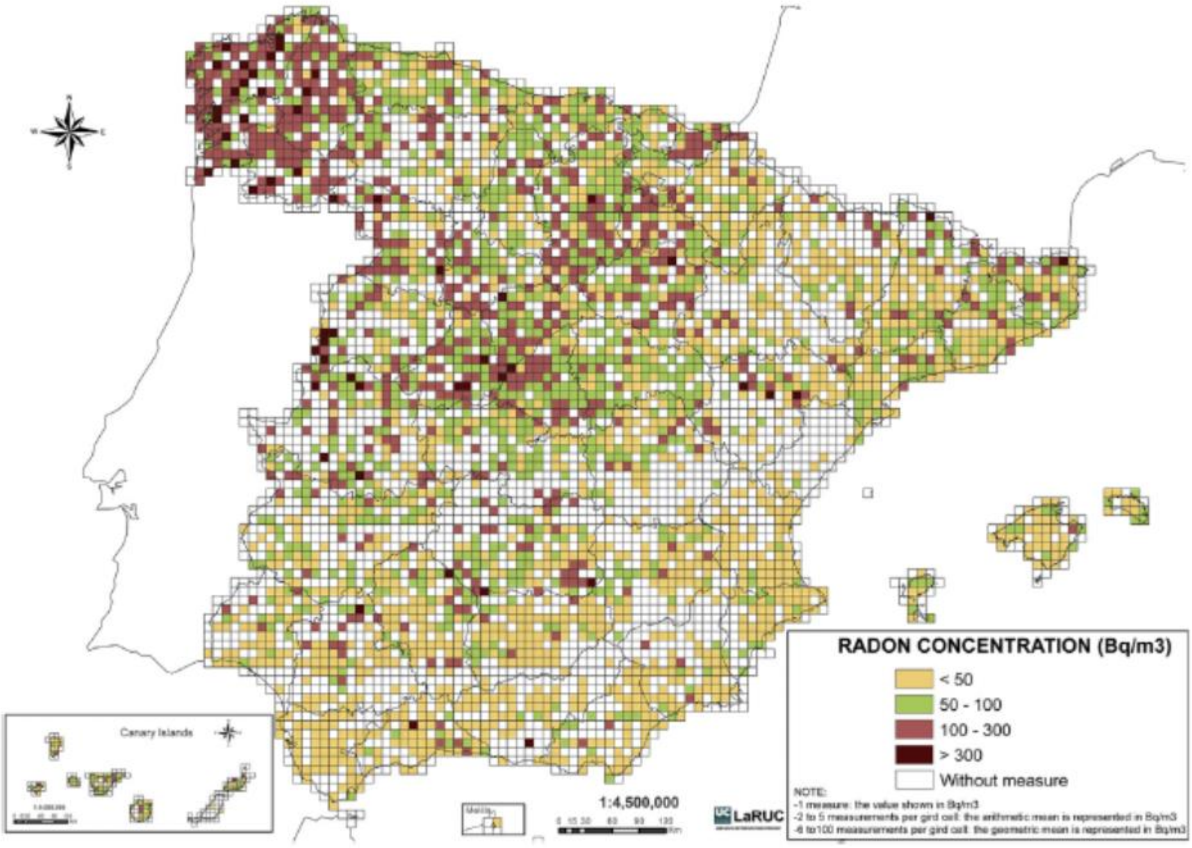
Table 41.2. Number of cells and data classified by 4 categories of radon concentration.

Range (Bq/m^3)	Number of cells	Number of data
<50	1606 (29%)	4294 (46%)
50–100	967 (18%)	2922 (32%)
100–300	602 (11%)	1902 (21%)
>300	42 (1%)	93 (1%)

Source: Fernandez, 2017.

In Figure 41.1 is presented an up-to-date Spanish indoor radon map based on 9211 measurements.

Figure 41.1. Map of indoor radon in Spain based on 9211 measurements.



Source: Fernandez, 2017.

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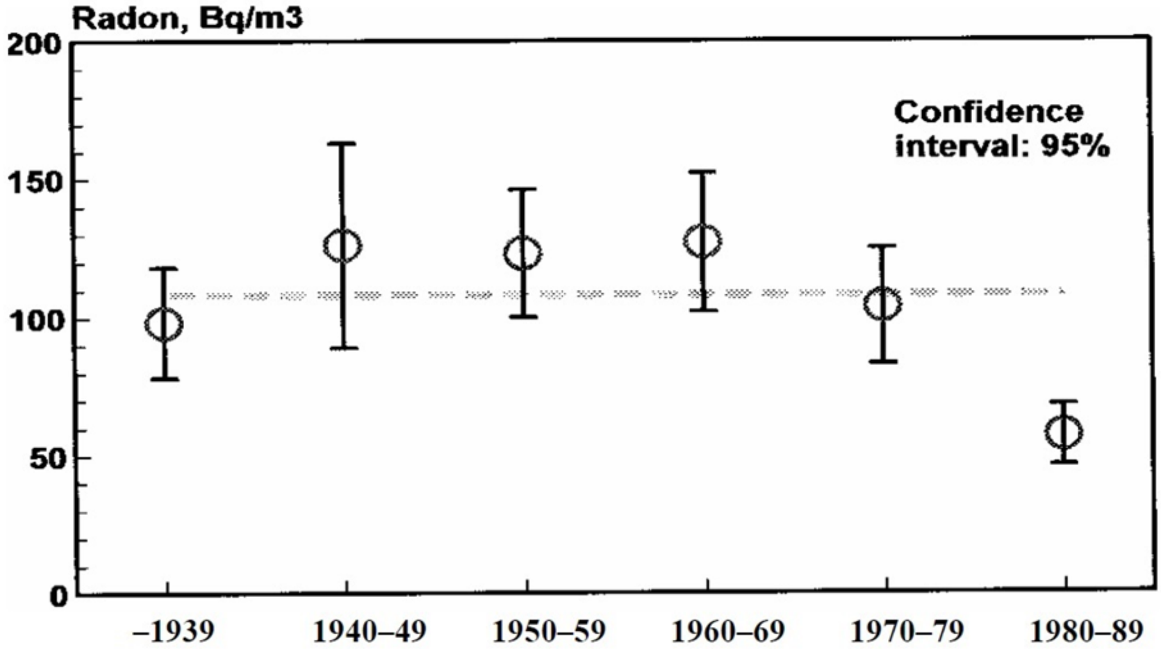
42 Sweden

A national energy and climate study was conducted in 1991 and 1992. A total of 1300 dwelling were randomly selected. Alpha track detectors were placed for 3 months in each dwelling during the heating season. Percentage of houses over the action level of 400 Bq/m^3 was determined for single family houses and multifamily houses, as well as the average radon concentration for buildings built during each decade since 1930s (Swedjermark et al, 1993, Swedjermark, 2002).

Figure 42.1. The arithmetical averages of radon concentrations in Swedish swellings as a function of the building year as measured in the investigation of the 1988 building stock.



Source: Swedjermark, 2002.

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43 Switzerland

Nationwide large-scale radon surveys have been conducted since the early 1980s to establish the distribution of indoor radon concentrations in Switzerland. The aim of this work was to study the factors influencing indoor radon concentrations in Switzerland using univariate analyses that take into account biases caused by spatial irregularities of sampling.

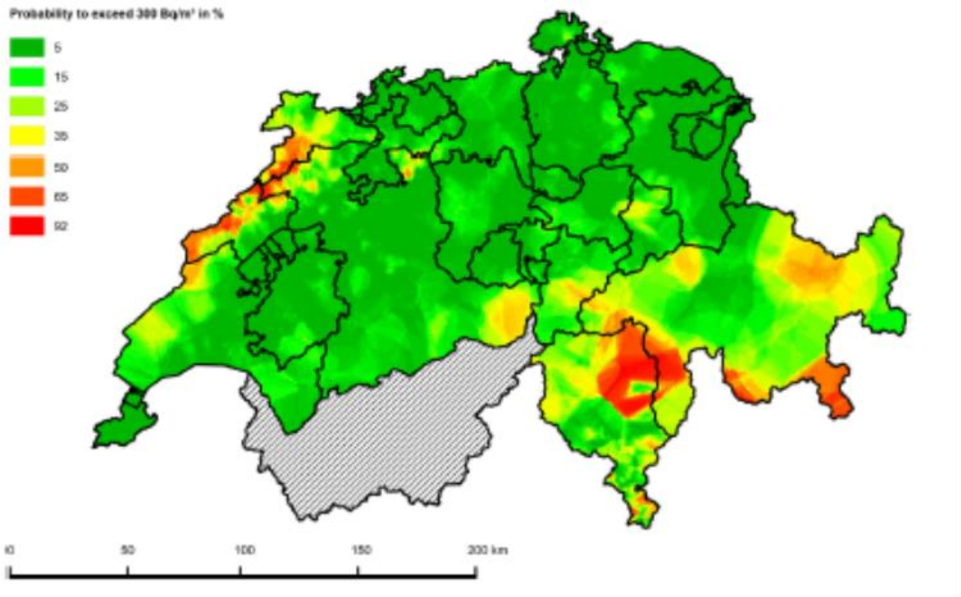
About 212,000 indoor radon concentrations measurements carried out in more than 136,000 dwellings were available for this study. A probability map to assess risk of exceeding an indoor radon concentration of 300 Bq/m^3 was produced using basic geostatistical techniques. Univariate analyses of indoor radon concentrations for different variables, namely the type of radon detector, various building characteristics such as foundation type, year of construction and building type, as well as the altitude, the average outdoor temperature during measurement and the lithology, were performed comparing 95% confidence intervals among classes of each variable. Furthermore, a map showing the spatial aggregation of the number of measurements was generated for each class of variable in order to assess biases due to spatially irregular sampling. Indoor radon concentrations measurements carried out with electret detectors were 35% higher than measurements performed with track detectors.

Regarding building characteristics, the indoor radon concentrations of apartments are significantly lower than individual houses. Furthermore, buildings with concrete foundations have the lowest indoor radon concentrations. A significant decrease in indoor radon concentrations was found in buildings constructed after 1900 and again after 1970.Moreover, indoor radon concentrations decreases at higher outdoor temperatures. There is also a tendency to have higher indoor radon concentrations with altitude.

Regarding lithology, carbonate rock in the Jura Mountains produces significantly higher indoor radon concentrations, almost by a factor of 2, than carbonate rock in the Alps. Sedimentary rock and sediment produce the lowest indoor radon concentrations while carbonate rock from the Jura Mountains and igneous rock produce the highest indoor radon concentrations. Potential biases due to spatially unbalanced sampling of measurements were identified for several influencing factors.

Significant associations were found between indoor radon concentrations and all variables under study. Spatial distribution of samples strongly affected the relevance of those associations (Kropat, 2014).

Figure 43.1. Map of Switzerland indicating the local probability to exceed 300 Bq/m^3.



Source: Kropat, 2014.

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44 Turkey

Reference (Can et al., 2012) describes surveys in selected regions (Kilis, Osmaniye and Antakya) in Turkey, with main goal to determine average indoor radon concentration in those selected areas. Surveys took place in spring seasons till 2011. Surveys covered 204 houses, and detectors were placed in living rooms. The detectors were exposed for 2 months. Effective dose was measured, too.

A Radosys radon measurement system was used for analysis. CR-39 track detectors were used. Detectors were chemically etched in a 4 M NaOH solution bath unit at 60 °C for 4 hours. After etching detectors were put into a 'radometer 2000' evaluation unit to count the number tracks on them. The track densities on detectors were determined automatically by a system with 500x microscope. Minimum, maximum and average indoor radon concentrations were reported. Average indoor radon concentrations were compared with global average. Indoor radon concentration levels for Kilis, Osmaniye and Antakya are 5–171, 6–209 and 4–135 Bq/m^3, respectively. Average radon concentration for Kilis, Osmaniye and Antakya were calculated as 50, 51 and 40 Bq/m^3, respectively. The radon concentrations in Kilis and Osmaniye are above global average radon concentration (40.3 Bq/m^3) while that for Antakya is slightly below the global average. Average annual effective doses are compared with the global average. No significant difference was found in comparison with the data acquired from other provinces of Turkey.

Table 44.1. Indoor ^{222}Rn activity concentrations and comparison with different part of Turkey.

District	Number of houses	Min.	Max.	^{222}Rn activity concentrations (Bq/m^3)	Effective dose (mSv/y)	References
Kilis	62	5	171	50	1.26	Present study
Osmaniye	70	6	209	51	1.29	Present study
Antakya	72	4	135	40	1.01	Present study
Manisa				97 (47–146)	4.83 (2.35–7.3)	[16]
Kastamonu				98.4 (29–177)	2.48 (0.73–4.46)	[17]
Giresun				130 (52–360)	3	[18]
Tekirdağ				87	2.01	[19]
Batman				84 (23–145)		[20]
Karabük				131.6	3.32	[21]
İstanbul				10–260	0.5–13	[22]

The ranges corresponding to data are given in parentheses

Source: Can et al., 2012.

Reference (Köksal et al., 2004) describes survey that was a part of a national program designed to determine public exposure to natural radiation. Indoor radon concentrations have been measured in 27 cities/towns and 1414 randomly chosen houses. Detectors were placed in living rooms and bedrooms. Monitoring was implemented in two 3-month periods during the winter and summer seasons. So, single measurement duration was 3 months.

Passive solid state nuclear track detectors (SSNTD type CR-39) in the diffusion chamber were used. CR-39 detectors were etched in a 30% NaOH at 70 °C for 17 hours. Subsequently the tracks on the etched film were counted manually with a microscope (200×).

The arithmetic mean value of radon concentration level in two different rooms was used as a measure of the indoor air concentration in the building. The mean value of summer and winter measurements is considered as the arithmetic mean value of the dwellings. Regions with higher natural background radiation were observed. The measured distribution of radon levels varied between 10 and 380 Bq/m^3. The arithmetic mean value of the radon concentration was found to be 35 Bq/m^3 with a standard deviation 12 Bq/m^3.

Figure 44.1. Arithmetic mean of indoor radon concentration in Turkey.

Source: Köksal et al., 2004.

Table 44.2. Indoor radon concentrations of Turkish dwellings.

Towns and cities under study	Number of surveyed houses	Number of houses of different radon concentrations				
		1–50 Bq·m^{-3}	51–100 Bq·m^{-3}	101–200 Bq·m^{-3}	201–300 Bq·m^{-3}	301–400 Bq·m^{-3}
Istanbul	524	267	234	23	–	–
Bursa	50	34	15	1	–	–
Eskişehir	50	12	37	1	–	–
Adana	25	3	22	–	–	–
Mersin	97	87	10	–	–	–
Kahramanmaraş	45	45	–	–	–	–
Adıyaman	43	42	1	–	–	–
Şanlıurfa	24	2	19	3	–	–
Elazığ	19	5	12	2	–	–
Erzurum	23	8	11	4	–	–
Kocaeli	81	78	–	3	–	–
Köprübaşı	15	8	7	–	–	–
Tosya	26	14	10	2	–	–
Afyon	25	4	19	2	–	–
Balıkesir	30	24	6	–	–	–
Sındırgı	19	10	8	1	–	–
Gaziantep	27	18	8	1	–	–
Kestanbolu Çanakkale	47	–	7	30	7	3
Zeytinburnu İstanbul	77	53	22	2	–	–
Yatağan Thermic Central	13	–	9	4	–	–
Antalya	23	19	4	–	–	–
Sakarya	27	13	9	2	1	2
Gölcük	27	16	5	5	–	1
Bolu	18	9	4	2	2	1
Düzce	18	12	–	5	1	–
Kırklareli	14	–	2	12	–	–
Malatya	27	18	9	–	–	–

Source: Köksal et al., 2004.

Regarding quality assurance, calibration of SSNTDs at standard radon atmosphere was repeated for each CR-39 foil using a 222 litre closed oil barrel containing a ^{226}Ra source. The calibration chamber was calibrated by sampling with Lucas flasks. Participations in the NRPB intercomparison took place in 1989, 1991, 1995 and 2000.

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45 Ukraine

First indoor radon survey in Ukraine is described in the reference (Pavlenko et al., 1997). It was conducted during 1989-93, and a main survey goal was to estimate a value and structure of the total exposure dose to the Ukrainian population, and to reveal the most "radon-dangerous" territories. More than 9500 measurements of indoor radon concentration were performed in dwellings (bedroom) of different types taking into account number of floors, type of building materials and scheme of the apartments all over Ukraine.

Table 45.1. The weighted average by types of buildings and structure of housing facilities effective population exposure doses for Ukraine.

Region	The average ^{222}Rn ECC, $Bq \cdot m^{-3}$			Weighted average values of the ^{222}Rn ECC, $Bq \cdot m^{-3}$	Weighted average values of the effective dose, $mSv \cdot year^{-1}$
	I type	II type	III type		
Vinnitsa	79	38	28	65	4.32
Volyn	19	13	10	16	1.34
Donetsk	102	89	34	65	4.34
Zhitomir	70	45	26	55	3.76
Zaporozh'e	94	43	24	56	4.54
Ivano-Frankovsk	55	38	20	45	3.14
Kyiv	54	29	23	34	2.42
Odessa	115	78	34	77	5.05
Poltava	44	32	23	36	2.57
Rivne	65	32	20	51	3.49
Sumy	36	18	13	27	2.00
Ternopil	132	48	33	104	6.74
Cherkassy	89	34	25	68	4.54
Chernigiv	38	24	20	32	2.34
Cherson	156	106	34	111	7.14
Chernovtsy	55	38	20	45	3.10
Chmelnitsk	75	49	30	61	4.07
Ukraine					***3.8***

Source: Pavlenko et al., 1997.

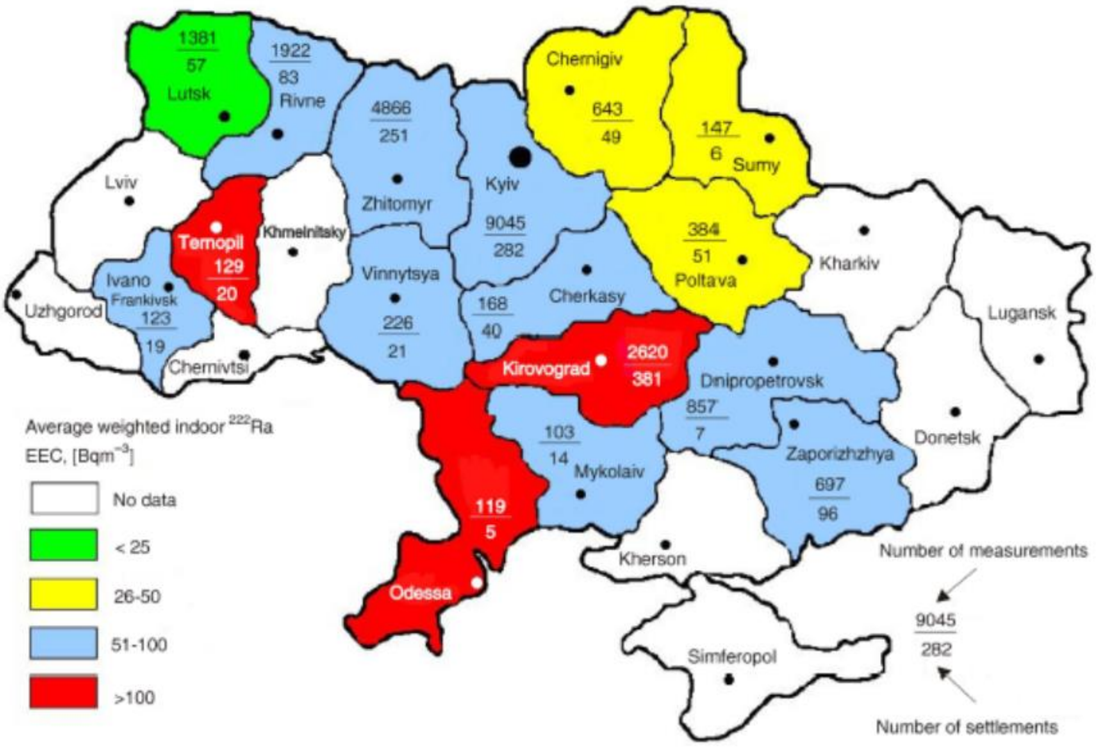
Simultaneously with radon detection system development, radon atmosphere was established in RCRM, Kiev, Ukraine. A national bureau for standardisation certified the atmospheres a primary source of measurements. Procedures of radiation services certification and intercomparison were elaborated. Thus a system of a quality assurance for Rn in air measurements was developed.

Measurements were performed by passive track dosimetry. Nitro-cellulose film, LRII5 II type (Kodak, France) or similar one of CND type produced by State Research Institute of Photochemical Industry (Pereslavl Branch, Russia) were used as a detector. Exposed detectors were processed at the spark counter "TRACK 2010Z" after a standard procedure of treating in NaOH solution. Exposure time was 1-2 months, and they took place during the Spring-Summer and Autum-Winter period. Results – data were processed by means of special computer databases. Equilibrium factor of 0.4 was used. An average value of the radon equilibrium concentration was calculated and weighted by type of buildings. Annual effective dose was calculated. It is found that hydrogeological peculiarities of a territory determine the number of buildings with an elevated radon concentration (Pavlenko et al., 1997).

Experimental data allowed optimizing the system of control of radon-222 taking account of possibilities of decreasing total exposure doses for population on the territories contaminated from Chernobyl. Basic directions for establishing the system of countermeasures against exposure to radon-222 were determined (Pavlenko et al., 1997).

Regional survey under the pilot project aiming reduction the radon risk in |Kirovograd region during 2010-13 are described in reference (Pavlenko et al., 2014). Under this project 1043 public buildings including 870 schools and nurseries were examined. Detectors used were passive track detector (LR-115 film). Chemical etching of the film was applied and track counting was performed with the spark counter. The sensitivity of the method: 8-10 Bq/m^3.The detectors were exposed for two months during the heating season (November-March).

Figure 45.1. Average radon EEC in Ukraine dwellings.



Source: Pavlenko et al., 2014

Analysis of the results included descriptive statistics and test for lognormality. The season correction factors were applied. Effective dose was calculated. The radon risk factors for the region were analyzed. Lognormal frequency distribution was established for Rn concentrations in school and nurseries. In 53% the limit of 50 Bq/m^3 was exceeded. Mean value was determined for schools and nurseries, building with the wooden and forced concrete floors. Radon activity is 1.2-2 times higher in the dwellings with slag filling (Pavlenko et al., 2014).

Efficiency calibration of the track detectors were done in the radon atmosphere at the IHME (secondary calibration source accredited by the National Standardization and Accreditation Authority of Ukraine). Additionally, each film production was tested and adjusted for the optimal etching parameter (Pavlenko et al., 2014).

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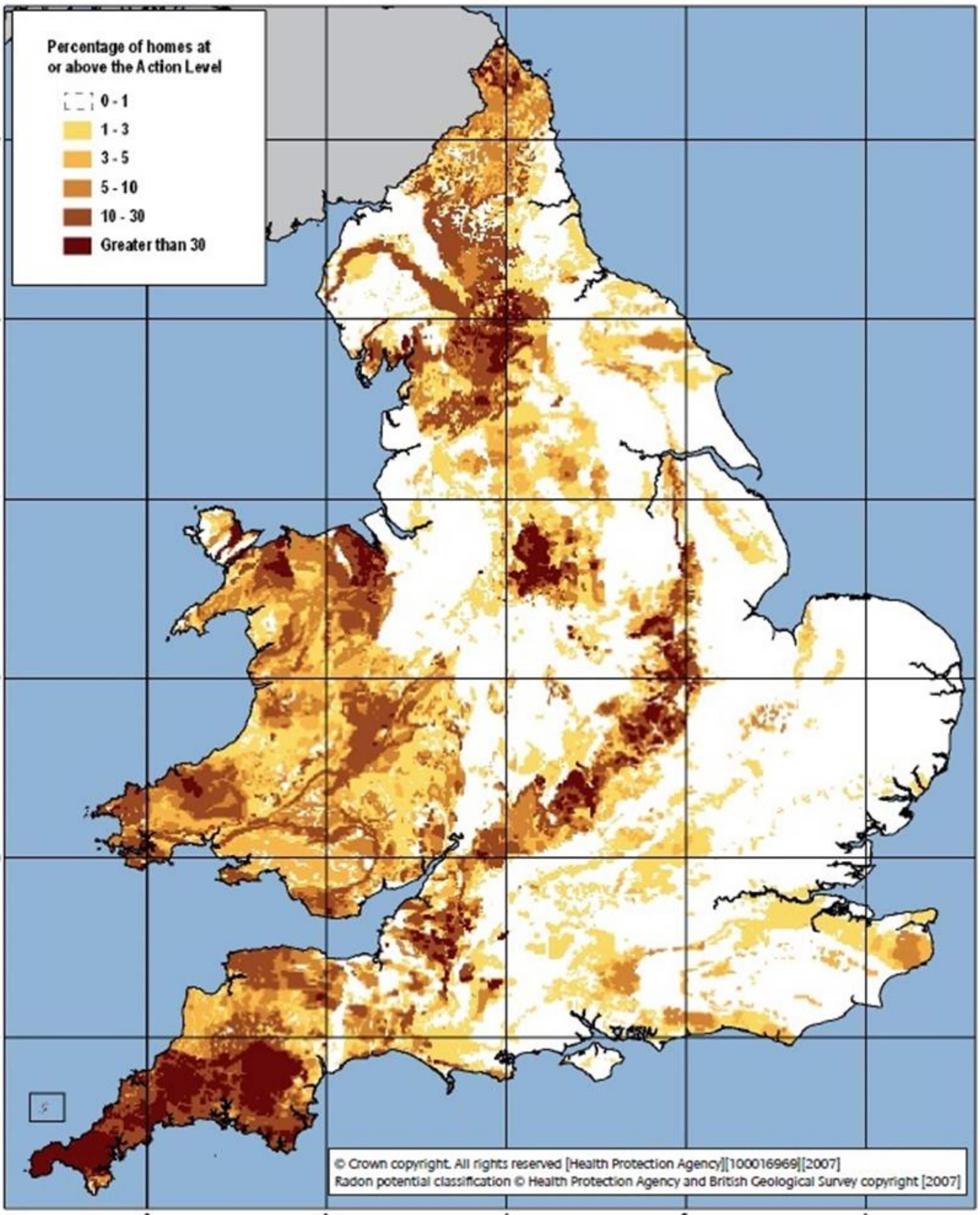
46 United Kingdom

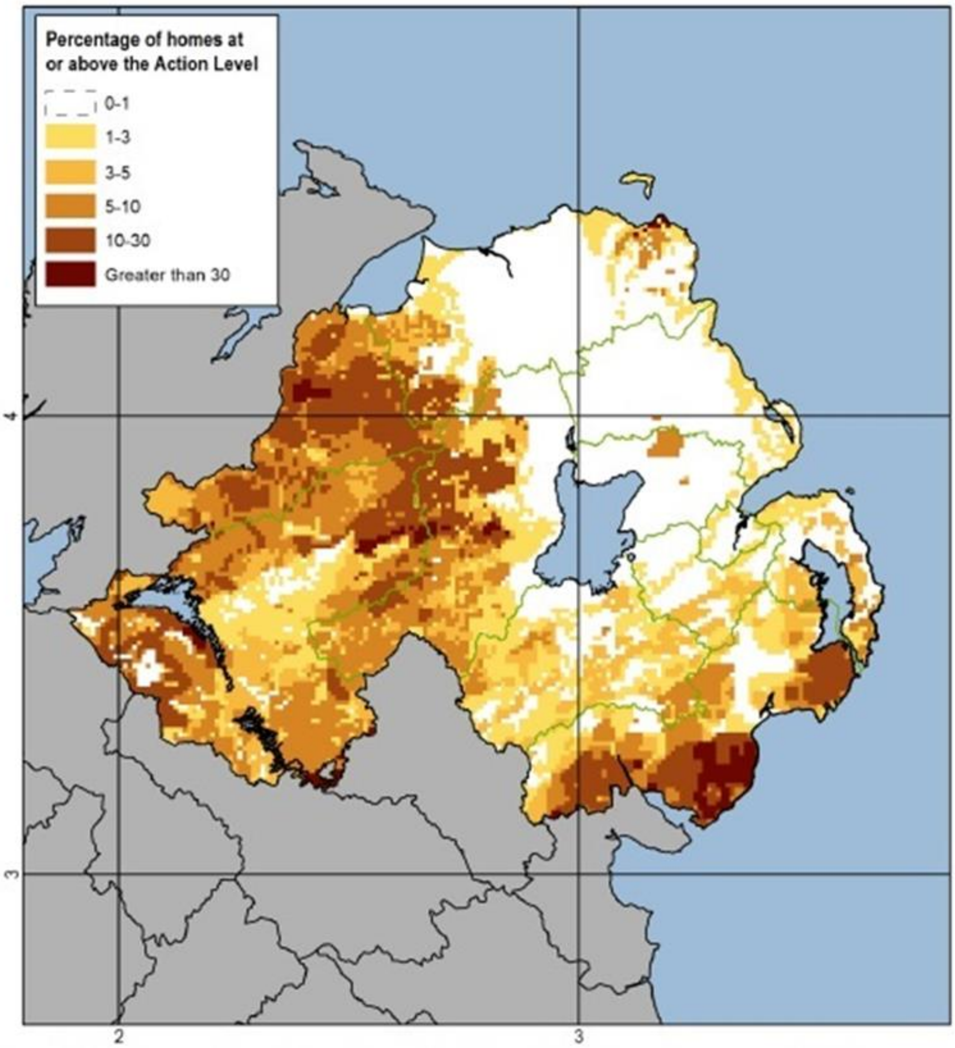
Multiple studies that covered the whole United Kingdom were aggregated to produce three Atlases, one for England and Wales, one for Northern Ireland and one for Scotland. The goal was to produce map of radon potential based on the number of homes with concentration over 200 Bq/m^3. Two passive integrating detectors were used in each dwelling, one in main living room and one in main bedroom. Individual exposures were 3 months long and seasonal correction factors were applied, as well as temperature corrections for different years. In total, 460000 houses were examined in England and Wales, 23000 in Northern Ireland and 19000 in Scotland. Results were evaluated by descriptive statistics. Radon map with 1 km^2 grid was produced (Miles et al, 2007; Daraktchieva et al, 2015; Miles et al, 2011).

Figure 46.1. Overall map of radon affected areas in England and Wales.



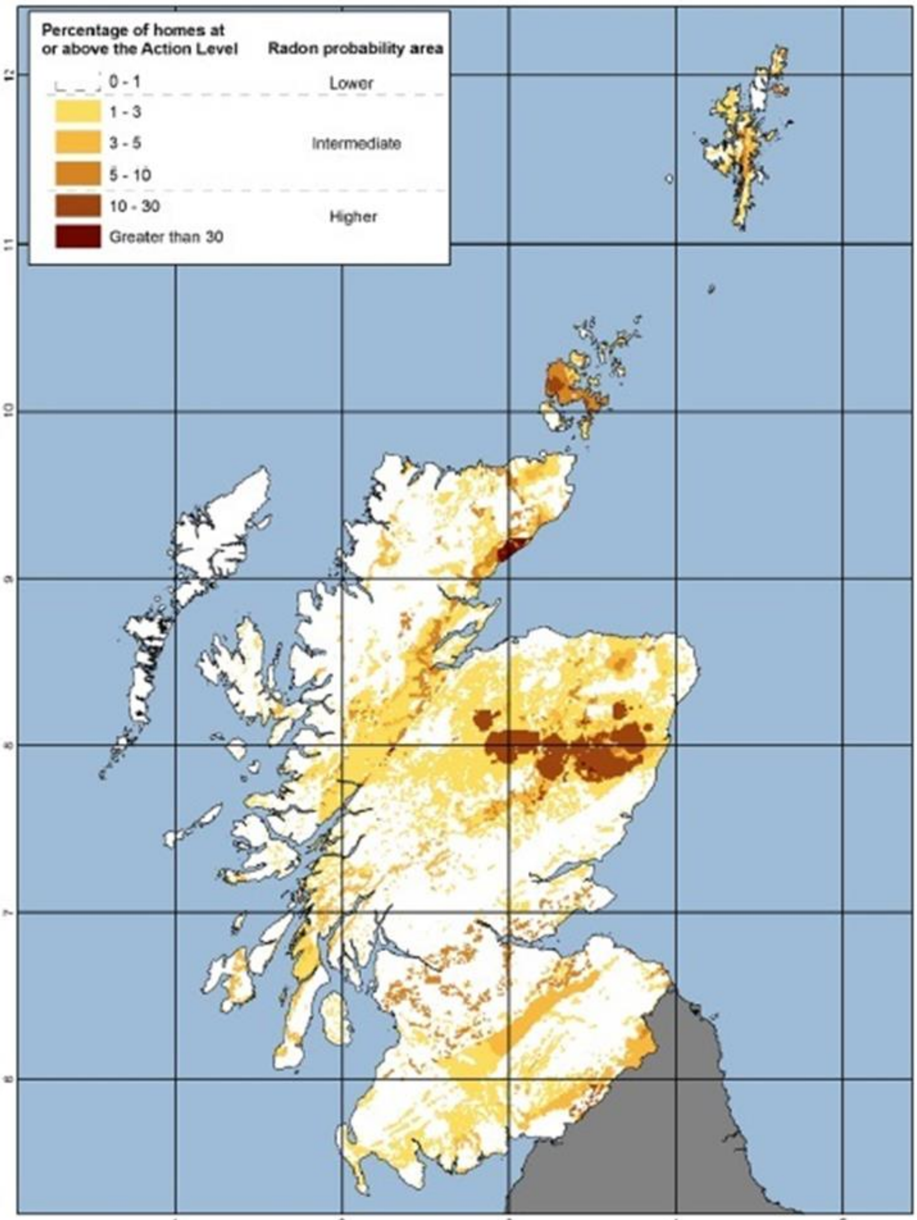
Source: Miles et al, 2007.

Figure 46.2. Overall map of radon affected areas in Northern Ireland.



Source: Daraktchieva et al, 2015.

Figure 46.3. Overall map of radon potential in Scotland.



Source: Miles et al, 2011.

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47 Conclusions

TO BE COMPLETED.

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List of abbreviations and definitions

EANR	European Atlas of Natural Radiation
EC	European Commission
IAEA	International Atomic Energy Agency
JRC	The Joint Research Centre of the European Commission
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
WHO	World Health Organisation

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Qualitative overview of indoor radon surveys in Europe

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ABSTRACT

The revised European Directive from 2013 regarding basic safety standard oblige EU Member States to establish a national action plan regarding the exposure to radon. At the same time, International Atomic Energy Agency started technical projects in order to assist countries to establish and implement national radon action. As a consequence, in recent years, in numerous countries national radon surveys were conducted and action plans established, which were not performed before. In this paper, a qualitative overview of radon surveys performed in Europe is given with a special attention to the qualitative and conceptual description of surveys, representativeness and QA/QC (quality assurance/quality control).

1. Introduction

Natural radioactivity is the main source of population exposure to ionising radiation. More than 80% of exposure comes from the natural radioactivity. Radon and its progenies contribute with more than 50% to annual effective dose received from all sources of ionising radiation (UNSCEAR, 2008).

Radon is a radioactive noble gas, with no stable isotopes. Three naturally occurring isotopes ^{222}Rn, ^{220}Rn and ^{219}Rn, are products of the decay of radium that originates from the decay chain of three primordial decay series ^{238}U, ^{232}Th and ^{235}U, respectively. The relative importance of radon isotopes increases with an increase of their half-lives and their relative abundance. Due to the short half-life of ^{219}Rn ($T_{1/2}$ = 3.98 s) compared to ^{222}Rn ($T_{1/2}$ = 3.82 d), and isotopic ratio of $^{235}U/^{238}U = 0.0072$, ^{219}Rn is always ignored. Although ^{220}Rn (in text referred as thoron) is relatively short-lived ($T_{1/2}$ = 55.8 s) compared to ^{222}Rn (in text referred as radon) and hence can travel much smaller distances, there are regions with exceptionally high $^{232}Th/^{238}U$ ratios leading to a much higher thoron concentration that cannot be neglected.

Being chemically inert, with a lifetime that is long compared to a breath rate, most of the inhaled radon is exhaled rather than decaying in human respiratory system. On the other hand, short-lived radon progenies are solids and tend to attach to surfaces, mainly aerosols. When inhaled they stick to epithelial surfaces and due to a short lifetime their decay sequence finishes before lungs can clean them out, irradiating therefore sensitive surfaces of bronchi and lungs. Hence, health hazards related to radon issue are not caused directly by radon, but by its short-lived progenies.

Historically speaking, radon problem dates from XV century when high death rate due to lung diseases has been observed among silver miners in the regions of Scneeberg in Saxony and Jachimov in Bohemiaas (Paracelsius, 1567). The illness was identified as lung cancer 4 centuries later by Haerting and Hesse (1879). A year after the Dorn's discovery of radon, Elster and Geiter have measured high radon concentration in air in mines of Schneeberg and Jachimov (Elster and Geitel, 1901), but high radon concentration was still not connected with lung cancer. Finally, Rajewsky and collaborators have assumed a link between high radon concentration and lung cancer in 1940 (Rajewsky, 1940) and afterwards in 1951, Bale suggested that radon short-lived progenies could be the main cause of lung cancer (Bale, 1951). From the analysis of the first cohort studies conducted between uranium miners in America (Lundin et al., 1971) and Czechoslovakia (Sevc et al., 1976) it was concluded that there is a monotonic increase of a lung cancer risk with the cumulative exposure to radon progenies. Numerous miner studies were followed, mainly based on above-mentioned studies, and in 1988 International Agency for Research on Cancer has ascribed radon as a human carcinogen (IARC, 1988).

The results of the first indoor radon survey, conducted in Sweden, were published in 1956, and among 225 investigated houses, a few of them had very high radon concentration (Hultqvist, 1956). In that time, the international scientific community considered these findings as a local Swedish problem. Only after 20 years, indoor radon concentration was investigated more seriously in a number of countries and national radon programmes and regulations had been introduced (UNSCEAR, 2000).

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Based on those investigations, recent radon pooling studies performed in China, Europe and North America have unambiguously shown connection between indoor radon concentration and lung cancer (Darby et al., 2006; Krewski et al., 2006; Lubin et al., 2004). Based on these studies, radon was identified as the second leading cause of lung cancer after cigarettes, being responsible for 3%–14% of all lung cancers (WHO, 2009).

The Joint Research Centre (JRC) of the European Commission decided to embark on a European Atlas of Natural Radiation (EANR) (De Cort et al., 2011), in line with its mission, based on the Euratom Treaty (European Union, 2016), which is to collect, validate and report information on radioactivity levels in the environment. The Atlas is a collection of maps of Europe displaying the levels of natural radioactivity caused by different sources: from cosmic radiation to terrestrial radionuclides. The digital version of the EANR is available on line at https://remon.jrc.ec.europa.eu/(Cinelli et al., 2019) and the publication is foreseen in 2019. As a first task, the JRC started to prepare a European Indoor Radon Map (EIRM), given its great radiological importance (WHO, 2009). A first overview of indoor radon surveys in Europe has been performed in 2005 by Dubois (2005). The review of surveys has shown heterogeneity of data, starting from the survey strategies, sampling strategy, measurement techniques, measurement duration and season. Therefore, a huge effort has been taken to summarise data of indoor radon concentrations from different countries and to integrate them in a homogeneous way to produce a European map of indoor radon levels using a 10 km × 10 km grid cells (Dubois et al., 2010).

The exposure of members of the public and of workers to indoor radon is now explicitly taken up in the scope of Basic Safety Standards (BSS) Directive – Directive 2013/59/Euratom laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation (Article 2 (2d)) (European Union, 2013). According to the 2013 BSS directive all member states are required to have a radon action plan and inform the population about their radon levels. Radon activities and radon surveys therefore were started or repeated in several countries in the last years and are still ongoing and maybe will be also increased in the next years. For non-EU-member states also IAEA BSS require radon surveys and IAEA guidelines how to perform radon surveys exist (IAEA, 2011).

Recently, a JRC report based on literature review of indoor radon surveys in Europe was given within the framework of MetroRADON project (Pantelić et al., 2018). Based on data from the report, this overview was prepared aiming to give an updated qualitative overview of radon surveys performed in European countries using literature data, with focus on the data which were not included in other survey overviews. Therefore, special attention is given to the qualitative and conceptual description of surveys such as types of surveys and their representativeness, sampling strategies and measurement techniques, applied corrections, interpretation of survey results and dealing with thoron issue.

The literature overview has shown that many sources do not present sufficient data on survey design and survey results, so in many cases the number of identified answers is lower than the number of surveys that was studied in this research.

2. Survey design and representativeness

Although the main source of indoor radon is soil subjacent to the dwelling, knowing only soil characteristics is not enough to obtain a reliable prediction of indoor radon concentration of specific dwelling, due to numerous factors influencing radon concentration. Since it is not feasible to perform a measurement for each dwelling it is important to carefully design radon survey in order to obtain representative distribution of radon concentration in dwellings. (IAEA, 2013).

Performing a truly representative indoor radon survey is rather difficult. In order to achieve truly representative survey, it is necessary to have a complete list of dwellings, which is seldom available, from which random selection of dwelling should be chosen. Any deviation from pure random sampling can cause biases (IAEA, 2013). It was shown that volunteer measurements could be biased due to the oversampling in radon priority areas (Burke and Murphy, 2011).

This type of survey based on random sampling is population-weighted survey, since more dwellings will be sampled in densely populated region. Another type of survey is geographically based radon survey in which a territory is divided into geographical units, such as rectangular grids of certain area or administrative boundaries (strata). Sampling within each geological unit should be representative for the population distribution within that unit. Therefore, with carefully designed survey, representativeness of both approaches can be achieved (IAEA, 2013).

The overview of radon surveys presented in this paper was conducted in such a way to identify the survey covering the largest territory for each European country – preferably a national survey. If a national survey was identified, no regional surveys were considered. If more than one national survey was found, then the most recent one was considered, or the most recent publication that covered results from previous surveys as well. In some cases, more than one regional survey was considered if they did not overlap significantly. Some special surveys were considered to point out different methodologies. It is likely that more recent surveys exist in some countries, but no literature was available. Some surveys continued past the publication date of the paper or document that was analysed for the purposes of this research, but the analysis is limited only to the published results.

Indoor radon surveys have been conducted in most European countries – existing surveys were identified, through extensive literature research, for all countries except Andorra, Liechtenstein, Monaco, San Marino and Vatican. At least one survey was conducted in each European Union (EU) member country. In some cases, scientific papers and other sources reporting radon concentrations aggregated results of several different surveys. For the purposes of this paper, if the overall coverage is national, it will be considered that a national survey was conducted, for brevity purposes.

National surveys were conducted in 22 EU countries: Austria (Friedmann, 2005) Croatia (Radolić et al., 2006), Czech Republic (Hůlka, 2014; Slezáková et al., 2013; Thomas et al., 2004), Denmark (Andersen et al., 2007, 2001), Estonia (Pahapill et al., 2003), Finland (Valmari et al., 2010; Weltner et al., 2002), France (Gambard et al., 2000; Rannou et al., 2006), Greece (Nikolopoulos et al., 2002), Hungary (Hámori et al., 2006; Nikl, 1996), Ireland (Dowdall et al., 2017; Fennell et al., 2002), Italy (Bochicchio et al., 2005; Carelli et al., 2009), Lithuania (Morkunas and Akelbrom, 1999), Luxembourg (Kies et al., 1997), Malta (Baluci et al., 2013), Netherlands (Lembrechts et al., 2001; Stoop et al., 1998), Poland (Przylibski et al., 2011), Portugal (Faisca et al., 1992), Slovakia (Vicanova et al., 1998; Vladár et al., 1996), Slovenia (Humar et al., 1995; Križman et al., 1996), Spain (Sainz Fernández et al., 2017), Sweden (Swedjemark, 2002; Swedjemark et al., 1993), United Kingdom (Daraktchieva et al., 2015; Miles et al., 2007, 2011). Only regional surveys were identified in 5 member states: Belgium (Cinelli et al., 2011; Poffijn et al., 1994; Tondeur et al., 1997; Zhu et al., 2001, 1998), Bulgaria (Ivanova et al., 2013), Cyprus (Anastasiou et al., 2003; Theodoulou et al., 2012), Germany (Kemski et al., 2004, 1996), Latvia (Dambis, 1996), Romania (Cucoş (Dinu) et al., 2017). Outside the EU, national surveys were conducted in Azerbaijan (Hoffmann et al., 2017), Belarus (Yaroshevich et al., 2012), Iceland (Jónsson et al., 2015), Macedonia (Stojanovska et al., 2012), Montenegro (Vukotic et al., 2018), Russia (Yarmoshenko et al., 2015), Serbia (Udovičić et al., 2016), Switzerland (Kropat et al., 2014), Ukraine (Pavlenko et al., 2014) and Norway (Jensen et al., 2004). Only regional surveys were identified for Albania (Bode Tushe et al., 2016), Armenia (IAEA, 2014), Bosnia and Herzegovina (Ćurguz et al., 2015; IAEA, 2014), Georgia (IAEA (International Atomic Energy Agency), 2014), Kazakhstan (Fyodorov et al., 2014), Moldova (Ursulean et al., 2013), and Turkey (Can et al., 2012; Köksal et al., 2004).

The number of measurement locations in the surveys covered in this paper differs by 4 orders of magnitude. This data are not always reliably identifiable from the references. In some cases, more than one measurement was performed per location, sometimes at the same time in different part of the building, sometimes at different time. However, in order to compare the surveys, only unique locations with valid measurement results were counted, as reported by the survey authors. Some of the surveys continued after the last publication of the results, so the numbers of measurement locations could be higher.

The minimum number of locations was selected in Malta national survey – 85 (Baluci et al., 2013) At the other end of the spectrum, radon measurements from more than 500,000 locations are available in UK (Daraktchieva et al., 2015; Miles et al., 2007, 2011). There are at least 5 countries besides UK with more than 50,000 measurement locations – Russia (Yarmoshenko et al., 2015), Czech Republic (Dubois et al., 2010), Switzerland (Kropat et al., 2014), Finland (Valmari et al., 2010) and Norway (Jensen et al., 2004).

Dividing the number of measurement locations by country territory or population can provide another perspective. The results are graphically shown in Fig. 1. For this graphics, only national surveys are represented. Population data are taken from Google public data for the year that is at the middle of the survey period, or the nearest year for which there are available data. Country area is in most cases excluding overseas territories (e.g. Greenland and Svalbard) but in other cases, territory outside of Europe is taken into account since the survey covers that territory (e.g. Russia and Azerbaijan). The ratios should be considered only as approximations. Frequency distribution of the natural logarithm of the number of measured locations normalised: per 1 million inhabitants and per 1000 km^2 are presented on the left hand side, and on the right hand side of Fig. 2.

In both cases, Switzerland, Finland, UK and Czech Republic are in top 5, as is the case when the absolute number of measurement locations is used. However, Russia is in the bottom half if the area is considered, and Malta is comparable with Finland.

In almost all indoor radon surveys, the great majority of measurement locations were dwellings. However, other measurement locations were also selected in some surveys: schools and kindergartens (Iceland (Jónsson et al., 2015), Luxembourg (Kies et al., 1997), Russia (Zhukovsky et al., 2012), Slovakia (Vicanova et al., 1998; Vladár et al., 1996), Slovenia (Humar et al., 1995; Vaupotic et al., 1992), Ukraine (Pavlenko et al., 2014)), industrial buildings and workplaces (Azerbaijan (Hoffmann et al., 2017), Moldova (Ursulean et al., 2013), Luxembourg (Kies et al., 1997), Italy (Carelli et al., 2009)), swimming pools (Iceland (Jónsson et al., 2015)), spa buildings and caves (Slovakia (Vicanova et al., 1998)) and underground Telecom inspection rooms (Italy (Carelli et al., 2009)).

Regarding the most recent surveys, many countries have published survey results in the previous 10 years, including Albania (Bode Tushe et al., 2016), Azerbaijan (Hoffmann et al., 2017), Belarus (Yaroshevich et al., 2012), Bulgaria (Ivanova et al., 2013), Iceland (Jónsson et al., 2015), Kazakhstan (Fyodorov et al., 2014), Malta (Baluci et al., 2013), Romania (Cucoş (Dinu) et al., 2017), Serbia (Udovičić et al., 2016), Turkey (Köksal et al., 2004), Ukraine (Pavlenko et al., 2014). Most of them were conducted, under the technical cooperation programmes with IAEA, aiming to develop policies and strategies according to

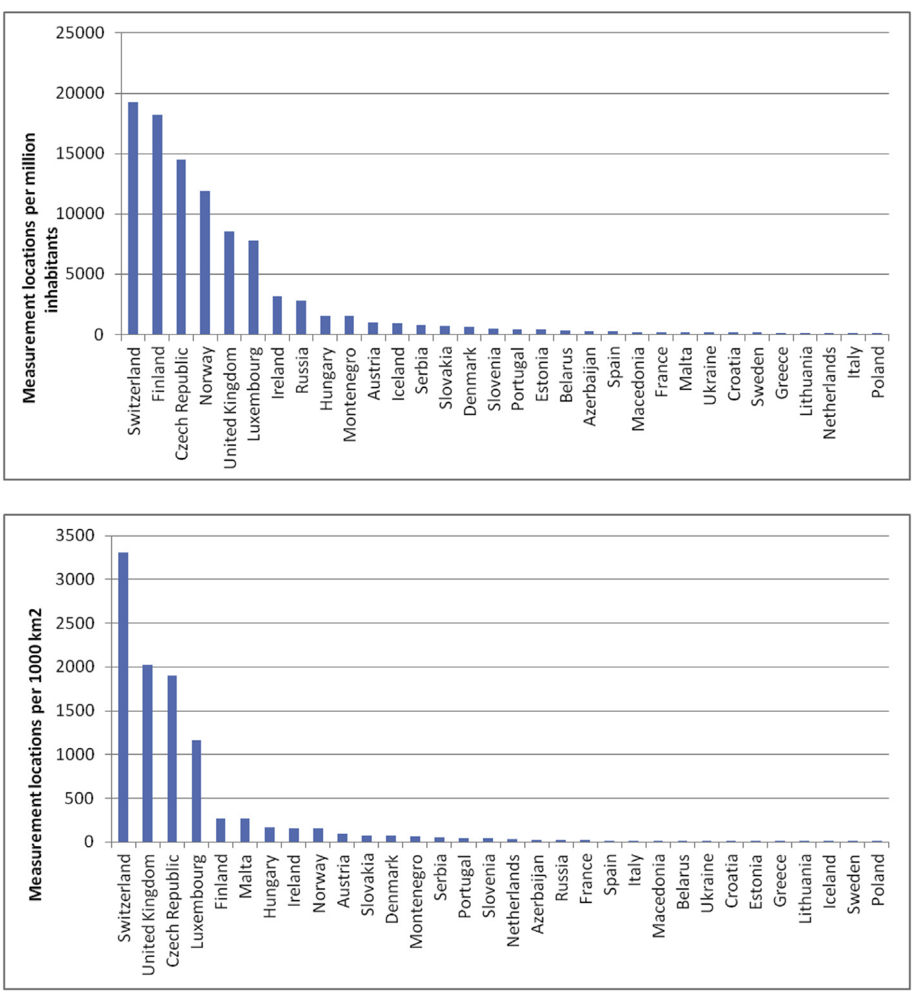

Fig. 1. Number of measurement locations per million inhabitants (top figure) and per 1000 km^2 (bottom figure).

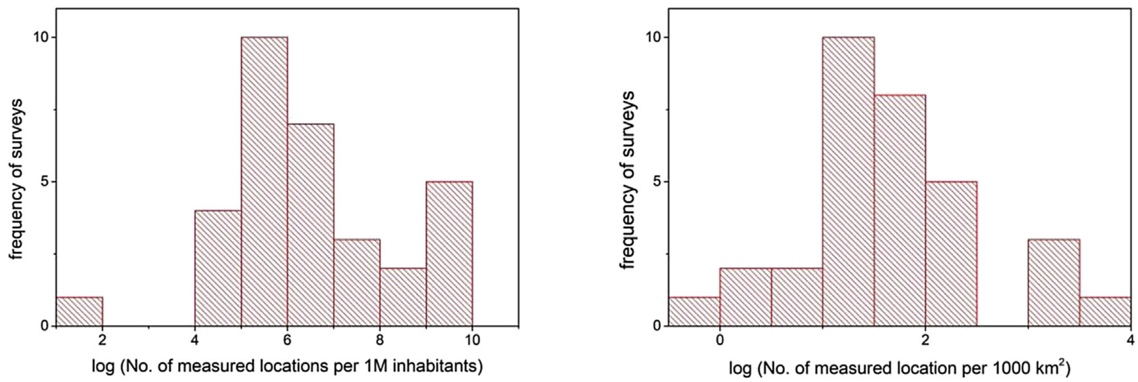

Fig. 2. Frequency distribution of the number of measured locations normalised: per 1 million inhabitants (left figure) and per 1000 km^2. X-axis is given is natural logarithm scale.

requirements of Basic Safety Standards (IAEA, 2011).

On the other hand, countries with long history in radon surveys often do not have any recent results published in the available literature. It is, however, probable that the indoor radon measurements are still on-going in these countries. Examples of such countries are United Kingdom, Austria, Czech Republic, Norway, Sweden, France, Hungary.

Survey goals were in most cases to produce an indoor radon map (i.e. to determine a geographical distribution of indoor radon levels), to identify radon priority areas, to assess the effective dose, to determine national mean concentration and to provide inputs for national legislation or action plans. In several cases, no map was created, but the descriptive statistics was performed for territorial units within the country. Regional studies were often conducted in the previously identified radon priority areas. In the study conducted by Carelli et al. (2009), the goal was to test a novel mapping method, and in the study conducted by Slezáková et al. (2013), to evaluate long term variability of radon concentrations.

The European Indoor Radon Map is based on the average indoor radon concentrations within 10 km × 10 km grid cells (Dubois et al., 2010). This sampling strategy is more prevalent in newer studies and it can be expected that it will be more so in the future for radon mapping purposes, which is a requirement of the 2013BSS (European Union, 2013). However, there is a large diversity within sampling strategies in existing radon surveys. In many countries, territory was subdivided into administrative units (Denmark (Andersen et al., 2007, 2001), France (Rannou, 1990) and Netherlands (Lembrechts et al., 2001; Stoop et al., 1998)) or grid cells – 10 km × 10 km (Albania (Bode Tushe et al., 2016), Azerbaijan (Hoffmann et al., 2017), Hungary (Nikl, 1996), Ireland (Fennell et al., 2002), Romania (Cucoş (Dinu) et al., 2017) and Spain (Sainz Fernández et al., 2017)), 5 km × 5 km (Malta (Baluci et al., 2013)), 1 km × 1 km (Cyprus (Theodoulou et al., 2012) and United Kingdom (Daraktchieva et al., 2015; Miles et al., 2007, 2011)) or even 0.5 km × 0.5 km (Montenegro (Vukotic et al., 2018)). In case of Poland, country was divided into geological regions (Przylibski et al., 2011). In other cases, density of measurement points was correlated to the population density or was higher in previously identified radon priority areas. Finally, in the study conducted by Istituto Superiore di Sanità building network of Telecom Italia was used (Carelli et al., 2009).

2.1. Representativeness

In most cases, authors of reviewed surveys did not go in details about survey design and its representativeness. Therefore authors of this overview of surveys did not try to estimate whether some surveys were representative or not. Instead, an overview to what extent representativeness was discussed in reviewed papers is given.

In most surveys, random sampling within each grid cell, territorial unit or the whole country was used. However, many surveys were based on volunteers within special cohorts (physics teachers, students, civil servants on municipal level etc.) or measurements in government buildings, usually schools or kindergartens. Some surveys based on volunteers could be biased toward higher concentrations since people suspecting to live in higher indoor radon concentration tend to volunteer more. Also, volunteers, such as students, could represent a specific part of population that is not necessarily representative of the whole population.

In Iceland it was underlined that although broad distribution of sample points was achieved, sampling locations were not random (Jónsson and Theódorsson, 2003; Jónsson et al., 2016).

In Estonian survey, it was underlined that a representative number of dwellings was used and that obtained results are representative for detached houses and flats on the ground floor for multiapartment buildings (Pahapill et al., 2003).

In Germany, a standardised procedure for radon and permeability measurements was developed to assure regional representativeness. Number of measurement per sampling area depended on the variability of geological patterns in the area (Kemski et al., 1996).

In population-weighted survey performed in Macedonia, representativeness was obtained by random selection of houses, covering all regions (Stojanovska et al., 2012).

Data obtained from the questionnaires sent to inhabitants during the first Hungarian radon survey were compared with data from Central Statistical Office in order to check the representativeness of the sample (Nikl, 1996). The second survey in Hungary was based on volunteers where teachers facilitated distribution of the detectors. It was concluded that due to large measurements performed, sampling could be considered representative (Hámori et al., 2006).

Due attention on representativeness of both national radon surveys in Ireland was given. By designing the first survey it was concluded that at least 5 dwellings per 10 km^2 grid square should be selected. In order to ensure at least this sample size, 70 householders per grid square were randomly selected from the Register of electors (Fennell et al., 2002). The second survey was carefully designed to assure radon measurements in the sample of homes are representative of radon risk and geographical location. By random selection from Geodirectory – a database of Irish postal addresses identified by geographical coordinates, a representative sample of dwelling types is provided. Finally, the representativeness of the grid squares was checked by the goodness of fit between distributions of geographic regions and risk categories (Dowdall et al., 2017).

The Italian national indoor radon survey was designed to obtain a representative estimate of the radon distribution in dwellings. Representative number of dwelling was selected in two stages: the first stage was a simple random sampling of towns over 100000 inhabitants and clustered and then random sampling of smaller towns. In the second step, dwellings were randomly sampled within each town with the sampling proportion of 1/4000 (Bochicchio et al., 2005). In the most recent Italian survey, conducted in the workplaces and employees' home of national telecom company, that encompassed about 7000 dwellings, representativeness was checked in details by comparing characteristics of dwellings with data from the latest National Census (Antignani et al., 2013).

It is estimated by Daraktchieva and coauthors that surveys performed in UK are seldom representative since many measurements targeted the areas where high radon concentrations were expected. The first UK survey performed by Wrixon and collaborators was the only population weighted survey (Daraktchieva et al., 2015; Wrixon et al., 1988).

In the report of Swedish Residential Radon Project, it is mentioned that a representative sample of Swedish housing stock was performed during 1976 and 1988 (Swedjemark, 2002).

In Austrian survey, dwellings were selected randomly from the telephone register to avoid a biased sample. In case of refusal, another house was randomly selected. Measurements were populated weighted, with 1 in 200 homes selected for the sample (Friedmann, 2005).

Ivanova et al. have emphasised that the main goal in the regional Bulgarian radon survey was to choose representative districts in order to obtain representative results of the indoor radon. Number of dwelling for each district was population weighted, but considering also a spatial distribution (Ivanova et al., 2013).

In Czech Republic, there is a continuous radon program going from early eighties with more than 150000 measurements. Representativeness is not directly discussed. It was mentioned only that first indoor radon survey performed in 1992/93 was representative (Hůlka and Thomas, 2004).

Radon survey in Greece was administratively designed. Sampling density was 1 per 1000 dwellings. A door-to-door approach was applied in order to minimise nonresponse and bias (Nikolopoulos et al., 2002).

Representativeness of radon survey in Lithuania was not discussed directly. Nevertheless, it is mentioned that random sampling of detached house was applied with density of one house in 1096 in rural areas and one house in 1120 in urban areas (Morkunas and Akelbrom, 1999).

Representative national survey of Croatia was obtained by random sampling of thousand addresses (Radolić et al., 2006). In Montenegro, an advice from construction expert was obtained in order to identify houses that could be considered as representative. One such house has been then identified in each grid square and selected for radon measurements (Vukotic et al., 2018).

Based on one of the regional surveys conducted in Serbia, a question was raised whether indoor radon survey in Serbian schools could produce results representative for radon exposure of the general population (Žunić et al., 2010a,b). Based on these results, in regional survey of indoor radon, thoron and its progenies in schools in Bosnia and Herzegovina, it was stated that representative measurements were performed due to correlation of primary schools with the number of residents (Ćurguz et al., 2015).

In some surveys (Belgium, Finland and Switzerland), that have oversampled areas, different techniques, such as declustering, were applied to achieve regional representativeness (Kropat et al., 2014; Valmari et al., 2010; Zhu et al., 1998).

In Cyprus survey, no direct discussion about representativeness is present. Nevertheless, it was mentioned that house owners were approached by phones to get their agreement. Although measurement per dwelling lasted only for 2 days, it is mentioned that, due to constant weather conditions, there is no reason for seasonal corrections. Finally, authors have mentioned representative overview of results, by their classification in different regions (Anastasiou et al., 2003).

In national radon survey of Iceland, volunteers were sought via webpage or by phone and therefore sampling locations were not randomly selected. Nevertheless, they tried to select dwellings following population density distribution (Jónsson et al., 2015).

From 2013 a comprehensive radon survey is on-going in Romania (Cucoş (Dinu) et al., 2017). Although, representativeness was not mentioned in the analysed paper, it is underlined that survey protocol designed on the basis on the European Indoor Radon Map (Tollefsen et al., 2014). At each 10 km × 10 km grid cell, deferent number of detectors, from 3 to 15 has been deployed depending on population density (Cucoş (Dinu) et al., 2017).

The Spanish indoor radon map was constructed based on a few surveys. Grid was generated according to the European Indoor Radon Map. The last survey was designed in such a way to add missing measurements in different grid cells in order to fulfil several criteria: surface criterion, population criterion, MARNA criterion increased number of measurement in areas with high radon potential, and lithostratigraphic criterion. Measurement locations at each cell were selected randomly. (Sainz Fernández et al., 2017).

For performing a representative survey, it is not sufficient only to have random, unbiased sampling of dwellings, but also appropriate measurement techniques should be used, appropriate measuring location. If the goal is to have a representative survey, it should also be part of the survey to test at the end, to what extend representativeness was reached (e.g. by comparison to national census data) that this in most or the surveys is not done yet (Antignani et al., 2013).

3. Measurement techniques

There are numerous techniques for radon measurement, which can be performed by direct measurement of radon, so called "radon alone" measurement or indirectly by measurement of radon progenies with or without radon itself. Since radon and some of its progenies - ^{218}Po, ^{214}Po and ^{210}Po - are alpha emitters, while ^{214}Pb, ^{210}Pb, ^{214}Bi and ^{210}Bi are beta emitters, and their decay is mostly followed by gamma-ray emission, radon measurements can be performed by detection of either alpha, beta or gamma rays. Some widely used techniques are: solid state nuclear track detectors, ionisation chambers and proportional counters, scintillators, semiconductors with surface barrier, gamma spectrometry, and adsorption.

A strong variation of radon concentrations in time was found. Roughly speaking, one can identify 2 types of variations of indoor radon concentrations: diurnal and seasonal. On daily basis, radon concentrations are higher during the night and early morning, while they decrease during the day. Radon concentrations are in general higher during the heating season, compared to non-heating season. Therefore, measurements should be long enough to enable averaging these variations.

Depending on the duration, measurements can be: 1) instantaneous measurements in which sample of radon gas is collected in the time interval of the order of minutes (known as grab sampling); 2) continuous measurements in which a radon concentration is continuously monitored with the radon concentration integrated over a certain period of time (of the order of minutes or hours); and 3) integrated measurements in which radon is measured and therefore averaged over a long period of time (of the order of days or months).

Thus, the choice of measurement technique depends on the purpose of radon measurement and since for radon surveys the goal is to obtain an average annual radon concentration the most appropriate would be long term measurement. (IAEA, 2013).

Indoor radon surveys in investigated European countries were performed with passive measurement techniques except in one country (Cyprus). Only in Cyprus, the indoor measurements were carried out by using a high sensitivity active portable radon monitors - RADIM3A (Anastasiou et al., 2003; Theodoulou et al., 2012).

An overview of used techniques for radon surveys is shown in Fig. 3. From 42 countries which were covered by this survey, passive ***electrets*** detectors were used in indoor radon surveys in five countries: Austria (Friedmann, 2005), Hungary (Nikl, 1996), Latvia (Dambis, 1996),

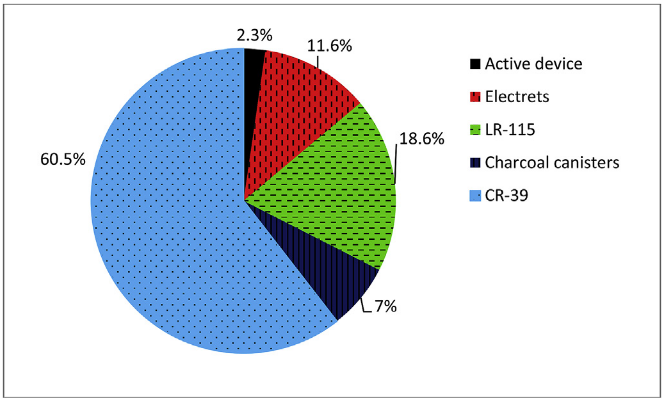

Fig. 3. Overview of used techniques for radon surveys.

Lithuania (Morkunas and Akelbrom, 1999), and Switzerland (Kropat et al., 2014). Different kind of passive track detector systems based on solid state track detectors ***LR-115*** were used in eight countries: Belarus (Yaroshevich et al., 2012), Croatia (Radolić et al., 2006), Czech Republic (Slezáková et al., 2013), France (Gambard et al., 2000; Rannou, 1990; Rannou et al., 2006), Italy (Bochicchio et al., 2005), Malta (Baluci et al., 2013), Portugal (Faisca et al., 1992), and Ukraine (Pavlenko et al., 2014, 1997). In two covered countries, indoor radon concentrations were measured by gamma ray spectrometry (NaI(Tl) or HPGe detectors) of exposed ***charcoal canisters*** in Austria (Friedmann, 2005), Belgium (Cinelli et al., 2011; Tondeur et al., 1997; Zhu et al., 2001).

Literature survey showed that the most commonly used measuring technique (in more than 60%) is alpha track detectors ***CR-39*** (polyallyl diglycol carbonate), etched with NaOH after exposure and track counting by different approaches.

Several countries used other kind of track detectors without specification what films were used, like Azerbaijan – Gammadata-Landauer type (Hoffmann et al., 2017), Finland – Alpha track detectors (Valmari et al., 2010; Weltner et al., 2002), Germany – solid state nuclear track detector (Kemski et al., 2004).

Results of a literature survey, regarding indoor radon measurement campaigns, also showed that in some countries different measurement techniques were combined, either in one survey or during the different conducted surveys.

3.1. Single measurement design and evaluation

The measurement time is mainly conditioned by the selected measuring technique. For indoor radon measurements by highly sensitive active portable monitors (in Cyprus) instrument was adjusted to record the data every 2 h over the 24 h period (or 2–4 h over 48 h). Drought-free areas in the sites were selected to place the radon monitor, such as basements, away from doors and windows, to record the maximum radon concentration. The detectors were always placed at a height of approximately 1 m above the ground (Anastasiou et al., 2003; Theodoulou et al., 2012).

Two 24 h measurements were obtained in each defined grid and the average value was recorded as the radon concentration value for the grid. Two measurements in each grid were conducted in different seasons of the year, so no seasonal corrections were applied.

Passive alpha track detectors were exposed for mostly 2–3 months, but also for the one year period in Croatia (Radolić et al., 2006), Denmark (Andersen et al., 2007, 2001), Finland (Valmari et al., 2010; Weltner et al., 2002), Greece (Nikolopoulos et al., 2002), Hungary (Hámori et al., 2006) Iceland (Jónsson et al., 2015), Ireland (Fennell et al., 2002), Italy (Bochicchio et al., 2005; Carelli et al., 2009) and Netherlands (Lembrechts et al., 2001; Stoop et al., 1998). Electrets were used in Austria (Friedmann, 2005) with time of exposure of 3 months; in Lithuania with minimum 3 weeks (Morkunas and Akelbrom, 1999); in Hungary with one year period of exposition (Nikl, 1996) and Switzerland for 3 months (Kropat et al., 2014).

Due to the method specificity, measurements with charcoal canisters lasted for few days, the most often three to four days.

Solid state track detectors, as well as charcoal canisters were mostly placed in pairs, at least 1 m above the ground, away from door and windows, in most cases in basement and in one room on the ground floor, or one in a bedroom and one in the living room or other most frequently used room. In Greece (Nikolopoulos et al., 2002) and Croatia (Radolić et al., 2006), for example, as an exception from the usual practice, one detector was used per surveyed home, but for the whole year period. The maximum number of detectors in one object, according to presented literature survey, was in Poland - 3 detectors for mean monthly concentration and 3 for mean quarterly concentrations (Przylibski et al., 2011). Thus, 12 monthly averages and 4 quarterly averages were calculated per building.

During the indoor radon survey, measurements of ambient gamma dose rate indoors were performed at the same time in Lithuania (Morkunas and Akelbrom, 1999) and Turkey (Can et al., 2012).

Uniquely, during the surveys in Finland (Valmari et al., 2010; Weltner et al., 2002) in single measurement evaluation, corrections based on the outdoor temperature and wind speed were taken into account.

Correction factor values were mainly took from the literature, but in some countries, like Albania and Austria (Bode Tushe et al., 2016; Friedmann, 2005) the correction factors were obtained by studying the variations in indoor radon concentration observed in summer and winter seasons with respect to the entire year in randomly selected dwellings located in different geographical regions. Different approach was chosen in Czech Republic where the seasonal corrections were calculated on the basis of the data of Moucka including 3000 weekly measurements in 24 objects in the Czech Republic (Slezáková et al., 2013).

Whole year measurements were performed in at least 12 European countries. In most cases, a single detector was exposed for approximately 1 year. In other cases, 2 detectors were deployed in consecutive 6 months periods (Italy (Bochicchio et al., 2005), Malta (Baluci et al., 2013) and Montenegro (Vukotic et al., 2018)) or 4 detectors in consecutive 3 months periods (Macedonia (Stojanovska et al., 2012)). In at least 10 surveys, measurements were performed only during winter or during the heating season. This period of year was often selected in Scandinavian and Baltic countries. Other surveys were performed at least partly outside the heating season, or the time of year was not specified in the literature source. Radon concentration variability in periods longer than 1 year was widely neglected, with notable exceptions (Slezáková et al., 2013).

4. Sampling procedure, sampling number and type of locations

Due to its long half-life, radon is assumed to be uniformly distributed within the room. Therefore, a detector can be placed at any position in a room, exposed to air. Nevertheless, due to the change of physical properties of detectors when exposed to heat (Fleischer et al., 1975), it should be avoided to place detectors close to a heat source. A vicinity of windows and doors should be avoided as well. Since one of the goals of radon surveys is to obtain reliable estimation of exposure to radon, detectors should be placed in rooms with high occupancy such as bedrooms or living-rooms. For passive radon detectors that have substantial sensitivity to thoron it is important to place detector away from walls, in order to reduce possible contribution from thoron.

Sampling procedures in most covered surveys were similar. Mainly, two detectors were deployed per dwelling at the same time in the most frequently used rooms (like living room, kitchen or bedroom), placed away from doors and windows and one to 2 m from the floor. But there are cases, like in Greece (Nikolopoulos et al., 2002) where one detector was used, and measurement lasted for a whole year. Detectors were exposed on ground level or basements. Also, in most cases detectors were distributed with questionnaires and instructions.

A due attention should be paid to handling detectors after being exposed. They should be sealed in radon-proof bags in order to reduce unwanted overexposure of detectors, or sent immediately to responsible institution. Detailed instructions are usually sent to householders regarding the deployment and handling of the detectors after the exposure. Although improper handling of the detectors could lead to a significant overexposure, these details were not discussed in any of the reviewed articles, neither in the form of applied corrections nor in the uncertainty budget.

5. Data analysis

The interpretation of the bulk results was conducted, on different level, for all surveys in all countries. The results were analysed according to the survey goal and the type of the analysis depended on the survey type and strategy as well as the duration and type of measurement. In almost all papers, the basic statistical analysis, consisting of calculation of average and annual mean values, standard deviation, minimum and maximum value was performed. This basic statistics, although it cannot determine the causal links between the measured values, was able to point out the outlier results, which, on the other hand can point to the areas with untypically high values of indoor radon. In some papers, a map depicting measured or averaged results was produced. A map provides in principle the same outlook as the descriptive statistics, but in the graphic format. Also, a test for log – normality of the obtained results was performed in some studies.

Results of descriptive statistic were presented in 55 papers, describing the analysis of measurement results from 39 countries In 27 papers, covering the results of surveys in Albania, Azerbaijan, Belarus, Belgium, Bulgaria, Denmark, Finland, France, Germany, Greece, Italy, Malta, Montenegro, Netherlands, Norway, Romania, Serbia, Slovakia, Spain, Sweden, Switzerland and Ukraine, authors used the obtained average values to assess the percentile, or number of houses where the indoor radon concentration exceeded some predetermined levels (Andersen et al., 2001; Baluci et al., 2013; Bochicchio et al., 2005; Bode Tushe et al., 2016; Cinelli et al., 2011; Cucoş (Dinu) et al., 2017; Hoffmann et al., 2017; Ivanova et al., 2013; Jensen et al., 2004; Kemski et al., 2004; Nikolopoulos et al., 2002; Pavlenko et al., 2014; Poffijn et al., 1994; Sainz Fernández et al., 2017; Stoop et al., 1998; Swedjemark, 2002; Swedjemark et al., 1993; Tondeur et al., 1997; Valmari et al., 2010; Vicanova et al., 1998; Vukotic et al., 2018; Weltner et al., 2002; Yaroshevich et al., 2012; Z.S. Žunić et al., 2010a,b; Žunić et al., 2009). In surveys conducted in Azerbaijan, Belgium and Spain, the correlation of the results of indoor radon measurement with the geological characteristics of the region was investigated, while in Albania, the comparison with known uranium concentration in soil was performed. Also, as a form of descriptive statistics, the frequency distribution was calculated in the following surveys: Albania (Bode Tushe et al., 2016), Austria (Friedmann, 2005), Azerbaijan (Hoffmann et al., 2017) and Belarus (Yaroshevich et al., 2012).

Besides this basic analysis, in 15 papers, tests for log normality were performed. The log-normality test is performed when there is a need to analyse a set of results dependents on many independent random variables. Such is the case of indoor radon where, if the data fits the log-normal distribution, the percentage of results exceeding some threshold can be easily calculated. These tests were done for surveys in Albania (Bode Tushe et al., 2016), Belgium (Tondeur et al., 1997; Cinelli and Tondeur, 2015), Bulgaria (Ivanova et al., 2013), Croatia (Radolić et al., 2006), Hungary (Hámori et al., 2006), Ireland (Dowdall et al., 2017), Italy (Bochicchio et al., 2005), Luxemburg (Kies et al., 1997), Montenegro (Vukotic et al., 2018), Netherlands (Stoop et al., 1998), Slovenia (Križman et al., 1996), Spain (Sainz Fernández et al., 2017), Switzerland (Kropat et al., 2014) and Ukraine (Pavlenko et al., 2014).

In some surveys declustering technique were applied to reduce the effect of the over-representation in the over-sampled area (Zhu et al., 1998).

Although many of the measurement were conducted in limited time span, only in 10 papers, seasonal corrections were applied in order to make the results valid for the whole year. Depending on the survey design, measurements were conducted in the winter (heating season), thus providing the highest values of the indoor radon. In these cases, application of the seasonal indices can be omitted if conservative approach is applied. The papers where the correction with the seasonal indices was performed are covering measurements in Albania, Austria, Italy, Romania, Slovenia, Serbia and UK (Bochicchio et al., 2005; Bode Tushe et al., 2016; Cucoş (Dinu) et al., 2017; Daraktchieva et al., 2015; Friedmann, 2005; Križman et al., 1996; Miles et al., 2007, 2011; Udovičić et al., 2016). In these papers, the goal was to ascertain the indoor radon concentration throughout the whole year.

Besides statistical analysis, in some papers a map was produced. These maps were in some cases the goal of the paper and they were associated with the European indoor radon map. In other cases, the map was the means to summarise the results. In most cases, the results were depicted in the form of mean radon risk map, which integrates a variety of data available, including geological maps, radon maps, grids or measured points and administrative boundaries. Maps were produced in papers covering the survey in Austria (Friedmann, 2005), Azerbaijan (Hoffmann et al., 2017), Belgium (Cinelli et al., 2011; Poffijn et al., 1994; Tondeur et al., 1997; Zhu et al., 2001), Cyprus (Theodoulou et al., 2012), Denmark (Andersen et al., 2001), Finland (Weltner et al., 2002), Iceland (Jónsson et al., 2015), Italy (Bochicchio et al., 2005), Latvia (Dambis, 1996), Macedonia (Stojanovska et al., 2012), Malta (Baluci et al., 2013), Norway (Jensen et al., 2004), Portugal (Faisca et al., 1992), Romania (Cucoş (Dinu) et al., 2017), Russia (Zhukovsky et al., 2012), Slovenia (Humar et al., 1995; Križman et al., 1996), Spain (Sainz Fernández et al., 2017), Switzerland (Kropat et al., 2014) and UK (Daraktchieva et al., 2015; Miles et al., 2007, 2011).

6. Quality assurance and quality control

Quality assurance (QA) is planned and systematic action necessary to provide adequate confidence that testing or calibration will satisfy quality requirements. Quality control (QC) contains the operational techniques and activities that are used to fulfil the requirements for quality. QA and QC are necessary to avoid mistakes before they are made and to reduce uncertainties, but also help to estimate the contribution of different input quantities to the final uncertainties.

Ensuring measurement quality is usually done through metrology certification, participation in inter-comparison measurements and periodical calibrations of detectors and monitors. The results of several inter-laboratory comparison exercises showed that precision and accuracy of passive radon devices can be quite different, even for the similar or identical devices (Howarth and Miles, 2002).

Different type of QA/QC procedures for radon measurements could be carried out and the most comprehensives were reported by (Friedmann, 2005):

- Intercalibration and intercomparison exercises between different laboratories with different detector systems in a traceable radon chamber;
- Comparison of parallel measurements with different detector systems in the same homes;
- Comparison of the density distribution of the results from different detector systems used in the same area;
- Repetition of investigations in some areas during another season and by measuring other homes;
- Additional measurements in municipalities with significantly higher or lower mean radon concentration than the adjacent municipalities

Table 1
Reported quality assurance and quality control of radon and/or radon decay products measurements during the indoor radon surveys.

Country	Periodical calibration (or accreditation ISO 17025)	Intercalibration and intercomparison	Comparison of the results from different detector systems	Duplicate detectors	None
Albania				x	
Austria		x	X		
Azerbaijan					x
Belarus					x
Belgium		x			
Bosnia and Herzegovina					x
Bulgaria					x
Croatia					x
Cyprus	x		X		
Czech Republic	x				
Denmark					x
Estonia					x
Finland					x
France		x			
Georgia					x
Germany	x				
Greece	x				
Hungary	x				
Iceland					x
Ireland	x			x	
Italy	x	x			
Kazakhstan					x
Latvia					x
Lithuania		x			
Luxembourg					x
Macedonia	x				
Malta	x				
Moldova					x
Montenegro			X	x	
Netherlands			X		
Norway		x			
Poland		x			
Portugal				x	
Romania		x			
Russia	x		X		
Serbia					x
Slovakia	x				
Slovenia	x	x			
Spain		x			
Sweden	x				
Switzerland					x
Turkey	x	x			
Ukraine	x	x			
United Kingdom		x			

(cluster analysis).

Many papers describe quality assurance and quality control for radon measurements, but authors who present indoor radon survey in European countries did not pay much attention to proper description of QA and QC.

Literature overview shows that in around 30% of references, authors did not describe any quality assurance and quality control of radon and/or radon decay products measurements during the indoor radon surveys (Table 1), but some of them (France, Portugal, Spain, United Kingdom) participated in intercomparisons which were held at the National Radiological Protection Board every year. In 2003, 49 laboratories from 17 countries participated (Howarth and Miles, 2007).

Periodical calibration of detectors or calibration through accredited laboratory services (accreditation according to ISO 17025) are the most common methods of quality control of measurement (Table 1).

Many countries have a system for calibration. In Belgium the calibration of the detectors was controlled by using two small radon reference chambers at ISIB and at the Ghent University (Tondeur, 1998). The detectors were calibrated in radon chamber at the Federal Office for Radiation Protection for measurements in Germany (Kemski et al., 2004), at the University of Athens for measurements in Greece (Nikolopoulos et al., 2002), in the reference radon and radon progeny measuring chamber at the State Metrological Centre of IPCM for the measurement in Slovakia (Vicanova et al., 1998). In Sweden the role of the SSI is to co-ordinate the work on radon and to be responsible for the calibration of measuring devices (Swedjemark, 2002).

In Ireland two radon detectors were placed per home. On return to the laboratory, the detectors were analysed using the Ireland's Environmental Protection Agency's Radon and Radiation Measurement Services test procedures which are accredited to ISO 17025 by the Irish National Accreditation Board (Dowdall et al., 2017).

In Ukraine laboratory used the quality assurance system for the indoor radon measurements which has been developed and implemented at the State institution The Marzeev Institute of Hygiene and Medical Ecology (Pavlenko et al., 2014). The quality assurance procedures included calibration of radon track detectors using the secondary calibration source of laboratory which is accredited by the National Standardization and Accreditation Authority of Ukraine.

Some countries use calibration facilities from other countries. For measurements in Hungary calibration was performed in Swedish Radiation Protection Institute (Nikl, 1996) and at NPRB in United Kingdom (Hámori et al., 2006). In Cyprus calibration over the whole dynamic range of the instrument is made and the accuracy of the calibration is then verified by the State Metrological Institute of the Czech Republic (Anastasiou et al., 2003; Theodoulou et al., 2012). In Italy, measuring system calibration was obtained by exposing a total of nine groups of radon passive devices in the radon chambers of the Heath Protection Agency, UK, and the Italian National Metrology Ionizing Radiation Institute (Carelli et al., 2009).

In Macedonia detectors exposed to known radon concentrations were used for the purpose of quality control of the system. They used full equipment, together with the detectors, the exposed detectors and the proper calibration factors which were commercially available from Hungary (Stojanovska et al., 2012).

After exposure, some countries sent detectors back to the manufacturer for reading, in a vacuum sealed plastic packages to prevent radon contamination during the travel (Serbia: (Udovičić et al., 2016); IAEA SRB/9/006, 2018). In Malta, retrieved detectors were analysed by a Health Protection Agency-accredited laboratory in UK (Baluci et al., 2013). In Russia the two versions of radon radiometers were calibrated in a radon calibration facility of the State Metrological Institute (Marenny et al., 1996).

Intercalibration and intercomparison exercises between different laboratories with different detector systems were also used. In Czech Republic the calibration was done through authorized metrological centre and verified internationally (Thomas et al., 2004) while in Belgium a long-term measurement were gathered by several Belgian laboratories, as well as through the participation in European intercomparisons (Howarth and Miles, 2007).

The measuring system has been tested through intercomparisons on national or international level in Italy (Bochicchio et al., 2005), Lithuania (Morkunas and Akelbrom, 1999), Norway (Jensen et al., 2004), Romania (Cucoş (Dinu) et al., 2017), Slovenia (Vaupotič, 2003), Spain (Sainz Fernández et al., 2017), Turkey (Köksal et al., 2004) and Ukraine (Pavlenko et al., 1997).

In Slovenia, all measuring devices have been regularly checked at the intercomparison experiments in order to comply with the QA/QC requirements, organized annually by the Slovenian Nuclear Safety Administration or by participation in the international intercomparison experiments in Austria and in Czech Republic (Humar et al., 1995; Vaupotič, 2003).

In order to make it possible to compare and compile the results obtained in several laboratories in Poland, a comparative experiment was carried out at CLOR (Mamont-Cieśla et al., 2010; Przylibski et al., 2011).

Duplicate measurements were also used for QC. Whenever possible, measurements were performed twice in each house in Portugal (Faisca et al., 1992). In Albania (Bode Tushe et al., 2016) for quality control purposes, duplicate detectors were placed in randomly selected dwellings while in Montenegro two dosimeters were placed together at each 10th measuring location (Vukotic et al., 2018).

In some surveys, beside the main passive radon detector a passive or active radon monitoring devices from other institute were used as an intercomparison result, for example in Montenegro, devices from Austria were used (Vukotic et al., 2018).

In Netherlands national surveys two type detectors were used. For the purpose of comparison the new survey with the previous one, the instruments and procedures applied in both surveys were compared (Stoop et al., 1998).

In Portugal the repetition of investigations in some areas was done during a different season (Faisca et al., 1992).

7. Thoron measurements

The results of radon measurements without radon-thoron discrimination might be overestimated if the detector is sensitive to thoron and the measurement is made by devices with no radon-thoron discrimination capability, such is a CR-39 detector (Nikezić and Yu, 1998). Therefore, the alpha-activity of thoron was measured at the same time as radon by closed CR-39 track detectors in Hungary (Hámori et al., 2006).

The short half-life of thoron limits the thoron exhalation from soil and building materials and thus the contribution of thoron to the radiation exposure of the population. For a good estimation of the radon and thoron doses, measurements of radon, thoron and their progeny concentrations should be carried out simultaneously (Janik et al., 2013).

The focus in indoor radon surveys is on ^{222}Rn, which gives the highest doses, so in over the 70% of surveyed papers thoron was not mentioned, while some authors have written that they did not correct measurements for possible errors due to thoron concentrations (Kropat et al., 2014).

In Italy, a national survey was conducted with detectors enclosed in a heat-sealed low density polyethylene bag, which blocks radon decay products and thoron (Bochicchio et al., 2005).

In Russia the exposure to thoron progeny is not considered to be an important problem in comparison with the radon progeny (Yarmoshenko et al., 2015).

Although in many indoor radon surveys thoron is not mentioned, there are lot of papers on local radon surveys, which describe that the indoor thoron levels are significant and should be taken into account during both radon measurements and radiation dose and risk assessment, for example in some regions of Balkan: south-eastern Serbia, Kosovo and Metohija and parts of Western Serbia (Žunić et al., 2009).

The RADUET detector was used for simultaneous measurement of the radon and thoron activity in the Visegrad countries (Hungary, Poland and Slovakia), Macedonia, Serbia and Bosnia and Herzegovina (Ćurguz et al., 2015; Mú;llerová et al., 2014; Stojanovska et al., 2012; Z.S. Žunić et al., 2010a,b). Detector consisted of two detector CR-39, fixed in the pot section of two diffusion chambers. The main diffusion chamber was sensitive to radon and the secondary chamber was sensitive to both radon and thoron.

In Austria the thoron progeny measurements were made in some houses in an area with a relatively high thorium concentration. Because in all cases except one, the mean effective dose of thoron progeny was less than 20% of that from radon progeny, the author concludes that the contribution of thoron to the effective dose can be neglected in most cases in Austria (Friedmann, 2005).

Some authors have estimated that thoron activity concentration is very low, but it was used for dose estimation (Yaroshevich et al., 2012).

8. Conclusion

The literature survey has shown that indoor radon surveys were performed in most European countries and in many cases the surveys covered the whole countries. Methodologies used in the surveys were very diverse, to such extent that it is impossible to find two complete same methodologies. This diversity makes comparison between different surveys difficult and likewise makes difficult compiling the data to produce an overall European radon map. Many sources omit some critical information on survey design, which makes it hard to evaluate the methodology or to replicate it. It was found that only in a few papers from the literature survey; authors have paid attention to the representativeness of the performed survey.

It would be very beneficial to create a uniform or at least recommended methodology for surveys aimed at contributing to European radon map and for surveys sponsored by national or international (such as International Atomic Energy Agency) authorities.

The reliability of radon measurement requires that laboratories producing analytical data are able to provide results of the required quality. The need for uniform results from laboratories at an international level therefore requires the implementation of a quality assurance programme, the harmonisation of criteria, sampling procedures, calculations and the reporting of results, agreed on the basis of fundamental principles and international standards. Due to 2013 BSS Directive more radon surveys and related work will be performed in the future and thus harmonisation and standardised methodology would be helpful.

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Appendix A. Supplementary data

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Annex 3

Report: Results of analysis of MetroRADON questionnaire data on indoor radon surveys

Report on Activity 3.1.2 of the EURAMET 16ENV10 MetroRadon project:

Results of analysis of MetroRADON questionnaire data on indoor radon surveys

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Acknowledgements

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All the persons that filled or has been consulted for filling the questionnaire are acknoledged.

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Abstract

One of the specific objects of MetroRADON project is to compare existing radon measurement procedures in different European countries and use the results to improve the consistency of indoor radon measurements across Europe.

For this purpose, a questionnaire was developed to collect information on indoor radon surveys in order to:

a) identify the rationale and methodologies used;

b) identify the extent and possible sources of inconsistencies in the results of indoor radon surveys;

c) propose approaches for reducing inconsistencies and improve harmonisation of indoor radon data;

Moreover, some information have been collected about how EU Member States intend to transpose (or have transposed) the latest Basic Safety Standards Directive into national law.

The questionnaire has been addressed to all European institutions working in this field (not only national authorities but also regional administrations, universities, research centres). They have been invited to complete a separate questionnaire for each survey.

Between December 2017 and July 2018, a total of 56 questionnaire forms on indoor radon surveys were completed and returned by universities, research institutions and competent authorities on national and regional surveys from 24 European countries.

In this report, results from the analysis of replies to the questionnaire are presented, highlighting similarities and differences on radon survey methodologies across Europe.

Introduction

MetroRADON (16ENV10) is 3-years research project on metrology for radon monitoring granted by the European Metrology Programme for Innovation and Research (EMPIR), the main programme for European research on metrology.

The European Council Directive 2013/59/EURATOM (EU-BSS) laying down basic safety standards (BSS) for protection against the dangers arising from exposure to ionising radiation, evokes new challenges for the metrology of radon measurements and calibrations in Europe. For the first time, the exposure of the public caused by radon will be part of legal metrology in Europe. Since the EU-BSS stipulates that the EU Member States' level of relevant activity concentration shall not exceed 300 Bq/m3, new calibration procedures for existing commercial radon monitors with their limited counting statistics have to be developed.

The project will provide SI traceable metrological resources (calibration and measurement) for the monitoring of radon, which essentially facilitate the harmonised implementation of the new EU-BSS in Europe. It will contribute to the creation of metrological infrastructure for radon in Europe suitable for the requirements of the radon action plan requested by the new European Directive.

Follow the progress of the project at http://metroradon.eu/! One of the specific objects is to compare existing radon measurement procedures in different European countries and use the results to optimise the consistency of indoor radon measurements across Europe.

For this purpose, a questionnaire was developed to collect information to analyse and evaluate indoor radon surveys in order to: identify the rationale and methodologies used, identify the extent and possible sources of inconsistencies in the results of indoor radon surveys and propose approaches to reduce inconsistencies and improve harmonisation of indoor radon data.

The questionnaire is addressed to all the institutions (i.e. central national authorities but also regional administrations, universities, researcher centres) that know the details of any performed indoor radon survey. If you performed more than one survey, please compille a separate questionnaire for each survey.

We invite you to fill the questionnaire for your country – region, or forward it to the person, who can best answer these questions.

The questionnaire is reported in Annex I.

The analysis of the replies is reported for each section of the questionnaire.

The analysis has been focused on the quantitative answers, while all the replies given by the respondent have been reported in Annex II.

1. Section 1 Information about respondent

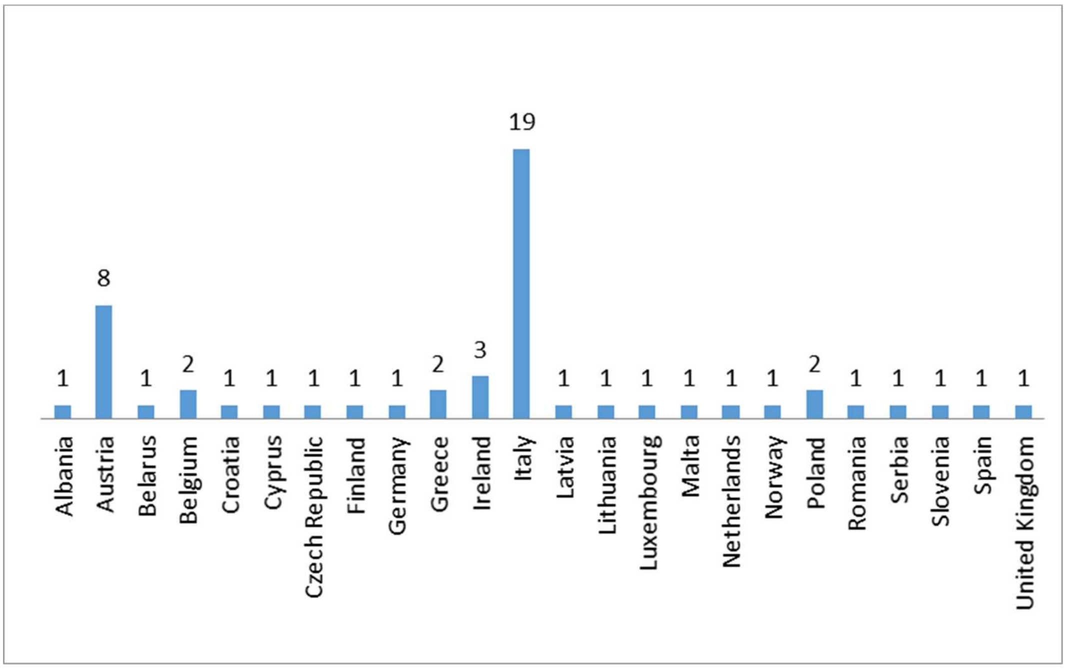
A total of 56 answers to the questionnaire were collected. There are 37 respondents from 24 countries. In some cases, the same respondent describes more than one survey.

Two respondents from Malta and Romania gave identical answers: so, for the analysis of the data, their replies were considered as one.

1.1 Country, please select

Replies from 24 countries has been colllected: Albania (AL), Austria (AT), Belarus (BY), Belgium (BE),Croatia (HR), Cyprus (CY), Czech Republic (CZ), Finland (FIN), Germany (DE),Greece (GR), Ireland(IRL), Italy (IT), Latvia (LV), Lithuania (LT), Luxembourg, Malta (M), Netherlands (NL), Norway (NO), Poland (PL), Romania (RO),Serbia (SRB), Slovenia (SLO), Spain (E), United Kingdom (UK).

In the following graph the number of surveys reported for each country is reported.



1.2 -1.3 Respondent's contact information (institution)

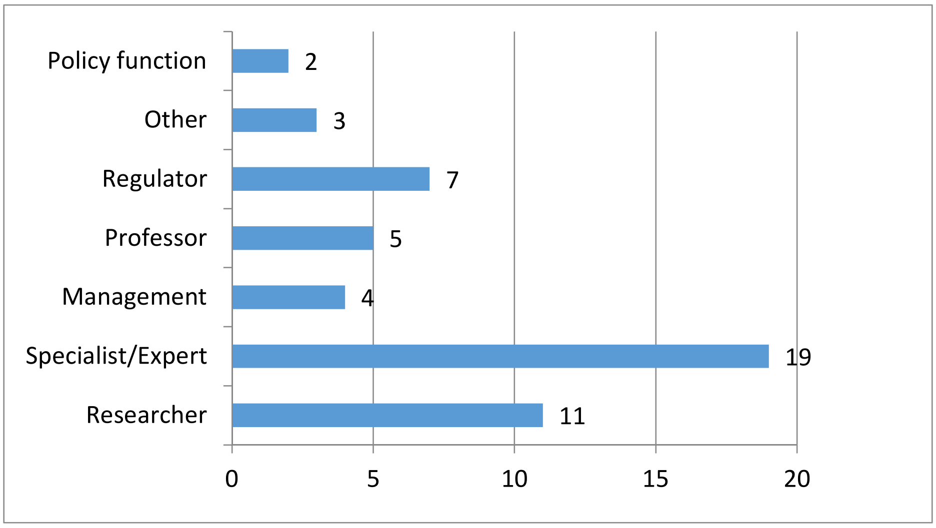
See list of institutions in the Annex II.

1.4 - 1.5 report information about individual respondent

Not provided in this report for privacy issue.

1.6 Role in the organization of the respondent to the questionnaire

Multiple answers were provided.



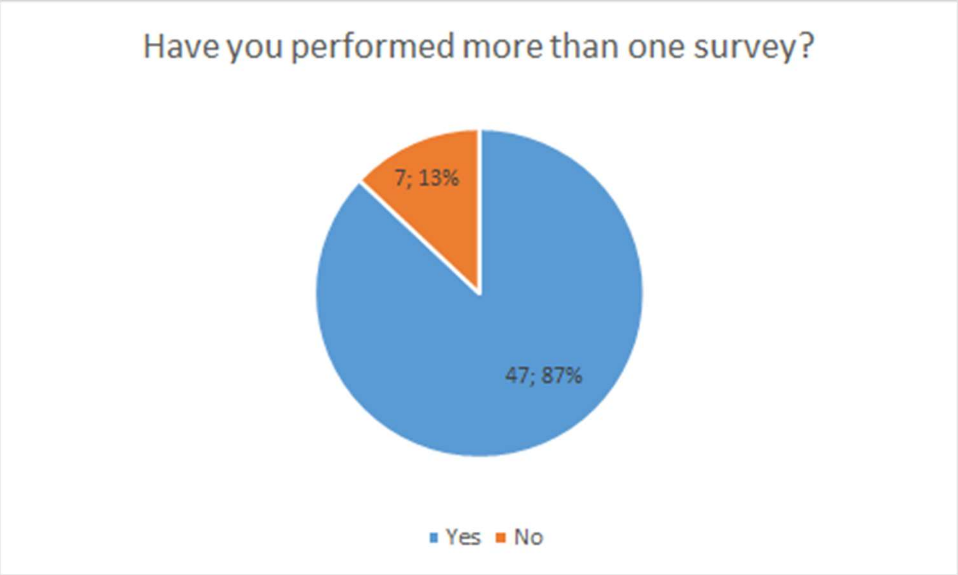
2. Section 2: Characteristics of Indoor Radon Survey

This section is dedicated to the description of each survey that has been reported by the Institutions.

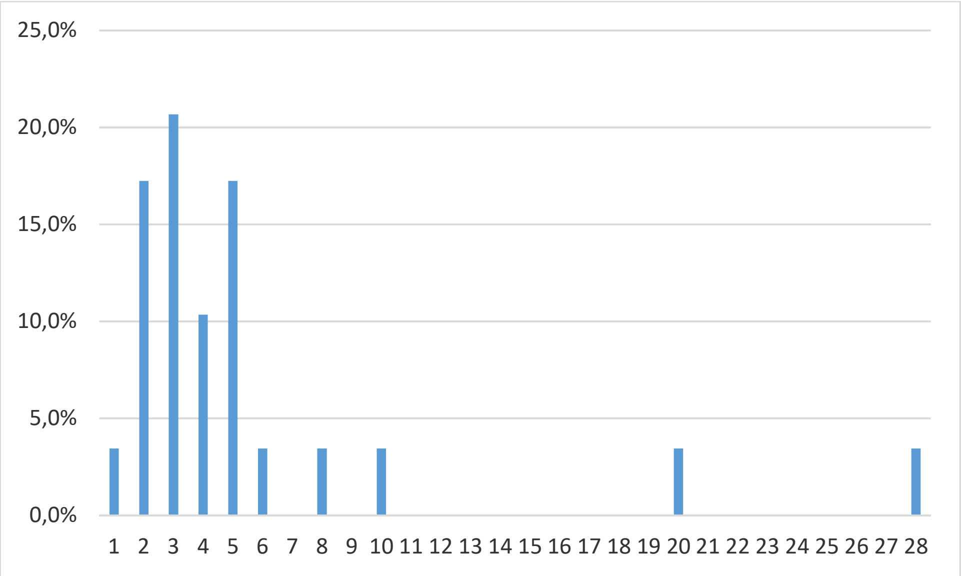
2.1 Have you performed more than one survey?

More than one survey has been performed in 20 Countries (by 87 % of the Institutions returning questionnaires).

Notably, as regards all these surveys, only 7 Institutions of 4 Countries have reported detailed information about them sending a questionnaire for each of the performed surveys.



2.2 If yes, how many surveys?



The number of surveys performed by each Institution (and Country) is very variable such as the fraction of the national territory covered by the surveys – most of them are regional or sub-regional – as well as the number of performed measurements (see answers of the section 4).

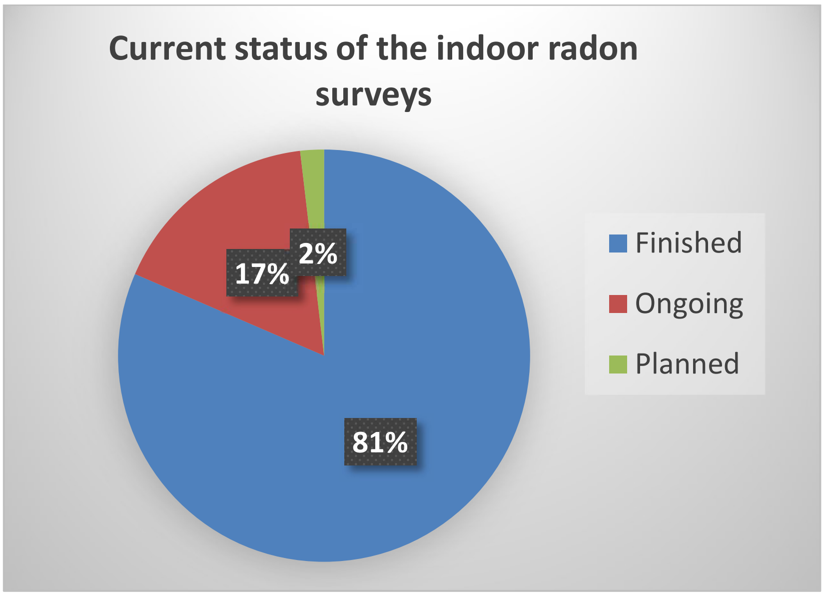
Most of respondents (about 65 %) performed from 2 to 5 surveys, with two important exception: the UK participant (UK_PHE) replied considering 20 surveys and the German participant (DE_BFS) 28 surveys. Notably, about half of the Institutions have reported to have carried out more than 5 surveys.

In three cases (BE_FANC, BE_ISIB and IT_ARPAP) respondents did not specify how many surveys they have performed. In some other cases participants gave generic answerers.

2.3 What is the current status of the indoor radon survey you are going to describe?

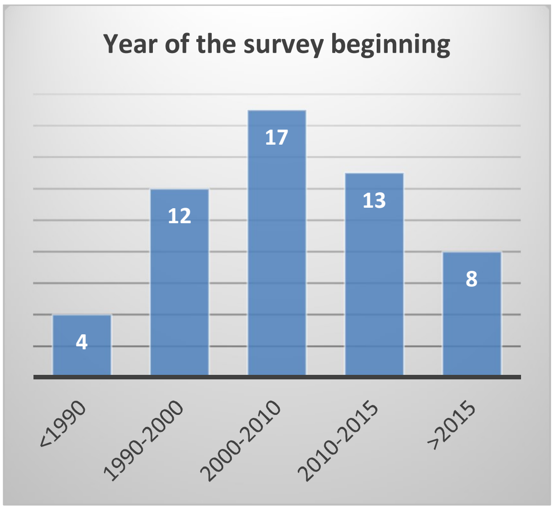
Up to mid-2018, most of the surveys (44) resulted to be finished (81% of them), whereas only 1 is planned and 9 (17 % of them) are still on-going (see graph below).

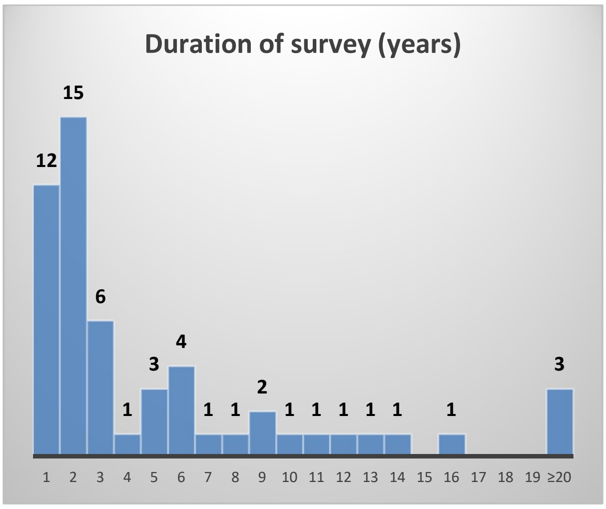
In three replies participants indicated multiple options: this is the case of Romania (RO_UBBCLUJ and RO_CNCAN) and Italy (IT_ARPAP).

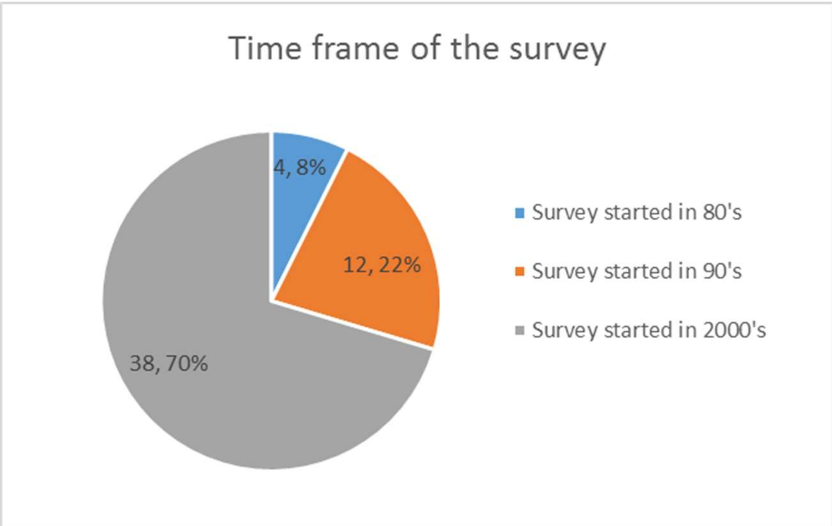


2.4 Please indicate the timeframe in which the survey has been performed

The time period of the surveys reported in the database is very wide. Few started at the end of the eighties, and the highest number between 2000 and 2010 (more than 30 % of them). Nine are still ongoing.





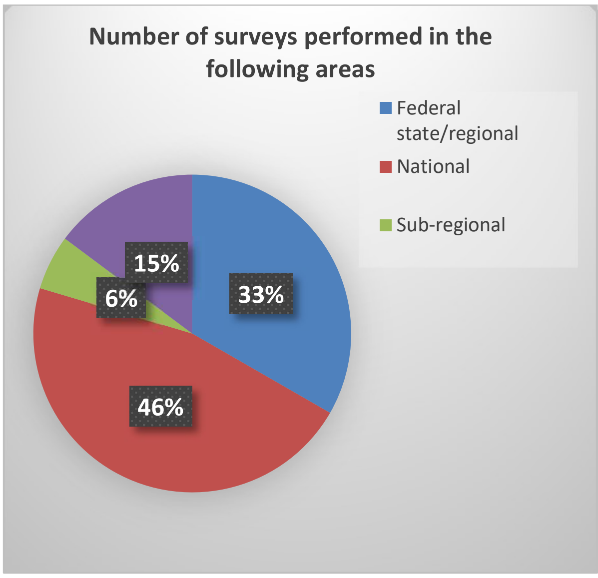


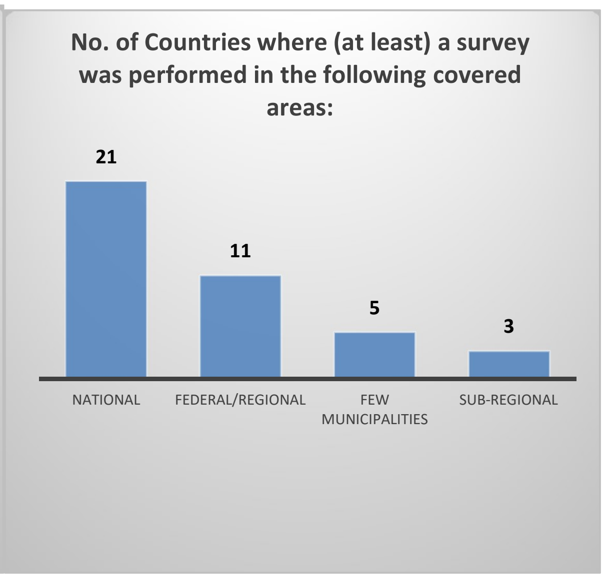
As reported on right graph above, most of the surveys had a duration lower than 5 years (50 % of them lower than 3 years) even if there are surveys with much longer duration (up to almost 30 years). However, these long-term surveys seem to be related to mapping of territory whose definition is generally carried out using results obtained by the means of surveys carried out over several years in order to cover all the areas (see details in Annex II).

Summarizing, the average duration considering all of surveys equals to 5 years (as arithmetic mean) and the median value is 2.

2.5 Please indicate the region covered by the survey:

Most of the surveys (46 % of them) have been indicated as nation-wide and federal/regional (33 %). However, it is worth noting that at least 1 national survey was performed in 21 Country (see graph below on the right).





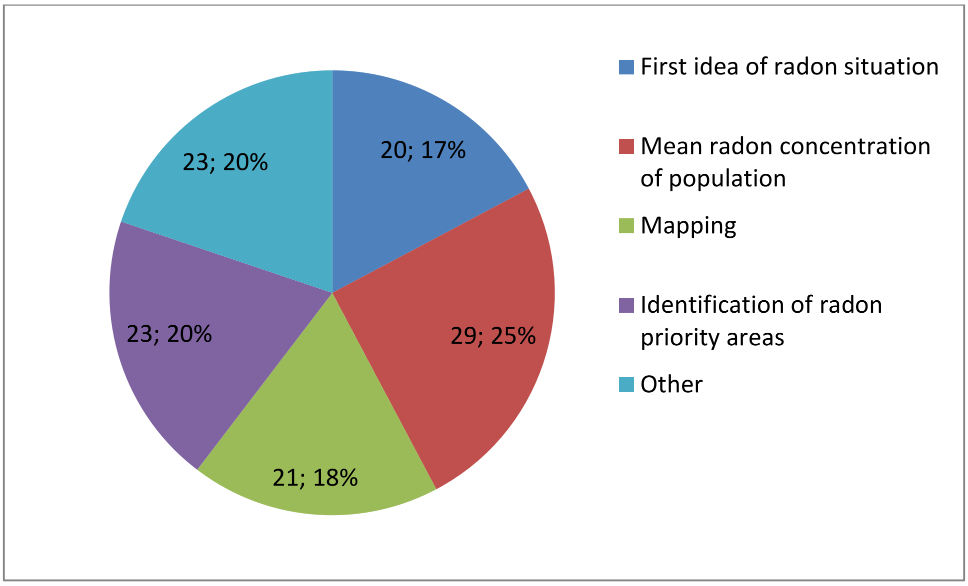
Regarding national surveys, for three Countries (Austria, Ireland, Italy) more than one national survey have been reported.

The category "Municipalities" includes cities and provinces.

2.6 Please select the main purpose of the survey:

Over 60 % of all the 54 surveys were reported to have more than one purpose.

Participants selected quite homogeneously all the proposed options: in particular, in the 25 % of answers the main purpose has been to evaluate the mean radon concentration of population, especially those performed nationwide (18 out of 25).



However, also the other purposes are considered for at least 20 surveys (about 40 % of them).

Among the *other* purposes, most are related to risk assessment of workers and limited target of the population (such as students or children in kindergartens), such as:

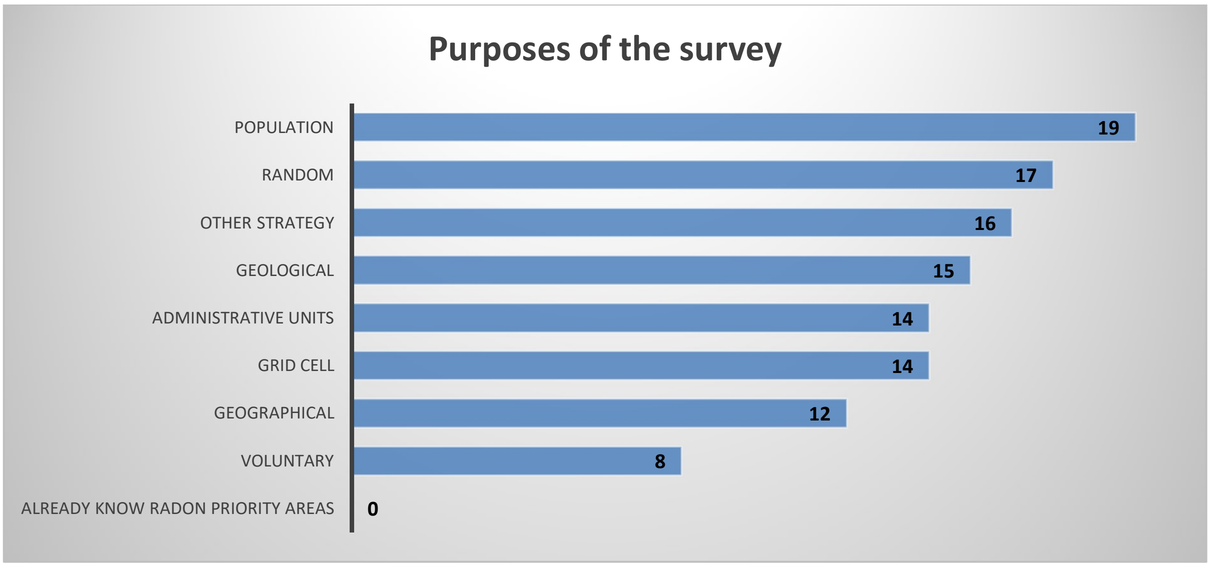
- surveys performed to evaluate the radon exposure of students in schools and kindergartens (this is in Austria, see AT_AGES3, AT_AGES3; in some Italian replies, see IT_INAIL, IT_APPATN3, IT_APPATN4, IT_APPATN5, IT_ARPAER);
- surveys to evaluate the radon exposure of workers (e.g. in Polonia underground tourist routes workers, see PL_IMP.LODZ2; in Italy caves workers, see IT_ARPAL2 and IT_ARPAL3; in Austria underground tourist mines and caves workers, see AT_AGES7; in Austria in administrative buildings, see AT_AGES3),
- surveys performed in all dwellings in 3 Austrian municipalities (see AT_AGES5, AT_AGES6);
- surveys performed to update national geographic weighted mean radon concentration (this is the case of Ireland, see IE_EPA3);
- surveys performed for legal obligations; protection of workers (this is the case of IT_ISPRA3).

More details are available in the Annex II.

2.7 Please select the main strategy on which the survey was based:

About the 50 % of the all 54 surveys were reported to have more than one strategy.

Most of the surveys were sampled in random and proportional way to population density. However, also other purposes have been distributed among the surveys (see graph below).

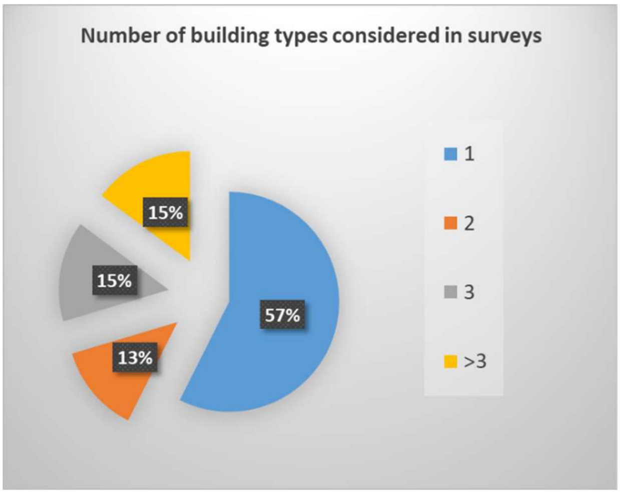


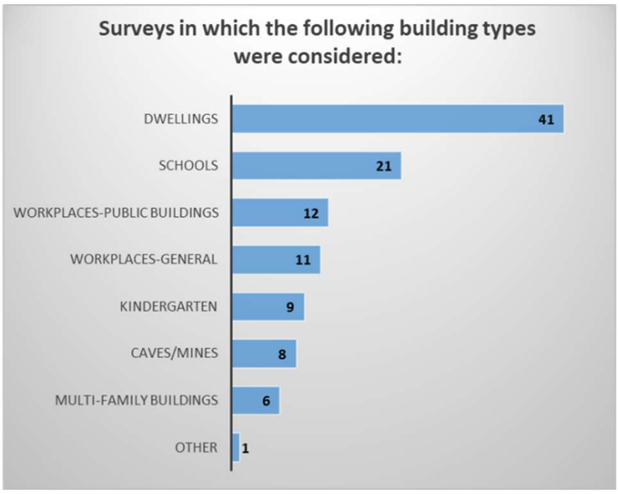
Regarding the nationwide surveys, about 50 % of them used a strategy based on population density, even if only 40 % of them reported to use random sampling.

Among the *other* strategies, most are related to systematic surveys in a specific type of buildings/locations (e.g., schools, caves).

2.8 Which building types have you considered in your survey?

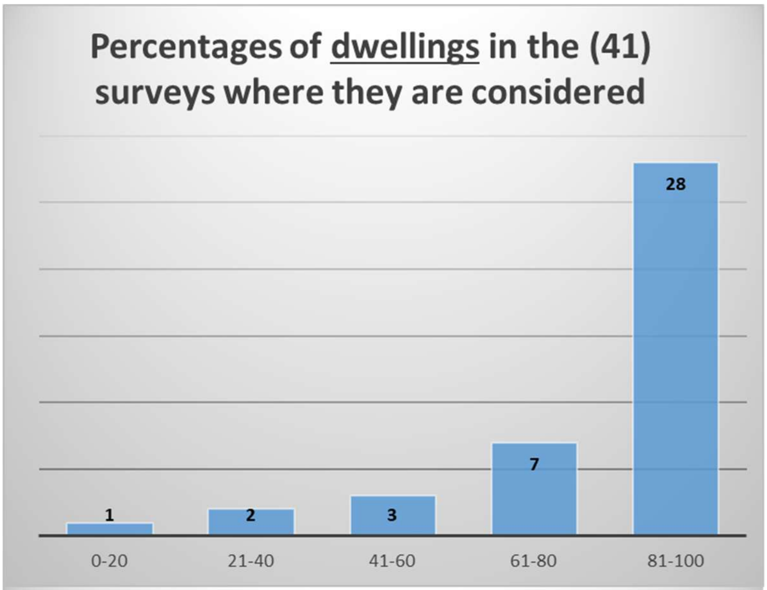
In almost 60 % of the surveys only one building type (mostly dwellings) are considered. Moreover, even for surveys with more than one building type considered, generally most of the measurements are performed in dwellings.

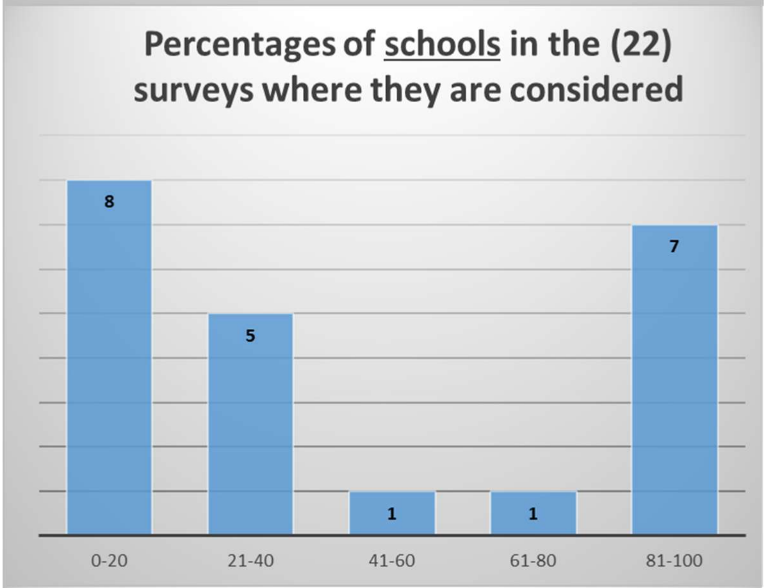


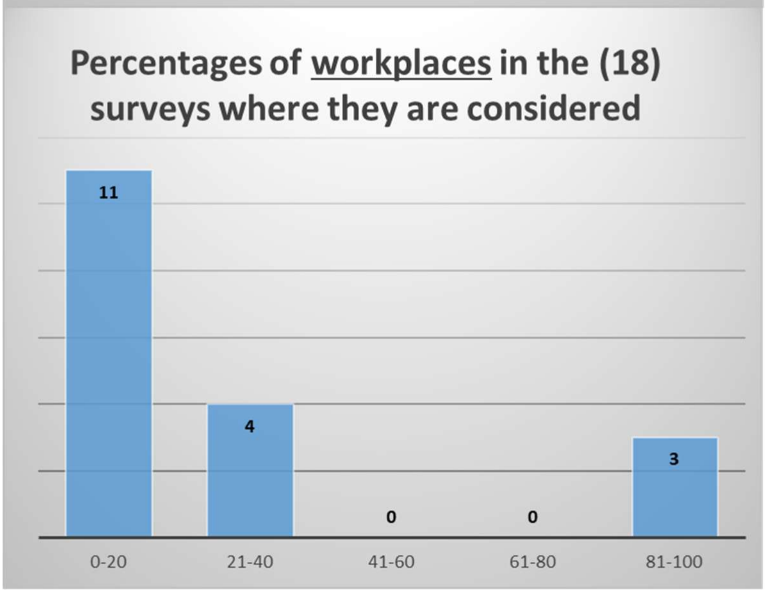


Notably, dwellings were considered in about 75 % of the surveys. However, also schools (including kindergarten) and workplaces are often considered in surveys (see right graph above).

In the graph below, the percentage of building types, for the surveys where they are considered, are reported for both dwellings, schools (including kindergartens) and workplaces. It is well recognized that in surveys where more than one building type, most of them are dwellings.


Percentages of dwellings in the (41) surveys where they are considered
28
7
1
2
3
0-20
21-40
41-60
61-80
81-100

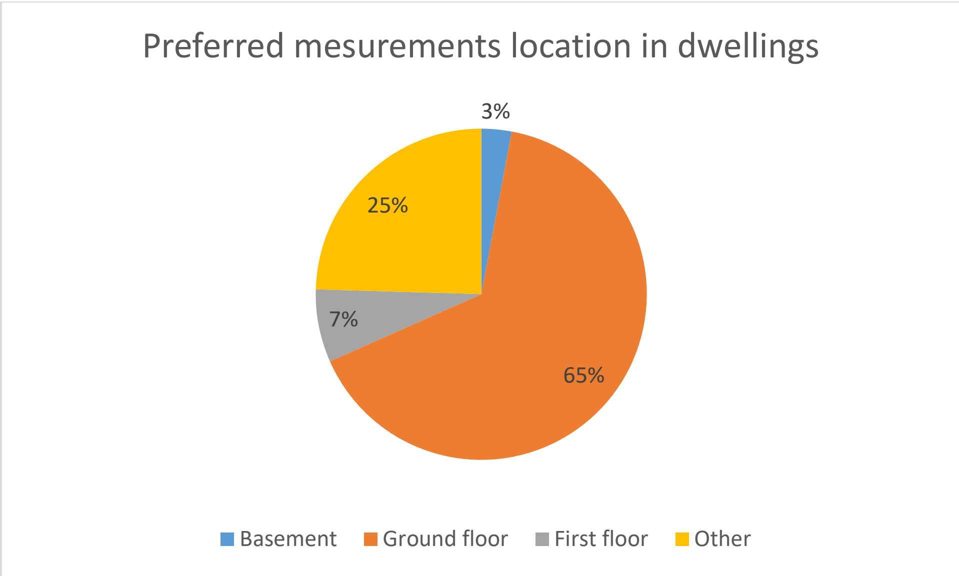

Percentages of schools in the (22) surveys where they are considered
8
7
5
1
1
0-20
21-40
41-60
61-80
81-100


Percentages of workplaces in the (18) surveys where they are considered
11
4
3
0
0
0-20
21-40
41-60
61-80
81-100

2.9 Have you chosen a preferred measurement location in dwellings?

Among the 37 surveys for which more than 50 % of dwellings were chosen as building type, only 22 % of them (8) have a single preferred measurement location in dwellings, which is generally the ground floor.

The others surveys are generally performed in rooms located at different floors.



The present analysis does not consider replies in which respondents gave answer not considering only the surveys performed in dwellings. Moreover, in 9 replies the preferred location in dwellings was not reported. So, only 29 replies were analysed: in this subset, about the 65 % of radon measurements was done in rooms located at ground floor and the 25 % to a level different from basement, first and ground floors.

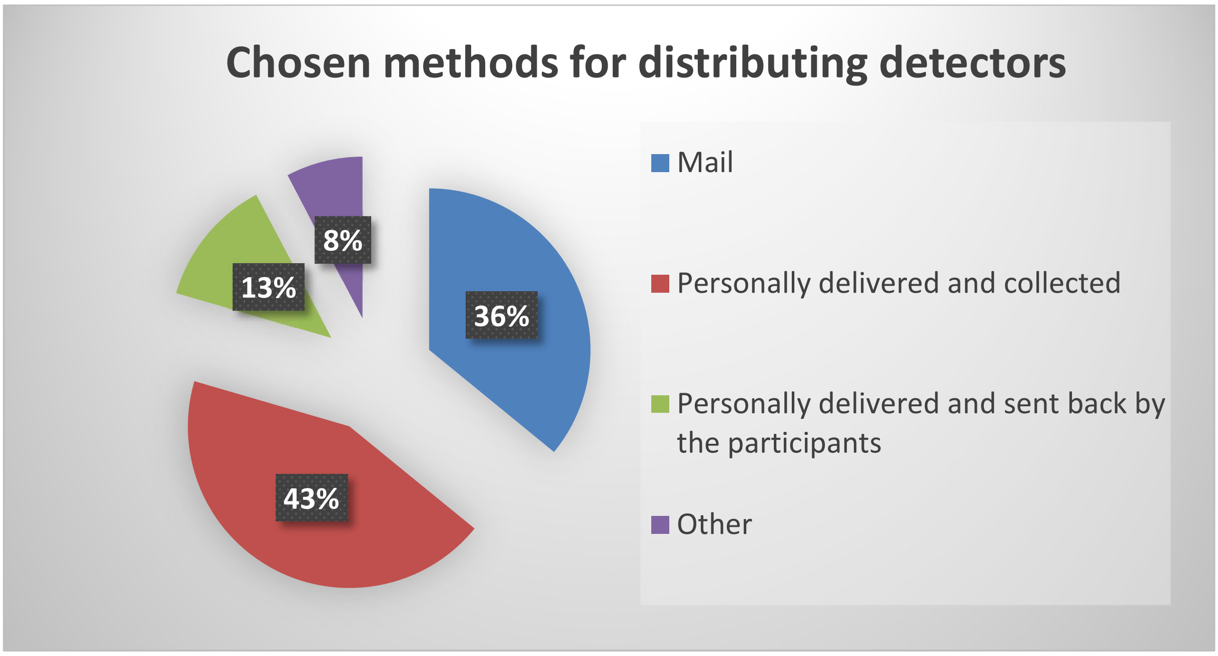
2.10 Please select which method you chose for distributing the detectors:

For 39 surveys a single method to distributing detectors was chosen.

For these surveys, the methods more frequently used to distribute detectors were: by mail and personally delivered and collected. In few cases, detectors were delivered and collected by a personnel of another organization, different from those that directly organize the survey.

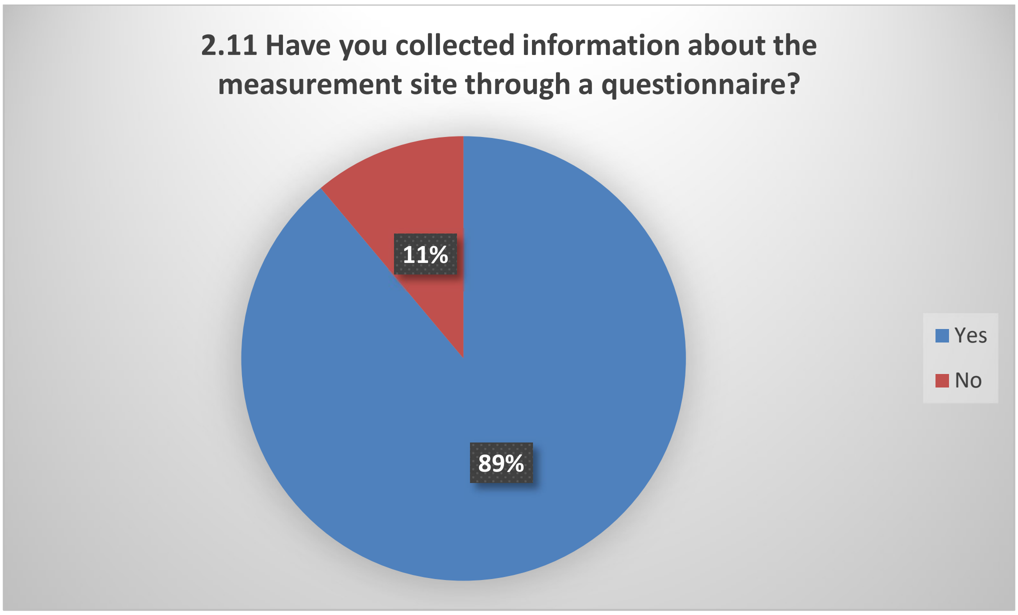
Arbitrarily, 53 respondents gave multiple answers and 2 participants did not provide any answer. Analysing data, the more preferred method for the distribution of detectors has been the personally delivering (35 %); for the return, usually it was used the same method, but in other cases it was asked to participants to send back by post (25 %). Detectors' delivery and return by mail was used in the 30 % of cases.

Moreover, 4 respondents (corresponding to the 6 %) reported they ignored the method for distributing detectors and in other 3 cases (IT_ARPAL1, IT_ARPALOMBARDIA2, IT_ISPRA1) detectors' distribution and collection of were made by a public health organization.

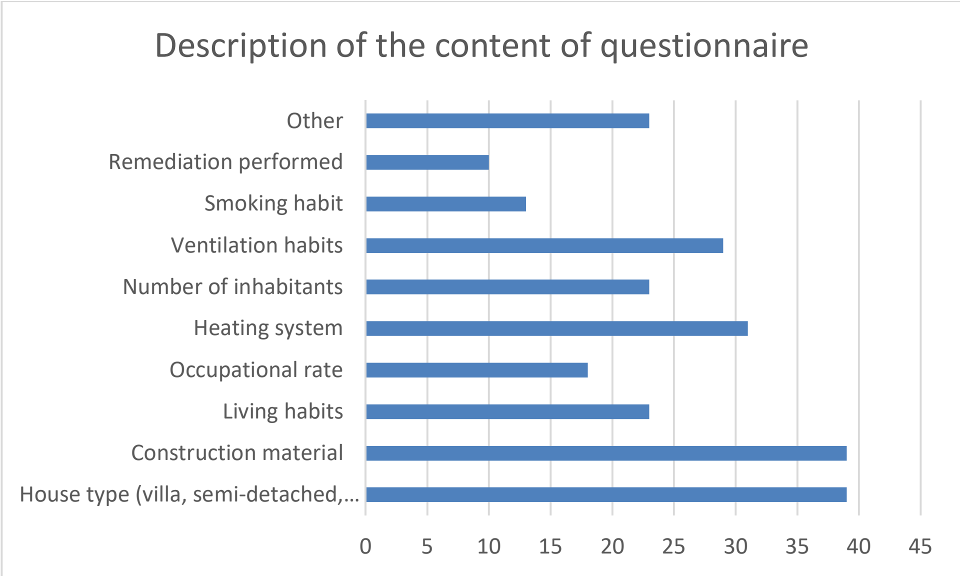


2.11 Have you collected information about the measurement site through a questionnaire?

Questionnaire have been prepared, distributed and collected for 48 surveys out of 54, i.e. in about 90 % of the surveys.



2.12 Please indicate which kind of information you have asked for the questionnaire



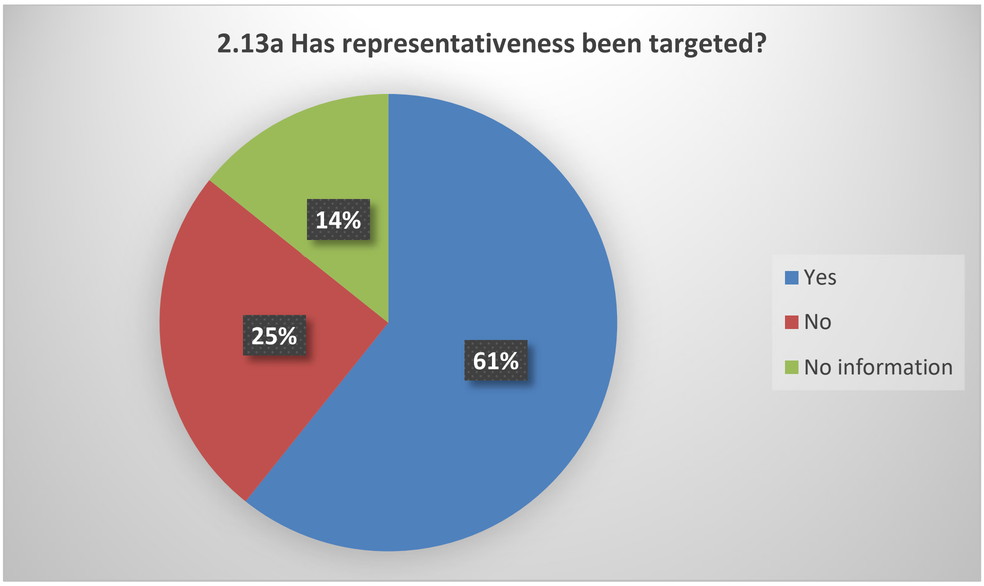
Six participants did not answer to this question. Information about the house type and building materials are more frequently collected, followed by information about the heating system and ventilation habits.

The category "other" (corresponding to the 9 % of options) consider interesting information such as year of construction of the building, information on floor-soil contact, number of floors, remediation performed, occupational rate, etc.

2.13 Representativeness:

Some information about if the survey is representative and if the target quantity calculated from the data is an unbiased estimate of the targeted true value of that statistic, has been reported for 48 surveys.

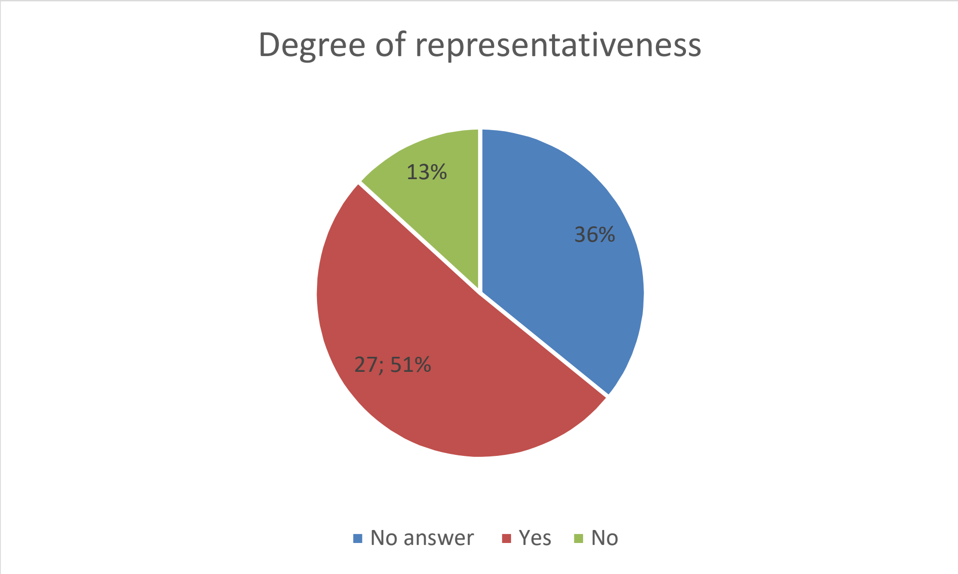
2.13a Has representativeness been targeted?



In 34 survey reported through the questionnaire the representativeness of the data has been targeted.

2.13b Has representativeness been targeted?

Among the 34 surveys that had representativeness as a target, 27 have achieved it to what is declared “a sufficient degree”. 8 survey didn’t achieved representativeness.



The 36 % of replies did not answer the question, the 51 % surveys seem to achieve a sufficient degree of representativeness and the 13 % not.

Taking into account for both the analysis results of 2.13a and 2.13b, overall results are controversial. So, it is evident that representativeness of surveys is an complex matter.

2.13c How has representativeness been assessed?

A description of how the representiveness has been assessed has been reported by the institutions for about 20 surveys. Their answers are reported in the Annex II.

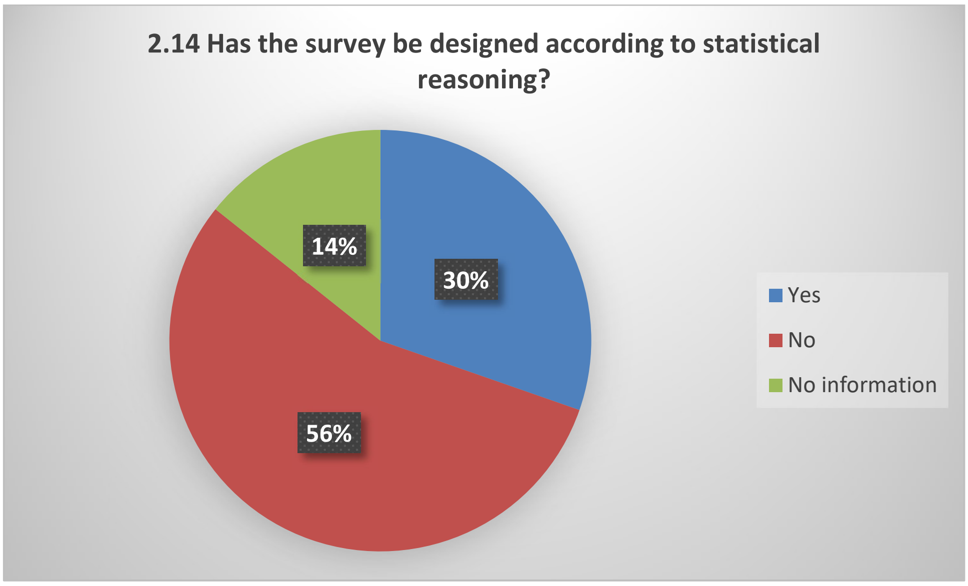
2.13d If assessed as not representative: which type or source of bias is believed to be present?

Only 7 replies have bee provided, they are reported in Annex II.

2.13e If representativeness was not achieved: any corrections or models applied to guarantee unbiased estimated over estimation support?

Only 10 replies have bee provided, and 4 of 10 are none. The complete answers are reported in Annex II.

2.14 Has the survey be designed according to statistical reasoning?



Survey has been designed according to statistical reasoning in 17 cases reported through the questionnaire.

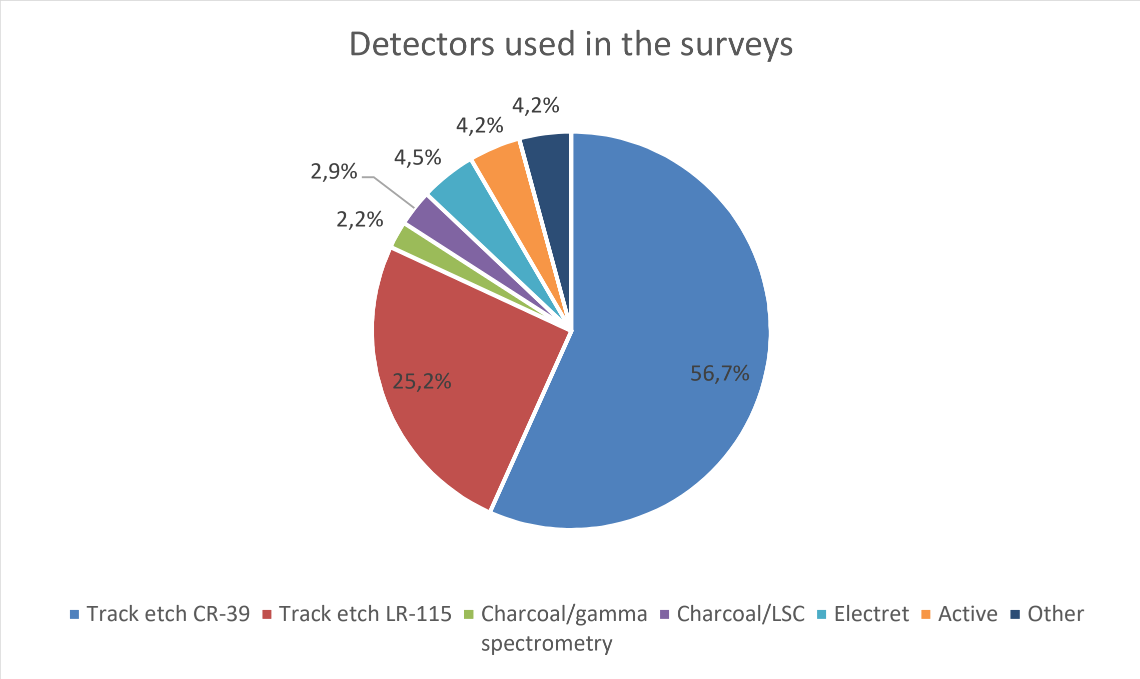
2.15 If YES in 0, please describe the estimation support and target quantity for the survey:

- 2.15a Estimation support
- 2.15b Target quantity (arithmetic mean, geometrical mean, % above reference level, etc.)
- 2.15c Target uncertainty score
- 2.16d Mean achieved uncertainty
- 2.17e Specifications

Detailed replies are reported in Annex II.

3. Section 3: Measurements methods

3.1 Which kind of detector have you used? Please indicate the percentage and the duration of the measurements:



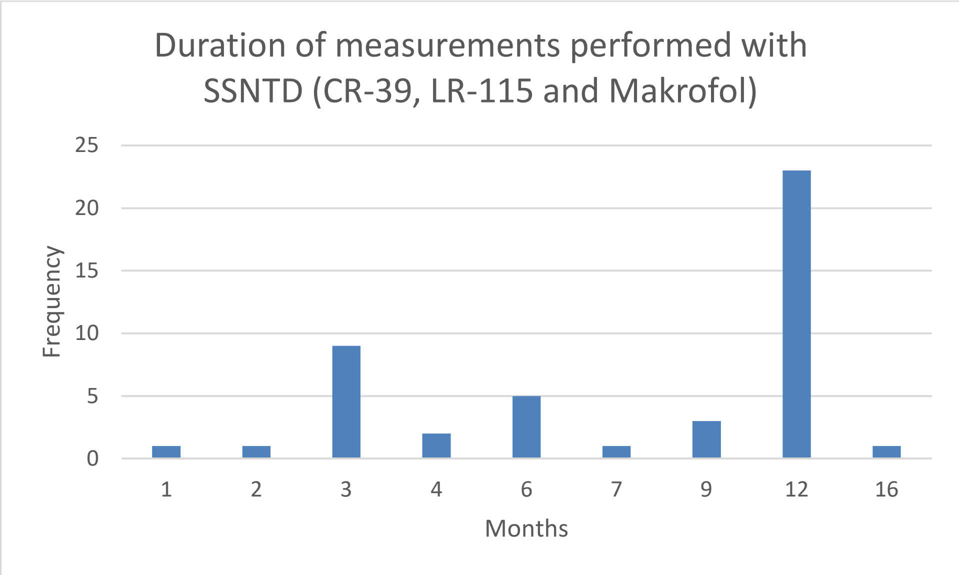
The 37 replies (68.5 %) described surveys using only one measurement method. Conversely, up to three different methods were used in the same survey (e.g. see AT_AGES1).

Most of the respondents used solid-state nuclear track detector - SSNTD (more than 82 %). In particular, the detector most frequently used was CR-39 (56.7 %).

In case of using LR-115 as detector, only few respondent specify if the detector used was open or closed. In 6 cases, respondents did not answer clearly about the different measurements methods distribution (percentage).

3.1a SSNTD

51 respondents gave information regarding the duration of the measurements. The duration of the measurements performed with all kind of SSNTD lasted from 1 up to 16 months. Half of the respondent performed measurements for 12 months and in 7 out of 23 split the 1 year in two semesters.

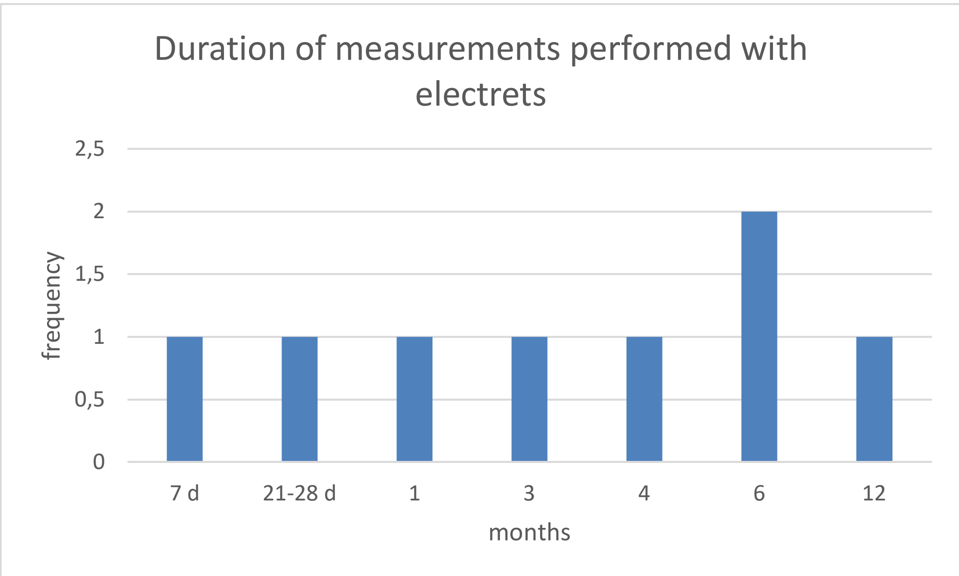


3.1b Charcoal (with LSC or Gamma spectrometry)

4 surveys were performed with charcoal detectors, respectively two together with LSC and 2 with Gamma spectrometry. The duration for measurements ranged from 2 to 4 days. None of these surveys were performed only with charcoal: in two cases (AT_AGES1 and AT_AGES3) they were used together with electrets while for BE_ISIB and RS_DF.UNS, SSNTD were used.

3.1c Electrets

8 surveys were performed with electrets. Only the Lithuanian survey (LT_RPC) performed all the measurements with electrets.



3.1d Active

4 surveys were performed with active monitors. Only one survey used active monitors together with other measurements methods (AT_AGES3) nor providing any information about the duration of the measurements for any devices.

The other 3 measurements lasted 6 (3+3), 9 and 12 (6+6) months.

In Romania active instruments were used for the diagnostic measurements and the testing of the remedial efficiency (between and after mitigation).

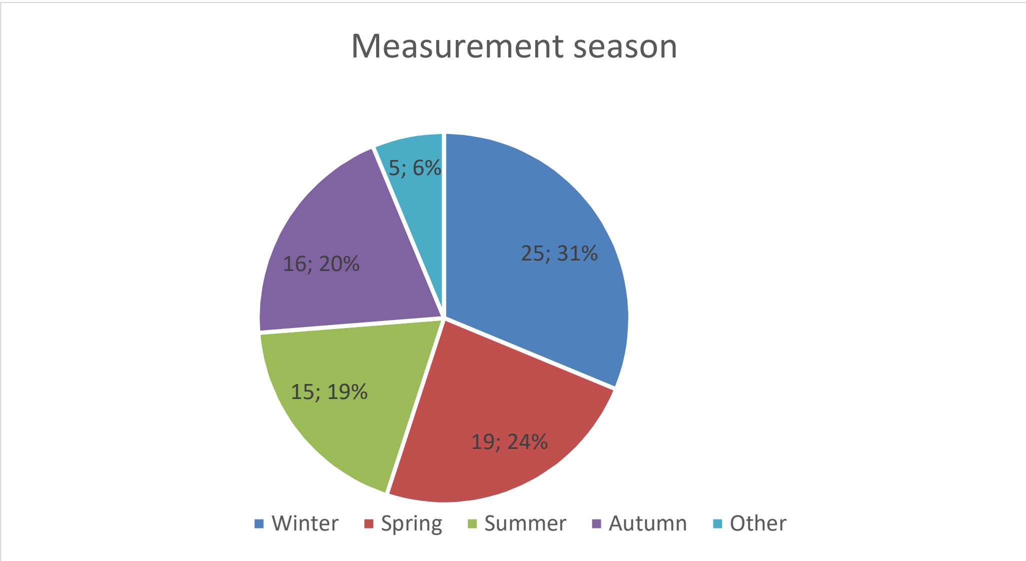
3.1e Other

In this category respondents include measurements performed with passive dosimeters having Makrofol as plastic detector. The analysis of these data were described in paragraph 3.1a.

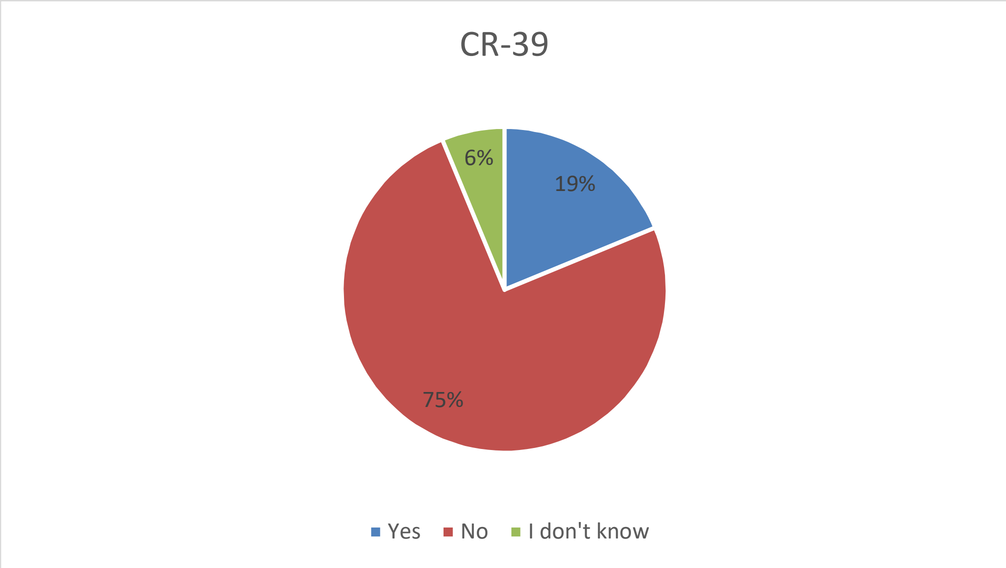
3.2a If applicable, please indicate the season in which the measurements have been performed (multiple seasons are allowed):

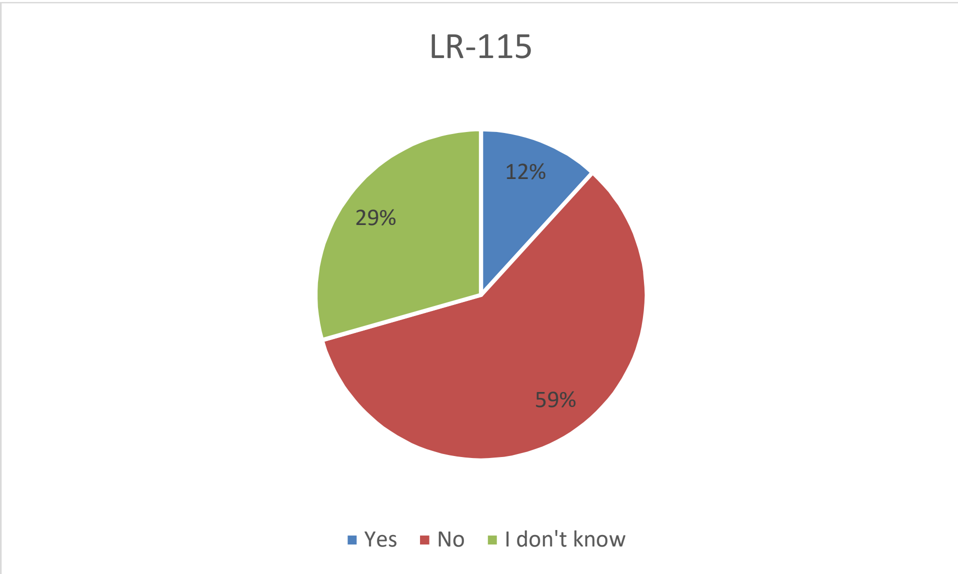
44 % of respondent performed one solar year measurements. In the other cases, measurements were performed mostly during the winter but often covered more than one season.

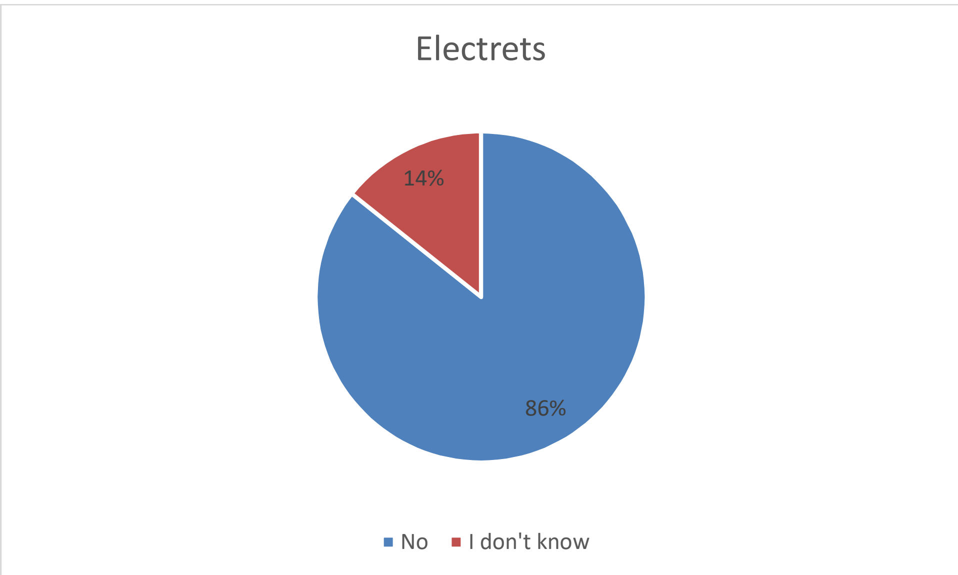
Sometimes seasonal correction factor was applied in order to estimate an annual average radon concentration (IE_EPA2, IE_EPA3).

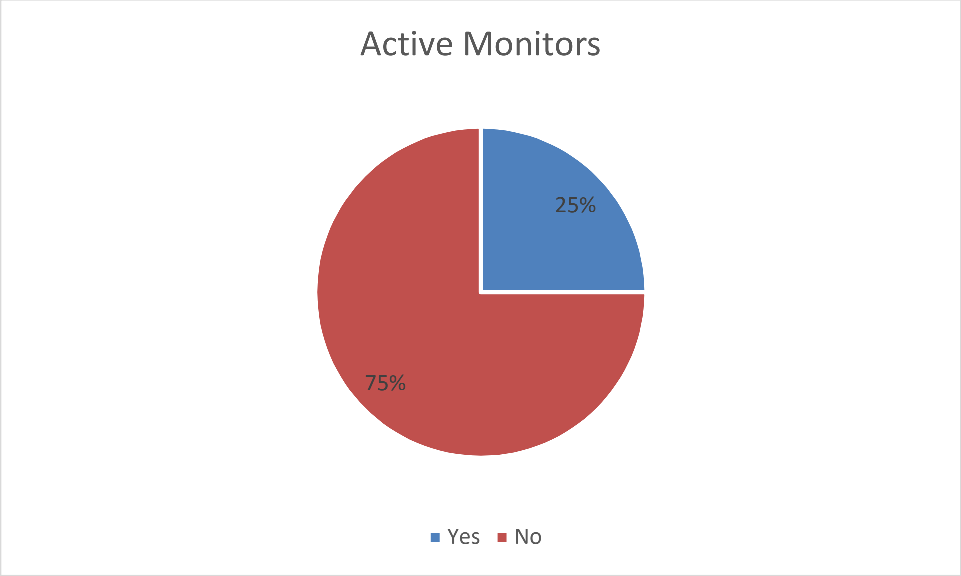


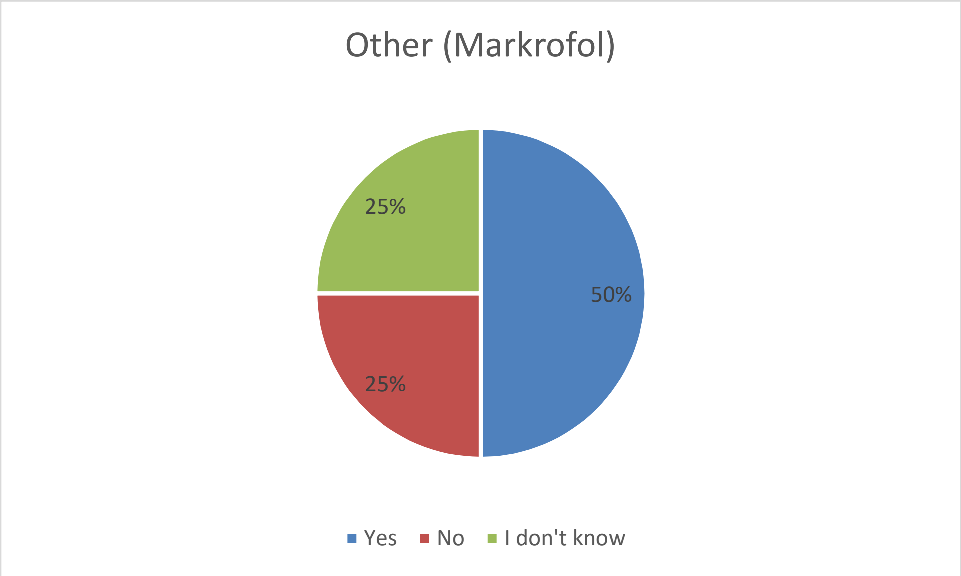
3.4 Are the detectors you used sensitive to thoron?











The answers were analysed and plotted based on the detectors. In case of CR-39, respondents seem to know well the features of the used methods: only the 6 % did not answered about the sensitivity to thoron of their devices. Moreover, the 19 % the answers were positive.

For LR-115, the percentage of "I do not know" increases up to 29 % and for electrets, the 86 % of replies reported the electrets are not sensitive to thoron and the 14 did not give an answer.

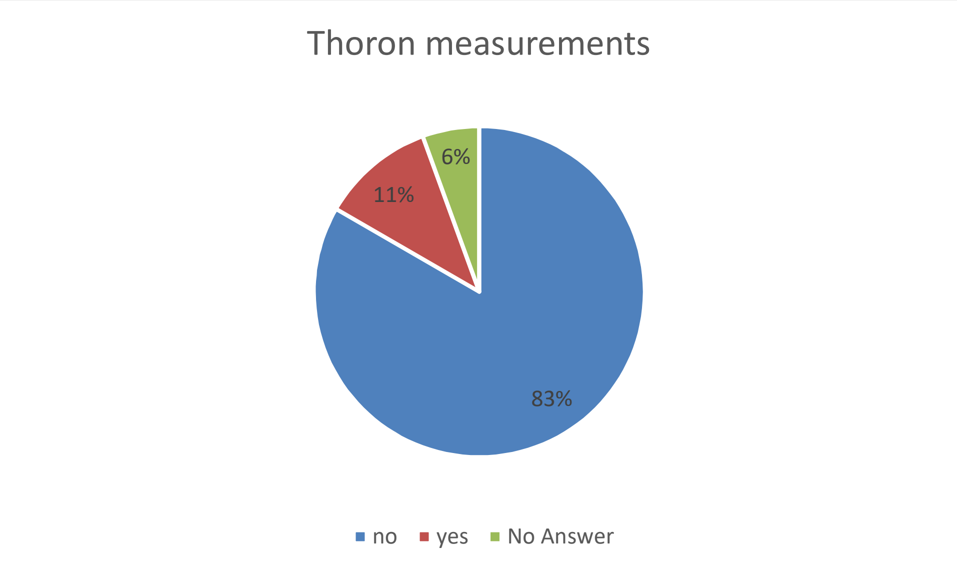
3.5 If YES in 3.4 please indicate if and how this has been corrected

Totally 12 respondents said that the used measurement methods were affected by thoron. Only one of them did not provide any answer about the correction.

Most of the participant (45 %) although knew the interference of thoron did not correct the measurement. For the 27 % of replies, usually the detectors are placed far from the walls in order to avoid the thoron interference.

3.6 Has thoron been measured?

In most of the survey thoron has not been evaluated (83 %), only in 6 cases also the measurement of thoron were carried out.



3.7 If YES in 3.6 please indicate the detector-methodology

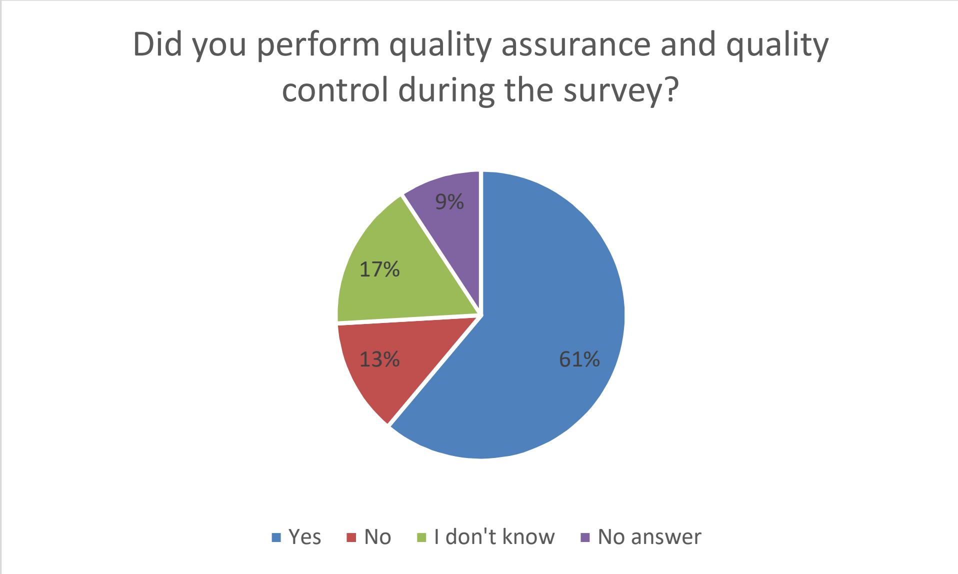
To measure the thoron activity concentration, 2 of 6 respondents (RO_UBBCLUJ and AT_AGES5) used RADUET Type detector: this detector type is designed to detect of radon and thoron activity at the same time. It consists of two detectors – a standard RSF type detector and a modified version, the latter with reduced response time. The main chamber is selective for the radon activity primarily. But the secondary chamber is sensitive for both radon and thoron. A simple linear calculation separates the radon and thoron activity data results.

1 respondent used electrets (IT_ARPAP), 2 used active monitors (IT_ARPAVDA and AT_AGES7) and 1 (NE_RIVM) passive dosimeter suitable for thoron and thoron progeny.

3.8 If YES in 3.6, please indicate how far the detector was positioned from thoron exhaling surfaces:

Only 4 of 6 respondents specify the distance of the detector from the wall. Detectors were positioned from very close to the wall (1 cm, NE_RIVM) up to 50 cm (RO_UBBCLUJ with RADUET detector)

3.9 Did you perform quality assurance and quality control during the survey?



In the 61 % of replies, respondents performed quality assurance and quality control during the survey, in the 13 % they did not. It is worth to note that in an important percentage (28 %) of replies there are no answers or "I don't know".

3.10 If YES in 3.9 please indicate how you did.

34 respondents declare that in the described survey they have performed some kind of quality assurance/control. Everyone specify how the quality of the measurements were guarantee (see Annex for details).

Many participants reported their participation to international radon intercomparisons and the calibrations of instrumentation at metrological institutes. Others refereed to internal procedure or internal QA Systems. In few cases, repeatability tests were carried out during the survey.

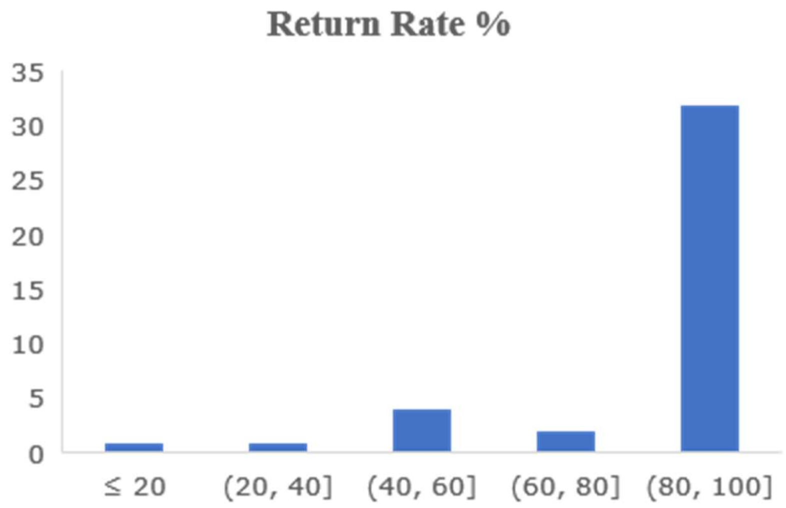
3.11 Please indicate the calibration period of the instruments.

In about 50 % of replies there is no answer. 28 respondents reported to carry out calibration in most of the cases with annually. In case of FI_STUK, recalibration are done only if the reference films deviate statistically significantly from the expected value (i.e. constant calibration checks).

4. Section 4: Data management, statistical treatment, aggregate and mapping

This section describe how the data have been treated after their collection, i.e. their management, their statistical treatment. Moreover general information on the surveys have been reported.

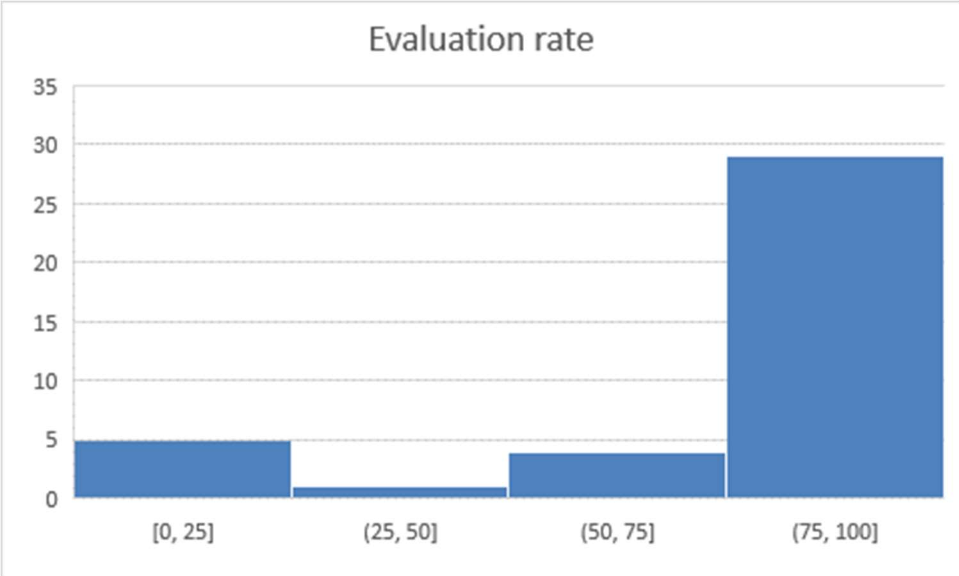
4.1 Please indicate the return rate (return rate = fraction of deployed detectors which could be collected):



The replies have been collected from more than 70 % of the surveys.

The return rates are higher that 80 % in more than 80 % of the surveys.

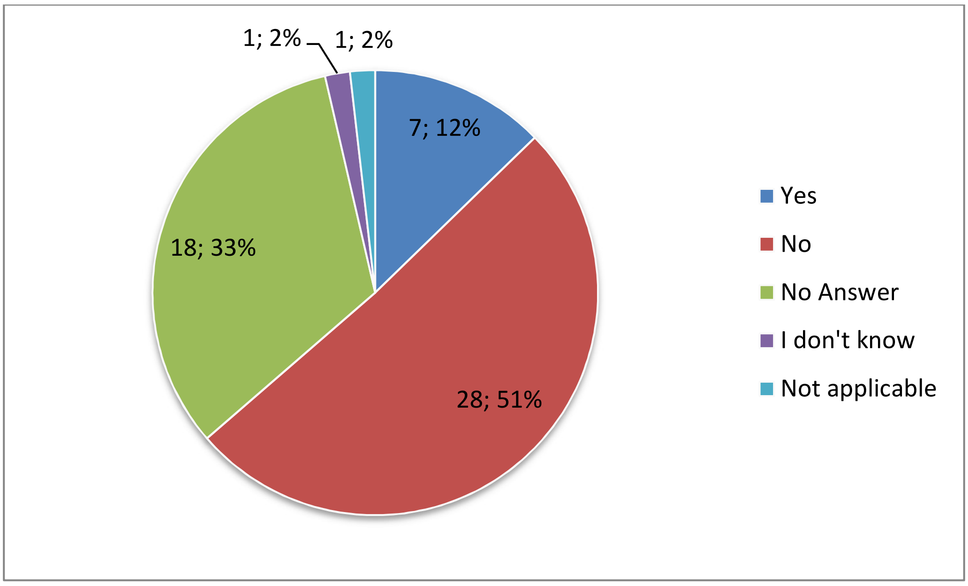
4.2 Please indicate the evaluated rate (evaluated rate = fraction of deployed detectors which could be evaluated and have plausible results. E.g., detectors which were returned but obviously not exposed or damaged etc., are excluded):



The replies have been collected from more than 70 % of the surveys.

The return rates are higher that 75 % in more than 70 % of the surveys.

4.3 The result has been corrected for lost detector? If so, how?

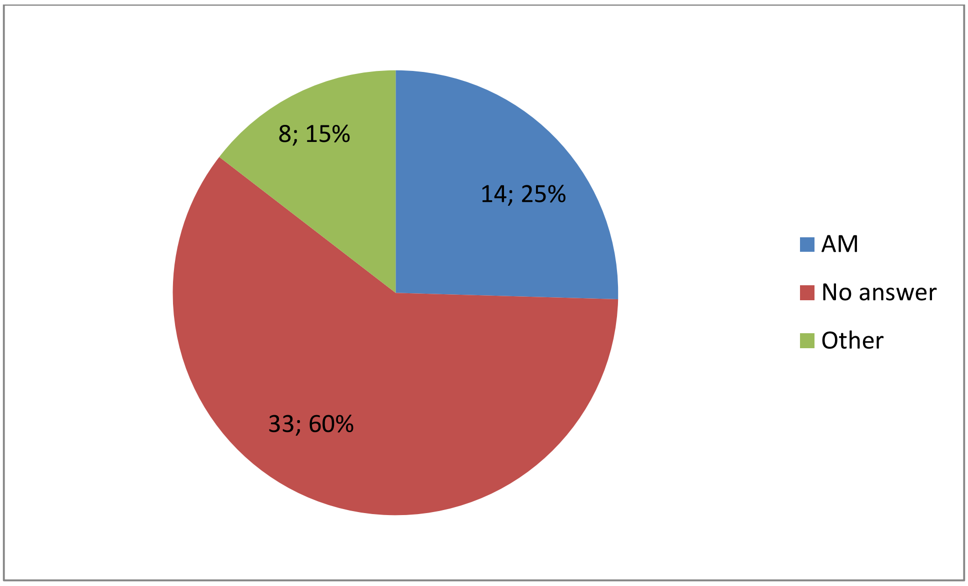


The results have been corrected for lost detector only in 7 surveys (12 %), more than 80 % replied no or they did not provided any answer. Below are reported some some answers given on how the results have been corrected, the detailed replies are reported in Appedix II:

- Results with lost detectors have been excluded from the data analysis
- They have been removed
- the annual measures are divided into 2 periods of about 6 months. If the detector of one period is lost, the concentration of that period is estimated from the other detector applying a calculated seasonal factor.
- always parallel use of two detectors for measurement in dwelling

- If one of the two detectors were missing the missing value was estimated using the value from the not missing detector multiplied with a typical difference between bedrooms and living rooms
- we had 2 type of detectors, if one was damaged we could use the second one. we left some detectors in 3-4 rooms of the dwelling, in case of loss one of the detector, we had no problem to estimate an average radon concentration for dwelling.

4.4 If you have performed parallel measurements at the same location-measurement point (see 3.3), please specify which value has been chosen to be representative of this point (arithmetic mean, geometrical mean, maximum, etc.)?

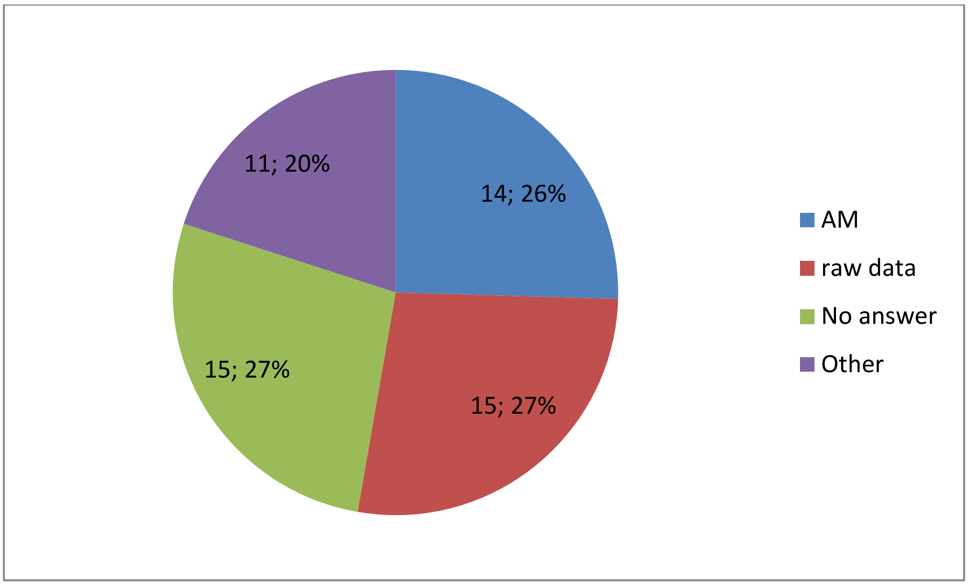


AM= arithmetic mean

The majority (60 %) have not given any answer. Beetween the replies more than 60 % use the arithmetic mean.

In other: Weighted mean, geometrical mean etc. (see Annex II).

4.5 If you have performed more than one measurement at the same dwelling/house/building, please specify which value has been chosen to be reported in your database (raw data, arithmetic mean, geometrical mean, maximum, etc.)?



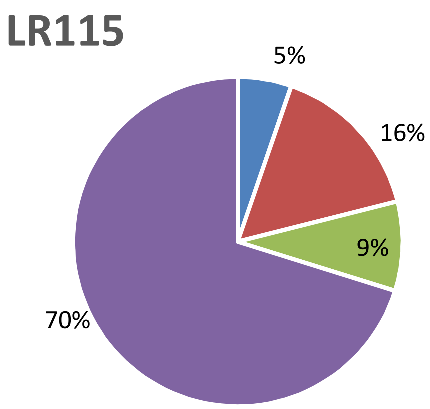
AM= arithmetic mean

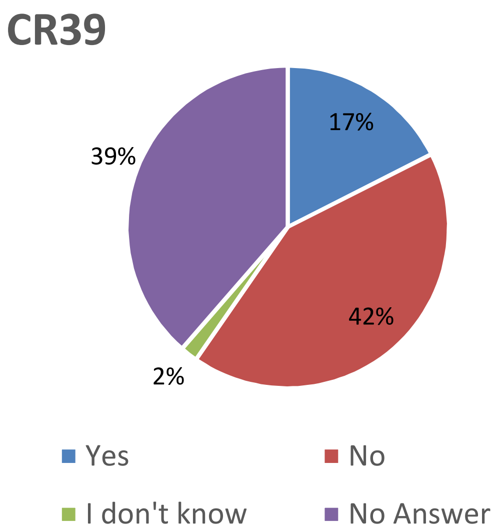
It seems that the replies have been equally distributed between AM, raw data, no answer and other.

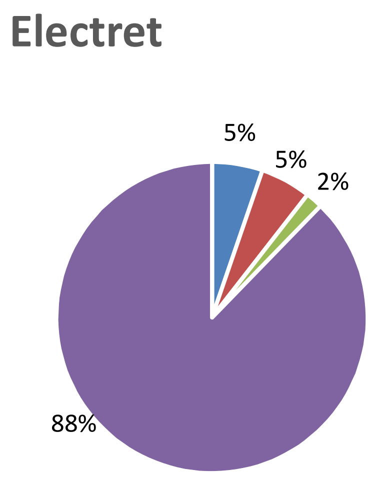
In other:

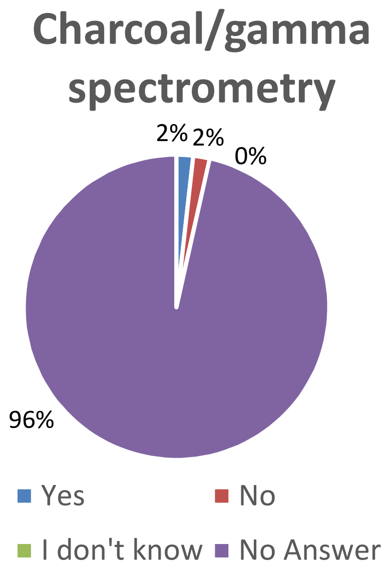
- highest ground floor data
- A house average based on occupancy factors for the two rooms measured - no seasonal correction was required as measurements for 1 year were collected
- Geometrical mean

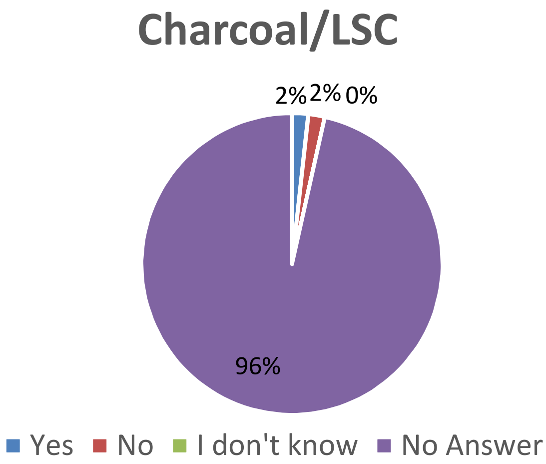
4.6a Have you applied seasonal correction?:

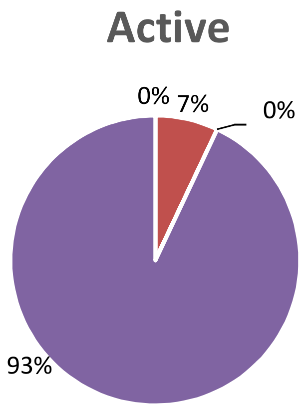


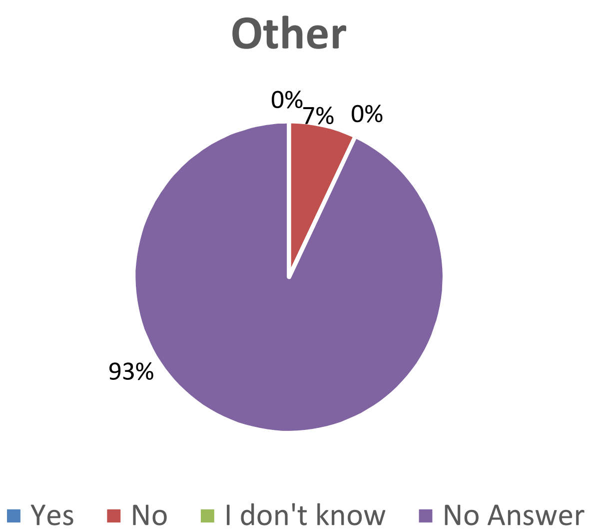



Electret
5%
5%
2%
88%

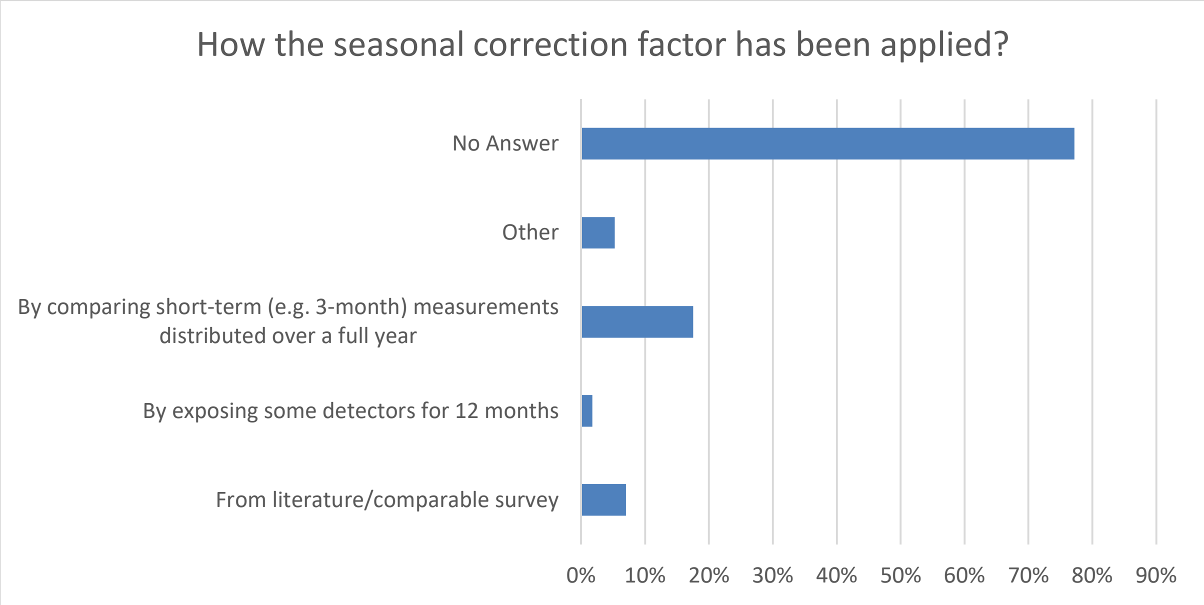

Charcoal/gamma spectrometry
2%
2%
0%
96%
Yes
No
I don't know
No Answer


Charcoal/LSC
2%
2%
0%
96%
Yes
No
I don't know
No Answer

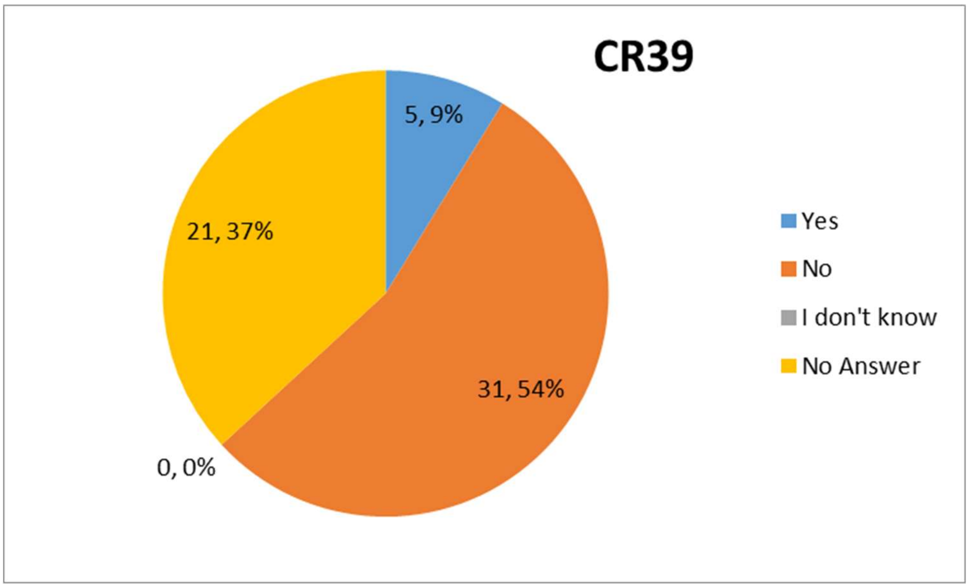

Active
0%
7%
0%
93%

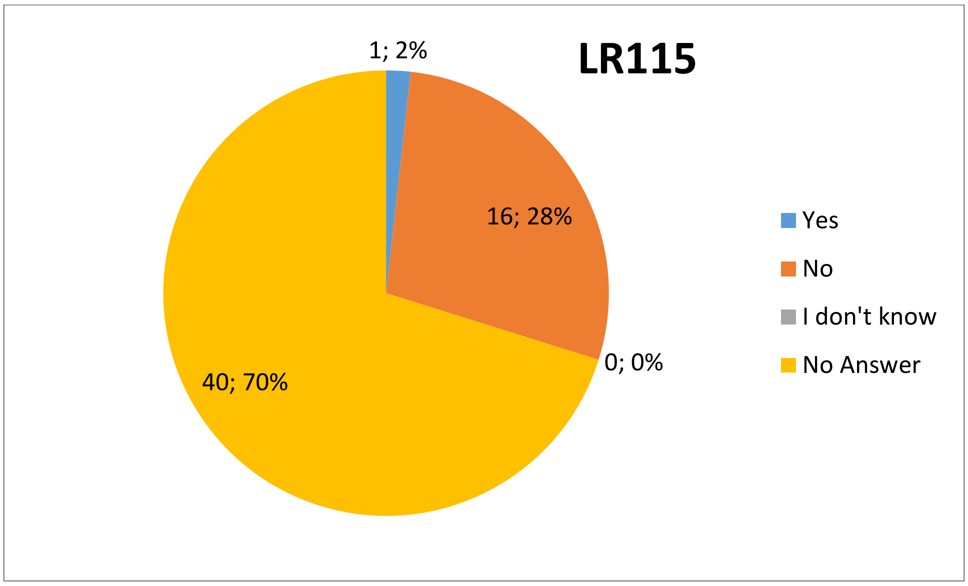

Other
0%
7%
0%
93%
Yes
No
I don't know
No Answer

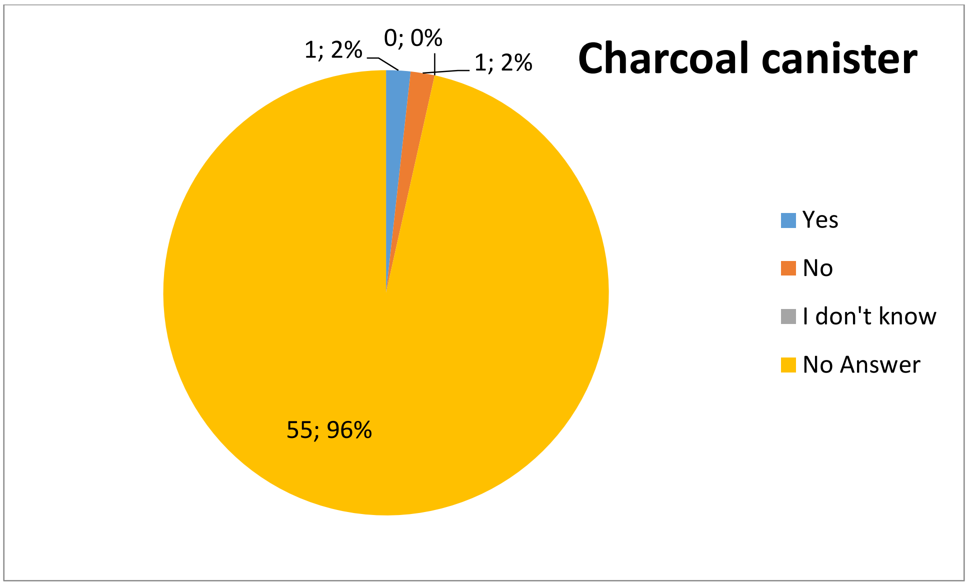
4.6b If YES in 4.6a, how was the seasonal correction factor obtained:

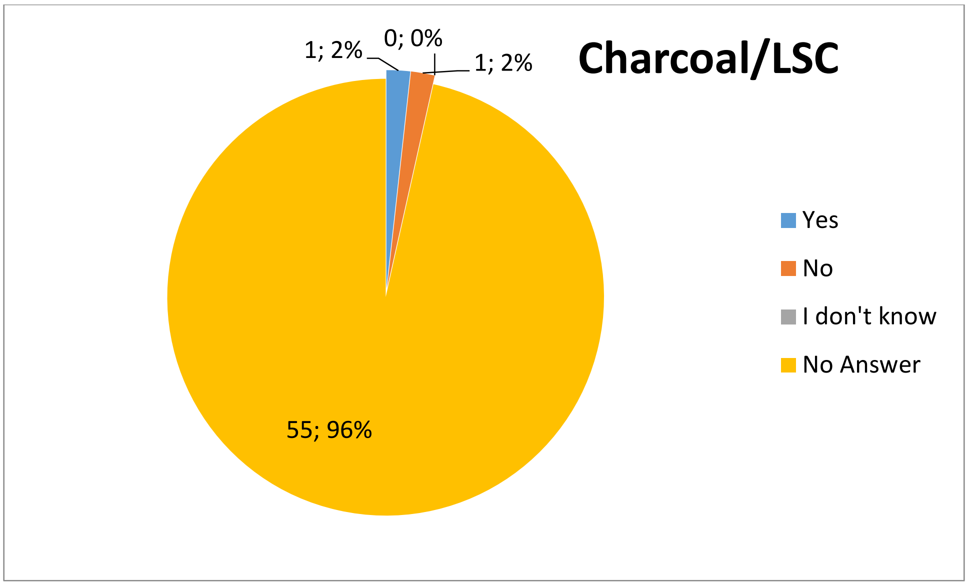


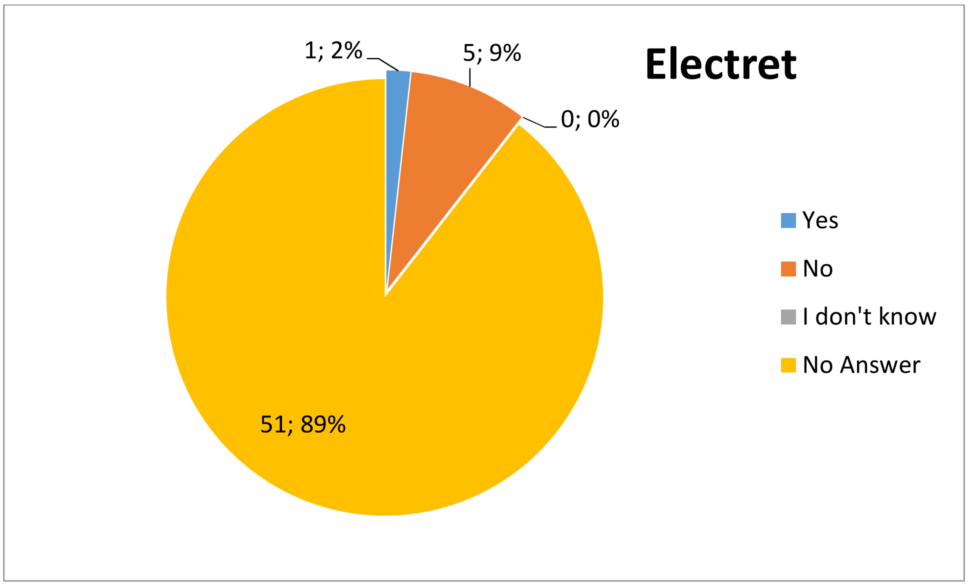
4.7 Have you applied any correction linked to building characteristics, in particular floor level?:



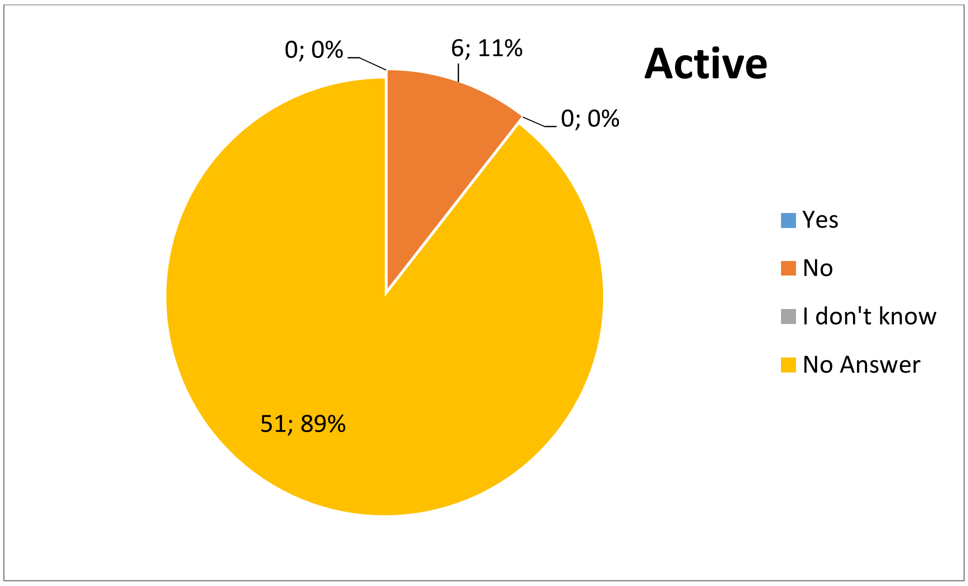

LR115
1; 2%
16; 28%
0; 0%
40; 70%
Yes
No
I don't know
No Answer


Charcoal canister
1; 2%
0; 0%
1; 2%
55; 96%
Yes
No
I don't know
No Answer

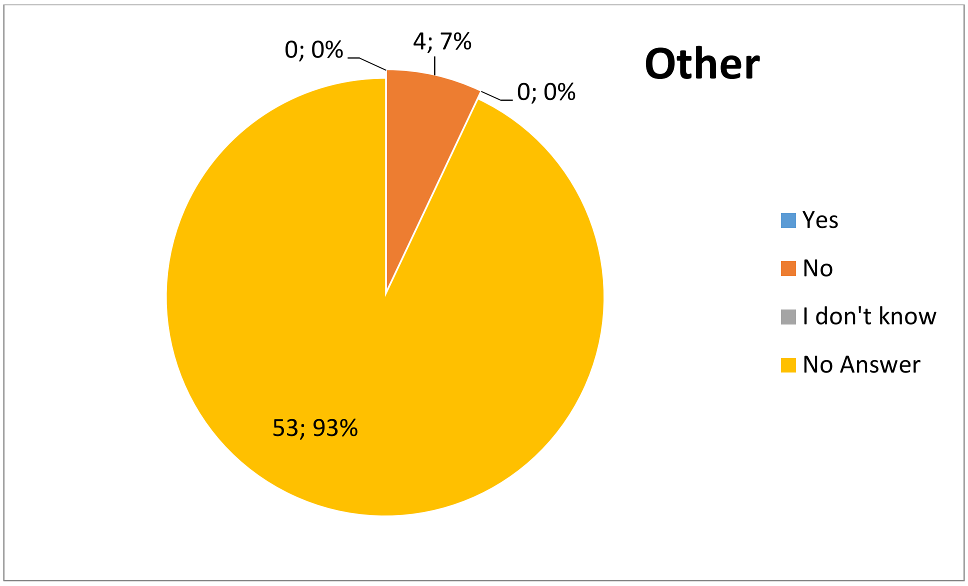

Charcoal/LSC
1; 2%
0; 0%
1; 2%
55; 96%
Yes
No
I don't know
No Answer



Electret
1; 2%
5; 9%
0; 0%
51; 89%
Yes
No
I don't know
No Answer



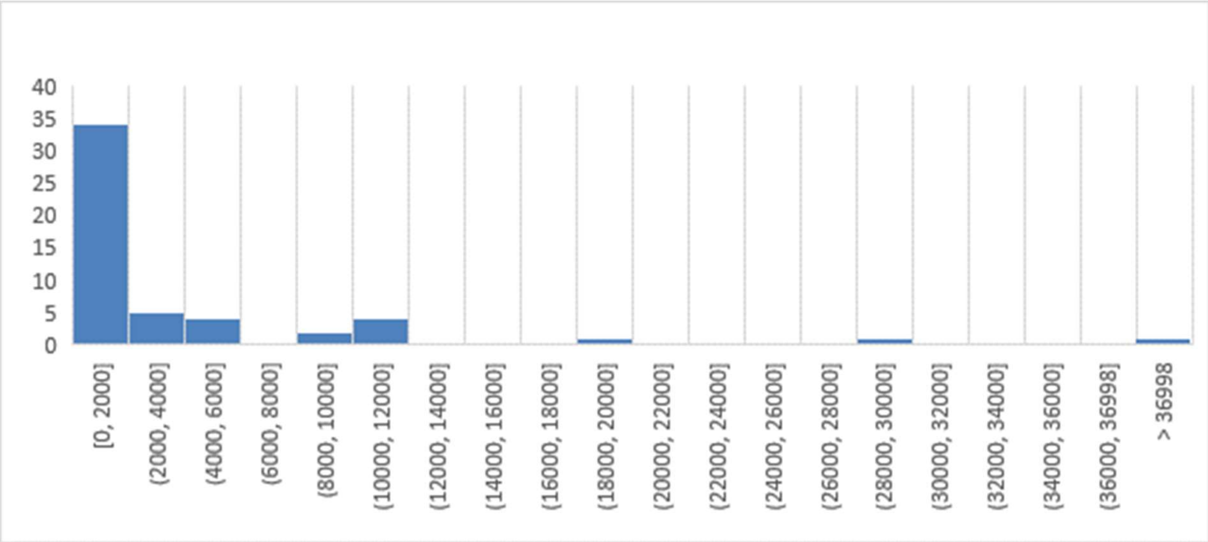
Active
0; 0%
6; 11%
0; 0%
51; 89%
Yes
No
I don't know
No Answer



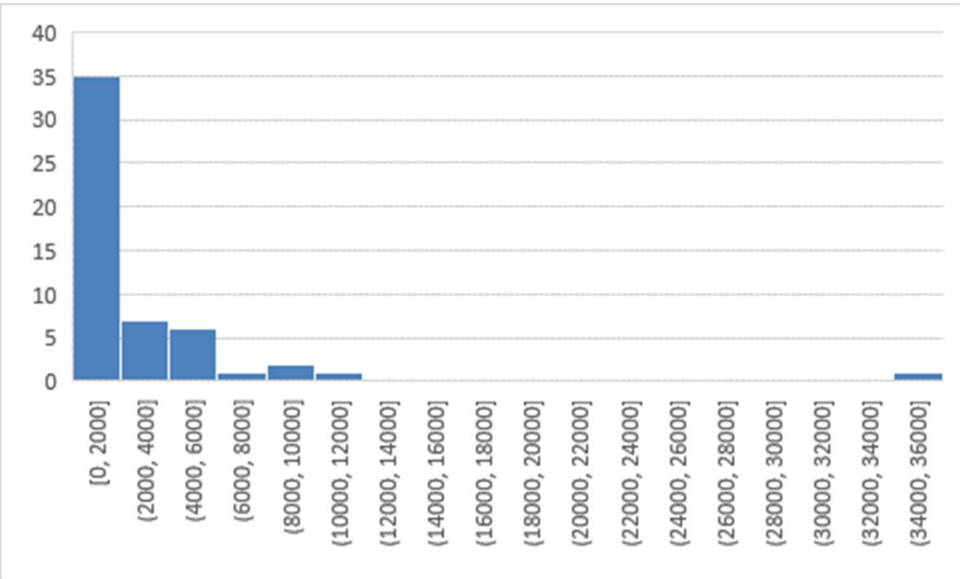
Other
0; 0%
4; 7%
0; 0%
53; 93%
Yes
No
I don't know
No Answer

4.8 Please provide the following information regarding the survey you are describing:

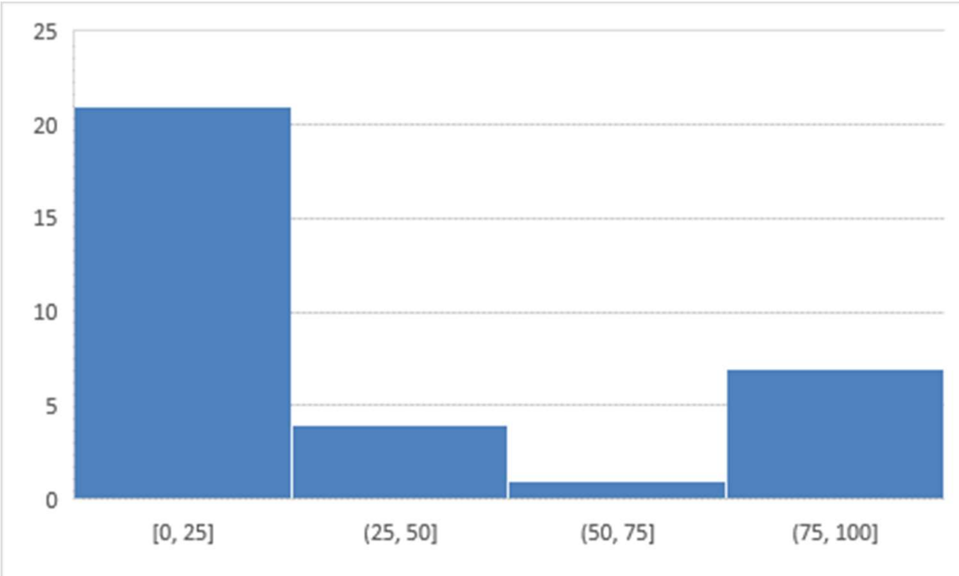
4.8a Total number of measurements;



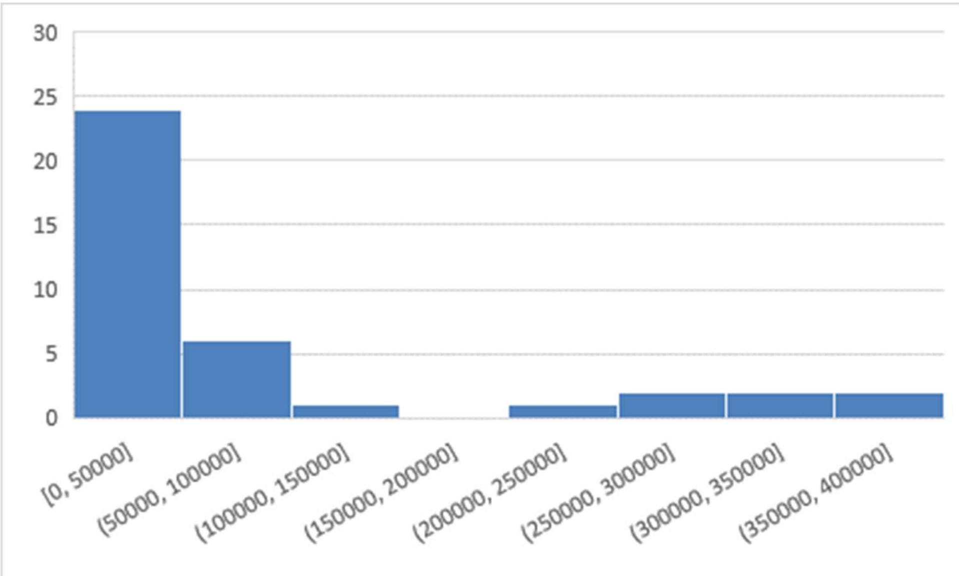
4.8b Total number of dwellings/buildings;



4.8c Percentage of dwellings/buildings measured in the area covered by the survey (%);

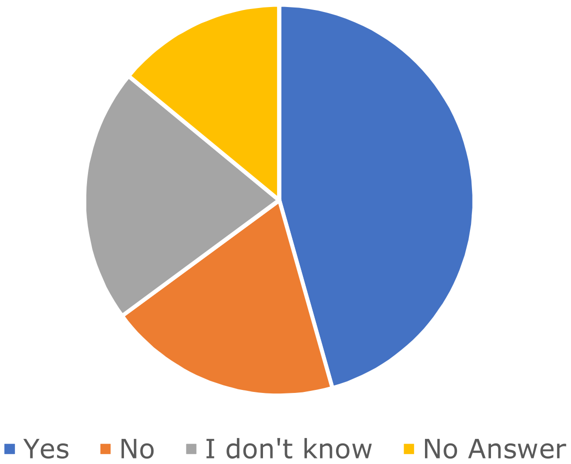


4.8d Area covered by the survey (km^2)

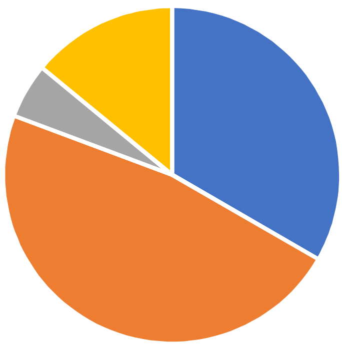


4.9 Please indicate how data from the survey were aggregated:

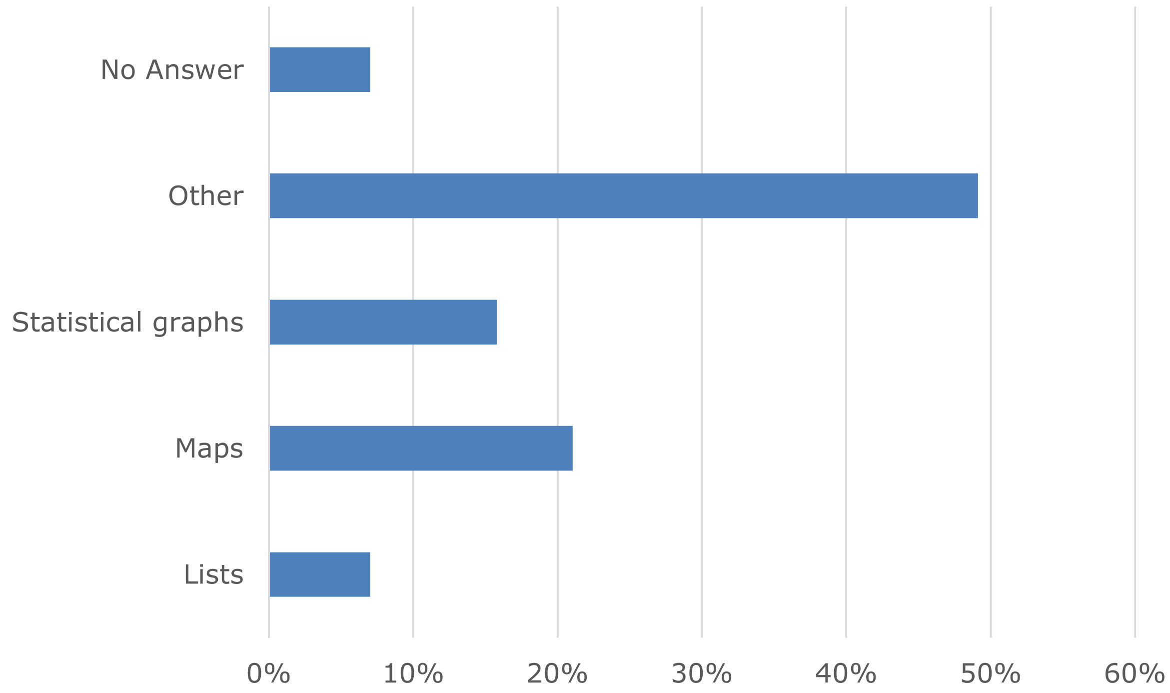
Simply target descriptive statistics of raw data



Modelling of raw data (standard house, spatial models - kriging, average within municipality, etc.)



4.10 Please indicate how data are presented to the population/authority



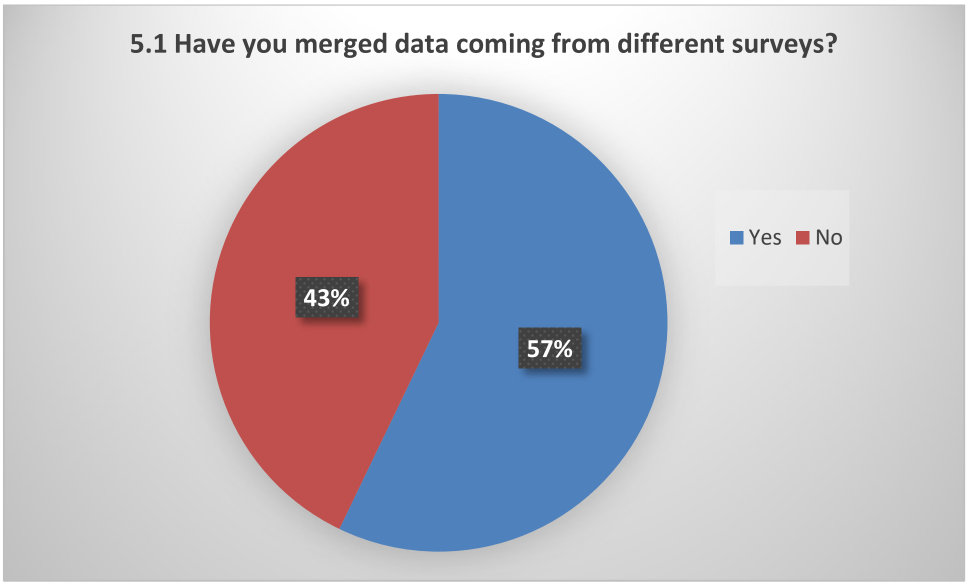
Other

- Direct communication (result letter) to the responsible of the administrative buildings, kindergartens, schools
- Result letter/single report to all households;
- Reports and scientific papers
- Reports for authorities
- Maps of web sites

5. Section 5: Policy on Indoor Radon

This section had to be filled only by the Institutions that represent the National Authority (one or more for each Country).

5.1 Merging of the data



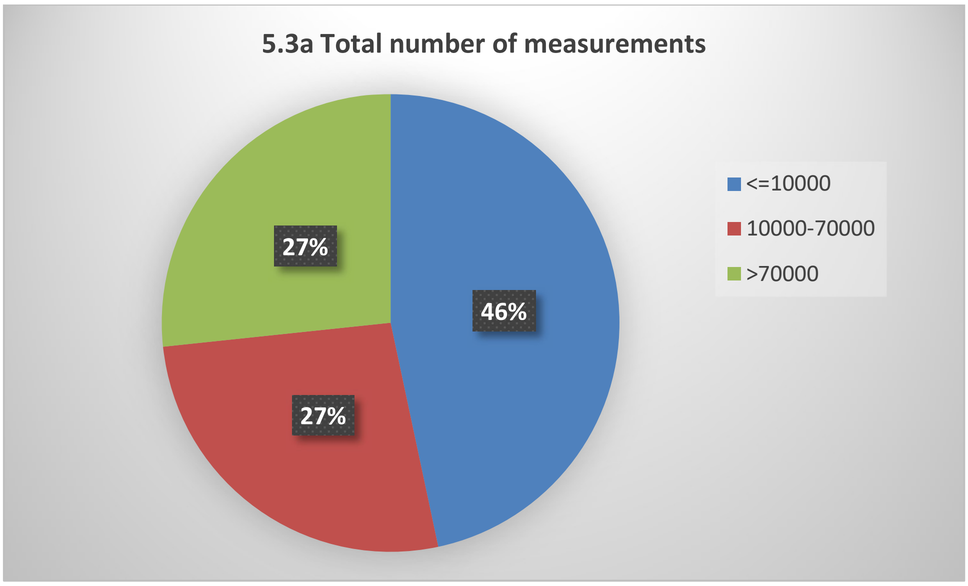
21 Institutions belonging to 18 Countries have answered the questions of this section. 12 of them have a database and merged data coming from different survey.

5.2 Description of the methodology followed to merge the data:

10 Institution described briefly the methodology followed to merge the data coming from different survey. Their answers are reported in the Annex II.

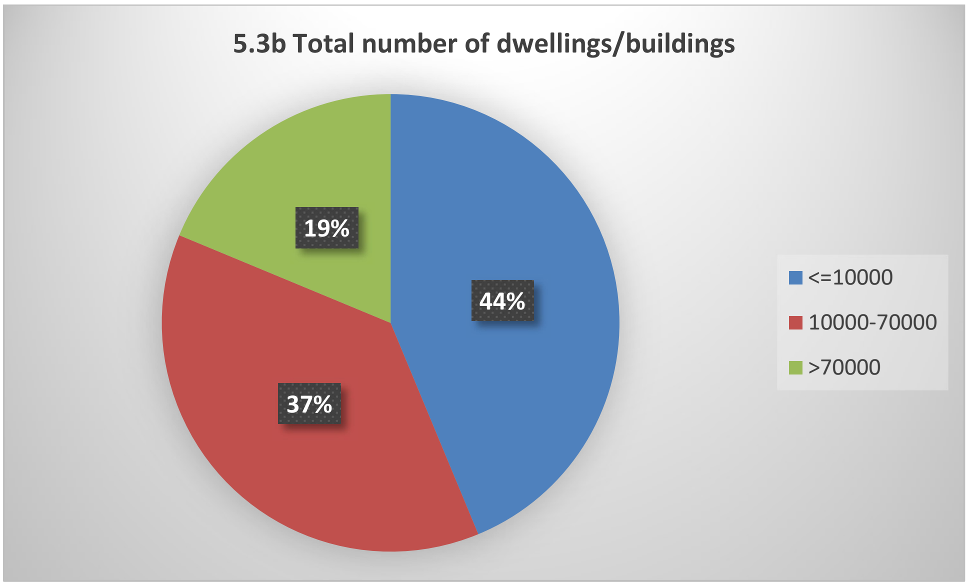
5.3 Information regarding the national database:

5.3aTotal number of measurements



15 Institution have answered this question. Only 4 of them have a database with more than 100000 radon measurements.

5.3bTotal number of dwellings/buildings



16 Institution have answered this question. Three of them have more than 100000 dwellings measured (with the measurements stored in the database).

5.3c Percentage of dwellings/buildings measured

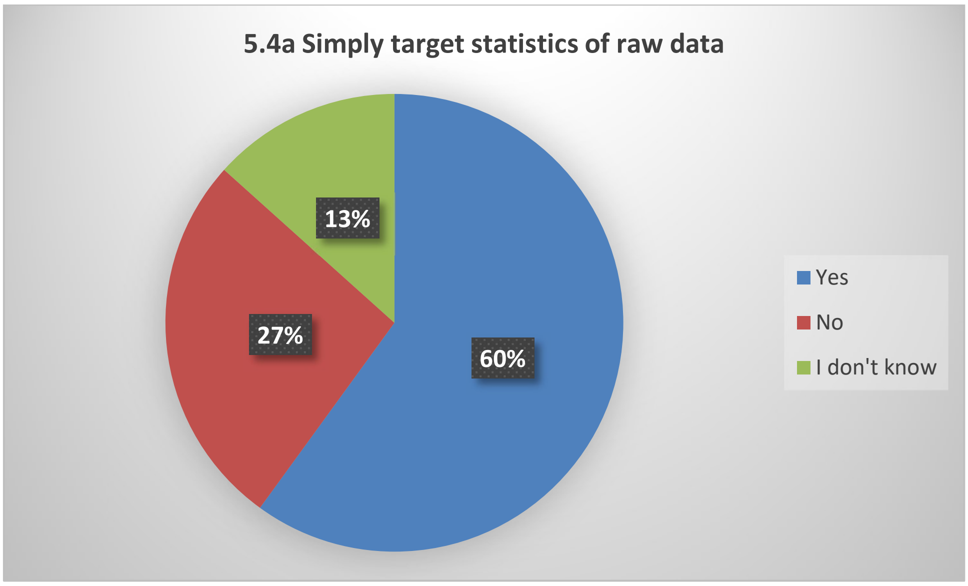
12 Institutions have answered this question. The percentage of coverage are generally low (<2 %) only Finland reported that 8 % of the buildings has been measured.

5.3d Area covered by the data contained in the database

10 Institution reported that the data in the database are nationwide. 4 Institution refer the data to part of the Country. 7 Institution didn't report the area covered by the data.

5.4 Information on the aggregation of the data from the national database:

5.4a Simply target statistics of raw data

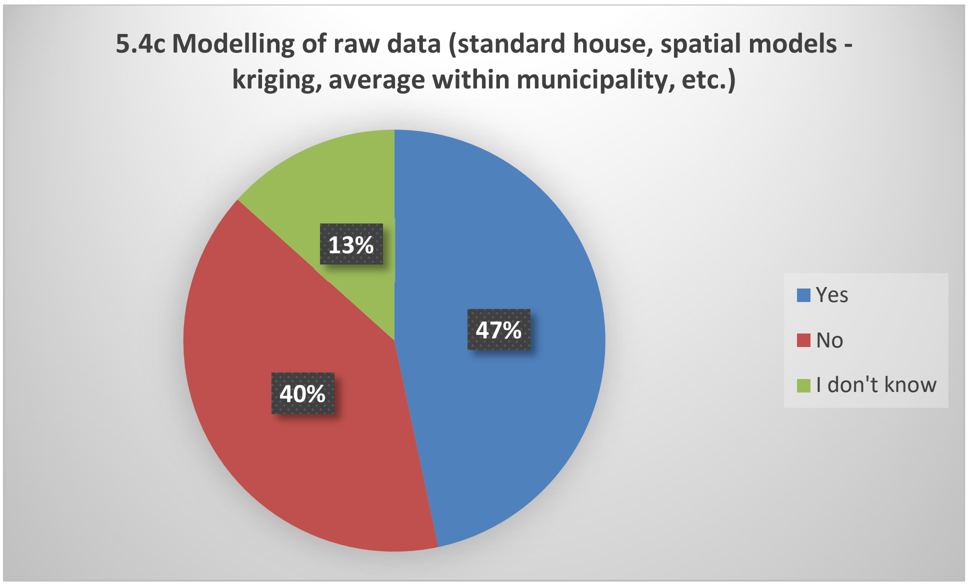


15 Institution have answered this question. Nine of them perform simply target statistics of raw data.

5.4b If Yes in 5.4a please describe the method

6 Institution described briefly the method followed. Their answers are reported in the Annex II.

5.4c Modelling of raw data (standard house, spatial models - kriging, average within municipality, etc.)



15 Institution have answered this question. Seven of them perform some modelling of raw data.

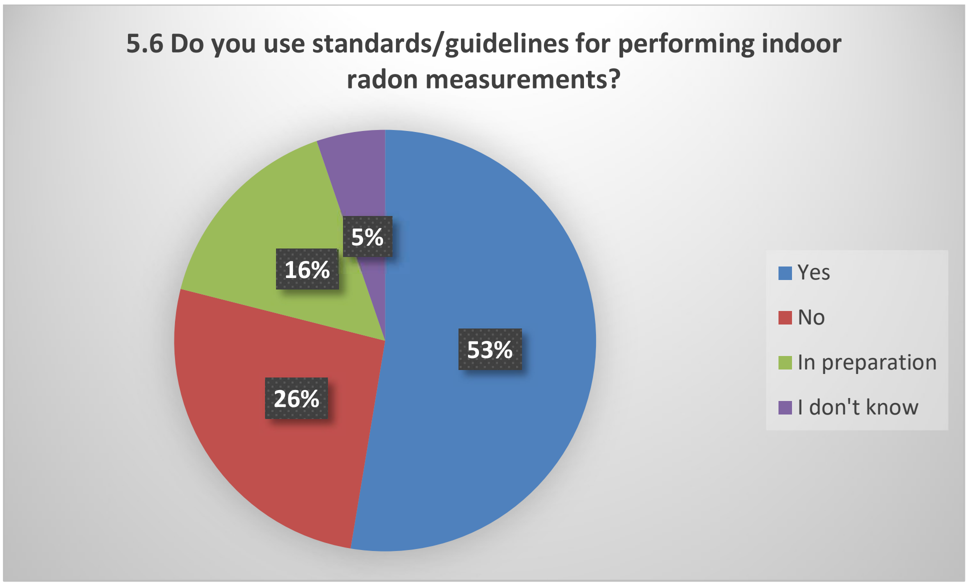
5.4d If Yes in 5.4c please describe the method

7 Institution described briefly the method used. Their answers are reported in the Annex II.

5.5 Indication of the date in which the National Radon Action Plan (as required by art. 103 of the European Council Directive 2013/59/EURATOM) has been established or will be:

Nine of the 15 Country that answered this question reported 2018 as the year in which the National Radon Action Plan has been established. Two Countries have established the Radon Action Plan before, Ireland in 2014 and Luxemburg in 2017. The remaining Countries reported the date of the current Radon Action Plan that is prior to the Directive.

5.6 Use of standards/guidelines for performing indoor radon measurements?



21 Institutions have answered this question. Ten of them have standards or guidelines to perform the measurements and are using them. Three Institution have standards/guidelines in preparation. Two institution reported both “yes” and “in preparation” to underline that they are updating their standards.

5.7 Reference level for indoor radon concentrations chosen and action that should be taken if it is exceeded?

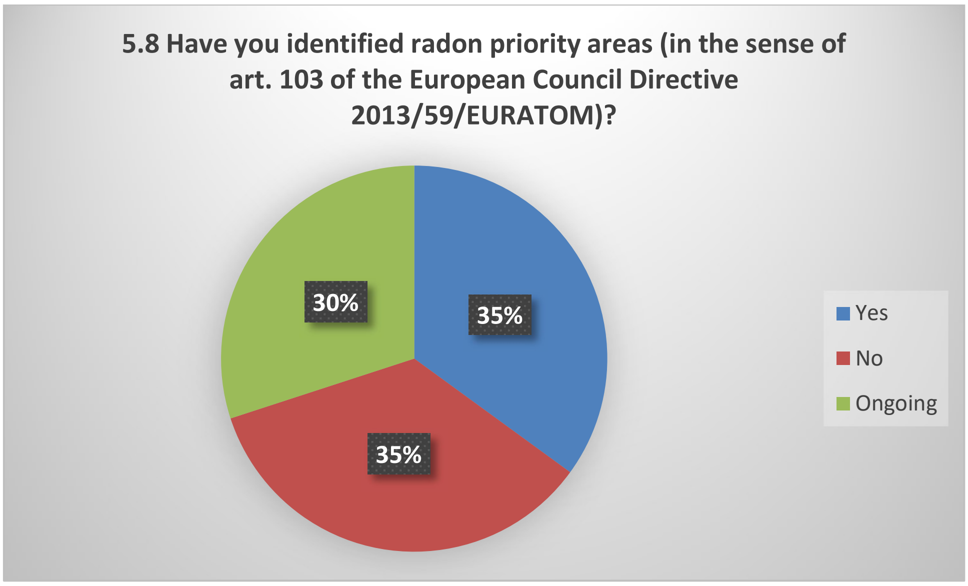
The Institutions have to report the reference level and the actions that should be taken if it is exceeded separately for: new dwellings, existing dwellings, public buildings and workplaces.

Twelve Country reported as reference level 300 Bq/m^3 for all the four situations above described. The action that should be taken is generally remediation but it is different for dwellings and workplaces: generally, for dwellings the remediation is recommended whereas for the workplaces (and public building) is obligatory.

For the other Country the situation is more mixed, in few cases the reference level is lower (100 or 200 Bq/m^3) for dwellings, both new and existing, whereas it is 300 Bq/m^3 for workplaces. As action that should be taken if the reference level is exceeded is generally reported: "remediation" The complete answers are reported in Annex II.

In few cases the reference level has not been established yet.

5.8 Identification of radon priority areas (in the sense of art. 103 of the European Council Directive 2013/59/EURATOM)



5.9 Data used to identify radon priority areas/classes?

For this question the Institutions had multiple choices. All the received answers (16) contained "indoor radon data". In 8 cases they used only indoor radon data. In 3 cases they used also geology information and in the remaining cases they used also radon in soil gas and gamma data.

5.10 Definition of radon priority area/class?

6 Institution reported that the radon priority areas have not been defined yet. 13 Institution described briefly their definition of radon priority areas. Their answers are reported in the Annex II.

5.11 Description of the classification criteria used

The classification criteria used have been reported by 9 Institutions. Their answers are reported in the Annex II.

5.12 Application of the classification criteria to the data

How the classification criteria have been applied has been reported by 9 Institutions. Their answers are reported in the Annex II.

5.13 Action that will be/have been taken in radon priority areas

The actions that have to be take (or have been taken) in radon priority areas are described by 11 Institutions. Their answers are reported in the Annex II.

Conclusions

The main objective of the questionnaire was to get information on indoor radon surveys in Europe. The questionnaire has been addressed to all European institutions working in this field such as: national authorities; regional administrations; Universities; and research centres. In the period from December 2017 and July 2018, there were 56 replies to questionnaire from 24 countries.
Apart from the details about respondent, the focus of the questionnaire was on 3 main topics:

1. Characteristics of indoor radon survey – design
2. Measurements methods
3. Data management, statistical treatment, aggregate and mapping

The questionnaire could provide an answer to the question whether existing indoor radon measurement procedures (include rationale, design, measurement methods, data analysis etc.) in different surveys are comparable in Europe.
From the answers given by the repondents it can be roughly concluded that European indoor radon surveys are:

1. not comparable for the characteristics of indoor radon survey – design;
2. comparable for the measuremnts methods;
3. too uncertanty in the answers to say if comparable or not for data management, statistical treatment, aggregate and mapping

Annexes

Annex 1. Questionnaire

Questionnaire on indoor radon survey (MetroRADON project)

Fields marked with * are mandatory.

Introduction

MetroRADON (16ENV10) is 3-years research project on metrology for radon monitoring granted by the European Metrology Programme for Innovation and Research (EMPIR), the main programme for European research on metrology.

The European Council Directive 2013/59/EURATOM (EU-BSS) laying down basic safety standards (BSS) for protection against the dangers arising from exposure to ionising radiation, evokes new challenges for the metrology of radon measurements and calibrations in Europe. For the first time, the exposure of the public caused by radon will be part of legal metrology in Europe. Since the EU-BSS stipulates that the EU Member States' level of relevant activity concentration shall not exceed 300 Bq/m3, new calibration procedures for existing commercial radon monitors with their limited counting statistics have to be developed.

The project will provide SI traceable metrological resources (calibration and measurement) for the monitoring of radon, which essentially facilitate the harmonised implementation of the new EU-BSS in Europe. It will contribute to the creation of metrological infrastructure for radon in Europe suitable for the requirements of the radon action plan requested by the new European Directive.

Follow the progress of the project at http://metroradon.eu/!

One of the specific objects is to compare existing radon measurement procedures in different European countries and use the results to optimise the consistency of indoor radon measurements across Europe. For this purpose, a questionnaire was developed to collect information to analyse and evaluate indoor radon surveys in order to: identify the rationale and methodologies used, identify the extent and possible sources of inconsistencies in the results of indoor radon surveys and propose approaches to reduce inconsistencies and improve harmonisation of indoor radon data.

The questionnaire is addressed to all the institutions (i.e. central national authorities but also regional administrations, universities, researcher centres) that know the details of any performed indoor radon survey. If you performed more than one survey, please compille a separate questionnaire for each survey.

We invite you to fill the questionnaire for your country – region, or forward it to the person, who can best answer these questions.

On behalf of the MetroRadon project consortium we thank you for your cooperation and help in obtaining these results that will help to improve radiation protection in Europe.

In the following sections:

- “you” is referred to your institution, not “personally”;
- indoor radon survey includes all the possibilities: national, regional (“Region” could be: national; federal state; district; region which was suspected for high Rn levels,…), in dwellings, in workplaces, in kindergartens, in public buildings etc

Fields marked with * are mandatory

Section 1. Information about respondent

*1.1 Country, please select

- Albania
- Andorra
- Armenia
- Austria
- Azerbaijan
- Belarus
- Belgium
- Bosnia and Herzegovina
- Bulgaria
- Croatia
- Cyprus
- Czech Republic
- Denmark
- Estonia
- Finland
- France
- Georgia
- Germany
- Greece
- Hungary
- Iceland
- Ireland
- Italy
- Kazakhstan
- Latvia
- Liechtenstein
- Lithuania
- Luxembourg
- Malta
- Monaco
- Montenegro
- Netherlands
- Norway
- Poland
- Portugal
- Republic of Moldova
- Romania
- Russian Federation
- San Marino
- Serbia

- Slovakia
- Slovenia
- Spain
- Sweden
- Switzerland
- The former Yugoslav Republic of Macedonia
- Turkey
- Ukraine
- United Kingdom

* 1.2 Name of the institution you represent (the public authority / international organisation / organisation or company):

1.3 Address of your institution:

* 1.4 Full name (first and last name) of the individual respondent: (The information you provide here is for administrative purposes only and will not be published)

1.5 Email address of the individual respondent: (The information you provide here is for administrative purposes only and will not be published)

1.6 Your role in the organisation:

- Management
- Professor
- Researcher
- Policy function
- Specialist/Expert
- Regulator
- Other

Please specify 'Other'

Section 2. Characteristics of Indoor Radon Survey

2.1 Have you performed more than one survey?

- Yes
- No
- I don't know

2.2 If yes, please specify how many:

2.3 What is the current status of the indoor radon survey you are going to describe?

- [ ] Not planned
- [ ] Planned
- [ ] Ongoing
- [ ] Finished
- [ ] I don't know

2.4 Please indicate the timeframe in which the survey has been performed:

From

To

2.5 Please indicate the region covered by the survey:
("Region" could be: national; federal state; district; region which was suspected for high Rn levels,…)

2.6 Please select the main purpose of the survey (multiple answers are allowed):

- [ ] First idea of radon situation
- [ ] Mean radon concentration of population
- [ ] Mapping
- [ ] Identification of radon priority areas
- [ ] Other

Please specify 'Other'

2.7 Please select the main strategy on which the survey was based (multiple answers are allowed):
geographical: samples uniformly over a geographical unit
random: without any defined scheme
population: sample density proportional to population density

- [ ] Geographical
- [ ] Geological
- [ ] Random
- [ ] Administrative units
- [ ] Population
- [ ] Already known radon priority areas
- [ ] Voluntary
- [ ] Grid cell
- [ ] Other strategy

Please specify 'Other strategy'

2.8 Which building types have you considered in your survey? Please indicate the percentages for each type:

2.8a Dwelllings

%

2.8b Schools

%

2.8c Kindergartens

%

2.8d Workplaces-general

%

2.8e Workplaces-public buildings

%

2.8f Caves/mines

%

2.8g Multi-family buildings

%

2.8h Other

%

Please specify 'Other'

2.9 Have you chosen a preferred measurements location in dwellings? Please indicate the percentages:

2.9a Basement

%

2.9b Ground floor

%

2.9c First floor

%

2.9d Other

%

Please specify 'Other'

2.10 Please select which method you chose for distributing the detectors:

- [ ] Mail
- [ ] Personally delivered and sent back by the participants
- [ ] Personally delivered and collected
- [ ] Other

Please specify 'Other'

2.11 Have you collected information about the measurement site through a questionnaire?

- [ ] Yes
- [ ] No
- [ ] I don't know

2.12 Please indicate which kind of information you have asked for the questionnaire?

- [ ] House type (villa, semi-detached, apartment, multi-family etc.)
- [ ] Construction material
- [ ] Living habits
- [ ] Heating system
- [ ] Ventilation habits
- [ ] Number of inhabitants
- [ ] Occupational rate
- [ ] Smoking habit
- [ ] Remediation performed
- [ ] Other

Please specify 'Other'

Can you please provide us with a copy of the questionnaire? (email going to giorgia.cinelli@ec.europa.eu)

2.13 Representativeness:
A survey is representative, if the target quantity calculated from the data is an unbiased estimate of the targeted true value of that statistic.

2.13a Has representativeness been targeted?
- Yes
- No

2.13b Has representativeness been achieved to a sufficient degree?
- Yes
- No

2.13c If applicable: how has representativeness been assessed?

2.13d If assessed as not representative: which type or source of bias is believed to be present?

2.13e If representativeness was not achieved: any corrections or models applied to guarantee unbiased estimated over estimation support?

2.14 Has the survey be designed according to statistical reasoning?
- Yes
- No

2.15 If YES in 2.14, please describe the estimation support and target quantity for the survey:
Estimation support is the unit, over which the survey is supposed to yield an estimate. Target quantity is the statistic which is attached to the estimation support. For example: Objective of a survey is to generate a list (or map) of arithmetic mean values over municipalities of long-term indoor Rn concentrations in living rooms of ground floor dwellings in buildings with basement, with targeted uncertainty (90% conf. int.) less than 20%. In this example, estimation support = municipality; target quantity = AM (concentration); uncertainty score = 20% of 90% conf.int.; specification = ground floor living rooms, building with basement. The achieved average uncertainty may be different from the targeted one, and could be given as a range, e.g. “between 15 and 30% of 90% conf. int.”.

2.15a Estimation support

2.15b Target quantity (arithmetic mean, geometrical mean, % above reference level, etc.)

2.15c Target uncertainty score

2.15d Mean achieved uncertainty

2.15e Specifications

Section 3. Measurements methods

3.1 Which kind of detector have you used? Please indicate the percentage and the duration of the measurements:

	Track etch – CR39	Track etch – LR-115	Charcoal/gamma spectrometry	Charcoal/LSC	Electret	Active	Other
Percentage (%)							
Duration (months)							
Duration (days) for charcoal_electret							

Please specify 'Other'

If 'Active' please specify the instrument:

If LR-115 please specify the type:

- ☐ Open
- ☐ Closed

3.2a If applicable, please indicate the season in which the measurements have been performed (multiple seasons are allowed):

- ☐ Winter
- ☐ Spring
- ☐ Summer
- ☐ Autumn
- ☐ Other

Please specify 'Other' (i.e. only in heating season)

3.3 If you have you performed parallel measurements at the same location, please indicate the purpose of these measurements and which percentage of the total measurements is concerned:

3.3a Purpose

3.3b Track etch-CR39

%

3.3c Track etch-LR-115

%

3.3d Charcoal/gamma spectrometry

%

3.3e Charcoal/LSC

%

3.3f Electret

%

3.3g Active

%

3.3h Other

%

3.4 Are the detectors you used sensitive to thoron?

	Yes	No	I don't know
Track etch - CR39	☐	☐	☐
Track etch - LR115	☐	☐	☐
Electret	☐	☐	☐
Active	☐	☐	☐
Other	☐	☐	☐

3.5 If YES in 3.4 please indicate if and how this has been corrected.

3.6 Has thoron been measured?

- ☐ Yes
- ☐ No
- ☐ I don't know

3.7 If YES in 3.6 please indicate the detector-methodology

3.8 If YES in 3.6, please indicate how far the detector was positioned from thoron exhaling surfaces:

cm

3.9 Did you perform quality assurance and quality control during the survey?

- ☐ Yes
- ☐ No
- ☐ I don't know

3.10 If YES in 3.9 please indicate how you did.

3.11 Please indicate the calibration period of the instruments.

Section 4. Data management, statistical treatment, aggregation and mapping

4.1 Please indicate the return rate (return rate = fraction of deployed detectors which could be collected):

%

4.2 Please indicate the evaluated rate (evaluated rate = fraction of deployed detectors which could be evaluated and have plausible results. E.g., detectors which were returned but obviously not exposed or damaged etc., are excluded):

%

4.3 The result has been corrected for lost detector? If so, how?

4.4 If you have performed parallel measurements at the same location-measurement point (see 3.3), please specify which value has been chosen to be representative of this point (arithmetic mean, geometrical mean, maximum, etc.)?

4.5 If you have performed more than one measurement at the same dwelling/house/building, please specify which value has been chosen to be reported in your database (raw data, arithmetic mean, geometrical mean, maximum, etc.)?

4.6a Have you applied seasonal correction?

	Yes	No	I don't know
Track etch - CR39	☐	☐	☐
Track etch - LR115	☐	☐	☐
Charcoal/gamma spectrometry	☐	☐	☐
Charcoal/LSC	☐	☐	☐

Electret	☐	☐	☐
Active	☐	☐	☐
Other	☐	☐	☐

4.6b If YES in 4.6a, how was the seasonal correction factor obtained:

- ☐ From literature/comparable survey
- ☐ By exposing some detectors for 12 months
- ☐ By comparing short-term (e.g. 3-month) measurements distributed over a full year
- ☐ Other

Please specify 'Other'

4.7 Have you applied any correction linked to building characteristics, in particular floor level?

	Yes	No	I don't know
Track etch - CR39	☐	☐	☐
Track etch - LR115	☐	☐	☐
Charcoal canister	☐	☐	☐
Charcoal/LSC	☐	☐	☐
Electret	☐	☐	☐
Active	☐	☐	☐
Other	☐	☐	☐

4.8 Please provide the following information regarding the survey you are describing:

4.8a Total number of measurements

4.8b Total number of dwellings/buildings

4.8c Percentage of dwellings/buildings measured in the area covered by the survey

%

4.8d Area covered by the survey

km2

4.9 Please indicate how data from the survey were aggregated:

4.9a Simply target descriptive statistics of raw data

- Yes
- No
- I don't know

4.9b If Yes in 4.9a please describe the method

4.9c Modelling of raw data (standard house, spatial models - kriging, average within municipality, etc.)

- Yes
- No
- I don't know

4.9d If Yes in 4.9c please describe the method

4.10 Please indicate how data are presented to the population/authority

- Lists
- Maps
- Statistical graphs
- Other

Please specify 'Other'

4.11 Have you estimated the occupancy factor of dwellings?

- Yes
- No
- I don't know

4.12 If Yes in 4.11, please provide the value and describe the method:

Section 5: Policy on Indoor Radon

Please fill Section 5 only if you represent the national authority

5.1 Have you merged data coming from different surveys?

- Yes
- No
- I don't know

5.2 If Yes in 5.1, please describe briefly the methodology followed to merge them:

5.3 Please provide the following information regarding the national database:

5.3a Total number of measurements

5.3b Total number of dwellings/buildings

5.3c Percentage of dwellings/buildings measured

%

5.3d Area covered by the data contained in the database

km2

5.4 Please indicate how data from the national database were aggregated:

5.4a Simply target statistics of raw data

- Yes
- No
- I don't know

5.4b If Yes in 5.4a please describe the method

5.4c Modelling of raw data (standard house, spatial models - kriging, average within municipality, etc.)

- Yes
- No
- I don't know

5.4d If Yes in 5.4c please describe the method

5.5 Please indicate approximately the date in which the National Radon Action Plan (as required by art. 103 of the European Council Directive 2013/59/EURATOM) has been established or will be:

5.6 Do you use standards/guidelines for performing indoor radon measurements?

- [ ] Yes
- [ ] No
- [ ] In preparation
- [ ] I don't know

5.6a If 'Yes', can you please provide us with a copy of these standards/guidelines? (email going to giorgia.cinelli@ec.europa.eu)

5.7 Please indicate which reference level for indoor radon concentrations you have chosen and if exceeded which action should be taken:

	Reference level (Bq/m3)	Actions
New dwellings		
Existing dwellings		
Public buildings		
Workplaces		

5.8 Have you identified radon priority areas (in the sense of art. 103 of the European Council Directive 2013/59/EURATOM)?

- [ ] Yes
- [ ] No
- [ ] Ongoing
- [ ] I don't know

5.9 Which input data have you used to identify radon priority areas/classes?

- [ ] Indoor radon data
- [ ] Geology
- [ ] Radon in soil gas
- [ ] Soil permeability
- [ ] Gamma dose rate
- [ ] Uranium concentration
- [ ] Other

Please specify 'Other'

5.10 How do you define a radon priority area/class?

5.11 Please briefly describe the classification criteria you used:

5.12 How do you apply the classification criteria to your data?

5.13 Which action will be/have been taken in radon priority areas?

Annex 2 _ Detailed replies

Section 1

1.1 Country, please select
1.2 Name of the institution you represent (the public authority / international organisation / organisation or company)
1.3 Address of your institution (1.4 and 1.5 not reported for privacy issue)
1.6 Your role in the organisation
1.7 Please specify 'Other'

CODE	1.1	1.2	1.3	1.6	1.5
AL_IANP	Albania	Institute Of Applied Nuclear Physics	Street " Thoma Filipeu" , Qesarake, PO Box: 85, Tirana, Albania	Researcher	
AT_AGES1	Austria	AGES	Wieningerstraße 8, 4020 Linz	Specialist/Expert	
AT_AGES2	Austria	AGES	Wieningerstraße 8, 4020 Linz	Specialist/Expert	
AT_AGES3	Austria	AGES	Wieningerstraße 8, 4020 Linz	Specialist/Expert	
AT_AGES4	Austria	AGES	Wieningerstraße 8, 4020 Linz	Specialist/Expert	
AT_AGES5	Austria	AGES	Wieningerstraße 8, 4020 Linz	Specialist/Expert	
AT_AGES6	Austria	AGES	Wieningestraße 8, 4020 Linz	Specialist/Expert	
AT_AGES7	Austria	AGES	Wieningerstraße 8, 4020 Linz	Specialist/Expert	
AT_AGES8	Austria	AGES	Wieningerstraße 8, 4020 Linz	Specialist/Expert	
BY_JINPR	Belarus	JINPR-Sosny of NAS of Belarus	P.O. box 119, 220109, Minsk, Belarus	Specialist/Expert; Researcher	
BE_FANC	Belgium	FANC	Ravensteinstraat 36, 1000 Brussels	Specialist/Expert	
BE_ISIB	Belgium	ISIB, Haute Ecole de Bruxelles-Brabant	150 rue Royale BE1000 Brussels BELGIUM	Other	retired professor, free researcher
HR_FIZIKA.UNIOS	Croatia	Department of Physics, University of Osijek	Trg Ljudevita Gaja 6, 31000 Osijek, Croatia	Management;Professor;Researcher	
CY_DLI.MLSI	Cyprus	Radiation Inspection and Control Service, Department of Labour Inspection	12, Apellis str., CY-1493, Lefkosia (Nicosia), Cyprus	Specialist/Expert; Regulator;Policy function	

CZ_SURO	Czech Republic	National Radiation Protection Institute (SURO)	Bartoskova 28, 140 00 Prague 4, Czech Republic	Researcher	
FI_STUK	Finland	STUK -- Radiation and Nuclear Safety Authority	P.O.Box 14; 00811 Helsinki, FI	Specialist/Expert; Regulator	
DE_BFS	Germany	Bundesamt für Strahlenschutz	Köpenicker Allee 120 - 130, 10318 Berlin	Specialist/Expert	
GR_AUTH	Greece	Aristotle University of Thessaloniki	Nuclear Physics Lab., School of Physics, Aristotle University of Thessaloniki, 54124 Thessaloniki	Professor	
GR_EEAE	Greece	Greek Atomic Energy Commission (EEAE)	P.O BOX 60092	Other	Head of the Department of Environment al Radioactivity Monitoring
IE_EPA1	Ireland	Environmental Protection Agency	McCumiskey House, Richview, Clonskeagh Road, Dublin 14, D14 YR62	Researcher	
IE_EPA2	Ireland	Environmental Protection Agency	McCumiskey House, Richview, Clonskeagh Road, Dublin 14, D14 YR62	Researcher	
IE_EPA3	Ireland	Environmental Protection Agency	McCumiskey House, Richview, Clonskeagh Road, Dublin 14, D14 YR62	Researcher	
IT_INAIL	Italy	INAIL - National Institute for Insurance against Accidents at Work	Research Center - Via Fontana Candida,1 Monteporzio Catone 00078 (Rome) Italy	Specialist/Expert	
IT_ISS	Italy	Istituto Superiore di Sanità	Viale Regina Elena 299, 00161, Roma Italy	Researcher	
IT_ARPACAL	Italy	Laboratory of Physics "Ettore Majorana" - Catanzaro District	Via Lungomare - Loc. Mosca - Catanzaro Lido - Italy	Specialist/Expert; Other	Laboratory Contact Person

		Department - ARPACAL:Calabrian Environmental Protection Agency			
IT_APPATN1	Italy	Local Environmental Protection Agency - APPA Trento	Via Lidorno 1, 38123 Trento (TN)	Specialist/Expert	
IT_APPATN2	Italy	Local Environmental Protection Agency - APPA Trento	Via Lidorno 1, 38123 Trento (TN)	Specialist/Expert	
IT_APPATN3	Italy	Local Environmental Protection Agency - APPA Trento	Via Lidorno 1, 38123 Trento (TN)	Specialist/Expert	
IT_APPATN4	Italy	Local Environmental Protection Agency - APPA Trento	Via Lidorno 1, 38123 Trento (TN)	Specialist/Expert	
IT_APPATN5	Italy	Local Environmental Protection Agency - APPA Trento	Via Lidorno 1, 38123 Trento (TN)	Specialist/Expert	
IT_ARPALOMBARDIA1	Italy	ARPA Lombardia (Regional Environmental Protection Agency in Lombardia)	via Rosellini 17, 24100 Milano	Specialist/Expert	
IT_ARPALOMBARDIA2	Italy	ARPA Lombardia (Regional Environmental Protection Agency - Lombardia)	via Rosellini 17 - 24100 Milano	Specialist/Expert	
IT_ISPRA1	Italy	ISPRA (National Institute for environmental protection and research)	Rome	Researcher	

IT_ISPRA2	Italy	ISPRA (National Institute for environmental protection and research)	Rome	Researcher	
IT_ISPRA3	Italy	ISPRA (National Institute for environmental protection and research)	Rome	Researcher	
IT_ARPAVDA	Italy	ARPA Valle d'Aosta	Loc, Grande Charrière 44, 11020 Saint-Christophe (AO)	Specialist/Expert	
IT_ARPAER	Italy	ARPAE Emilia-Romagna, Sezione di Piacenza, CTR Radioattività ambientale	Via XXI Aprile, 48 - 29121 Piacenza - Italia	Management	
IT_ARPAL1	Italy	ARPAL - Agenzia Regionale per la Protezione dell'Ambiente Ligure	Via Bombrini, 8 - 16149 Genova - Italy	Specialist/Expert	/
IT_ARPAL2	Italy	ARPAL - Agenzia Regionale per la Protezione dell'Ambiente Ligure	Via Bombrini, 8 - 16149 Genova - Italy	Specialist/Expert	/
IT_ARPAL3	Italy	ARPAL - Agenzia Regionale per la Protezione dell'Ambiente Ligure	Via Bombrini, 8 - 16149 Genova - Italy	Specialist/Expert	/
IT_ARPAP	Italy	ARPA Piemonte (Environmental Protection Agency of Piemonte)	Via Jervis, 30 - 10015 IVREA (TO)	Management;Researcher	
LV_RSC	Latvia	Radiation Safety Centre of State	Rupniecibas street 23, Riga, LV-1045, Latvia	Regulator	Project coordinator

		Environmental Service of Republic of Latvia			
LT_RPC	Lithuania	Radiation Protection Center	Kalvariju str. 153, Vilnius, Lithuania	Specialist/Expert; Regulator	
LU_MS.ETAT	Luxembourg	Ministry of Health	Allée Marconi, 2120 Luxembourg	Specialist/Expert	
MT_EHD	Malta	Environmental Health Directorate		Specialist/Expert	
MT_RPB	Malta	Radiation Protection Board	17 Edgar Ferro Street, Pieta, PTA1533, Malta	Regulator	
NE_RIVM	Netherlands	RIVM	PO Box 1, 3720 BA Bilthoven, The Netherlands	Specialist/Expert; Researcher	
NO_NRPA	Norway	Norwegian Radiation Protection Authority	Statens strålevern, Postboks 329 Skøyen,0213 Oslo	Specialist/Expert	
PL_IMP.LODZ1	Poland	Nofer Institute of Occupational Medicine	św. Teresy od Dzieciątka Jezus 8	Specialist/Expert	
PL_IMP.LODZ2	Poland	Nofer Institute of Occupational Medicine	św. Teresy od Dzieciątka Jezus 8	Specialist/Expert	
RO_CNCAN	Romania	National Commission for Nuclear Activities Control (CNCAN)	14 Libertatii Bdv., 5 Bucharest, 050206	Regulator	
RO_UBBCLUJ	Romania	Babeş-Bolyai University	Fantanele street, 30, Cluj-Napoca, Romania	Management;Rese archer	
RS_DF.UNS	Serbia	University of Novi Sad, Faculty of Sciences, Department of Physics, Nuclear Physics Laboratory	Trg Dositeja Obradovica 4, 21000 Novi Sad, Serbia	Professor;Researc her	
SI_SRPA	Slovenia	Slovenian Radiation Protection Administration	Ajdovscina 4, 1000 Ljubljana	Professor;Regulato r;Policy function	
ES_UNICAN	Spain	University of Cantabria	Cardenal Herrera Oria SN-39011-Santander-Cantabria-Spain	Professor	

UK_PHE	United Kingdom	Public Health England (Centre for Radiation, Chemical and Environmental Hazards) PHE-CRCE	Chilton, Didcot, Oxon OX11 0RQ, UK	Management;Specialist/Expert	

Source: IIIIIIIx.

Annex 2 Section 2

2.1 Have you performed more than one survey?
2.2 If yes, please specify how many
2.3 What is the current status of the indoor radon survey you are going to describe?
2.4 Please indicate the timeframe in which the survey has been performed:
2.5 Please indicate the region covered by the survey: ("Region" could be: national; federal state; district; region which was suspected for high Rn levels,…)

ID	**2.1**	**2.2**	**2.3**	**2.4 From**	**2.4 To**	**2.5**
AL_IANP	Yes	3	Finished	10/01/2003	20/05/2014	Tirana city
AT_AGES1	Yes	8	Finished	01/01/1992	31/12/2001	national
AT_AGES2	Yes	8	Finished	01/01/2008	31/12/2008	Upper Austria (federal state)
AT_AGES3	Yes	8	Finished	01/01/2000	01/06/2001	Upper Austria (federal state)
AT_AGES4	Yes	8	Finished	01/06/2001	31/12/2002	Upper Austria (federal state)
AT_AGES5	Yes	8	Finished	01/06/2009	31/12/2010	3 municipalities in Upper Austria
AT_AGES6	Yes	8	Finished	01/06/2012	31/12/2013	3 municipalities in Styria
AT_AGES7	Yes	8	Finished	01/06/2009	31/12/2011	national
AT_AGES8	Yes	8	Ongoing	01/01/2014	01/06/2019	nationl
BY_JINPR	No		Ongoing	01/01/2016	31/12/2020	national
BE_FANC	Yes		Finished	01/01/1995	01/01/2000	national
BE_ISIB	Yes	several surveys during about 25 years	Finished	01/01/1989	31/12/2014	Walloon region and Brussels region
HR_FIZIKA.UNIOS	Yes	1 at National level, several targeted surveys	Finished	01/09/2003	01/03/2005	national
CY_DLI.MLSI	Yes	4	Finished	01/01/2007	31/12/2011	National (main urban areas)

CZ_SURO	No		Finished	01/01/1993	31/12/1994	national survey
FI_STUK	Yes	three country-wide surveys (1990, 1996, 2006) + special surveys (kindergartens, radon at work and at leasure time, new buildings, area-specific surveys, monthly variation survey)	Finished	01/05/2006	30/04/2007	national
DE_BFS	Yes	28	Planned	01/05/2018	31/05/2020	national
GR_AUTH	Yes	2	Planned	01/09/1989	01/06/1994	City of Thessaloniki
GR_EEAE	Yes	1 ongoing national, 3 regional	Ongoing	01/01/2015	31/12/2020	national
IE_EPA1	Yes	3	Finished	01/01/1992	31/12/1999	National
IE_EPA2	Yes	3	Finished	01/07/2016	31/05/2017	National
IE_EPA3	Yes	3	Finished	15/07/2014	31/05/2015	National
IT_INAIL	No		Finished	30/09/2005	01/10/2007	province
IT_ISS	No		Finished	01/05/2010	01/05/2013	National
IT_ARPACAL	Yes	2	Planned	01/04/2010	12/04/2018	Calabria - Italy
IT_APPATN1	Yes	5	Finished	20/09/1994	14/02/2007	Trentino region
IT_APPATN2	Yes	5	Finished	01/11/1998	09/05/2001	Trentino region
IT_APPATN3	Yes	5	Finished	01/09/1992	30/06/1994	Trentino region
IT_APPATN4	Yes	5	Finished	12/10/2000	08/06/2001	Trentino region
IT_APPATN5	Yes	5	Finished	20/09/2001	07/06/2002	Trenitno region
IT_ARPALOMBARDIA1	Yes	2	Finished	15/10/2003	15/12/2004	Lombardia
IT_ARPALOMBARDIA2	Yes	2, (this is the second one)	Finished	15/09/2009	15/10/2010	Region Lombardia, (77 administration units, 5 % of the total)
IT_ISPRA1	Yes	3	Finished	01/01/1989	31/12/1997	national
IT_ISPRA2	Yes	3	Finished	01/01/2005	31/12/2010	regional
IT_ISPRA3	Yes	3	Finished	23/03/2016	23/03/2018	municipality
IT_ARPAVDA	Yes	2	Ongoing	01/01/2004	31/12/2016	Valle d'Aosta
IT_ARPAER	No		Finished	01/10/1994	30/04/1995	Emilia-Romagna
IT_ARPAL1	Yes	3	Finished	01/10/2010	30/09/2011	Municipality of: Albissola Marina, Albisola Superiore, Celle Ligure, Varazze

IT_ARPAL2	Yes	3	Finished	31/05/2010	14/10/2011	Bergeggi Caves
IT_ARPAL3	Yes	3	Finished	22/12/1994	17/09/1995	Toirano Caves
IT_ARPAP	Yes		Planned; Ongoing; Finished	01/01/1991	30/06/2018	Piemonte Region
LV_RSC	Yes	Two large scale (with detailed measurement location and building data), in midle of the ninties measurements was done without detailed information of location	Ongoing	01/02/2016	30/06/2018	National
LT_RPC	Yes	10	Ongoing	01/01/1994	22/01/2018	Whole Country
LU_MS.ETAT	Yes	3	Finished	01/10/2016	01/04/2017	national
MT_EHD	No		Finished	01/11/2010	01/11/2011	national
MT_RPB	No		Finished	01/11/2010	01/11/2011	National of the Maltese Islands
NE_RIVM	Yes	4 surveys have been performed, only the last will be described	Finished	01/01/2013	01/01/2015	national
NO_NRPA	Yes	NRPA have performed 6 surveys of different types since 2000 (national appr. random, use of geological strategy in selected municipalities, radon remediated dwellings, newly built houses 2008 and 2016, exposure of the population 2013/14). I will report on only the last one	Finished	01/03/2013	01/08/2014	National
PL_IMP.LODZ1	Yes	5	Finished	01/06/2013	15/07/2015	region which was suspected for high Rn levels- Kowary city, Poland

PL_IMP.LODZ2	Yes	5	Finished	01/01/2012	31/12/2013	Whole country -Poland- underground polish tourist routes
RO_CNCAN	Yes	5	Ongoing; Finished	01/01/2003	31/12/2017	20 districts from the total number of 43 counties of Romania; Stei-Baita (Bihor) region which was suspected for high Rn levels
RO_UBBCLUJ	Yes	5	Ongoing; Finished	01/01/2003	31/12/2017	20 districts from the total number of 43 counties of Romania; Stei-Baita (Bihor) region which was suspected for high Rn levels
RS_DF.UNS	Yes	5	Finished	01/01/1996	01/01/2003	Vojvodina Province, Serbia
SI_SRPA	Yes	surveys are performed periodically on 3-5 years, so we have performed 5 surveys during last 20 years	Ongoing	15/01/2018	15/11/2018	Regions suspected for high Rn levels, according to the previous surveys. 24 local communities were identified where the radon concentration as an annual average in a significant number of buildings is expected to exceed the national reference level of 300 Bg/m3.
ES_UNICAN	No		Finished	01/01/2010	01/01/2014	National
UK_PHE	Yes	Over 20 of differeing types (Population weighted, regional, mapping, targeted to high areas)	Finished	01/01/1986	01/01/1988	UK

2.6 Please select the main purpose of the survey (multiple answers are allowed) LIST OPTIONS
2.7 Please select the main strategy on which the survey was based (multiple answers are allowed) LIST OPTIONS

ID	2.6	Please specify 'Other'	2.7	Please specify 'Other '
AL_IANP	First idea of radon situation;Identification of radon priority areas		Random;Grid cell;Population	
AT_AGES1	Mean radon concentration of population;Mapping;Identification of radon priority areas		Population	

AT_AGES2	First idea of radon situation;Other	First idea of Radon Situation in administrative buildings; Protection of employees in administrative buildings	Other strategy	Measurements in all administrative buildings (e.g. town halls) in Upper Austria
AT_AGES3	First idea of radon situation;Other	Radon concentration in Kindergartens; Radon exposure for Upper Austrian children	Other strategy	Radon measurements in all Kindergartens in Upper Austria
AT_AGES4	First idea of radon situation;Other	Radon concentration in Schools; Radon exposure for Upper Austrian children	Already known radon priority areas;Other strategy	Schools with earthbound rooms in municipalities in class 3 according to the Austrian radon potential map and neighbouring municipalities
AT_AGES5	Other	Measurement of all dwellings in 3 municipalities (together with soil gas and gamma dose rate measurements)	Other strategy	Selection of 3 municipalities; aim: measurement in all dwellings in these municipalities
AT_AGES6	Other	Measurement of all dwellings in 3 municipalities (together with soil gas and gamma dose rate measurements)	Other strategy	Selection of 3 municipalities; aim: measurement in all dwellings in these municipalities
AT_AGES7	First idea of radon situation;Other	First idea of Radon Situation and dose for workers in Austrian visitor mines and caves	Geological;Other strategy	Possibly different mines and Caves (different geology, different mining product) geographically distributed over Austria
AT_AGES8	Mapping		Geological;Grid cell;Administrative units	
BY_JINPR	First idea of radon situation;Mean radon concentration of population;Mapping;Identification of radon priority areas		Already known radon priority areas;Geological;Grid cell;Administrative units	
BE_FANC	First idea of radon situation;Identification of radon priority areas		Geographical;Voluntary;Random;Administrative units	

BE_ISIB	Mapping;Identification of radon priority areas		Geological;Voluntary; Other strategy	Survey organised with voluntary schools
HR_FIZIKA.UNIOS	First idea of radon situation;Mean radon concentration of population		Population	
CY_DLI.MLSI	Mean radon concentration of population;Mapping;Identification of radon priority areas		Geographical;Voluntary;Administrative units;Population	
CZ_SURO	Mean radon concentration of population		Population	
FI_STUK	Mean radon concentration of population		Random	
DE_BFS	Mean radon concentration of population;Mapping;Identification of radon priority areas		Random;Population	
GR_AUTH	Mean radon concentration of population;Mapping		Geographical;Geological	
GR_EEAE	First idea of radon situation;Mean radon concentration of population;Mapping;Identification of radon priority areas		Geographical;Geological;Administrative units;Population	
IE_EPA1	First idea of radon situation;Mean radon concentration of population;Mapping;Identification of radon priority areas		Geographical;Voluntary;Grid cell	
IE_EPA2	Mean radon concentration of population		Grid cell;Population	
IE_EPA3	Other	Updating Ireland's national geographic weighted mean radon concentration	Geographical;Random;Grid cell	
IT_INAIL	Mean radon concentration of population;Other	Mean radon concentration in schools of the province	Geographical	
IT_ISS	Mean radon concentration of population;Identification of radon priority areas		Random;Other strategy;Population	The surveys were conducted in a random sample of homes of employees of a national company. This kind of survey can be considered as a proxy of a population representative survey (more

				details on Antignani et al., Rad Meas 50 (2013), 136–140
IT_ARPACAL	First idea of radon situation;Mean radon concentration of population;Mapping;Identification of radon priority areas		Geographical;Random;Grid cell;Administrative units;Population	
IT_APPATN1	Mean radon concentration of population		Voluntary;Random	
IT_APPATN2	Other	I don't know	Other strategy	all City Hall
IT_APPATN3	Other	Mean radon concentration of young students (less than 10 years)	Other strategy	All primary schools
IT_APPATN4	Other	mean radon concentration of students (approx. 11-13 years old)	Other strategy	secondary schools
IT_APPATN5	Other	mean radon concentration to students (approx. 14-19 years old)	Other strategy	high schools
IT_ARPALOMBARDIA1	Identification of radon priority areas		Grid cell	
IT_ARPALOMBARDIA2	Mean radon concentration of population;Other	this survey had several other purposes: assessing the representativeness of the previous survey (2003-2004), studying the effect of the floor on radon concentration, comparing the results of data analysis performed with simple statistic methods and with geostatistics,	Other strategy	We selected administrative units where the mean value of radon concentration was high, medium and low according to the results of the previous survey (2003-2004), then measurement points were casually extracted
IT_ISPRA1	First idea of radon situation;Mean radon concentration of population;Other	Frequency distribution	Random;Administrative units;Population	

IT_ISPRA2	Mean radon concentration of population;Mapping;Identification of radon priority areas		Geographical;Geological;Random;Grid cell;Administrative units;Population	
IT_ISPRA3	Other	legal obligations; protection of workers	Other strategy	measurements in public schools and workplaces-public buildings
IT_ARPAVDA	First idea of radon situation;Mean radon concentration of population;Mapping;Identification of radon priority areas		Geological;Voluntary;Administrative units;Population	
IT_ARPAER	Other	Evaluate the radon exposure of the preschool population in the Emilia-Romagna Region	Random	
IT_ARPAL1	First idea of radon situation	/	Geological;Grid cell	/
IT_ARPAL2	Other	Mean radon concentration of workers	Geological	/
IT_ARPAL3	Other	Mean radon concentration of workers	Geological	/
IT_ARPAP	Mean radon concentration of population;Mapping;Identification of radon priority areas		Geological;Random;Administrative units;Population	
LV_RSC	First idea of radon situation;Mapping;Identification of radon priority areas		Geological;Voluntary;Administrative units;Population	
LT_RPC	First idea of radon situation;Mean radon concentration of population;Mapping;Identification of radon priority areas		Already known radon priority areas;Geological;Voluntary;Random;Grid cell;Administrative units	
LU_MS.ETAT	First idea of radon situation;Mean radon concentration of population;Mapping;Other	passive houses	Random	

MT_EHD	Mean radon concentration of population;Mapping;Identification of radon priority areas		Geographical;Grid cell;Population	
MT_RPB	Mapping;Identification of radon priority areas		Grid cell	
NE_RIVM	Identification of radon priority areas;Other	representative distribution of radon across the country	Other strategy	representative for different building periods since 1930
NO_NRPA	Mean radon concentration of population	Not finally analysed yet	Random	
PL_IMP.LODZ1	Mean radon concentration of population;Other	correlation of radon concentration in homes with mutagenic effect of radon on	Random	
PL_IMP.LODZ2	Other	investigation of tourist route workers exposure	Other strategy	all underground tourist routes in Poland
RO_CNCAN	First idea of radon situation;Mean radon concentration of population;Mapping;Identification of radon priority areas		Geographical;Already known radon priority areas;Grid cell;Population	
RO_UBBCLUJ	First idea of radon situation;Mean radon concentration of population;Mapping;Identification of radon priority areas		Geographical;Already known radon priority areas;Grid cell;Population	
RS_DF.UNS	First idea of radon situation;Mapping;Identification of radon priority areas		Administrative units	
SI_SRPA	Mean radon concentration of population;Mapping		Already known radon priority areas	
ES_UNICAN	Mean radon concentration of population;Mapping;Identification of radon priority areas		Geographical;Geological;Random;Administrative units;Population;Already known radon priority areas;Grid cell	

UK_PHE	First idea of radon situation;Mean radon concentration of population;Identification of radon priority areas;Other	To determine the magnitude of individual exposures and those with unduly high results so that the need for standards could be asessesed - further details in NRPB report R190 (1988)	Population	

2.8 Which building types have you considered in your survey? Please indicate the percentages for each type:

2.8a Dwellings; 2.8b schools; 2.8c Kindergartens; 2.8d Workplaces-general; 2.8e Workplaces-public buildings; 2.8f Caves/mines; 2.8g Multi-family buildings; 2.8 Other

ID	2.8a	2.8b	2.8c	2.8d	2.8e	2.8f	2.8g	2.8h	Please specify 'Other'
AL_IANP	10	3		3					
AT_AGES1	100								
AT_AGES2					100				
AT_AGES3			100						
AT_AGES4		100							
AT_AGES5	100								
AT_AGES6	100								
AT_AGES7						100			
AT_AGES8	100								
BY_JINPR	96	1	1		2				
BE_FANC	100	0	0	0	0	0	0	0	
BE_ISIB	98	1		1					
HR_FIZIKA.UNIOS	85						15		
CY_DLI.MLSI	50	30			20				
CZ_SURO	100								
FI_STUK	79						21		We understood 2.8g as apartment building
DE_BFS	100								
GR_AUTH	100					100			

GR_EEAE	100								
IE_EPA1	100								
IE_EPA2	100								
IE_EPA3	100								
IT_INAIL		100							
IT_ISS	100								
IT_ARPACAL	38	25	5	5	26	1			
IT_APPATN1	100	0	0	0	0	0	0		
IT_APPATN2	0	0	0	0	100	0	0		
IT_APPATN3	0	100	0	0	0	0	0		
IT_APPATN4	0	100	0	0	0	0	0		
IT_APPATN5	0	100	0	0	0	0	0		
IT_ARPALOMBARDIA1	48	14		38					
IT_ARPALOMBARDIA2	100								
IT_ISPRA1	100								
IT_ISPRA2	100								
IT_ISPRA3		70			30				
IT_ARPAVDA	75	19		4	2				
IT_ARPAER			30						
IT_ARPAL1	100	0	0	0	0	0	0	0	/
IT_ARPAL2	0	0	0	0	0	100	0	0	/
IT_ARPAL3	0	0	0	0	0	100	0	0	/
IT_ARPAP	61.4	31.5			7.1				
LV_RSC	65	14	10	11					
LT_RPC	82	1.5	1.5	1	1	0	11		
LU_MS.ETAT	100								
MT_EHD	60	20		4	16				
MT_RPB	62.4	20	0	17.6	0	0	0	0	
NE_RIVM	76						13	11	caravan, houseboat, independent elderly homes + unknown
NO_NRPA	90						10		
PL_IMP.LODZ1	66.6			33.3					
PL_IMP.LODZ2	66.6			100		100			
RO_CNCAN	95	4.6	0.3		0.1	0.1	0.1		
RO_UBBCLUJ	95	4.4	0.3		0.1	0.1	0.1		

RS_DF.UNS	100	20	20						
SI_SRPA	30	25	25	8	10	2	0		
ES_UNICAN	100								
UK_PHE	100	0	0	0	0	0	0	0	

2.9 Have you chosen a preferred measurements locations in dwellings? Please indicate the percentage:

2.9a Basement; 2.9b Ground floor; 2.9c First floor; 2.9d Other; Please specify 'Other'

ID	**2.9a**	**2.9b**	**2.9c**	**2.9d**	**Please specify 'Other'**
AL_IANP		60	40		
AT_AGES1					
AT_AGES2					preferable measurements in the Offices with the longest occupancy time of employees in the lowest floors (preferable rooms with direct contact to ground - "earth bound")
AT_AGES3					preferable measurements in the rooms with direct contact to ground ("earth bound") where children spend time
AT_AGES4				100	class room in direct contact with ground (earth-bound)
AT_AGES5					
AT_AGES6					
AT_AGES7				100	At places within the visitor mine/cave, where workers/guides spend time
AT_AGES8	70				
BY_JINPR		100			
BE_FANC	0	100	0	0	
BE_ISIB		100			Small percentage of data available from basement or floors higher than ground floor, but only GF data are kept in the database
HR_FIZIKA.UNIOS		85	15		
CY_DLI.MLSI	30	50		20	Long-term closed rooms/stores
CZ_SURO					no - randomly chosen addresses (flats)
FI_STUK		100			in apartment buildings on the floor where the apartment is
DE_BFS		100			

GR_AUTH				100	third and fourth floor
GR_EEAE		95		5	other floors
IE_EPA1					Main bedroom and main living room
IE_EPA2				100	Main living area and main bedroom
IE_EPA3				100	Main bedroom and main living room
IT_INAIL	25	50	25		
IT_ISS					
IT_ARPACAL					
IT_APPATN1	0	36	27	37	mezzanine and second floor
IT_APPATN2	1	26	50	23	mezzanine, second floor
IT_APPATN3	5	24	48	23	mezzanine, second floor
IT_APPATN4	31	38	17	14	mezzanine, second and third floor
IT_APPATN5	28	31	9	33	mezzanine, second floor
IT_ARPALOMBARDIA1		100			
IT_ARPALOMBARDIA2	3	41	38	18	Second, third, fourth floors
IT_ISPRA1				100	random in bedrooms
IT_ISPRA2					
IT_ISPRA3					No dwellings. In schools and public buildings: 100 % basement, 100 % ground floor.
IT_ARPAVDA	6	66	24	3	second floor
IT_ARPAER	4	80	15	1	> first floor
IT_ARPAL1	0	94	3	3	Second floor
IT_ARPAL2	0	0	0	0	/
IT_ARPAL3	0	0	0	0	/
IT_ARPAP	12.9	62.8	19.3	5	
LV_RSC	1	99			
LT_RPC	2	85	5	8	
LU_MS.ETAT		100			
MT_EHD		100			
MT_RPB	0	100	0	0	
NE_RIVM	0	89		11	depends on living floor in multi-family buildings
NO_NRPA					

PL_IMP.LODZ1		80	20		
PL_IMP.LODZ2	100	80	20		
RO_CNCAN	0.1	94.9	5		
RO_UBBCLUJ	0.1	94.9	5		
RS_DF.UNS	20	74			
SI_SRPA	30	60	10		
ES_UNICAN				100	Possibility of placement in basement, ground floor or first floor: where the inhabitants made their daily life
UK_PHE	0			100	Two detectors: Main Living area and Bedroom (independent of floor level)

2.10 Please select which method you chose for distributing the detectors: LIST
Please specify 'Other'

2.11 Have you collected information about the measurement site through a questionnaire?

2.12 Please indicate which kind of information you have asked for the questionnaire? (LIST)

ID	2.10	Other	2.11	2.12	Other
AL_IANP	Personally delivered and collected		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Living habits;Occupational rate	
AT_AGES1	Mail;Personally delivered and sent back by the participants;Personally delivered and collected		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Number of inhabitants;Occupational rate;Other	year of construction, floor number, tightness of windows
AT_AGES2	Mail		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Heating system;Other	number of floors, Basement yes/no, construction year, Windows
AT_AGES3	Mail;Personally delivered and collected	First Phase of Survey: Detectors sent by post to all participants (644); Second	Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction	number of floors, Basement yes/no, construction year, Windows

		Phase: On-site inspection and start of measurements (active, electret) in Kindergartens with higher Radon concentration in first measurement (33)		material;Heating system;Ventilation habits;Other	
AT_AGES4	Mail		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Heating system;Ventilation habits;Remediation performed	Year of construction, Type of School, Number of floors,
AT_AGES5	Personally delivered and collected		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants	year of construction, floor number, tightness of windows
AT_AGES6	Personally delivered and sent back by the participants		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants;Other	Year of construction, floor number, tightness of windows
AT_AGES7	Personally delivered and collected		No		
AT_AGES8	Personally delivered and collected		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Heating system;Number of	year of construction, floor number, earth bound (does the building have a

				inhabitants;Remediation performed	Basement), tightness of windows
BY_JINPR	Personally delivered and sent back by the participants;Personally delivered and collected		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Heating system;Ventilation habits;Other	Basement depth, water supply
BE_FANC	Personally delivered and sent back by the participants		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Living habits;Heating system;Ventilation habits;Number of inhabitants;Smoking habit	
BE_ISIB	Mail;Personally delivered and sent back by the participants;Personally delivered and collected;Other	delivered and collected by school teachers	Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Ventilation habits;Smoking habit;Other	soil/subsoil nature, presence of basement or crawl space Under the measured room
HR_FIZIKA.UNIOS	Mail		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Number of inhabitants;Occupational rate;Smoking habit	
CY_DLI.MLSI	Personally delivered and collected		No		
CZ_SURO	Mail		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction	

				material;Heating system;Number of inhabitants	
FI_STUK	Mail		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Heating system;Ventilation habits;Remediation performed;Other	foundation and base floor stucture (this is most important factor affecting radon concentration)
DE_BFS	Personally delivered and sent back by the participants		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Ventilation habits;Other	year of construction, type of construction, existing of basement, thermal insulation, humidity protection, kind of the foundation, situation of humidity in basement
GR_AUTH	Personally delivered and collected		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants;Occupational rate	
GR_EEAE	Mail		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Smoking habit	

IE_EPA1	Mail		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Other	House age, type of water supply
IE_EPA2	Mail		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Smoking habit;Other	Build date of dwelling, type of ground floor construction, type of windows, has insulation been added and if so when
IE_EPA3	Mail		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Smoking habit;Other	Build date of dwelling, type of ground floor construction, type of windows, has insulation been added and if so when
IT_INAIL	Personally delivered and sent back by the participants		Yes	Construction material;Heating system;Ventilation habits;Occupational rate	school type, age of construction
IT_ISS	Mail;Other	The company internal mail service was used to send/receive detectors	Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants;Smoking habit;Other	Several questions were equal to some reported in the Italian Census questionnaire. It allows to check if the sample can be considered representative of the whole Italian population.
IT_ARPACAL			Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of	

				inhabitants;Occupational rate;Remediation performed	
IT_APPATN 1	Other	not known	Yes	Construction material;Other	building year, frame quality, room type
IT_APPATN 2	Other	I don't know	No		
IT_APPATN 3	Other	I don't know	Yes	Construction material	building year, frame quality
IT_APPATN 4			Yes	Construction material	building year, frame quality
IT_APPATN 5	Other	I don't know	Yes	Construction material	building year, frame quality
IT_ARPALOMBARDIA1	Other	Detectors were delivered and collected by local public health organizations	Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Heating system;Ventilation habits	Caracteristics of the building
IT_ARPALOMBARDIA2	Other	delivered and collected by local public health organizations	Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Heating system;Ventilation habits;Smoking habit;Other	Characteristics of the building
IT_ISPRA1	Personally delivered and collected		Yes	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants;Occupational rate;Other	floor, year of construction.

IT_ISPRA2	Mail;Personally delivered and collected			House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants;Occupational rate;Smoking habit	floor; year of construction
IT_ISPRA3	Personally delivered and collected			Construction material;Heating system;Number of inhabitants;Occupational rate;Other	information on floor-soil contact, year of construction of the building
IT_ARPAVDA	Personally delivered and collected		66	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants;Occupational rate;Remediation performed;Other	Type of window frames
IT_ARPAER	Other	The detectors were personally delivered and collected by health personnel from the region (Public Hygiene Services)	80	Construction material;Heating system;Occupational rate;Other	N° floors of the building, year of construction
IT_ARPAL1	Personally delivered and collected	/	94	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation	/

				habits;Number of inhabitants;Occupational rate	
IT_ARPAL2	Personally delivered and collected	/	0		/
IT_ARPAL3	Personally delivered and collected	/	0		/
IT_ARPAP	Personally delivered and collected		62.8	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Remediation performed;Other	windows type
LV_RSC	Personally delivered and sent back by the participants;Personally delivered and collected;Other	Organised distribution and collection of detectors in 8 SES structural units across all country.	99	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants;Occupational rate;Smoking habit;Other	
LT_RPC	Personally delivered and collected		85	House type (villa, semi-detached, apartment, multi-family etc.);Construction material	"the questionnaire was changed, and now we are collecting more information, online registration form is placed on our web site.
LU_MS.ETAT	Mail		100	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Ventilation	

				habits;Number of inhabitants;Remediation performed	
MT_EHD	Personally delivered and collected		100		https://docs.google.com/forms/d/e/1FAIpQLSeHg0dizCySj5b9mi_MSPzV9xpqvWyrDk8PGjZLV7M4btoDdA/viewform"
MT_RPB	Personally delivered and collected		100		
NE_RIVM	Mail		89	House type (villa, semi-detached, apartment, multi-family etc.);Ventilation habits;Smoking habit;Other	
NO_NRPA	Mail			House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Remediation performed;Other	
PL_IMP.LODZ1	Personally delivered and collected		80	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Occupational rate;Smoking habit	size and shape of measurement room/space
PL_IMP.LODZ2	Mail		80	Number of inhabitants;Occupational rate	water supply

RO_CNCAN	Personally delivered and sent back by the participants		94.9	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants;Occupational rate;Smoking habit;Remediation performed;Other	
RO_UBBCLUJ	Personally delivered and collected		94.9	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants;Occupational rate;Smoking habit;Remediation performed;Other	
RS_DF.UNS	Personally delivered and collected		74	House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Number of inhabitants;Occupational rate	Indoor air quality and thermal comfort, residents' level of satisfaction with indoor air quality, humidity, temperature, medical issues, etc.
SI_SRPA	Mail;Personally delivered and sent back by the participants		60	House type (villa, semi-detached, apartment, multi-family etc.);Living habits;Number of inhabitants;Occupational rate;Remediation performed	Indoor air quality and thermal comfort, residents' level of satisfaction with indoor air quality, humidity, temperature, medical issues, etc.

ES_UNICAN	Mail;Personally delivered and sent back by the participants;Personally delivered and collected			Construction material;Living habits;Ventilation habits;Number of inhabitants	
UK_PHE	Mail			House type (villa, semi-detached, apartment, multi-family etc.);Construction material;Living habits;Heating system;Ventilation habits;Number of inhabitants;Other	

2.13 Representativeness:

2.13a Has representativeness been target?

2.13b Has representativeness been achieved to a sufficient degree?

2.13c If applicable: how has representativeness been assessed?

2.13d If assessed as not representative: which type or source of bias is believed to be present?

2.13e If representativeness was not achieved: any corrections or models applied to guarantee unbiased estimated over estimation support?

ID	2.13a	2.13b	2.13c	2.13d	2.13e
AL_IANP					
AT_AGES1	Yes	Yes	comparison with national census data		
AT_AGES2	Yes	Yes	Representativeness for administrative buildings in Upper Austria (459) - 93 % of all administrative buildings (425) participated		
AT_AGES3	Yes	Yes	Representativeness for Upper Austrian Kindergartens; 99 % of all Schools were measured (633 of 712)		

AT_AGES4	No				
AT_AGES5	Yes	Yes	Measurement of 92 % of all dwellings in 3 municipalities - representative for these municipalities		
AT_AGES6	Yes	No		Aim: Measure all dwellings in the municipality, but only about 50 % were measured	no
AT_AGES7	Yes	Yes			
AT_AGES8	No				
BY_JINPR	Yes	Yes			
BE_FANC	No				
BE_ISIB	No				
HR_FIZIKA. UNIOS	Yes	Yes	by comparison with data from national census		
CY_DLI.MLS I	Yes	Yes	About 67 % of the total population of the country live in the urban areas covered by this survey.		
CZ_SURO	Yes	Yes	number of houses (family houses and block of flats) in districts compared with the census		
FI_STUK	Yes	Yes	statistical methods		
DE_BFS	Yes				
GR_AUTH					
GR_EEAE	Yes	No		seasonal variation, building characteristics, population	seasonal correction based on measurements, floor and population weighted mean
IE_EPA1	Yes	Yes	Survey was geographically based with measurements carried out using the Irish national grid of 10 km x 10 km grid squares		
IE_EPA2	Yes	Yes	Stratified sampling by population was carried out based on small area population data and the results for stratified sample groups were checked for log normality		
IE_EPA3	Yes	Yes	Stratified sampling by radon risk category and geographic area was carried. The results for stratified samples were checked for outliers, log normality and bias due to duration of measurement.	Homes are not representative of those used in the 2002 National Radon Survey	A weighting factor was applied.
IT_INAIL	Yes	Yes	all the schools of the target area have been measured		
IT_ISS	Yes		The analysis is on-going		If the representativeness is not achieved, we are planning to

					correct data by the means of weighting factors that take into account the possibility (for examples) that some kind of buildings were oversampled.
IT_ARPACAL	Yes	Yes			
IT_APPATN1	No				
IT_APPATN2	No				
IT_APPATN3	No				
IT_APPATN4	No				
IT_APPATN5	No				
IT_ARPALOMBARDIA1	Yes	Yes	The representativeness was assessed with a second survey		
IT_ARPALOMBARDIA2	Yes	Yes	comparing the results of this survey with the ones of the previous survey (2003-2004)		
IT_ISPRA1					
IT_ISPRA2					
IT_ISPRA3	No				
IT_ARPAVDA	No	No	REGION: Aosta Valley is the smallest, least populous, and least densely populated region of Italy. Resident population(01/01/2016): 127.319 inhabitants Municipalities: 74 Average population density: 39 inhabitants/km2 Covered area: 3263 km2 Average altitude: 2100 m METHODS: •Campaign carried out on municipal basis. •Dosimeters are placed in one dwelling per 100 inhabitants, with a minimum, for smaller municipalities, of 10 homes •Dwellings chosen to ensure the coverage of the entire		

			municipal territory Data are collected in order to achieve a territorial mapping of radon distribution.		
IT_ARPAER					
IT_ARPAL1	No	No	/	Data number insufficiency	None
IT_ARPAL2	Yes	Yes	/	/	None
IT_ARPAL3	Yes	Yes	/	/	None
IT_ARPAP	Yes	Yes	See specific publications		
LV_RSC	No				
LT_RPC	Yes	Yes	not assessed		
LU_MS.ETAT	Yes	Yes	houses selected randomly in 2 different geographical units		
MT_EHD					
MT_RPB					
NE_RIVM	Yes	Yes	1. random selection took place in complete housing stock; 2. number of dwellings in survey was compared with no. in housing stock per period of 10 years		
NO_NRPA	Yes	No		Less People in multifamily homes responded	Corrections will be made
PL_IMP.LODZ1	Yes	Yes	By a random choose of the habitant		
PL_IMP.LODZ2	Yes	Yes	By asking for help all underground tourist routes		
RO_CNCAN	Yes	Yes	Our major objective was to measure radon concentrations in a large number of buildings, with passive detectors systematically distributed in ground floor rooms of each surveyed house in order to develop and implement the most effective remedial techniques to reduce indoor radon levels and associated lung cancer risks. In the framework of the SMART_RAD_EN project, the Romanian indoor radon map was extended this year with new data displayed on the map, for five major agglomerations with a high density of population and settlements. The local grids cover in details our major populated areas from Romania, as a combination of	The design of our survey was establish as a compromise between our main research interests and objectives and the technical resources. Due to lack of financial support, some areas were not integrally covered in the previously researches, according to population density.	The design of our survey was establish as a compromise between our main research interests and objectives and the technical resources. Due to lack of financial support, some areas were not integrally covered in the previously researches, according to population density.

			geographically based and population-weighted survey. We apply door-to-door methodology in our measurements campaigns and we include a large number of ground-floor houses in our survey in each agglomeration, from both urban and rural area.		
RO_UBBCL UJ	Yes	No	Our major objective was to measure radon concentrations in a large number of buildings, with passive detectors systematically distributed in ground floor rooms of each surveyed house in order to develop and implement the most effective remedial techniques to reduce indoor radon levels and associated lung cancer risks.In the framework of the SMART_RAD_EN project, the Romanian indoor radon map was completed this year with new data displayed on the map, for five major agglomerations with a high density of population and settlements. The local grids cover in details our major populated areas from Romania, as a combination of geographically based and population-weighted survey. We apply door-to-door methodology in our measurements campaigns and we include a large number of ground-floor houses in our survey in each agglomeration, from both urban and rural area.	The design of our survey was establish as a compromise between our main research interests and objectives and the technical resources. Due to lack of financial support, some areas were not integrally covered in the previously researches, according to population density.	The design of our survey was establish as a compromise between our main research interests and objectives and the technical resources. Due to lack of financial support, some areas were not integrally covered in the previously researches, according to population density.
RS_DF.UNS					
SI_SRPA	No	No			
ES_UNICAN	Yes	No			
UK_PHE	Yes	Yes	Sample selection was based on the address file of all homes in the UK - a 1 in n sample was taken from the listing. Resultatant questionnaires were checked against national statistics for house type etc	A non-biased sample of homes was selected for invitation to test but householders chose to take part, this resulted in bias toward deteched homes compared to the standard housing stock	Corrections were applied to account for the bias at the analysis stage

2.14 Has the survey be designed according to statistical reasoning?

2.15 If Yes in 2.14, please describe the estimation support and target quantity for the survey:

2.15a Estimation support; 2.15b Target quantity (arithmetic mean, geometrical mean, % above reference level, etc.); 2.15c Target uncertainty score; 2.15d Mean achieved uncertainty; 2.15e Specifications

ID	2.14	2.15a	2.15b	2.15c	2.15d	2.15e
AL_IANP						
AT_AGES1		Municipality	AM of Radon potential (Annual mean Radon concentration in a Standard Situation)			
AT_AGES2	No					
AT_AGES3	No					
AT_AGES4	No					
AT_AGES5	No					
AT_AGES6	No					
AT_AGES7	No					
AT_AGES8	No					
BY_JINPR	No					

BE_FANC	Yes	municipalities	% > AL	?	?	ground floor single family houses
BE_ISIB		geological unit	geometrical mean & % above reference level			
HR_FIZIKA.UNIOS	No					
CY_DLI.MLSI	Yes	According to population occupancy. Schools, workplaces, houses in urban areas.				
CZ_SURO	Yes	Districts	geometric mean	10 %	5 to 15 %	0,1 % of the building stock spread according the census accross all 76 districts
FI_STUK	No					
DE_BFS	Yes	Germany, all dwellings	arithmetic mean; geometrical mean; % above reference level	0.05; 0.05; 0.01		All dwellings
GR_AUTH	No					
GR_EEAE	Yes	region	arithmetic mean, geometrical mean, % above reference level	arithmetic mean: less than 20 % of 90 % conf. int.	the survey is ongoing	bedroom and living room of dwellings
IE_EPA1	Yes	Map of radon risk, geographic weighted national average and	% above reference level, arithmetic mean			

		population weighted national average				
IE_EPA2	Yes	Objective of the survey is to establish the current population weighted national average radon concentration (arithmetic mean) for Ireland using a random sample of homes stratified by population density. The number of homes selected from the targeted areas were chosen to achieve a standard deviation of 3.5 Bq/m3. The achieved uncertainty is between 91 and 106 Bq/m3 (95% confidence interval).	Arithmetic mean			
IE_EPA3	Yes	Current national geographic weighted national average radon concentration. The number of homes selected from the targeted areas were chosen to achieve a sufficient level of accuracy which is a standard deviation of 3.5 Bq/m3.	Arithmetic mean			
IT_INAIL	No					
IT_ISS	Yes	All the Italian Provinces	Arithmetic mean, geometric mean, geometric standard	The sample size was chosen (of about 6000) in order to have a	The analysis in still on going. But considering that the refusals	

			deviation and % above reference level	precision of about 20 % on geometric and arithmetic mean.	and the loss of detectors were quite low, the achieved uncertainty will be probably not different from the target uncertainty score	
IT_ARPACAL	Yes					
IT_APPATN1	No					
IT_APPATN2	No					
IT_APPATN3	No					
IT_APPATN4	No					
IT_APPATN5	No					
IT_ARPALOMBARDIA1	Yes	Units of grid with three different dimensions: standard 8 km x 5 km; in plain: 16 km x 10 km; in mountain areas 4 km x 2,5 km	% above reference levels (400 Bq/m3 and 200 Bq/m3)			5 -10 measurement points were selected in each grid unit
IT_ARPALOMBARDIA2						
IT_ISPRA1	Yes	national and regional administrative boundaries	average concentration weighted for the		standard error: national 1.4 %; regional 2-14%	

			population; % above reference levels		(68 % conf. int.)	
IT_ISPRA2	Yes	municipal boundaries; square grid;	Municipal boundaries: arithmetic mean; Square grid: geometric mean, % above reference level		standard error (68 %conf. int.) : 6-59 %	
IT_ISPRA3	No					
IT_ARPAVDA	No					
IT_ARPAER						
IT_ARPAL1	No	/	/	/	/	/
IT_ARPAL2	No	/	/	/	/	/
IT_ARPAL3	No	/	/	/	/	/
IT_ARPAP	Yes		Arithmetic mean, % above given level, log-normal distribution			
LV_RSC	No					
LT_RPC	No					
LU_MS.ETAT	No					
MT_EHD						
MT_RPB						

NE_RIVM	Yes	housing stock in 10-year periods (since 1930)	arithmetic mean	within factor 2-3 (90 % conf. interval) [low values have large variations]		(ground floor) living room
NO_NRPA	No					
PL_IMP.LODZ 1	No		arithmetic mean,	between 20 and 30 %		a dwelling and workplace if applicable
PL_IMP.LODZ 2	No		arithmetic mean,	between 20 and 30 %		underground tourist routes/ mines, post military buildings, caves, urban underground tourist places
RO_CNCAN	Yes	estimation support = district/ county	AM arithmetic mean, % above reference level	between 15 and 20 % of 90 % conf. int.		
RO_UBBCLUJ	Yes	estimation support = district/ county	AM arithmetic mean, % above reference level	between 15 and 20 % of 90 % conf. int.		
RS_DF.UNS						
SI_SRPA	No					
ES_UNICAN	No					
UK_PHE	No					

Annex2_Section 3

3.1 Which kind of detector have you used? Please indicate the percentage of the measurements (%):

ID	Track etch – CR39	Track etch – LR-115	Charcoal/gamma spectrometry	Charcoal/ LSC	Electret	Active	Other	Specify 'other'
AL_IANP								
AT_AGES1	33			49	18			
AT_AGES2	100							
AT_AGES3				92	7	1		
AT_AGES4	50				50			
AT_AGES5	100							
AT_AGES6	100							
AT_AGES7						100		
AT_AGES8	100							
BY_JINPR		100						
BE_FANC							100 %	track etch Makrofol
BE_ISIB	12 %		85 %				3 %	track etch makrofol
HR_FIZIKA.UNIOS		100						
CY_DLI.MLSI						100		
CZ_SURO		100						
FI_STUK							100	Makrofol SSNDT, two subsequent measurements each 6 months
DE_BFS	0 - 100	0 - 100					0 -100	MACROFOL, type of detector depends from the outcome of the tender process
GR_AUTH	100	100						
GR_EEAE	100							
IE_EPA1	100							
IE_EPA2	100							

IE_EPA3	100							
IT_INAIL	97				3			
IT_ISS	100 %							
IT_ARPACAL	90				10			
IT_APPATN1		80			20			
IT_APPATN2		100						
IT_APPATN3		100						
IT_APPATN4		100						
IT_APPATN5		100						
IT_ARPALOMBARDIA1	100							
IT_ARPALOMBARDIA2	100							
IT_ISPRA1	n.d.	n.d. (majority)						
IT_ISPRA2	100							
IT_ISPRA3	100							
IT_ARPAVDA		100						
IT_ARPAER		100						
IT_ARPAL1	100	0	0	0	0	0	0	/
IT_ARPAL2	0	100	0	0	0	0	0	/
IT_ARPAL3	0	100	0	0	0	100	0	/
IT_ARPAP	70.6	29.4						
LV_RSC	100							
LT_RPC					100			
LU_MS.ETAT	100							
MT_EHD								alpha-track detectors using Kodak LR115 film,
MT_RPB		100						
NE_RIVM	100							
NO_NRPA	100							
PL_IMP.LODZ1	100 %	50						
PL_IMP.LODZ2	100 %	100 %						
RO_CNCAN	100 %							
RO_UBBCLUJ	100							

RS_DF.UNS	80		20					
SI_SRPA	90				10			
ES_UNICAN	100 %							
UK_PHE	100							

3.1 Which kind of detector have you used? Please indicate the duration of the measurements (months):

ID	Track etch – CR39	Track etch – LR-115	Charcoal/gamma spectrometry	Charcoal/ LSC	Electret	Active	Other	If active specify	If LR-115 specify
AL_IANP	3								
AT_AGES1	3		3 days		3				
AT_AGES2	6								
AT_AGES3			2 times 3 days (during week, during Weekend)		6			Alpha Guard	
AT_AGES4	4				4				
AT_AGES5	6								
AT_AGES6	4								
AT_AGES7						6 + 6		Alpha Guards, EQF 3120 (Sarad), RTM (Sarad), Radim 3A, Radim 5	
AT_AGES8	6								
BY_JINPR		3							Closed
BE_FANC			3-4 days				3		
BE_ISIB	3						3		
HR_FIZIKA.UNI		12							Closed
CY_DLI.MLSI						3+3			
CZ_SURO		12							Open
FI_STUK							12		
DE_BFS	12								Closed

GR_AUTH	2	2							Open;Closed
GR_EEAE	6								
IE_EPA1	12								
IE_EPA2	3								
IE_EPA3	3								
IT_INAIL	12				6				
IT_ISS	12								
IT_ARPACAL	6				6				
IT_APPATN1		12			12				
IT_APPATN2		12							
IT_APPATN3		9							
IT_APPATN4		7							
IT_APPATN5		9							
IT_ARPALOMBA	12								
IT_ARPALOMBA	12								
IT_ISPRA1	12 (6+6)	12 (6+6)							Closed
IT_ISPRA2	12 (2 periods)								
IT_ISPRA3	12 schools: 3+3+6 public buildings: 6+6								
IT_ARPAVDA		6+6							Closed
IT_ARPAER		6							Closed
IT_ARPAL1	12	/	/	/	/	/	/	/	
IT_ARPAL2	/	16	/	/	/	/	/	/	Closed
IT_ARPAL3	/	9	/	/	/	9	/	Portable Radiation Monitor Pylon Model AB-5 coupled with Lucas Cells Model 300A or Model CPRD	Closed
IT_ARPAP	12 (6+6)	12 (6+6)							Closed
LV_RSC	4-10								
LT_RPC			21-28 days		1				

LU_MS.ETAT									
MT_EHD									
MT_RPB		2 issues of 6 months							
NE_RIVM	12								
NO_NRPA	12								
PL_IMP.LODZ1	3month or 1 year for dwellings 1 month for workplaces								Open
PL_IMP.LODZ2	1-2								Open
RO_CNCAN	3-6							*	
RO_UBBCLUJ	3-6 months							*	
RS_DF.UNS	3		2 days						
SI_SRPA	1-2				7days			Alphaguard (Saphymo), RAD7(Urridge), Canary Pro (Airthines), Alpha E (Saphymo)	
ES_UNICAN	3 months-								
UK_PHE	2 x 6 months								

* Active instruments were used for the diagnostic measurements and the testing of the remedial efficiency (between and after mitigation) in 21 houses of Stei-Baita radon priority area. Our active detectors are: an ALPHAGUARD PQ 2000 radon detector (Genitron Instruments GmbH, Germania, 2010) –allows simultaneous monitoring for temperature, pressure, humidity and radon progenies.
A RAD7 radon and thoron detector (DURRIDGE Company, USA, 2010).
Five RADIM electronic devices (JiríPlch-SMM Company, Prague, Czech Republic, 2003-2012) for radon measurements and radon exhalation.
Four LuK 3A-C devices (JiríPlch-SMM Company, Prague, Czech Republic, 1996-2012) and their additional components used for radon measurements in soil and water and for emanation rate measurements from soil and construction materials.
Two RTM 1688-2 Radon/ Thoron Gas Monitor (SARAD, 2016)
Two Soil radon monitoring systems RM – 2 (RadonVos, 2016)
RADON-JOK equipment for in situ permeability measurements (Radon VOS, Prague, Czech Republic, 2011).
Eight SARAD instruments (Sarad GmbH, Dresden, Germany, 2010) for radon detection.
Eight RAMON integrated electronic measuring devices (Ramon 2.2, Norway, 2005 and 2010).
Doseman Pro personal dosimeter (Sarad, 2002) for radon progeny measurements.
Two dosimeters for air gamma dose rates measurements (Geiger Gamma-Scout detector, 2012).

One TESTO complete equipment for calculating the thermal resistance of the walls (Testo, 2016)
Four Portable Meter for indoor air quality, (IAQ) - CO_2 + CO + RH/T (CO2 Meter, 2016)

3.2a If applicable, please indicate the season in which the measurements have been performed (multiple seasons are allowed):

ID	3.2a	Please specify 'Other' (i.e. only in heating season)
AL_IANP	Winter;Spring	
AT_AGES1	Winter;Spring;Summer;Autumn	
AT_AGES2	Winter;Spring;Summer	6 months measurement, half winter, half summer
AT_AGES3	Winter	winter for short term measurements; winter/summer for long term
AT_AGES4	Winter;Spring;Summer;Autumn	
AT_AGES5	Winter;Spring;Summer;Autumn	
AT_AGES6	Winter;Spring	
AT_AGES7	Winter;Summer;Autumn	
AT_AGES8	Winter;Spring;Summer;Autumn	
BY_JINPR	Winter;Spring;Autumn	
BE_FANC	Winter;Spring;Autumn	
BE_ISIB	Winter;Spring;Autumn	
HR_FIZIKA.UNIOS	Other	one year of exposure
CY_DLI.MLSI	Winter;Summer	
CZ_SURO	Other	one year
FI_STUK	Other	two subsequent measurements each 6 months
DE_BFS	Other	12 months
GR_AUTH	Winter;Spring;Summer;Autumn	
GR_EEAE	Winter;Spring;Summer;Autumn	
IE_EPA1	Other	One year measurement period
IE_EPA2	Winter;Autumn;Other	Three month measurement period when seasonal correction factors are close to
IE_EPA3	Winter;Autumn	Three month measurement period when seasonal correction factors are close to
IT_INAIL	Winter;Spring;Summer;Autumn	
IT_ISS		
IT_ARPACAL	Winter;Summer	
IT_APPATN1		
IT_APPATN2		
IT_APPATN3	Other	from september to june
IT_APPATN4		from october to may

IT_APPATN5	Other	from september to june
IT_ARPALOMBARDIA1		
IT_ARPALOMBARDIA2		
IT_ISPRA1	Winter;Spring;Summer;Autumn	
IT_ISPRA2	Winter;Spring;Summer;Autumn	
IT_ISPRA3	Winter;Spring;Summer;Autumn	
IT_ARPAVDA	Winter;Spring;Summer;Autumn	
IT_ARPAER	Other	Winter semester
IT_ARPAL1	Winter;Spring;Summer;Autumn	/
IT_ARPAL2	Winter;Spring;Summer;Autumn	/
IT_ARPAL3	Winter;Spring;Summer	/
IT_ARPAP		
LV_RSC	Winter;Spring;Summer;Autumn	
LT_RPC	Winter	heating season, usually it'is winter
LU_MS.ETAT	Winter;Spring;Autumn	
MT_EHD	Winter;Summer	
MT_RPB	Winter;Summer;Other	Each site issued two Track etch detectors periods: Nov 2010 to June 2011
NE_RIVM	Winter;Spring;Summer;Autumn	
NO_NRPA	Other	One year measurements
PL_IMP.LODZ1	Winter;Spring;Summer;Autumn	
PL_IMP.LODZ2	Spring	
RO_CNCAN	Winter;Spring;Summer;Autumn	
RO_UBBCLUJ	Winter;Spring;Summer;Autumn	
RS_DF.UNS	Winter;Spring;Autumn	
SI_SRPA	Winter;Other	
ES_UNICAN	Winter;Spring;Summer;Autumn	
UK_PHE	Winter;Spring;Summer;Autumn	

3.3 If you have you performed parallel measurements at the same location, please indicate the purpose of these measurements and which percentage of the total measurements is concerned:

3.3a Purpose; 3.3b Track etch-CR39; 3.3c Track etch-LR-115; 3.3d Charcoal/gamma spectrometry; 3.3e Charcoal/LSC; 3.3f Electret; 3.3g Active; 3.3h Other

ID	3.3a	3.3b	3.3c	3.3d	3.3e	3.3f	3.3g	3.3h
AL_IANP								
AT_AGES1	2 measurements (rooms) per dwelling; for Charcoal each measurement (room) consist of 2 measurements, placed next to each other for QA				100			
AT_AGES2								
AT_AGES3	Outlier					100		
AT_AGES4	QA, Large and small Diffusion chamber					100		
AT_AGES5								
AT_AGES6								
AT_AGES7								
AT_AGES8								
BY_JINPR								
BE_FANC								
BE_ISIB								
HR_FIZIKA.UNIOS	to assess precision of radon measurement detectors; 10 % of duplicate detectors were exposed		100					
CY_DLI.MLSI	consideration of seasonal variations						70	
CZ_SURO								
FI_STUK								
DE_BFS								
GR_AUTH								
GR_EEAE	adjustment of model parameters to achieve unbiased estimation	100						
IE_EPA1								
IE_EPA2	None							

IE_EPA3	None							
IT_INAIL	a pilot study perfomed in a restricted sample of schools (10 % of school buildings) to achieve preliminary information about radon distribution					100		
IT_ISS								
IT_ARPACAL	comparison of instrument	5				5		
IT_APPATN1								
IT_APPATN2								
IT_APPATN3								
IT_APPATN4								
IT_APPATN5								
IT_ARPALOMBARDIA1	Couples of detectors were positioned one near the other to check repeatability of the method	10						
IT_ARPALOMBARDIA2	couples of detectors were used to check repeatibility	8						
IT_ISPRA1	better estimate of value		100					
IT_ISPRA2								
IT_ISPRA3	no parallel measurements in the same location but parallel measurements in different rooms of the same building. In order to know the annual mean concentration of the specific room.							
IT_ARPAVDA	Comparison	2.5						
IT_ARPAER								
IT_ARPAL1	/	0	0	0	0	0	0	0
IT_ARPAL2	/	0	0	0	0	0	0	0
IT_ARPAL3	Comparison of different measurement methods	0	100	0	0	0	100	0
IT_ARPAP	Remediation						1	
LV_RSC	To check detector and measurement service quality	0.2						
LT_RPC	sin 2016 year parallel measurements was performed, purpose is to compare measurement results with Electret (measurement duration 21 day) and with CR39 (measurement duration 3 month)							
LU_MS.ETAT	/							

MT_EHD								
MT_RPB	none performed							
NE_RIVM	Thoron was measured at a small number of locations (ca. 100) in special setups in combination with thoron daughters to find a correlation (if possible)	100						
NO_NRPA								
PL_IMP.LODZ1	Checking the actual radon concentrations in another decade -after the introduction of new construction technologies	75	5					
PL_IMP.LODZ2	Checking the actual radon concentrations in another decade -after the introduction of new construction technologies	75	5					
RO_CNCAN	To check he difference between medians in the two sets of measurements and also to verify the seasonal correction factors	2						
RO_UBBCLUJ	To check he difference between medians in the two sets of measurements and also to verify the seasonal correction factors	2						
RS_DF.UNS								
SI_SRPA	finding the radon source (electret) after track etch CR 39 average is over 300 Bq/m3 and in caves, mines, spas and other underground workplaces to determine aerosol characteristics, equilibrium factor F between radon and its progeny (10 % of the total number of measurements)					10		
ES_UNICAN								
UK_PHE								

3.4 Are the detectors you used sensitive to thoron?

3.5 If YES in 3.4 please indicate if and how this has been corrected

ID	3.4 Track etch -	3.4 Track etch -	3.4 Electret	3.4 Active	3.4 Other	3.5
AL_IANP	I don't know					
AT_AGES1	No		No			
AT_AGES2	No					
AT_AGES3			No	No		
AT_AGES4	No		No			
AT_AGES5	No					
AT_AGES6	No					
AT_AGES7				No		
AT_AGES8	No					
BY_JINPR		Yes				Design of integral
BE_FANC					Yes	distance from the
BE_ISIB	No				No	
HR_FIZIKA.UNIOS		No				
CY_DLI.MLSI				No		
CZ_SURO		Yes				has not been
FI_STUK					I don't know	
DE_BFS	No	No			Yes	
GR_AUTH						
GR_EEAE	No					
IE_EPA1	No					
IE_EPA2	No					
IE_EPA3	No					
IT_INAIL	No		No			
IT_ISS	Yes					The interference
IT_ARPACAL						
IT_APPATN1		I don't know	I don't know			
IT_APPATN2		I don't know				

IT_APPATN3		I don't know				
IT_APPATN4		I don't know				
IT_APPATN5		I don't know				
IT_ARPALOMBARDIA1	No					
IT_ARPALOMBARDIA2	No					
IT_ISPRA1	No	No				
IT_ISPRA2	Yes					no correction
IT_ISPRA3	Yes					no correction
IT_ARPAVDA	Yes	No				No correction
IT_ARPAER		No				
IT_ARPAL1	Yes					No correction
IT_ARPAL2		No				/
IT_ARPAL3		No		Yes		No correction
IT_ARPAP	No	No				
LV_RSC	I don't know					
LT_RPC	No		No			
LU_MS.ETAT	No					
MT_EHD						
MT_RPB		I don't know				
NE_RIVM	Yes;No					Rn no, but Tn
NO_NRPA	Yes					Not corrected
PL_IMP.LODZ1	No	No				
PL_IMP.LODZ2	No	No				
RO_CNCAN	No					
RO_UBBCLUJ	No					
RS_DF.UNS						
SI_SRPA	No		No			
ES_UNICAN	No					
UK_PHE	I don't know					

3.6 Has thoron been measured?
3.7 If YES in 3.6 please indicate the detector-methodology
3.8 If YES in 3.6, please indicate how far the detector was positioned from thoron exhaling surfaces:
3.9 Did you perform quality assurance and quality control during the survey?
3.10 If YES in 3.9 please indicate how you did.

ID	**3.6**	**3.7**	**3.8**	**3.9**	**3.10**	**3.11**
AL_IANP	No			No		
AT_AGES1	No			Yes	Check of randomness, intercalibration and intercomparison exercises, comparison of parallel measurements with different detector Systems in the same homes, QA System of laboratories - Validation measurements in laboratory for each detector batch; plausibility checks by comparing results from different Interviewers; telephone interviews to check for correct detector Installation and exposure time; Repetition of investigations in some Areas during another season	
AT_AGES2	No			Yes	QA procedure of the measurement laboratory (AGES)	
AT_AGES3	No			Yes	Standard QA System of measurement laboratories; parallel measurements for Electret; plausibility tests	
AT_AGES4	No			Yes	QA Systems of laboratories; parallel measurements for electrets	
AT_AGES5	Yes	Raduet, Radosys		Yes	QA System of laboratory	
AT_AGES6	No			Yes	QA System of laboratory	
AT_AGES7	Yes	EQF 3120, RTM		Yes	Validation and comparison measurements with all active instruments for 3 weeks in one mine; QA System for all active instruments by the laboratory	annually
AT_AGES8	No			Yes	QA System of laboratory and detector provider	
BY_JINPR	No			Yes	Complex of measuring tools is calibrated	1 year
BE_FANC	No			No		
BE_ISIB	No			I don't know		
HR_FIZIKA.UNIOS	No					

CY_DLI.M LSI	No			Yes	Detectors were sent to the manufacturer	
CZ_SURO	No			I don't know		
FI_STUK	No			Yes	With each etching batch, a film exposed to know radon concentration and time is etched and read.	Recalibration only if the reference films deviate statistically significantly from the expected value (i.e. constant calibration checks)
DE_BFS	No	Can be named only after assignment in contractor	20	Yes	participation of the supplier in measuring comparison of the calibrating lab in the BfS or other accredited calibrating lab	The last measuring comparison dates back less than one year
GR_AUTH	No			No		
GR_EEAE	No			Yes	iso standards	100-3000KBqh/m3
IE_EPA1				Yes	Background values and sensitivity factors were determined for each sheet of plastics	
IE_EPA2	No			Yes	Yes, the laboratory is accredited to ISO 17025. We participate in inter-comparisons. We analyse detectors exposed to a known amount of radon in a radon chamber with each batch of detectors. We include blank detectors with each batch. Quality control detectors are counted daily.	Both our ATMOS instruments are calibrated annually
IE_EPA3				Yes	Yes, the laboratory is accredited to ISO 17025. We participate in inter-comparisons. We analyse detectors exposed to a known amount of radon in a radon chamber with each batch of detectors. We include blank detectors with each batch. Quality control detectors are counted daily.	Both our ATMOS instruments are calibrated annually
IT_INAIL	No			Yes	Participation to NRPB radon passive device intercomparison	during the same years of the survey
IT_ISS	No			Yes	Repeatability test (using the same set of detectors) were performed every time detectors were readout using the automatic readout system. Moreover, we also checked the in-field background and the effect of	Calibration was perfomed in 2012 and 2014

					ageing and fading in a sub-sample of about 50 dwellings (where measurements were performed: every 3 months, every 6 months and for a whole 1-year period).	
IT_ARPACAL						
IT_APPATN1	No			I don't know		
IT_APPATN2	No			I don't know		
IT_APPATN3	No			I don't know		
IT_APPATN4	No			I don't know		
IT_APPATN5	No			I don't know		
IT_ARPALOMBARDIA1	No			Yes	Repeatibility check on detectors response (by positioning couples of detectors); check on the reader efficiency (by reading reference detectors)	The system is calibrated every time we start using a new batch of detectors (every one or two years)
IT_ARPALOMBARDIA2	No			Yes	Repeatibility check on detectors response (by positioning couples of detectors); check on the reader efficiency (by reading reference detectors)	The system is calibrated every time we start using a new batch of detectors (every one or two years)
IT_ISPRA1	No			I don't know		
IT_ISPRA2	No			Yes	Calibration at the national primary metrological institute. Participation at intercomparison exercise	1 - 2 years
IT_ISPRA3	No			Yes	Calibration at the national primary metrological institute. Participation at intercomparison exercise	One - two years
IT_ARPAVDA	Yes	Active alpha spectrometry of thoron progeny	20	Yes	International intercomparison	Yearly
IT_ARPAER	No			Yes	Detectors calibration	April 1994
IT_ARPAL1	No	/	0	No	/	Calibration date: June 2009

IT_ARPAL 2	No	/	0	No	/	Calibration date: April 2009
IT_ARPAL 3	No	/	0	No	/	Untracked Information
IT_ARPAP	Yes	Measurements with electrets and acitive monitors in very few cases, where thoron presence was expected.	2	Yes	Calibration and intercomparison exercises	Calibrations were performed for each detector lot
LV_RSC	No			Yes	At least 2 detectors in each building, in public buildings detectors was deployed by RSC SES staff. Each household received instructions and best practice guidelines of detector location.	Measurement service was provided as outsourcing in Sweden
LT_RPC	No			Yes;No	Sins 2017 year annual intercomparison tests in BFS using CR-39	annual intercomparison tests in BFS using CR-39
LU_MS.ET AT	No			Yes	already exposed detectors used during the etching in order to valide this operation	every years
MT_EHD	No					
MT_RPB	No			I don't know		Detectors were analysed in the UK by a laboratory accredited by the Radiation Protection Division of the Health Protection Agency (UK).
NE_RIVM	Yes	Flonex Japan (thoron decay product detector (see: Tokonami Rad.Prot.Dosim. 141(4):335-339 (2010)); Radonova, Sweden (radon and thoron in special setups) (see: Smetsers et al. J of Env. Rad. 165:93-102 (2016)). For 3.8: 1 and 5 cm in special setup	1	Yes	1. We provided a set of instructions on how to handle the detectors; 2. We asked participants to send in pictures of the detectors in their environment to check on the way they were installed.	? Detectors are passive and are used immediately following delivery
NO_NRPA	No			No		

PL_IMP.LODZ1	No			Yes	we randomly checked where the detectors were placed	every batch of detectors was calibrated
PL_IMP.LODZ2	No				we randomly checked where the detectors were placed	every batch of detectors was calibrated
RO_CNCAN	Yes	RADUET Type detector- This detector type is dedicated to combination detection of radon and thoron activity at the same time. It consists of two detectors – a standard RSF type detector and a modified version, the latter with reduced response time. The main chamber is selective for the radon activity primarily. But the secondary chamber is sensitive for both radon and thoron. A simple linear calculation separates the radon and thoron activity data results.	50	Yes	A quality assurance program along with good laboratory practices was implemented. This is based on the metrology certification of detectors and periodical international intercomparisons to calibrate the instruments	Annually we calibrate RadoSys system and also our active detectors. Occasionally we perform calibration for University Laboratories. Our major activity at present is related with our research projects and the intercomparisons with other European laboratories (BfS from Germany, NIRS from Japan, Pannonia University from Hungary, NRPI from Czech Republic, LaRUC from Spain etc.) in the frame of our research activities.
RO_UBBCLUJ	Yes	Some answer given by RO_CNCAN	50	Yes	Some answer given by RO_CNCAN	Some answer given by RO_CNCAN
RS_DF.UNS	No					
SI_SRPA	No			Yes	calibration factors from manufacturer (BfS)	calibration period 4 years and continuous QA/QC
ES_UNICAN	No					
UK_PHE	No			Yes	Calibration of the detectors was made at regular intervals using a standard radon exposure from a known activity Ra-226 source	

Section 4. Data management, statistical treatment, aggregation and mapping
4.1 Please indicate the return rate (return rate = fraction of deployed detectors which could be collected):
4.2 Please indicate the evaluated rate
4.3 The result has been corrected for lost detector? If so, how?
4.4 If you have performed parallel measurements at the same location-measurement point (see 3.3), please specify which value has been chosen to be representative of this point (arithmetic mean, geometrical mean, maximum, etc.)?
4.5 If you have performed more than one measurement at the same dwelling/house/building, please specify which value has been chosen to be reported in your database (raw data, arithmetic mean, geometrical mean, maximum, etc.)?

ID	**4.1**	**4.2.2**	**4.3**	**4.4**	**4.5**
AL_IANP					arithmetic mean
AT_AGES1	95	85	no	AM	all
AT_AGES2	96	96	no		raw data
AT_AGES3	98	98	no	Weighted mean	raw data;
AT_AGES4	94	94	no	weighted mean	raw data
AT_AGES5	92	90	no		raw data, AM for dwelling
AT_AGES6	99	99	no		raw data; AM for dwelling
AT_AGES7	100	100			raw data; AM per mine/cave
AT_AGES8	85	75	no		raw data; AM per dwelling
BY_JINPR	99	90	No		arithmetic mean
BE_FANC	80				
BE_ISIB	95	99	no		highest ground floor data
HR_FIZIKA.UNIOS	85	80		arithmetic mean	arithmetic mean
CY_DLI.MLSI			This part is not applicable for this survey	Arithmetic mean	Maximum
CZ_SURO	65	65	no		
FI_STUK	57	84	no		mean of 6 + 6 month result = yearly average
DE_BFS					raw data
GR_AUTH	100	100			
GR_EEAE	60	59	no	arithmetic mean	raw data
IE_EPA1					
IE_EPA2	88	88	Results with lost detectors have been excluded from the data analysis	Not applicable	Not applicable

IE_EPA3	86	86	They have been removed		
IT_INAIL	90	0	no	arithmetic mean of indoor radon annual activity concentration achieved by SSNTD	arithmetic mean
IT_ISS	94	95	No. But the check of representativeness (on going) – which is required considering the adopted sampling strategy – will consider also the lost detectors.		
IT_ARPACAL	98	2		geometrical mean	raw data, arithmetic mean, geometrical mean
IT_APPATN1					
IT_APPATN2					
IT_APPATN3					
IT_APPATN4					
IT_APPATN5					
IT_ARPALOMBARDIA1	97	96.5	No	arithmetic mean of the values	
IT_ARPALOMBARDIA2	98	98	no	arithmetic mean	each measurement has been considered for the different purposes of this survey; only the results of measurements performed at ground floors were used for mapping, together with the results obtained in the previous survey (2003-2004)
IT_ISPRA1				arithmetic mean	arithmetic mean

IT_ISPRA2			the annual measures are divided into 2 periods of about 6 months. If the detector of one period is lost, the concentration of that period is estimated from the other detector applying a calculated seasonal factor.		Two location (bedroom and living room) have been measured for two esposure periods (about 6 months each) Concentration value of the dwelling for the single exposure period is given by arithmetic mean of the concentrations of the two locations. Annual concentration in bed room or in living room is given by the weighted mean (over time exposure) of the concentrations of the two exposure periods. Annual concentration value for dwellings is given by the aritmetic mean of annual concentration in bedroom and annual concentration in living room.
IT_ISPRA3	99	99	no		exposition, time, concentration of the single periods, annual mean concentration

IT_ARPAVDA	100	99	No	We have performed parallel measurements for validation method purpose. We use this results in order to validate a new measurements method, not for the survey.	arithmetic mean
IT_ARPAER			No		Raw data
IT_ARPAL1	100	66	No	/	Arithmetic mean
IT_ARPAL2	100	100	No lost detector	/	Arithmetic mean
IT_ARPAL3	100	100	No lost detector	Representative values: LR-115 measures only	Arithmetic mean
IT_ARPAP					
LV_RSC	96.1	98.1			raw data
LT_RPC	99.9	0.1	always parallel use of two detectors for measurement in dwelling	arithmetic mean	arithmetic mean
LU_MS.ETAT	50	50	/	/	raw data
MT_EHD	98	96	no		
MT_RPB	98	98	Not known	no parallel measurements	2 detectors placed for each of the six moth period, mean value taken
NE_RIVM		89	no, there was no effect on representativeness	only national survey values (Rn and Tnd) were used; the subset for Tn vs Tnd was kept separate. For 4.2: 86 % (Tnd)	1. in national survey only 1 measurement of Rn and 1 m. of Tnd; 2. in subset up to 5 measurements in the same dwelling

NO_NRPA	33	3	If one of the two detectors were missing the missing value was estimated using the value from the not missing detector multiplied with a typical difference between bedrooms and living rooms		raw data
PL_IMP.LODZ1	95	90	we had 2 type of detectors, if one was damaged we could use the second one. we left some detectors in 3-4 rooms of the dwelling, in case of loss one of the detector, we had no problem to estimate an average radon concentration for dwelling	arithmetic mean	arithmetic mean
PL_IMP.LODZ2	60	5	we had 2 type of detectors, if one was damaged we could use the second one. we left 3-4 detectors per route, in case of loss one of the detector, we had no problem to estimate an average radon concentration for the route anyway	arithmetic mean	arithmetic mean
RO_CNCAN	95	94.5	no	The both arithmetic mean and geometrical mean	The both arithmetic mean and geometrical mean
RO_UBBCLUJ	95	94.5	No	The both arithmetic mean and geometrical mean	The both arithmetic mean and geometrical mean
RS_DF.UNS					
SI_SRPA	95	100	No.	arithmetic mean	raw data
ES_UNICAN	10		no	Arithmetic mean	Arithmetic mean
UK_PHE	87.7	87.7	Lost detectors were not included in the above return / analysis rates		A house average based on occupancy factors for the two rooms measured - no seasonal correction was required as measurements for 1 year were collected

4.6a Have you applied seasonal correction?
4.6b If YES in 4.6a, how was the seasonal correction factor obtained:From literature/comparable survey; By exposing some detectors for 12 months; By comparing short-term (e.g. 3-month) measurements distributed over a full year; Other

ID	4.6a Track etch - CR39	4.6a Track etch - LR115	4.6a Charcoal/gamma spectrometry	4.6a Charcoal/ LSC	4.6a Electret	4.6a Active	4.6a Other	4.6b	Other
AL_IANP	Yes							By comparing short-term (e.g. 3-month) measurements distributed over a full year	
AT_AGES1	Yes			Yes	Yes			From literature/comparable survey;By comparing short-term (e.g. 3-month) measurements distributed over a full year	
AT_AGES2	No								
AT_AGES3				No	No	No			
AT_AGES4	No				No				
AT_AGES5	No								
AT_AGES6	No								
AT_AGES7						No			
AT_AGES8	No								
BY_JINPR		Yes						From literature/comparable survey;By comparing short-term (e.g. 3-month) measurements distributed over a full year	
BE_FANC							No		
BE_ISIB	No		No				No		
HR_FIZIKA.UN		No							
CY_DLI.MLSI						No			
CZ_SURO		No							

FI_STUK							No	By comparing short-term (e.g. 3-month) measurements distributed over a full year	
DE_BFS	No						No		
GR_AUTH									
GR_EEAE	Yes							By comparing short-term (e.g. 3-month) measurements distributed over a full year	
IE_EPA1	No								
IE_EPA2	Yes							Other	Seasonal
IE_EPA3	Yes							Other	Seasonal
IT_INAIL	No								
IT_ISS	No								
IT_ARPACAL	Yes				Yes			By exposing some detectors for 12 months;By comparing short-term (e.g. 3-month) measurements distributed over a full year	
IT_APPATN1		I don't			I don't				
IT_APPATN2		I don't							
IT_APPATN3		I don't							
IT_APPATN4		I don't							
IT_APPATN5		I don't							
IT_ARPALOMB	No								
IT_ARPALOMB	No								
IT_ISPRA1	No	No							
IT_ISPRA2	No								
IT_ISPRA3	No								
IT_ARPAVDA		No							
IT_ARPAER		No							
IT_ARPAL1	No								

IT_ARPAL2		No							/
IT_ARPAL3		No				No			/
IT_ARPAP		Yes						Other	Only for a
LV_RSC	I don't								
LT_RPC	No				No				
LU_MS.ETAT	No								
MT_EHD									
MT_RPB		No							
NE_RIVM	No								
NO_NRPA	No								
PL_IMP.LODZ1	Yes	Yes						By comparing short-term (e.g. 3-	
PL_IMP.LODZ2	No	No							
RO_CNCAN	Yes							From literature/comparable survey;By comparing short-term (e.g. 3-month) measurements distributed over a full year	
RO_UBBCLUJ	Yes							Some answer given by RO_CNCAN	
RS_DF.UNS									
SI_SRPA	No								
ES_UNICAN	No								
UK_PHE	No								

4.7 Have you applied any correction linked to building characteristics, in particular floor level?
4.8 Please provide the following information regarding the survey you are describing: 4.8a Total number of measurements; 4.8b Total number of dwellings/buildings; 4.8c Percentage of dwellings/buildings measured in the area covered by the survey (%); 4.8d Area covered by the survey (km^2)

ID	**4.7 Track etch-CR39**	**4.7 Track etch-R115**	**4.7 Charcoal canister**	**4.7 Charcoal/LSC**	**4.7 Electret**	**4.7 Active**	**4.7 Other**	**4.8a**	**4.8b**	**4.8c**	**4.8d**
AL_IANP	No							400	250	10	280
AT_AGES1	Yes			Yes	Yes			30000	9000	0.3	84000
AT_AGES2	No							1619	425	93	12000
AT_AGES3				No	No	No		1400	633	89	12000
AT_AGES4	No				No			600	388	42	12000
AT_AGES5	No							1360	680	90	37
AT_AGES6	No							1912	963	51	156
AT_AGES7						No		120	9	16	84000
AT_AGES8	Yes							70000	35000	1	84000
BY_JINPR		No						804	402		70000
BE_FANC							No	10000	10000	0.2	30000
BE_ISIB	No		No				No		6000		18000
HR_FIZIKA.UNIOS		No						1000			
CY_DLI.MLSI						No		407	407	100	189
CZ_SURO		No						4810	2405	0.06	
FI_STUK							No	5732	2866	0.12	338000
DE_BFS	No						No	12	6	100	357000
GR_AUTH											
GR_EEAE	Yes							12000	6000		132000
IE_EPA1	No							11319	11319		
IE_EPA2	No							653	653	0.04	
IE_EPA3	No							649	649	0.04	
IT_INAIL	No							2342	500	86	2759
IT_ISS	No							11000	5500	0.02	300000
IT_ARPACAL	No				No			604	229		

IT_APPATN1		No			No			3068	1534		
IT_APPATN2		No						460	230		
IT_APPATN3		No						449	287		
IT_APPATN4		No						180	90		
IT_APPATN5		No						116	58		
IT_ARPALOMBARDIA1	No							3534	3534		
IT_ARPALOMBARDIA2								966	344		
IT_ISPRA1	No	No							5361	0.03	16108
IT_ISPRA2	No							20000	5300	0.2	17000
IT_ISPRA3	No							1100	26		
IT_ARPAVDA	No	No						1455	611		1886
IT_ARPAER		No						1553	607	30	
IT_ARPAL1	No							66	33	10	25
IT_ARPAL2		No						39	0	0	0.01
IT_ARPAL3		No				No		26	0	0	0.01
IT_ARPAP	Yes	Yes						4124	3069		25400
LV_RSC	No							1854	702		
LT_RPC	No				No			5688	3012	0.6	65300
LU_MS.ETAT	No							918	393		2586
MT_EHD								328	86		316
MT_RPB		No						334	85		316
NE_RIVM	No							2567	2867	0.03	36500
NO_NRPA	No							2000	1000	0.04	385200
PL_IMP.LODZ1	No	No						643	87	1	33
PL_IMP.LODZ2	No	No						240	66	33	312679
RO_CNCAN	No					No		10184	6564	0.07	87600
RO_UBBCLUJ	No					No		10184	6564	0.07	87600
RS_DF.UNS											
SI_SRPA	No							800	650	1	6000
ES_UNICAN	No							9211	4745	100	294000
UK_PHE	No							2208	2208		242500

4.9 Please indicate how data from the survey were aggregated:
4.9a Simply target descriptive statistics of raw data; 4.9b If Yes in 4.9a please describe the method
4.9c Modelling of raw data (standard house, spatial models - kriging, average within municipality, etc.); 4.9d If Yes in 4.9c please describe the method

4.10 Please indicate how data are presented to the population/authority: Lists; Maps; Statistical graphs; Other
4.11 Have you estimated the occupancy factor of dwellings?
4.12 If Yes in 4.11, please provide the value and describe the method:

ID	**4.9a**	**4.9b**	**4.9c**	**4.9d**	**4.10**	**Please specify 'Other'**	**4.11**	**4.12**
AL_IANP								
AT_AGES1	Yes	AM for house; AM, Median, Maximum for municipality and federal states	Yes	Radon potential (Annual Rn Concentration for standard house); AM of the Radon potentials of all measured dwellings of municipality - Radon potential for municipality	Other	Lists and Maps	Yes	Men: Approx. 0.6; Women: approx. 0.7 (derived from questionnaire) for dwellings
AT_AGES2	Yes	Maximum per building (for assessment of necessary remediation measures and for the protection of the employees)	No		Other	Direct communication (result letter) to the responsible of the administrative buildings (e.g. Major); public available end Report of the Project	No	

AT_AGES3	Yes	Maximum per building (for assessment of necessary remediation measures and for the protection of the children); mean per kindergarten	No		Other	Direct communication (result letter) to the responsible of the kindergarten (director); public available end Report of the Project	No	
AT_AGES4	Yes	Maximum per building (for assessment of necessary remediation measures and for the protection of the children); mean per school	No		Other	Direct communication (result letter) to the responsible of the school (director, major); public available end Report of the Project	No	
AT_AGES5	Yes	AM for dwelling, AM for Municipality	Yes	Standard house, Radon potential for municipality	Other	Result letter to all households, Map/List for Radon potential of municipalities	No	
AT_AGES6	Yes	Am for dwelling, AM for municipality	Yes	Standard house, Radon potential for municipality	Other	Result letter to all households, Map/List for Radon potential of municipalities	No	
AT_AGES7	Yes	AM mean per season per mine and cave; AM per mine/cave	No		Other	result letter to responsible; public available end Report of Project; paper	No	
AT_AGES8	Yes	AM per dwelling	Yes	Standard house	Maps	Results letter to the participants;	No	

BY_JINPR	No		No		Lists		No	
BE_FANC	I don't know		No		Maps		No	
BE_ISIB	Yes		Yes	moving average of log[Rn], correction of variance of short-term data	Other	no communication to the population for 10 years, previously: maps	No	
HR_FIZIKA.UNIOS			No		Statistical graphs		No	
CY_DLI.MLSI	Yes	Median +- MAD; GM+-SD; Cumulative frequency	No		Other	Lists, Maps, Statistical graphs, Journal publication	No	
CZ_SURO	Yes				Statistical graphs	letter for home owners	No	
FI_STUK	Yes		Yes	population weighing of results	Other	report + radon maps, on the www-page (radon search based on postal copde/municipality)	Yes	Mäkeläinen, Moisio, Reisbacka, Turtiainen. Indoor occupancy and radon exposure in Finland. In: McLaughlin et al (Eds.) The natgural radiation environment VII.2005
DE_BFS	Yes	Can be named only after assignment in contractor	Yes	The data will processed together with already available with geostatistics for mapping	Maps		No	
GR_AUTH			No		Lists			
GR_EEAE	No		Yes	average within region	Maps		No	

IE_EPA1	Yes		No		Other	Report	No	
IE_EPA2	Yes	Weighting of data, estimation of arithmetic mean	No		Other	EPA reports and scientific papers are currently being prepared, the findings will be presented at meetings of Nation radon control strategy group	Yes	Using small area census statistics and address database
IE_EPA3	Yes	Arithmetic mean	No		Other	An EPA report and a scientific paper have been published. The findings have been reported at meetings of Irelands National Radon Control Strategy group.	No	
IT_INAIL	Yes	parametric tests (t-test, ANOVA-one way) and non parametric tests (Kruskal Wallis test)	Yes	average within municipality	Other	average in the municipality	Yes	2000 hours/y
IT_ISS	I don't know		I don't know				No	
IT_ARPACAL	Yes	average within municipality	Yes	average within municipality	Statistical graphs		Yes	population
IT_APPATN1	I don't know		No		Statistical graphs		No	
IT_APPATN2	I don't know		No		Statistical graphs		No	
IT_APPATN3	I don't know		No		Statistical graphs		No	

IT_APPATN4	I don't know		No		Other	I don't know	No	
IT_APPATN5	I don't know		No		Other	I don't know	No	
IT_ARPALOMBARDIA1	No		Yes	We used geostatistical methods to calculate the spatial distribution of probability of exceeding reference levels	Other	Single reports for the dwellings owners, reports for authorities, maps on web site	No	
IT_ARPALOMBARDIA2			Yes	Geostatistic methods were used to calculate the mean radon concentration in each administrative unit of Lombardia	Other	Single reports for the dwellings owners, reports for authorities, maps on web site	No	
IT_ISPRA1	Yes	frequency distribution	Yes	National: weighted average for the regional population; Regional: weighted average for the municipality population;	Other	List and thematic map	Yes	
IT_ISPRA2	Yes	Frequency distribution	Yes	grid square method (Miles, 1994); disjunctive kriging (Raspa et al., 2010)	Other	List and maps	No	

IT_ISPRA3	No		No		Other	list of annual radon concentrations in the rooms of the buildings and planimetry with indication of the annual radon concentration values	No	
IT_ARPAVDA	No		No		Other	Lists and Maps	Yes	Asked in the questionary
IT_ARPAER	Yes	Statistical distribution of data (histogram)	No		Statistical graphs		Yes	18 %. Through the questionnaire, the hours/weeks and weeks/year of attendance at the school were obtained
IT_ARPAL1	No	/	Yes	Average within municipality	Lists	/	No	/
IT_ARPAL2	No	/	Yes	Average within caves	Lists	/	No	/
IT_ARPAL3	No	/	Yes	Average within caves	Other	Lists and statistical graphs	Yes	The occupancy factor of guides in the caves as been calculated on the base of the mean concentration measured value. It is conservatively assumed equal to 1000 h/year
IT_ARPAP	Yes	Log-normal distribution for each unit	Yes	Average within municipality	Maps		Yes	Only for a small subset of the data
LV_RSC	I don't know				Statistical graphs		No	

LT_RPC	Yes	excel descriptive statistic tool	No		Maps		No	
LU_MS.ETAT	Yes	/	No		Maps		No	
MT_EHD						publication	No	
MT_RPB	I don't know		I don't know		Maps		No	
NE_RIVM	Yes	Averages and stddev for dwelling types, year of construction (period), ventilation types, smoking (yes/no), volume of measurement space, type of space/room. For 4.8a: 2457 for Tnd	No		Maps	except 'Lists' all methods were used; participants also received measurement data of own dwelling	No	
NO_NRPA					Other	Not published yet	Yes	90 % based on a survey (2012) performed by Statistics Norway
PL_IMP.LODZ1	I don't know				Other	not presented yet	Yes	0,7. We calculated a percentage of the average value of dwelling occupancy in relation to the full daily occupancy-24h

PL_IMP.LODZ2	I don't know				Statistical graphs	in descriptive article as a table and a graph	Yes	0,3. We calculated a percentage of the average value of work time in underground tourist routes in relation to the full annual work occupancy-2000h
RO_CNCAN	No		No		Other	Individual letters with results bulletins and specific recommendations depending on the outcome	No	
RO_UBBCLUJ	No		No		Maps		No	
RS_DF.UNS								
SI_SRPA	No		No		Other	written report	Yes	Information from the inhabitants.
ES_UNICAN	Yes	Geographic Information System	No		Maps		No	
UK_PHE	I don't know		I don't know		Other	Scientific report	Yes	0.45 Living area; 0.55 Bedroom Based on general statistics of occupancy of rooms within the homes

Section 5.

5.1 Have you merged data coming from different surveys?

5.2 If Yes in 5.1, please describe briefly the methodology followed to merge them:

5.3 Please provide the following information regarding the national database: 5.3a Total number of measurements; 5.3b Total number of dwellings/buildings; 5.3c Percentage of dwellings/buildings measured(%); 5.3d Area covered by the data contained in the database (km^2);

5.4 Please indicate how data from the national database were aggregated: 5.4a Simply target statistics of raw data; 5.4b If Yes in 5.4a please describe the method; 5.4c Modelling of raw data (standard house, spatial models - kriging, average within municipality, etc.); 5.4d If Yes in 5.4c please describe the method

ID	**5.1**	**5.2**	**5.3a**	**5.3b**	**5.3c**	**5.3d**	**5.4a**	**5.4b**	**5.4c**	**5.4d**
AL_IANP										
AT_AGES1	Yes	For national Survey: Survey was done federal state by federal state over several years and then combined; methodology was the same for all federal states	50	12	0.4	84000	Yes	AM for house	Yes	Radon potential (Standard house) per house
AT_AGES2										
AT_AGES3										
AT_AGES4										
AT_AGES5										
AT_AGES6										
AT_AGES7										
AT_AGES8										
BY_JINPR										
BE_FANC	Yes		20000	20000	0.4	30000	Yes		Yes	average within

BE_ISIB						30000				
HR_FIZIKA.UNIOS										
CY_DLI.MLSI	No		1015	820	1	500	Yes		No	
CZ_SURO	Yes	for free measurement in public buildings and houses provided to municipalities and interested individuals from the public	480000	180000	0.5		No		Yes	geom mean, percentage above the ref. value for administrative units, maps, statistical modelling used for radon prone arease demarcation
FI_STUK	Yes	in radon mapping, all data is pooled	250000	120000	8	338000	I don't know		I don't kno w	
DE_BFS	Yes	geostatistics, calculation of transfer factors (indoor concentration/predictet soil concentration	60	27	0.2	200000	Yes	calculation of transfer factors from indoor concentration and forecasted soil gas	Yes	geostatistics with part of data (P. Bossew)
GR_AUTH										
GR_EEAE	Yes		2400	1200		45000	No		Yes	average within
IE_EPA1	No		62600	62600	0.04		No		No	
IE_EPA2	No			62600	4		No		No	
IE_EPA3	No		62600	62600	4		No		No	
IT_INAIL	No									
IT_ISS										
IT_ARPACAL										
IT_APPATN1										
IT_APPATN2										
IT_APPATN3										
IT_APPATN4										

IT_APPATN5										
IT_ARPALOMBARDIA1										
IT_ARPALOMBARDIA2										
IT_ISPRA1	Yes	Calculation of mean concentration for some municipalities from different surveys.		45000			Yes	arithmetic mean over municipalities; weighted mean (for regional population) at regional level. (No national database has yet been made. Data available from one national survey and many regional surveys/databases are stored.)	Yes	Different spatial models (kriging/simulation) for different areas (administrative regions)
IT_ISPRA2	Yes	Calculation of mean concentration for some municipalities from different surveys.		45000			Yes	arithmetic mean over municipalities; weighted mean (for regional population) at regional level. (No national database has yet been made. Data available from one national survey and many regional surveys/databases are stored.)	Yes	Different spatial models (kriging/simulation) for different areas (administrative regions)

IT_ISPRA3	Yes	Calculation of mean concentration for some municipalities from different surveys.		45000			Yes	arithmetic mean over municipalities; weighted mean (for regional population) at regional level. (No national database has yet been made. Data available from one national survey and many regional surveys/databases are stored.)	Yes	Different spatial models (kriging/simulation) for different areas (administrative regions)
IT_ARPAVDA										
IT_ARPAER										
IT_ARPAL1										
IT_ARPAL2										
IT_ARPAL3										
IT_ARPAP										
LV_RSC	No		1854	702						
LT_RPC	Yes	collecting to common data base	5688	3012	0.6	65300	Yes	excel descriptive statistic tool	No	
LU_MS.ETAT	Yes	brough the data together				2586	Yes		No	
MT_EHD	No									
MT_RPB	No		334	85		316	I don't know		I don't know	
NE_RIVM	No		2567	2867	0.03	36500	Yes	see 4.9b. For 5.3a: 2457 for Tnd	No	

NO_NRPA	No		135000			385200				
PL_IMP.LODZ1					1	33				
PL_IMP.LODZ2										
RO_CNCAN	No				0					
RO_UBBCLUJ										
RS_DF.UNS										
SI_SRPA	Yes	All surveys were financed by Slovenian Radiation Protection Administration, so they are planed in a way that could be merged together. The same reporting type.	2500	2000	0.3	10	No		No	
ES_UNICAN										
UK_PHE	Yes	All data are measurements made by PHE and it's predecessor organisations so are stored in the same format (Raw data and annual average for each dwelling, together with location data etc)	700000	595000	2	242500				

5.5 Please indicate approximately the date in which the National Radon Action Plan (as required by art.103 of the European Council Directive 2013/59/EURATOM) has been established or will be:

5.6 Do you use standards/guidelines for performing indoor radon measurements?

5.7 Please indicate which reference level for indoor radon concentrations you have chosen and if exceeded which action should be taken:

RL: Reference Level; ND: New Dwellings; ED: Existing Dwellings; PB: Public Buildings; WP:Workplaces

ID	**5.5**	**5.6**	**5.7ND: RL Bq/m³**	**5.7ND: Actions**	**5.7ED: RL Bq/m³**	**5.7 ED: Actions**	**5.7: PB: RL Bq/m³**	**5.7 PB: Actions**	**5.7 WP: RL Bq/m³**	**5.7 WP: Actions**
AL_IANP										
AT_AGES1	31/12/2018	Yes; In preparation	300	remediation recommended	300	remediation recommended	300	remediation obligatory, if not possible to reduce concentration below 300 Bq/m³ - obligagory dose estimation; above 6 mSv/a - permanent dose control	300	remediation obligatory, if not possible to reduce concentration below 300 Bq/m³ - obligagory dose estimation; above 6 mSv/a - permanent dose control
AT_AGES2										
AT_AGES3										
AT_AGES4										
AT_AGES5										
AT_AGES6										
AT_AGES7										
AT_AGES8										
BY_JINPR										

BE_FANC	01/06/2007	Yes	100	remediation	300	remediation	300	remediation	300	remediation
BE_ISIB										
HR_FIZIKA.UNIOS										
CY_DLI.MLSI	31/12/2018	No	300	Encourage by technical or other means, radon concentration-reducing measures in these dwellings.	300	Encourage by technical or other means, radon concentration-reducing measures in these	300	Encourage by technical or other means, radon concentration-reducing measures in these	300	Optimisation Encourage by technical or other means, radon concentration-reducing measures in these Notification to the regulatory body of those cases where the radon concentration (as an annual average), continues to exceed the national reference level.
CZ_SURO	01/01/2009	Yes	300	optimisation	300	optimisation, corrective actions	300	optimized corrective actions (obligatory)	300	personal doses assessment
FI_STUK	01/08/2018	Yes	200	remediate	300	remediate	300	remediate	300	remediate

DE_BFS	31/12/2018	No	300	All dwellings: construction in accordance with standards of humudity protrction In radon areas: additional measures to avoid konvection of soil gas and diffusion of radon into building	300	recommendation of remediation measures	300	recommendation of remediation measures	300	statutory requirement of remidietion measures, in case of unsuccessful remidiation radiation protection measures required by the responsible authority
GR_AUTH										
GR_EEAE	31/05/2018	Yes	300	remediation	300	remediation	300	remediation	300	remediation
IE_EPA1	17/02/2014	Yes	200	Remediation recommended	200	Remediation recommended	300	required within 12 months of test	300	required within 12 months of test

IE_EPA2	17/02/2014	Yes	200	Recommend remediation	200	Recommend remediation	300	required within 12 months of test	300	required within 12 months of test
IE_EPA3	17/02/2014	Yes	200	Remediation recommended	200	Remediation recommended	300	Remediation and verification required within 12 months of test	300	required within 12 months of test
IT_INAIL		I don't know	300		300		300		300	
IT_ISS										
IT_ARPACAL										
IT_APPATN1										
IT_APPATN2										
IT_APPATN3										
IT_APPATN4										
IT_APPATN5										
IT_ARPALOMBARDIA1										
IT_ARPALOMBARDIA2										

IT_ISPRA1		Yes							500	remedial action and dose evaluation
IT_ISPRA2		Yes							500	remedial action and dose evaluation
IT_ISPRA3		Yes							500	remedial action and dose evaluation
IT_ARPAVDA										
IT_ARPAER										
IT_ARPAL1										
IT_ARPAL2										
IT_ARPAL3										
IT_ARPAP										

Annex 4

List of references regarding CD/DVD method

List of relevant publications

1. **Pressyanov D.** (2013) Use of polycarbonate materials of high radon absorption ability for measuring radon. ***Rom J. Phys.*** **58, p. S221.**

2. **Pressyanov D.** (2012) Retrospective measurements of thoron and radon by CDs/DVDs: a model approach. ***Radiat. Prot. Dosim.*** **149, p. 141.**

3. **Pressyanov D., Foerster E., Georgiev S., Dimitrova I., Mitev K.** (2013) Traceability of CDs/DVDs used as retrospective ^{222}Rn detectors to reference STAR laboratory ***Radiat. Meas*** **59, p.165.**

4. **Pressyanov D., Dimitrova I., Georgiev S., Mitev K.** (2013) Pilot experiments on retrospective thoron measurements by CDs/DVDs. ***Radiat. Meas.*** **50, p. 218.**

5. **Dimitrova I., Pressyanov D., Georgiev S., Yankov P.** (2011) Logistic of surveys of retrospective radon concentrations by home stored CDs/DVDs. ***Radiat. Prot. Dosim.*** **145, p. 300.**

6. **Dimitrova I., Mitev K., Pressyanov D., Georgiev S., Boshkova T.** (2010) Measurement of ^{222}Rn and ^{226}Ra in water by absorption of radon in polycarbonates and etching alpha-tracks. ***Radiat. Meas.*** **46, p. 119**.

7. **Pressyanov D., Mitev K., Georgiev S., Dimitrova I.** (2010) Radon mapping by retrospective measurйements – an approach based on CDs/DVDs. ***J. Envir. Radioact.*** **101, p. 821.**

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14. **<u>Pressyanov D.</u>, Buysse J., Poffijn A., Meesen G., Van Deynse A.** (2000) Polycarbonates: a long-term highly sensitive radon monitor. ***<u>Nucl. Instrum. Methods. Phys. Res</u>.*** **A 447, p. 619.**

15. **Mitev K., Madzhunkov Y., Gerganov G., Dimitrova I., Georgiev S., <u>Pressyanov D.</u>** (2010) Automatic counting of electrochemically etched tracks in compact discs. Application to retrospective measurements of Rn-222. ***<u>IEEE Trans. Nucl. Sci.</u>*** **57, p. 300.**

16. **<u>Pressyanov D</u>**. (2013) Measuring Radioactive Noble Gases by Absorption in Polycarbonates and Other Organics: From Radon Indoors to Nuclear Safety. ***AIP Conf. Proc.*, 1544, p. 130**.

17. **Georgiev S., Dimitrova I., <u>Pressyanov D.</u>, Mitev K.** (2012) Retrospective Rn-220 measurements by compact discs. ***IEEE-NSS Record*: Art. Nr. 6551102, pp. 250-252.**

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31. **Pressyanov D.** (2010) Nuclear tracks in polycarbonates with high radon absorption ability: Opportunities for measuring ^{222}Rn. **Chapter 4 IN:** ***Nuclear Track Detectors: Design, Methods and Applications***. Nova Science Publishers, Inc., New York, ISBN: 978-1-60876-826-4.

32. **Пресиянов Д.** (2013) **RADIOLOGICAL PROBLEMS RELATED TO RADON AND NEW METHODS FOR THEIR INVESTIGATION. Dissertation for acquiring the scientific degree of Doctor of the Physical Sciences.**

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49. **Георгиев С., Митев К., Пресиянов Д., Герганов Г., Димитрова И.** (2011) Компютърен код за прецизно пресмятане на активността и дълбочинното разпределение на радиоактивни благородни газове абсорбирани в поликарбонати. ***Сб. XXI национален научен симпозиум с международно участие "Метрология и метрологично осигуряване 2011"*** - Созопол 10-14.09.2011, сс. 278-283.

50. **Dimitrova I., Georgiev S., Mitev K., Boshkova T., Pressyanov D.** (2010) Correction for finite sample volume in ^{222}Rn in water measurements by absorption in polycarbonates. ***Proc. 20th Symp. on Metrology and Metrological Assurance***, September 2010, Sozopol, Bulgaria, p. 254.

Annex 5

Report on Activity A.3.1.4

SUBG: Report on WP3, activity A3.1.4 and on the start-up of WP4 joint research SUBG&UC

Activity A3.1.4:

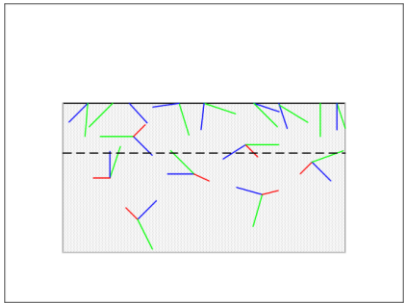
- **SUBG will analyse existing information and data related to the method of retrospective indoor Rn measurements using CDs/DVDs and will evaluate the applicability of this approach for indoor radon surveys.**

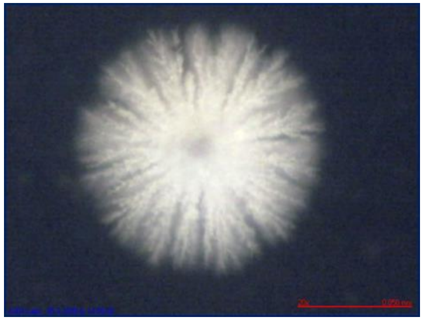
- **The method employs CDs/DVDs as radon detectors (from the available stock stored indoors) and provides long term (> 1 year) retrospective indoor radon concentration results. The method covers the entire range of radon concentrations that can be found indoors and is suitable for identification of buildings with elevated radon concentrations, epidemiology and radon mapping. A very recent development is the possibility to evaluate the impact of the energy-efficiency house retrofit on indoor radon by analysis of 2 CDs/DVDs of different ages.**

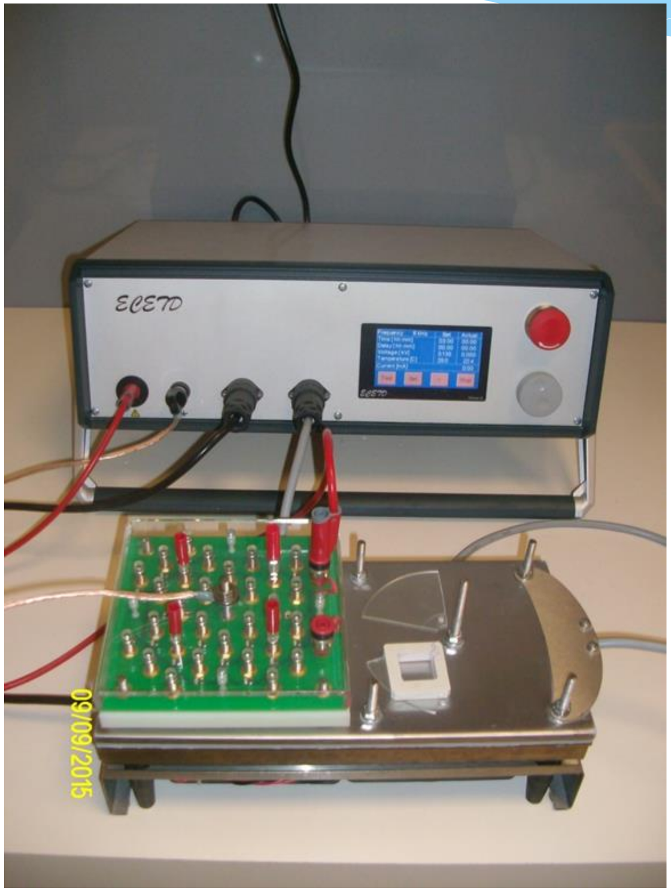
Main directions of use of the CD/DVD method studied to date (based on > 50 publications in 1999-2017) and related to MetroRADON tasks.

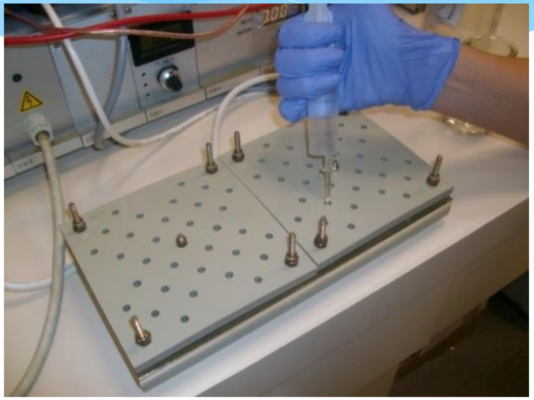
- **Retrospective dosimetry of radon and thoron (incl. for the purposes of radon mapping);**
- **Identification of radon prone areas and buildings with radon problem (annual average $^{222}Rn > 300$ Bq m^{-3});**
- **Retrospective evaluation of the effect of building retrofit on radon levels;**
- Measurements in working places (incl. mines);

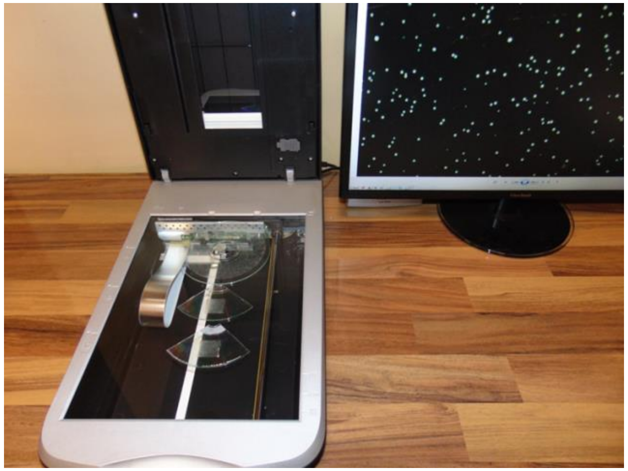
Laboratory infrastructure: equipment for processing CDs/DVDs.



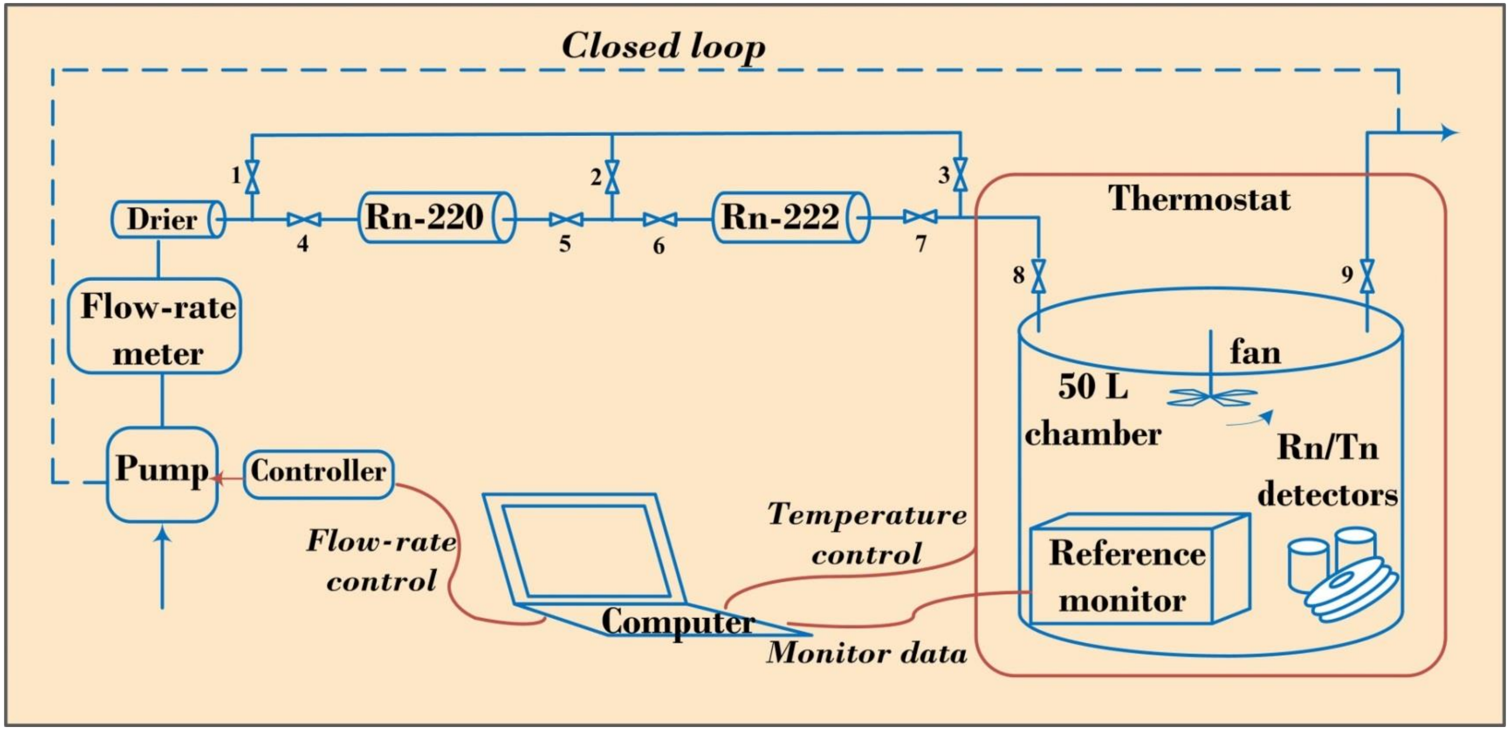








Laboratory infrastructure: exposure/calibration facility. Possibility for *standard* and *a posteriori* calibration under conditions close to that during the real exposure (*J. Envir. Radioact.* 166 (2017)181-187).



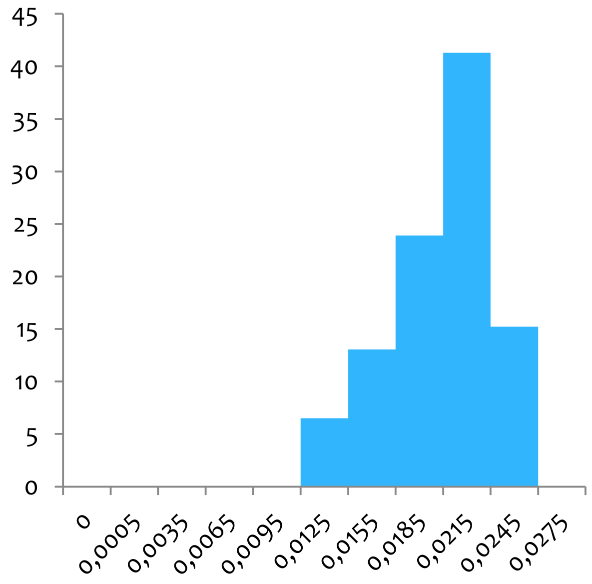
The installed in SUBG exposure/calibration facility.

Data processing with the CD/DVD method: counting statistics, calibration and disk dating.

$$C = \frac{n - n_b}{CF.t} = \frac{n_0}{CF.t}$$

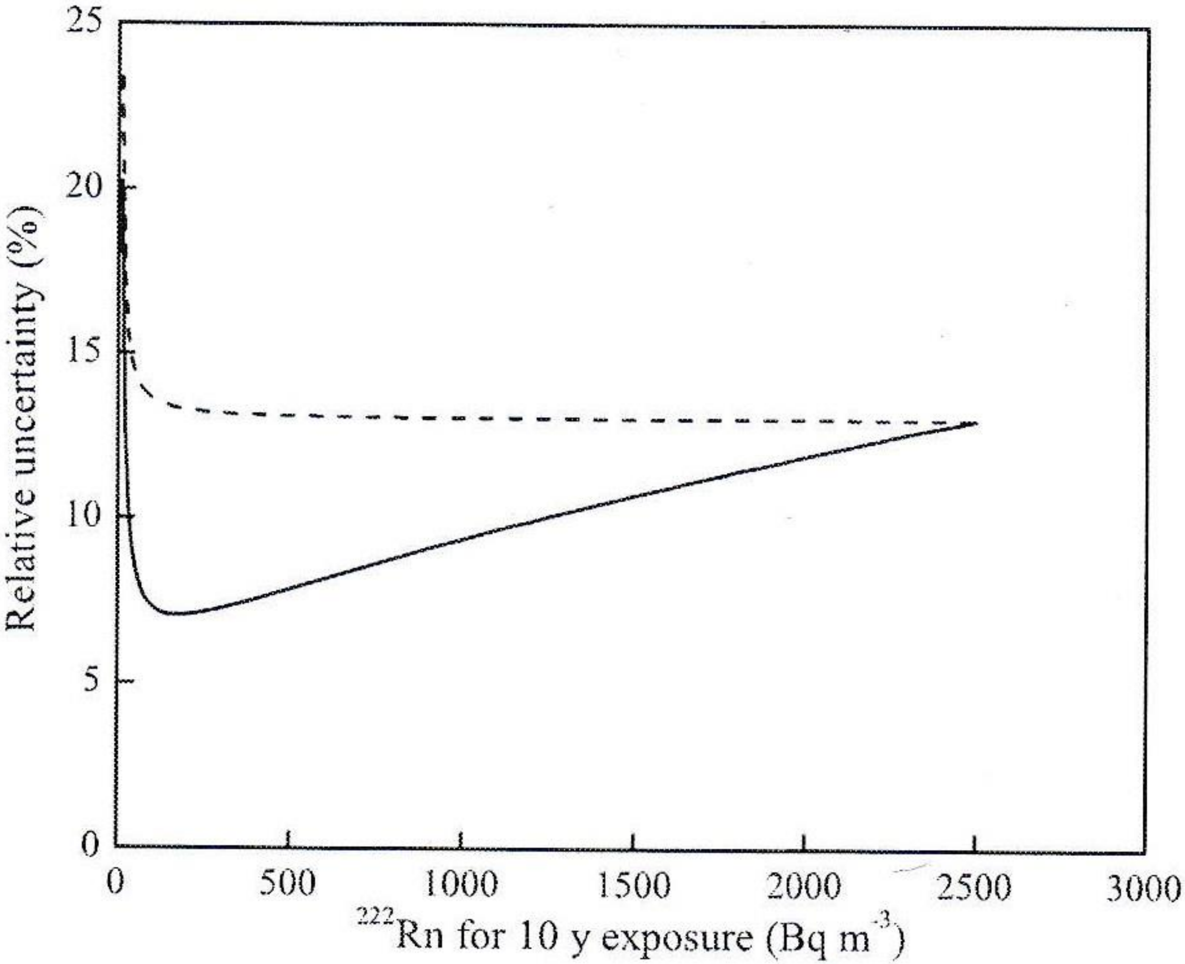
$$\frac{u(C)}{C} = \sqrt{\frac{u^2(n_0)}{n_0^2} + \frac{u^2(CF)}{CF^2} + \frac{u^2(t)}{t^2}}$$

- **Track-counting statistics (Poisson);**
- **Disk dating (*t*; $\Delta = t_{max} - t_{min}$; $u(t) = 0.289\Delta$);**
- **Calibration (*CF*): standard and individual (*a posteriori*).**



CF (cm^{-2}/kBq h m^{-3})

Modeling the uncertainty under exact dating scenario (*standard* and *a posteriori* calibration)



Verification of the reliability and quality of the CD/DVD method for ^{222}Rn: STAR traceability (with certificate).

DEUTSCHER KALIBRIERDIENST **DKD**

Kalibrierlaboratorium / *Calibration laboratory*

Akkreditiert durch die / *accredited by the*
Akkreditierungsstelle des Deutschen Kalibrierdienstes

Bundesamt für Strahlenschutz
Standort Berlin
Köpenicker Allee 120 – 130
10318 Berlin

DKD-K-23001

Kalibrierschein
Calibration certificate

Kalibrierzeichen
Calibration mark

Nr. 523
DKD-K-23001
2010-08

Gegenstand *Object*	***Radon measurement devices using solid state nuclear track detectors***
Hersteller *Manufacturer*	**University of Sofia Laboratory of Dosimetry and Radiation Protection**
Typ *Type*	**CD / DVD**
Fabrikat/Serien-Nr. *Serial number*	**50 disks see table on page 3**
Auftraggeber *Customer*	**Dr. Dobromir S. Pressyanow Laboratory of Dosimetry and Radiation Protection, Faculty of Physics University of Sofia "St. Kliment Ohridski" 5 James Bourchier Blvd. Sofia BG-1164, Bulgaria**
Auftragsnummer *Order No.*	**209**
Anzahl der Seiten des Kalibrierscheines *Number of pages of the certificate*	**3**
Datum der Kalibrierung *Date of calibration*	**19.08.2010**

Dieser Kalibrierschein dokumentiert die Rückführung auf nationale Normale zur Darstellung der Einheiten in Übereinstimmung mit dem Internationalen Einheitensystem (SI).
Der DKD ist Unterzeichner der multilateralen Übereinkommen der European co-operation for Accreditation (EA) und der International Laboratory Accreditation Cooperation (ILAC) zur gegenseitigen Anerkennung der Kalibrierscheine.
Für die Einhaltung einer angemessenen Frist zur Wiederholung der Kalibrierung ist der Benutzer verantwortlich.

This calibration certificate documents the traceability to national standards, which realize the units of measurement according to the International System of Units (SI).
The DKD is signatory to the multilateral agreements of the European co-operation for Accreditation (EA) and of the International Laboratory Accreditation Cooperation (ILAC) for the mutual recognition of calibration certificates.
The user is obliged to have the object recalibrated at appropriate intervals.

Dieser Kalibrierschein darf nur vollständig und unverändert weiterverbreitet werden. Auszüge oder Änderungen bedürfen der Genehmigung sowohl der Akkreditierungsstelle des DKD als auch des ausstellenden Kalibrierlaboratoriums. Kalibrierscheine ohne Unterschrift und Stempel haben keine Gültigkeit.
This calibration certificate may not be reproduced other than in full except with the permission of both the Accreditation Body of the DKD and the issuing laboratory. Calibration certificates without signature and seal are not valid.

Stempel *Seal*	Datum *Date*	Stellv. Leiter des Kalibrierlaboratoriums *Deputy Head of the calibration laboratory*	Bearbeiter *Person in charge*	
Deutscher Kalibrierdienst DKD-K-23001	13.12.2010	H. Buchröder	E. Foerster	C. Wegner

Radiation Measurements 59 (2013) 165–171

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journal homepage: www.elsevier.com/locate/radmeas

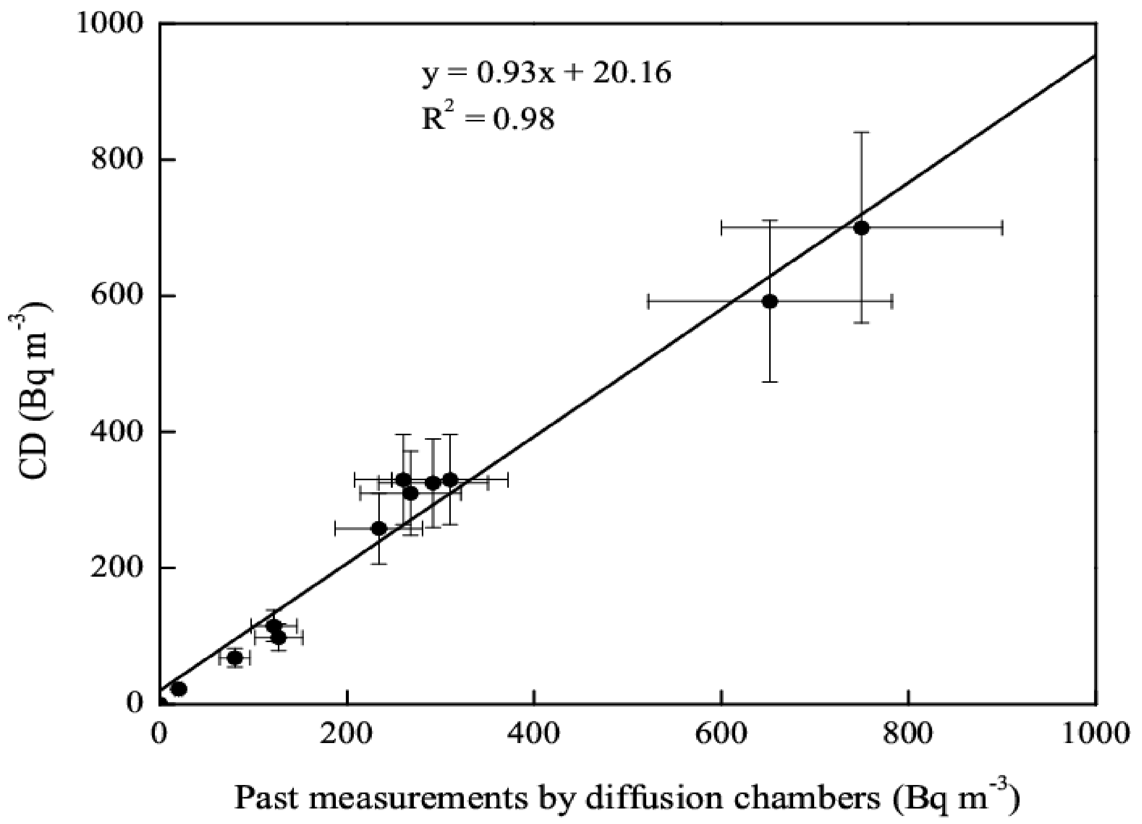
ELSEVIER

Traceability of CDs/DVDs used as retrospective ^{222}Rn detectors to reference STAR laboratory

D. Pressyanov[a,*], E. Foerster[b], S. Georgiev[a], I. Dimitrova[a], K. Mitev[a]

[a] Sofia University St. Kliment Ohridski, Faculty of Physics, 5 James Bourchier Blvd., Sofia, Bulgaria
[b] Radon Calibration Service Laboratory, Federal Office for Radiation Protection (BfS), Berlin, Germany

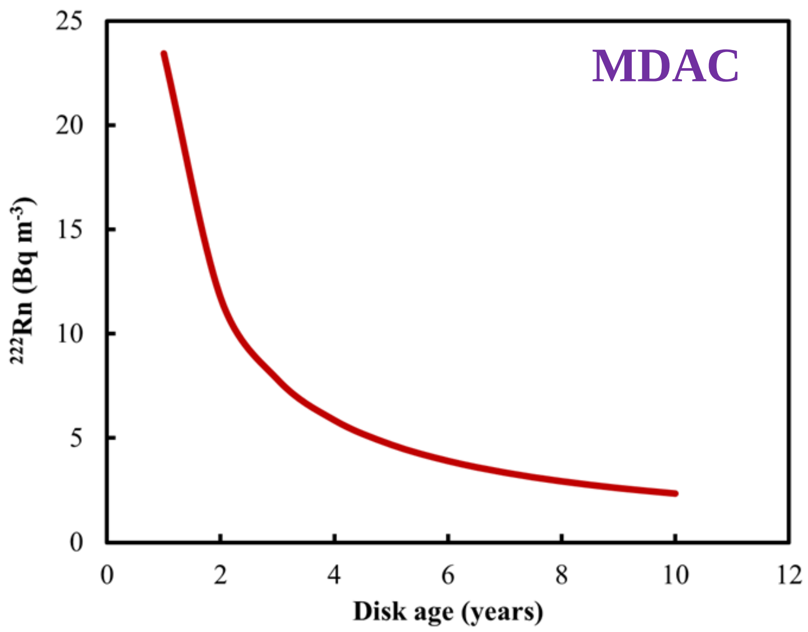
Comparison of retrospective measurements by CD/DVDs with diffusion chambers exposed in the past (*J. Env. Radioact.* 101 (2010) 821-825):

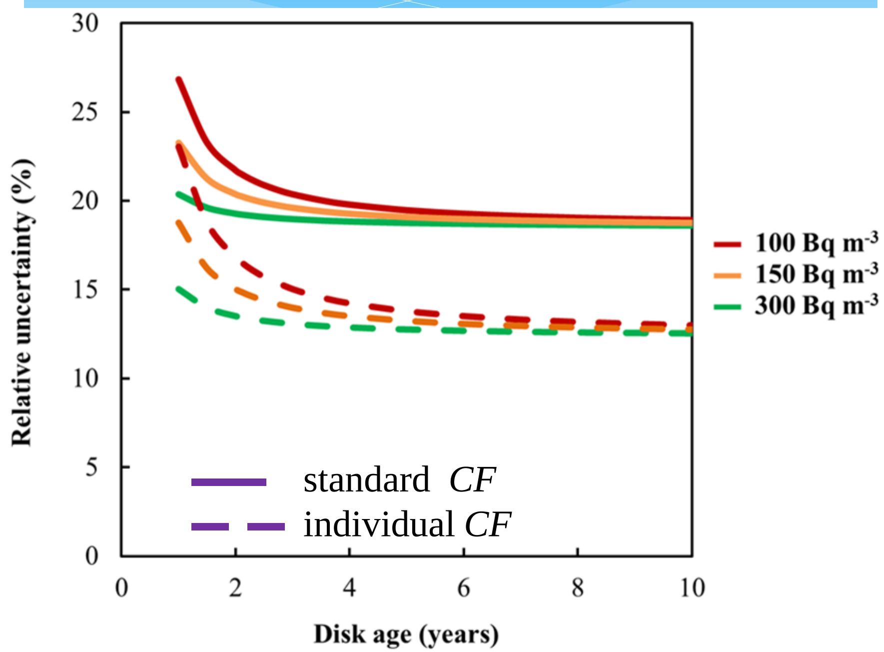


Verification of the reliability and quality of the CD/DVD method for ^{222}Rn: planed work within WP4.

- **Long-term exposure experiment started at UC. Four sets, each of 10 CDs and 10 DVDs were placed at the exposure site (where ^{222}Rn levels are continuously followed). Every 6 months the disks from one set will be analyzed. Short-term exposures (1-3 months) will be organised starting from the next year.**
- **Participation in PHE 2017 international radon inter-comparison is planned with CD/DVDs.**

CD/DVD method in radon surveys practice: sensitivity and uncertainty…





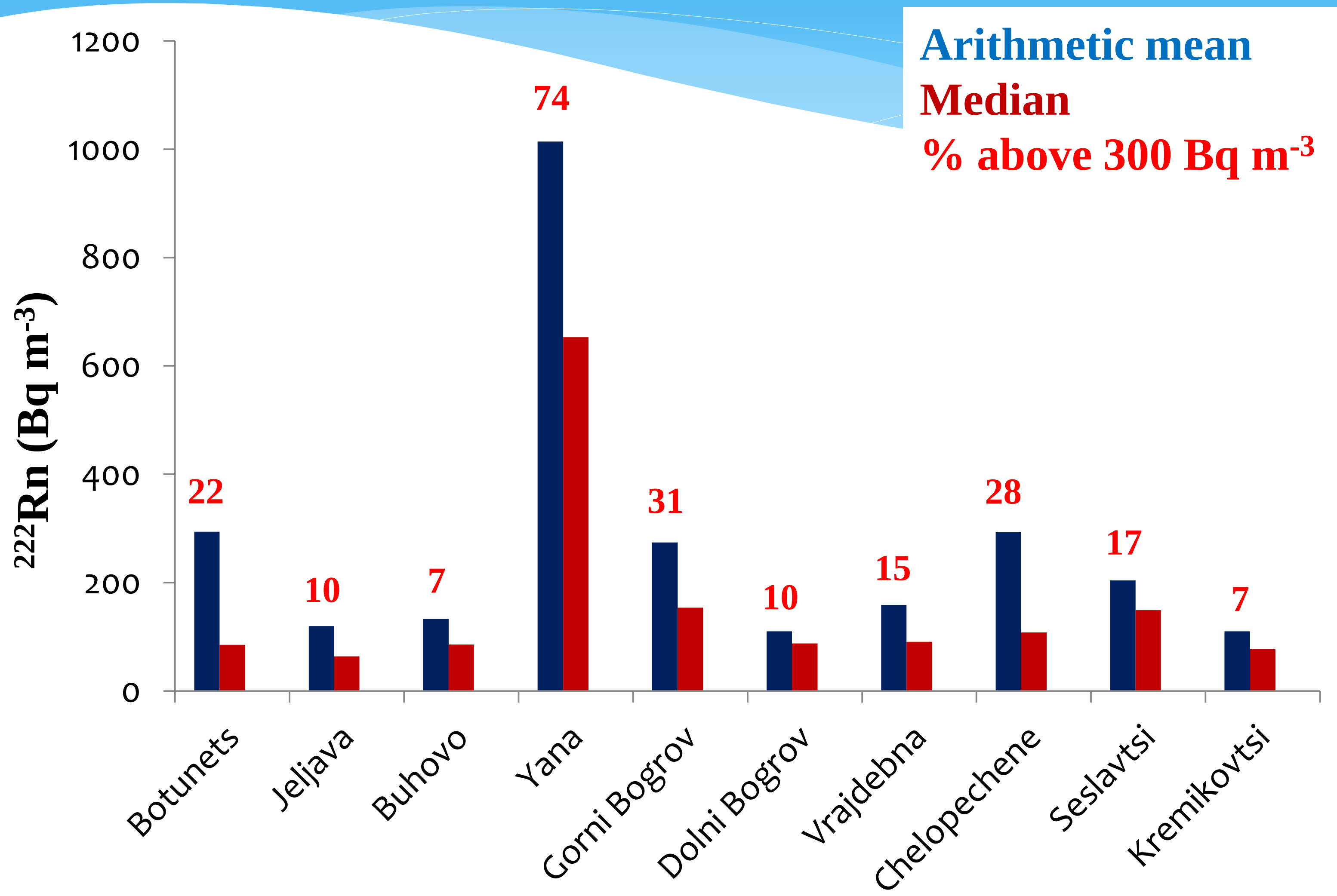
Dating within interval (t_{min}, t_{max})

$\Delta = t_{max} - t_{min}$ = **0.25*t*** ***(e.g. 4 y old disk is dated within 1 year, 8y old within 2 years etc.);*** $u(t) = 0.289\Delta$

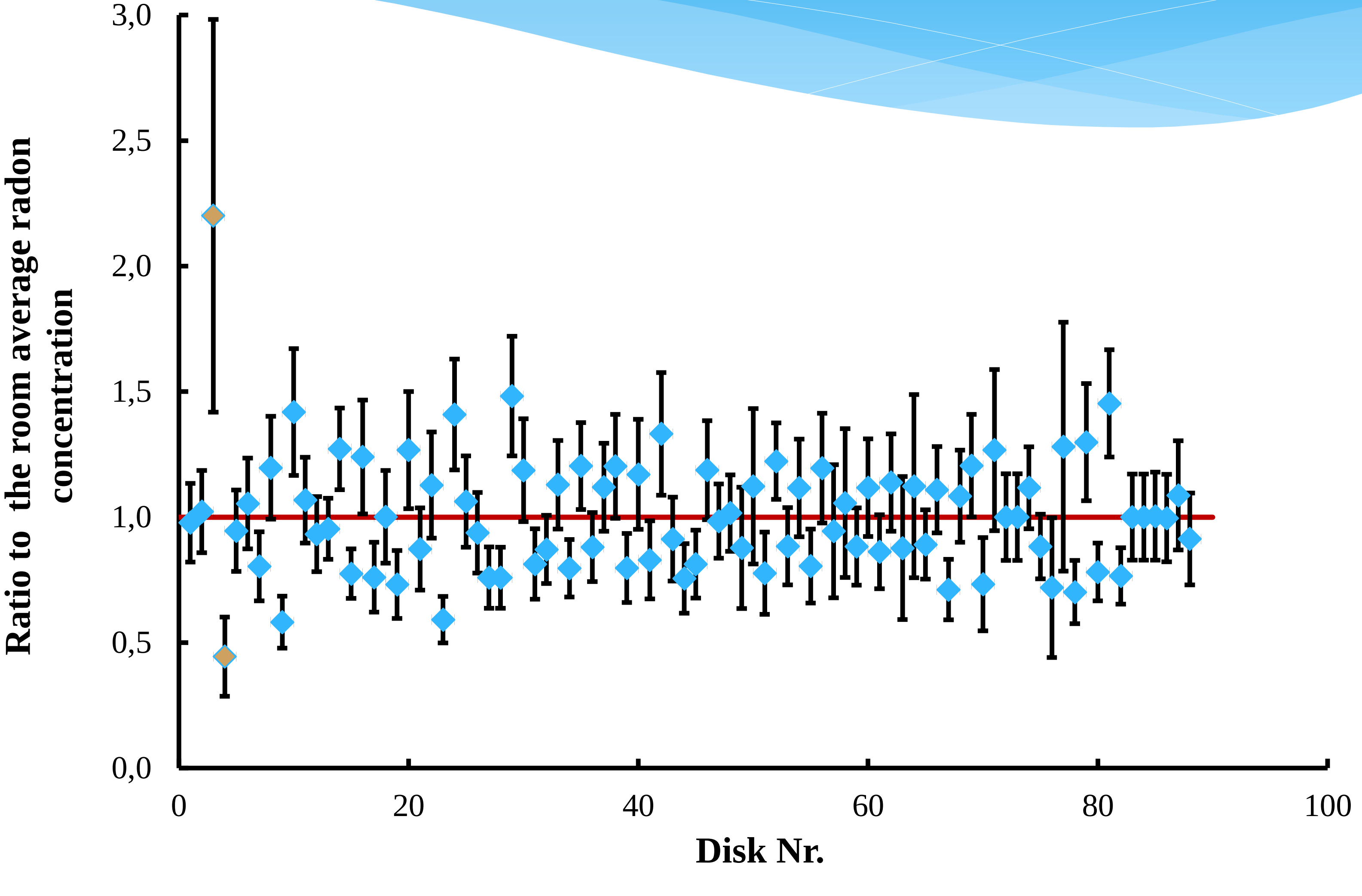
Detection of the radon problem in dwellings (EU-BSS: based on the annual average radon concentration). How long does it take? Why the CD/DVD method is suited for this step?

* "Traditional" prospective measurements: 3-12 months. <u>Too long time just to tell whether there is a problem</u>;
* CD/DVD method: one working day (8 hours). Radon problem (> 100 Bq m^{-3}!) can be identified by any home stored CD/DVD that is more than one year old;
* The probability for false alarm with CDs/DVDs is 5% with one year old disk and even less with older. No probability to skip the problem, provided that the disk is correctly dated.

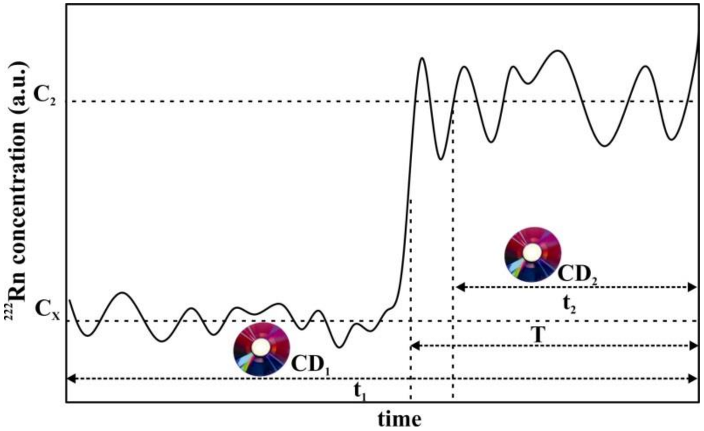
Identification of radon prone areas by CD/DVDs: a survey in 10 suburbs of Sofia, Bulgaria, carried-out in 2015.



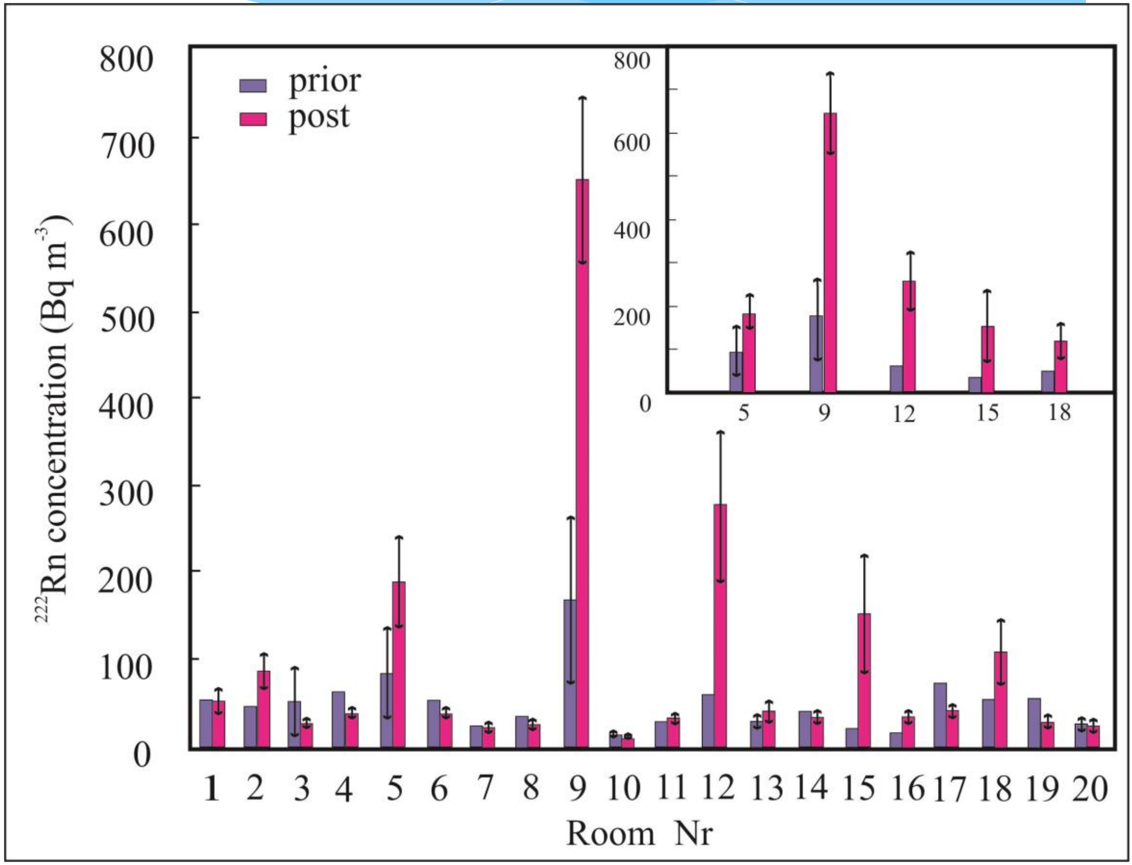
The effect due to the subjective choice of disk for analysis: coherence between results when 2-3 different disks from one room were analysed (2015 survey: 6 rooms with 3 CD/DVDs, 35 rooms with 2 CD/DVDs = 88 disks). Ratio = disk result/room average (from the 2 or 3 analysed disks). SD = 24% (SD = 20% if the two “outliers” are excluded).



CDs/DVDs and energy-efficiency retrofit: two disks of different age can be used to study retrospectively the effect of building reconstruction on radon levels (*J. of Envir. Radioact.* 143 (2015) 76 - 79).



* In 35% of the rooms a statistically significant increase (95% level) of ^{222}Rn concentrations was observed;
* The increase was observed in 4 out of 5 (80%) of the rooms with ^{222}Rn > 100 Bq m^{-3};
* No case of significant decrease!



Conclusions:

- **Comprehended research output to date proves that the CD/DVDs from the stock stored indoors can be used as ^{222}Rn detectors in radon surveys. They can provide in short time estimate of the annual average ^{222}Rn concentration (averaged over the years of exposure) within relative uncertainty better than 24%. Eventually, the uncertainty can be much better, when individual calibration and corrections are applied. Retrospective evaluation of the effect of building retrofit on ^{222}Rn levels is possible by 2 CD/DVDs of different age;**
- **Within WP4 long term (6 months – 2 years) comparative measurements were started together with UC in the UC radon exposure site.**

Thank you!

Annex 6

Report on Activity A3.2.1

Geogenic Radon Potential
Summary of literature

Report of EURAMET 16ENV10 MetroRadon

László szűcs, Zsófia Nagyné Szilágyi, Ádám Nagy
Dr. Péter Nagy, Renáta Botos, Ferenc Árva, Norbert Szabó, Károly Rózsa, Dénes Párkányi

Report on the geogenic radon potential and radon mapping in Europe

Introduction

Radon is a radioactive noble gas, originating from the soil's uranium and thorium content. Radon is considered responsible for more than half the average natural radiation dose for humans and one of the major causes of lung cancer (Pásztor et al. 2016, Bossew 2015). The health concerns of radon made regulatory control necessary and many countries implemented some measures for handling exposure to radon. The usual regulatory approach is specifying dose limits, an amount of radiation dose that is acceptable, these would be translated to reference levels, meaning permissible activity concentrations in various media (set in a way not to reach the dose limits). These reference levels then would be compared to the measured activity concentrations and if those concentrations exceed the reference levels the appropriate measures set in the national regulations would have to be implemented. Developments in the dose conversion calculations (Harrison and Marsh 2012) further raised the importance of radon (the conversion factors were approximately tripled from the previously used ICRP 65). The European Union has included exposure to radon in the 2014 Basic Safety Standards, which requires the Member States to introduce reference levels for indoor radon concentrations not exceeding (as an annual average) 200 Bq m^{-3} for new dwellings and new buildings with public access, 300 Bq m^{-3} for existing dwellings, and 300 Bq m^{-3} for existing buildings with public access, allowing for low occupancy time a maximum of 1000 Bq m^{-3} (Gruber et al 2013). Since regulating radon concentrations requires a large number of measurements some method is necessary to optimize the allocation of the limited resources available for each country. The indoor radon concentration and the exposure from radon are dependent on many factors, but an assumption can be made that geology is a major control on the variation of indoor radon (Appleton and Miles 2010). This radon potential can be described by many different ways (Szabó et al. 2014).

Geogenic radon potential concepts

The EU BSS describes radon-prone areas as a geographic area or administrative region where surveys indicate that the percentage of dwellings expected to exceed national reference levels is significantly higher than in other parts of the country (Bossew 2015). This is a good concept for national regulations, however it can't be used across borders, it is highly dependent on national regulations and gives only a sense of risk related to the average concentration of the particular country, as high or as low it may be.

One of the often (Gruber et al. 2013, Szabó et al. 2014, Bossew 2015, Pásztor et al. 2016) used methods assessing the geogenic radon potential is the continuous variable originally proposed by Neznal et al. 2004.

$$GRP = \frac{c_{\infty}}{-log_{10}(k) - 10}$$

, where *GRP* is the geogenic radon potential, c_{∞} is the equilibrium soil gas radon activity concentration at a definite depth (0.8–1 m) (kBq m^{-3}) and *k* is the soil gas permeability (m^2). Based on research conducted in the Czech Republic, three categories of GRP were set: low (GRP < 10), medium (10 < GRP < 35) and high (35 < GRP) (Szabó et al. 2014). In practice there are some variations on providing the values for *c* and *k* (Gruber et al. 2013).

If *C* and *k values* are not available, then the radon potential is usually estimated from proxies. Such proxies are the standardised indoor radon concentration (measured in defined standard conditions such as ground floor rooms, presence of a basement, etc. to 'factorise out' anthropogenic factors) The standardised indoor radon concentration is correlated to the GRP, with inaccuracies caused by remaining unaccounted for or poorly assessed factors. Other quantities such as equivalent uranium (eU) or dose rate have similarly describable relations to the GRP, however these relations can be locally different, according to the regional predominance of some factors. The controlling factors have to be taken into account when using substitutes for the soil radon in the formula (Gruber et al. 2013).

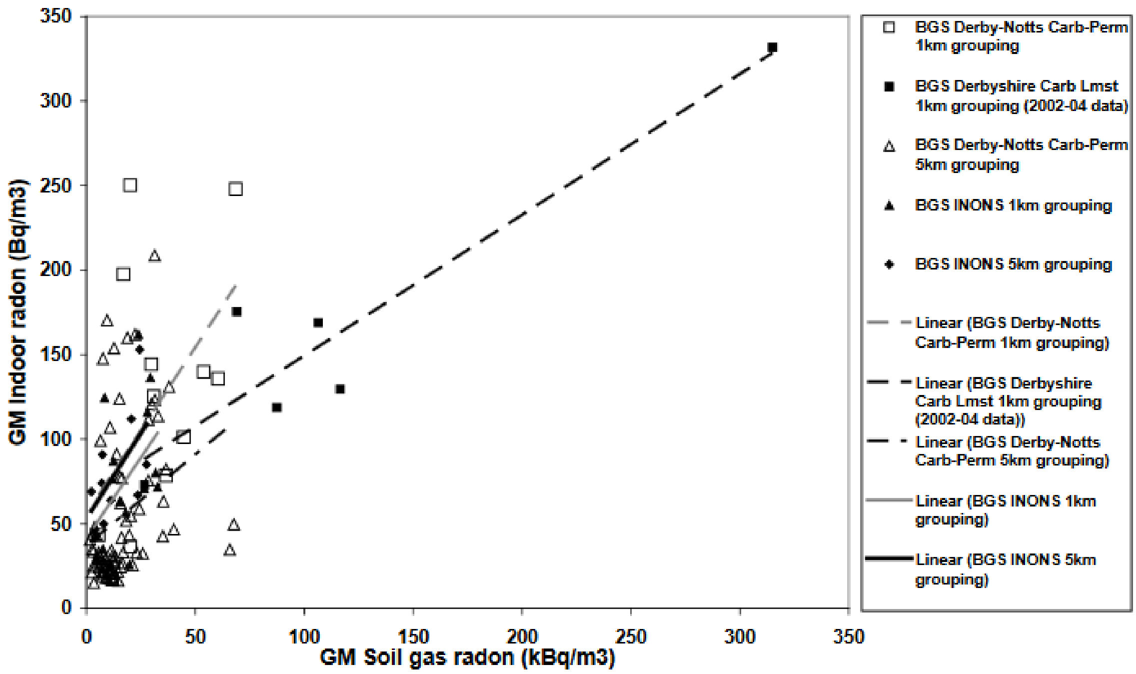
A different way of defining radon potential is based on multivariate cross-tabulation. This method results in an index with a categorical-ordinal quantity, the results are given in classes such as (I, II, III, IV) or (low, medium, high). Classes are assigned based on scores either assigned to a combination of input quantities or calculated as the sum of points delegated to the input quantities. The second type allows for the consideration of multiple factors. Available quantities are soil radon, permeability, standardised indoor concentration, equivalent uranium concentration or other geochemical quantities, external terrestrial gamma dose rate, geological categories, quantities related to tectonics, and the presence of ‘special features’ like mines, caves, water bodies and other extraordinary conditions, which are coded binary (yes, no) (Gruber et al. 2013).

For compiling maps, similarly to the definition, several options exist. First the definition of the target variable has to be decided upon. Then the mentioned variable has to be matched to spatial units (area), which will serve as the basis of the map. These spatial units can take various shapes and forms such as administrative or geological units or a grid cells. Geographical units might be a practical choice for the radon potential, and if desired those units can be decompiled into a grid system. The spatial units are then assigned a value derived from the measured target variables inside (arithmetic mean, geometric mean, median, etc.) (Gruber et al. 2013). If insufficient data is available for the mean calculation to be representative of the area that technique shouldn’t be used. Various estimation or interpolation techniques (local regression methods, disjunctive kriging, Bayesian inference or extensive Monte Carlo simulations) can be implemented during the construction of such maps, but it should be kept in mind that the interpolated concentration is only an estimate, not the actual radon concentration, even though it can be useful for the visualisation of the data and in defining areas with higher risk probability (Cafaro et al. 2014). The different spatial units offer different advantages and disadvantages. Administrative boundaries make administrative action easier, but disregard the relation between the radon potential and the geology and soil properties. Grids makes mapping independent from other variables, but ignores variation within the grid cells. Geological boundaries are much more closely related to the radon potential but still there can be variations in the radon potential inside the geological units (Ielsch et al. 2010). In case of sufficient data density maps can be made by displaying each point of data, without interpolation for the areas between the data points, which would still give an instinctive grasp of the overall situation (McKinley 2015).

Relationship between various parameters used in the estimation of geogenic radon potential

In case of the multivariate cross-tabulation values can be assigned to the various parameters or qualitative categories can be set up. For example, in case of a study on Bourgogne a five step qualitative scale was used to define radon source potential based on lithology and uranium content, while for the geogenic radon potential map they narrowed down the number of categories to three and included the various artefacts such as mines and hot springs into the analyses (Ielsch et al. 2010).

In case of the geogenic radon potential formula reliant on soil gas and soil permeability measurements there are some methods correlating various other parameters if the input is not directly available. Appleton and Miles performed least squares (LS) regression analysis to establish empirical relationships between estimated uranium in the <2mm fraction of topsoils derived from airborne gamma spectrometry data, U measured in the <2mm fraction of topsoil geochemical samples soil gas radon and indoor radon concentrations based on observations in the United Kingdom (Appleton and Miles 2010). The linear relationships were compared to those described for other countries. The described relationships are dependent on the underlying geological units. Similar relationships were described by other authors for Germany, Croatia and the Czech Republic (Appleton and Miles 2010).

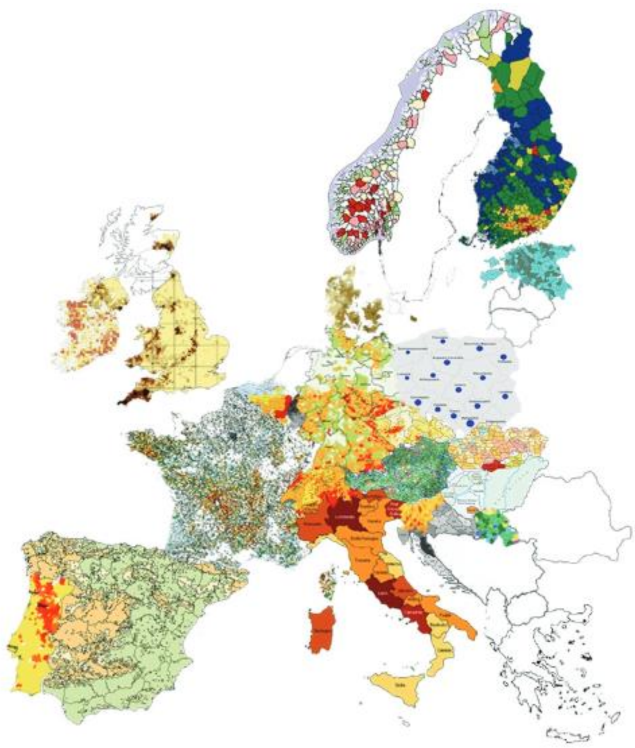


The relationship between indoor radon concentration and soil gas radon by least square regression analysis (Appleton and Miles 2010).

Various log - ratio transformation methods (pairwise, additive, isometric, etc.) have been also used for the eliminating the constant sum closure effects caused by the relative nature of geochemical data (McKinley 2015). Yet another method is using correlation coefficient matrices either on the original data or if lognormal distribution is assumed then the logarithms of the data (Pereira et al. 2017). In some cases, (for example the Portugal C2-type granites) the correlation might not be made between the desired parameters due to the high variability of the data. Some other examples are the Global Ordinary Least Squared and the Geographically Weighted Regression, the latter being suggested favourable due to the inclusion of local geographical parameters (De Novelis et al. 2014, Ciotoli et al. 2017).

Spatial distribution of radon in Europe

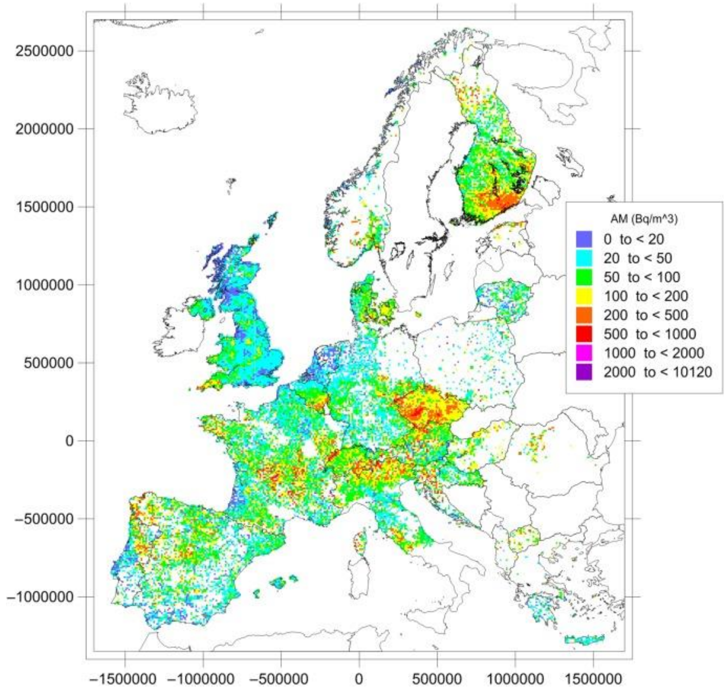
The 2005 Overview of radon surveys in Europe by the Joint Research Centre (JRC) of the European Commission was an attempt to give an overall picture of the radon situation of Europe. This map has been included to show the significant differences in the approach for handling and presenting data even amongst the Member States of the European Union.



Mosaic of published European radon maps conducted separately from each other (Dubois 2005)

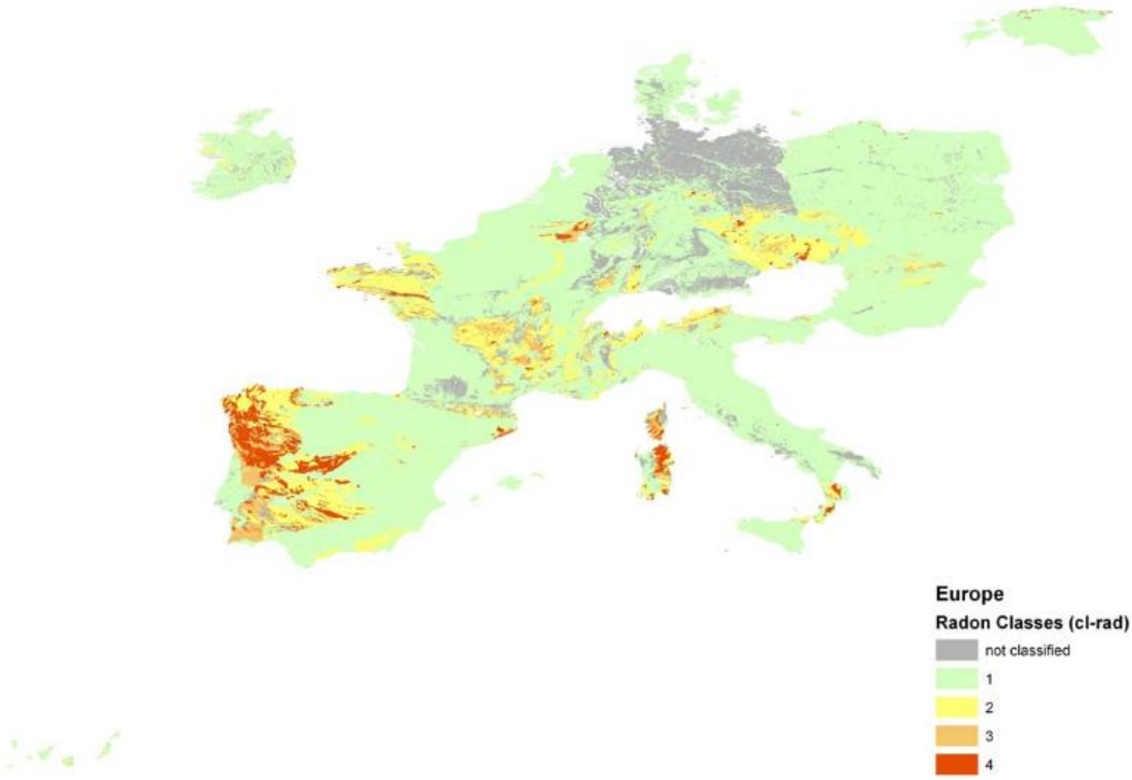
The various countries chose different approaches, some using administrative boundaries, some using grid patterns, some only concentrating on specific areas, some using interpolation and geostatistics. This led to increased interest in higher levels of coordination and cooperation in further such projects (Dubois 2005).

The Joint Research Centre (JRC) of the European Commission made significant efforts to produce a more usable map than the one compiled in 2005. To achieve this goal, they have recruited the national authorities of the Member States and standardized the input data as means over 10×10 km grid cells of (mean) annual indoor radon concentration in ground-floor rooms of dwellings. The grid was provided by the JRC and using the GISCO-Lambert azimuthal equal area projection. The participants were asked to aggregate their original data into the grid and calculate the arithmetic mean (AM), standard deviation (SD), AM and SD of ln-transformed data, minimum, median and maximum, as well as to provide the number of measurements per cell using annual, averaged measurements made on ground floor of residential houses (Tollefsen et al. 2014). Other connected projects are also being implemented, such as the metroRADON project that covers measurement methodology and calibration issues.



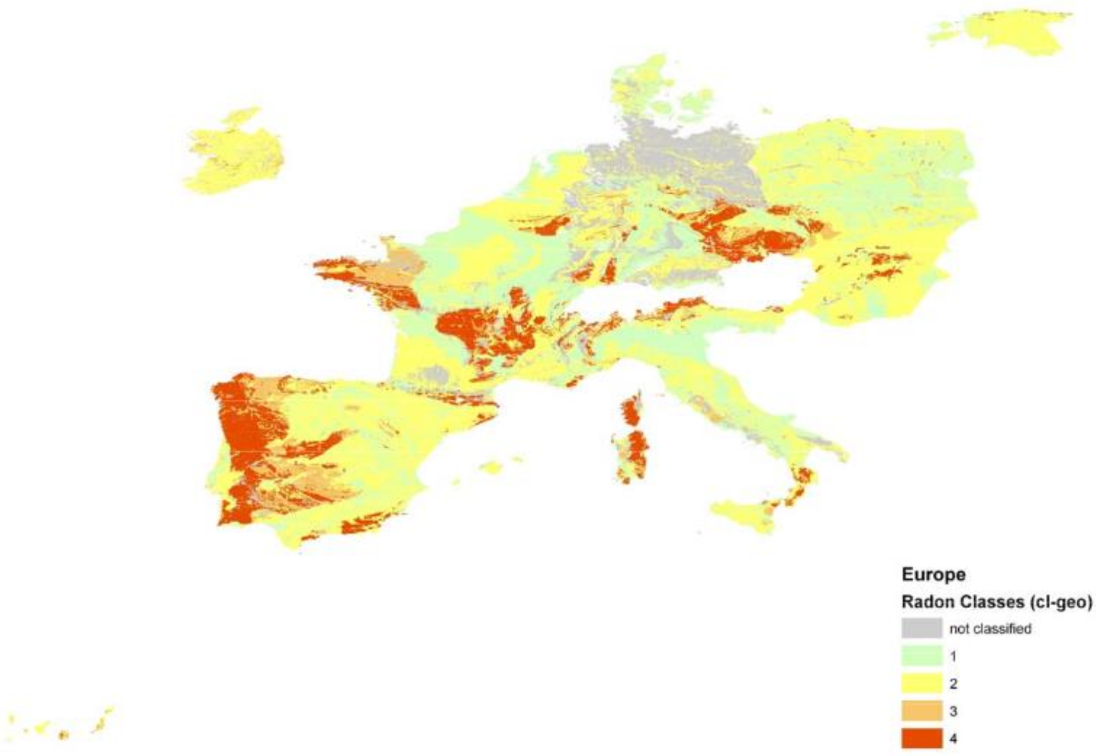
Arithmetic means over 10 × 10 km cells of long-term radon concentration in ground-floor rooms based on data provided by national authorities from 2006-2014 (Tollefsen et al. 2014)

Similar maps are being constructed by the Joint Research Centre of the European Commission for the Geogenic Radon Potential, however that project is still ongoing and has many issues to be solved before completion. Gruber and her colleagues presented a trial version of the European Geogenic Radon Map based on the definition of geogenic radon potential proposed by Neznal (Gruber et al. 2012). The input variables were transformed via transfer models into the input parameters of the equation. The input variables were also assigned scores for classification. The maps would be based on a Geogenic Radon database which would in turn be based on a radon-relevant geological classification. The preferred method of classification was the use of OneGeology, the geological types were assigned an index value from 1-4 based on German geotypes. This posed some problems due to countries that are not part of the OneGeology and the problems of geology classification (types missing, different classification systems used, difficult classification, incomplete data, etc.).

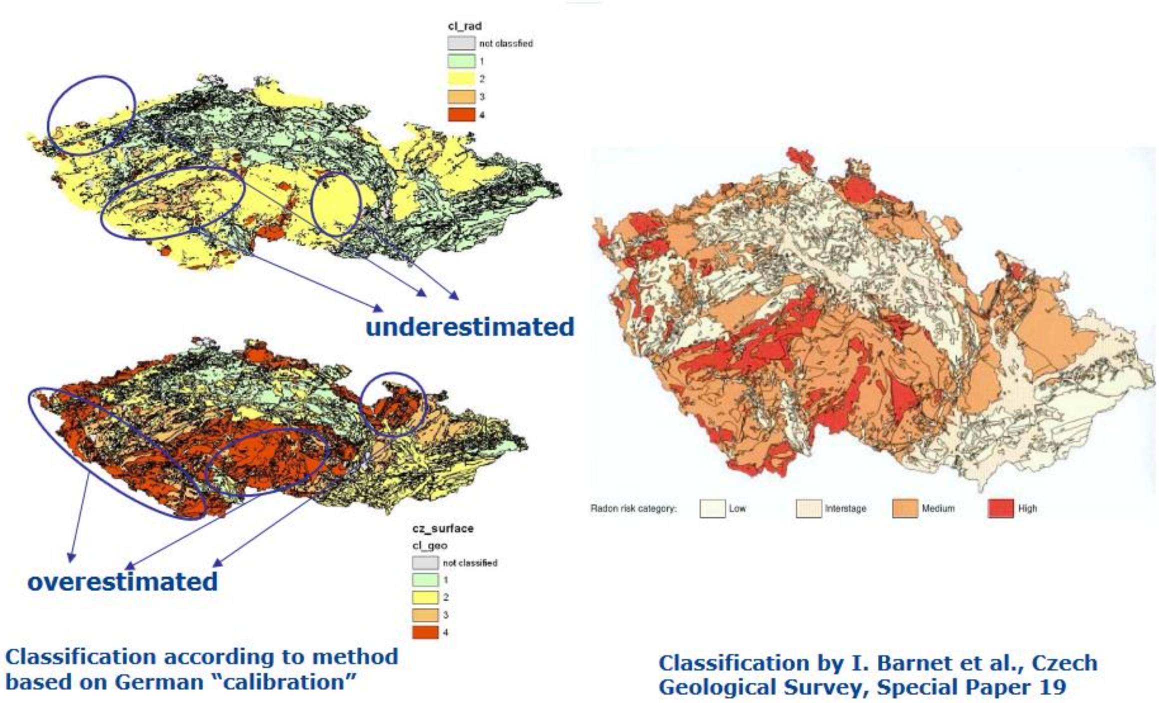


Trial version of the European Geogenic Radon Map (EGRM) with „radiological" radon classes

(Gruber et al. 2012)



Trial version of the European Geogenic Radon Map (EGRM) with „geological" radon classes (Gruber et al. 2012)



Possible issues with the trial version of the European Geogenic Radon Map (Gruber et al. 2012)

While the EGRM presents a unified picture of the collected data the trial version was calibrated using German geotypes, so for other countries analogies were used. For the improvement of the map an iterative approach is necessary, with feedback from the experts of other countries. The EGRM has to be supplemented by data on the geotypes not present in Germany, while in other countries the geological analogies have to be confirmed and validated.

Distribution of radon measurement methods and measurement devices in Europe

Assessing the radon measurement methods and measurement devices in Europe would be a major project on its own and would require a significant amount of man hours. In the following points methods used in big national and international surveys are listed, with the addition of methods presented in some articles. Some microstates don't have their own national radon surveys or are covered by international agreements with neighbouring countries.

Albania

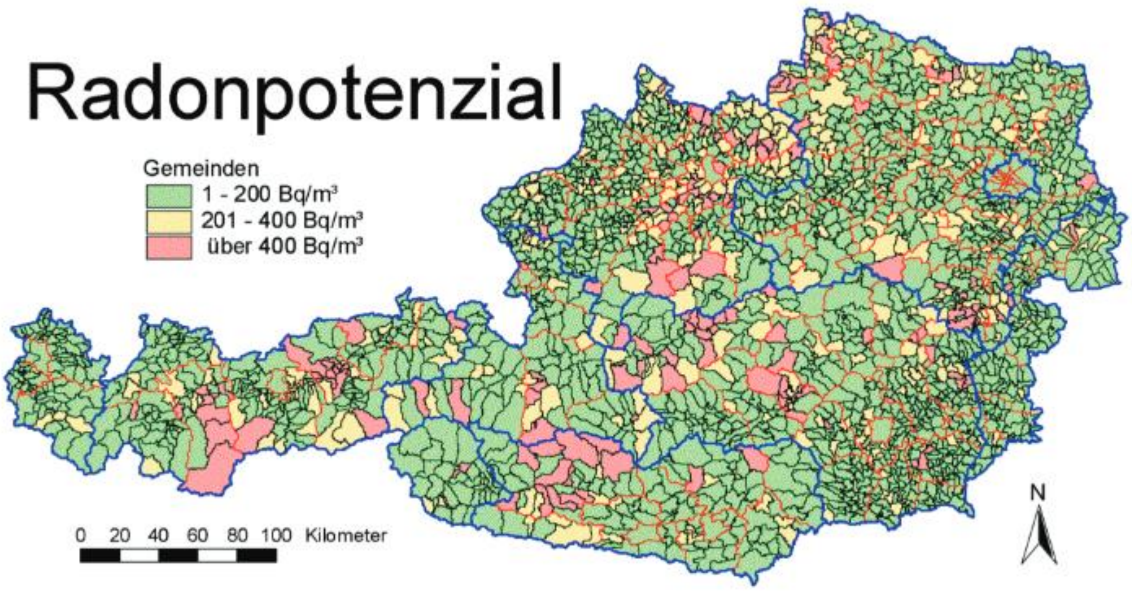
The Institute of Applied Nuclear Physics of the State University of Tirana has access to CR-39 (SSNTD) based passive monitoring with digital microscope evaluation (Daci and Bode 2016). For soil gas radon concentration measurements Luk-4 type equipment (based on Lucas-cells) was reported to be used (Dogjani et al. 2017).

Armenia

Armenia has used a RAD7 type active device, which exchanged FAS-2-P type radon meters, related to conduct earthquake research (Saghatelyan et al. 2010).

Austria

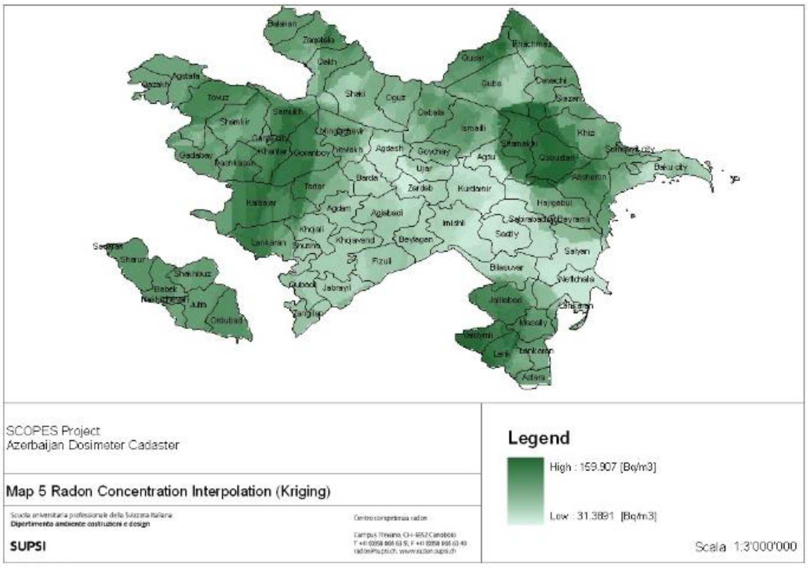
Austria used solid state nuclear track detectors with the Karlsruhe 2 system, E-PERM, and charcoal with LSC measurements (Picorad). In the same report they used AlphaGUARD type active device for the measurement of soil gas (Dubois 2005). Never articles also mention AlphaGuard based soil gas measurements and the permeability being calculated according to the formula of Damkjaer and Korsbech from the flow rate and pressure (Gruber et al 2008).



Radon potential in Austria defined mainly as the annual mean radon concentration in a commonly used living- or bedroom on the ground floor in a house without basement (Dubois 2005).

Azerbaijan

The Geology Institute of Azerbaijan National Academy of Sciences GIA conducted a joint survey with the Radon Competence Centre (RCC) of the University of Applied Sciences of Southern Switzerland (SUPSI) using the Swiss methodology and radon Gammadata dosimeters (Veliyeva et al. 2012).



Map of indoor radon concentration of Azerbaijan by interpolated by krieging (Veliyeva et al. 2012).

Belarus

An indoor radon survey was conducted using LR-115 type track detectors (Chunikhin et al. 2016) The Belarusian State Institute of Metrology also has access to an AlphaGUARD PQ 2000 EF 1481, which was used in the COOMET.RI(II)-S1.Rn-222 (169/UA/98) intercomparison exercise.

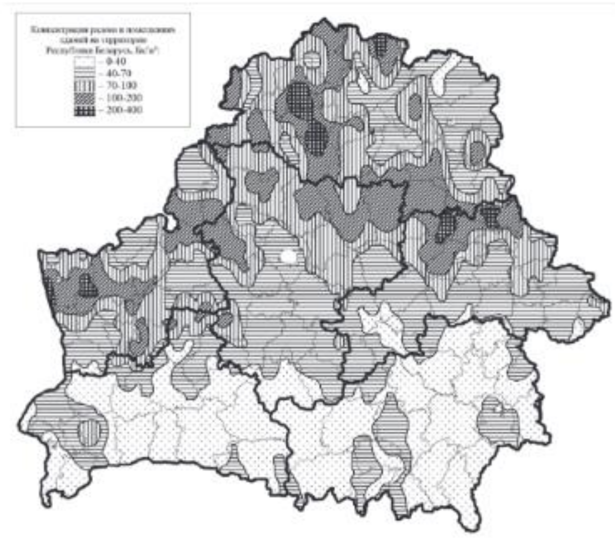
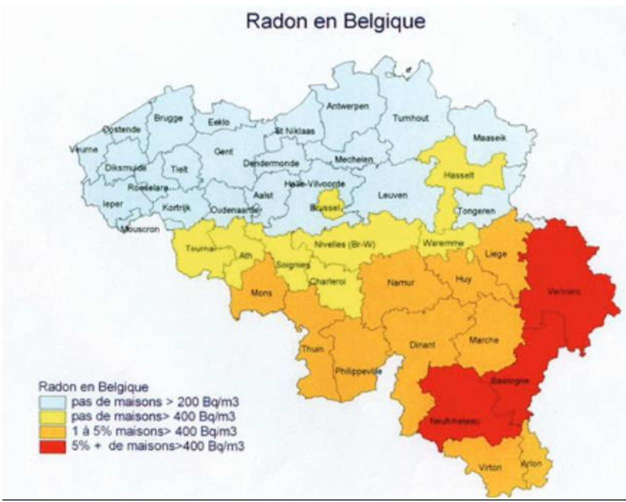


Рис. Карта ОА радона в помещениях жилых зданий
на территории Республики Беларусь
[**Fig**. The Republic of Belarus radon indoor map]

Indoor radon map (Chunikhin et al. 2016)

Belgium

The Federal Agency for Nuclear Control (FANC) used Makrofol type track-etch detectors for the long term monitoring of indoor radon (Dubois 2005). A more recent article speaks of measurements with charcoal detectors evaluated by gamma spectrometry and track-etch detectors and a map constructed based on geological units and geometrical mean radon concentration (GM) (Tondeur et al. 2014).



Percentage of houses exceeding 200 and 400 Bq/m^3 (Dubois 2005).

Bosnia and Herzegovina

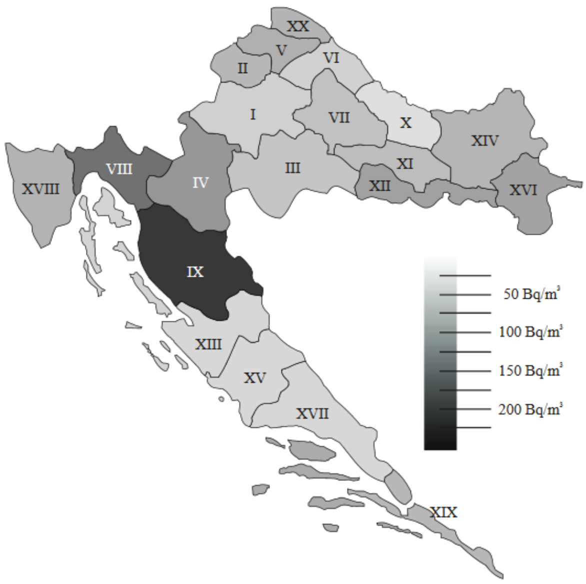
Bosnia and Herzegovina has access to Alpha GUARD PQ 2000 Pro type active devices (including supplementary devices such as AquaKIT, AlphaPUMP and Radon-Box) and solid state nuclear track detectors with the Radosys evaluation system (IAEA TC Project 9127).

Bulgaria

Bulgaria uses Alpha Guard active devices, solid state nuclear track detectors with the Radosys evaluation system and the E-PERM system (IAEA TC Project 9127). A retrospective dosimetry method based on polycarbonates (CD-s) was also described by Pressyanov (Pressyanov 2010). A study of indoor radon in kindergartens was conducted by RSKS type nuclear track detectors, which use CR-39 chips inside (Ivanova et al. 2014).

Croatia

The Laboratory for Low-Level Radioactivity at the Department of Physics, University of Osijek) uses LR-115 II type solid state nuclear track detectors, as well as AlphaGUARD type ionization chambers and Radhome II type silicon detectors (IAEA TC Project 9127). LR-115 was used also for soil gas monitoring (Dubois 2005).



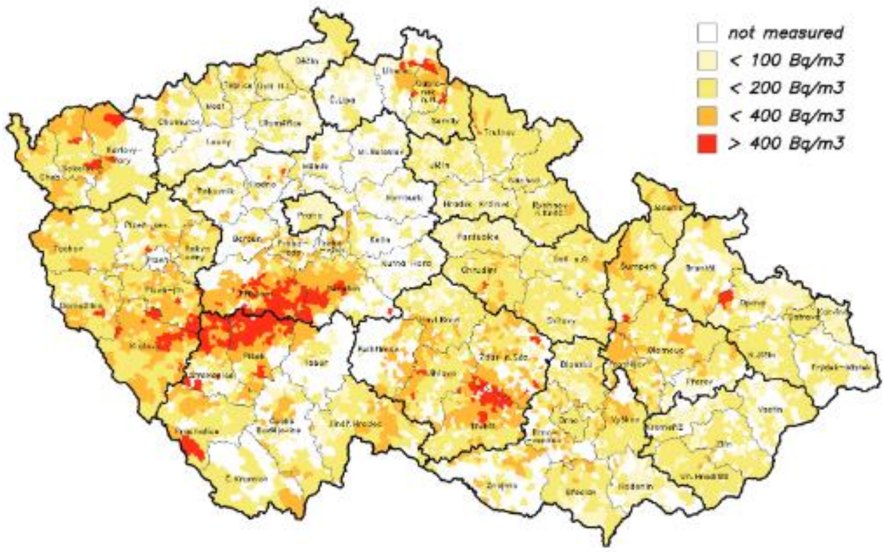
Annual mean indoor radon concentrations in Bq/m^3 shown on a regional level (Dubois 2005).

Cyprus

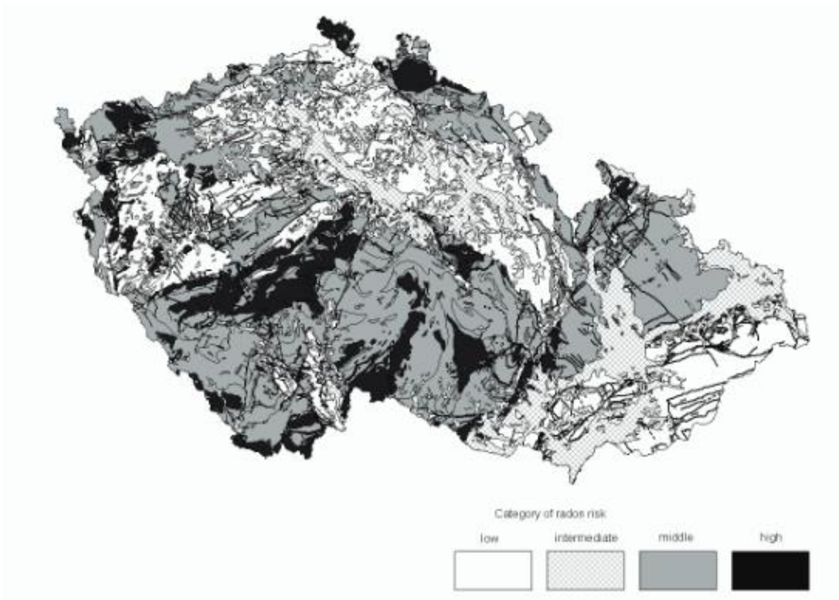
The Department of Physics, University of Cyprus used Radim-3 type Passive electronic radon detectors for the monitoring of radon (Dubois 2005).

Czech Republic

The National Radiation Protection Institute (SURO) used LR 115 type track-etch detectors for the monitoring of indoor radon, the soil surveys were conducted using various scintillation devices (Dubois 2005). For the survey of building sites, a method was described by using at least 15 steel probes to cover the area in question with their tips at 0.8 m depth. Surface air would be removed from the tube, the soil permeability would be measured by resistance against pumping, and samples of soil air would be measured by Lucas cells. The third quartile (75% quantile) of the results would be taken as the true value of radon concentration in soil air (Neznal et al 2004, Gruber et al. 2013).



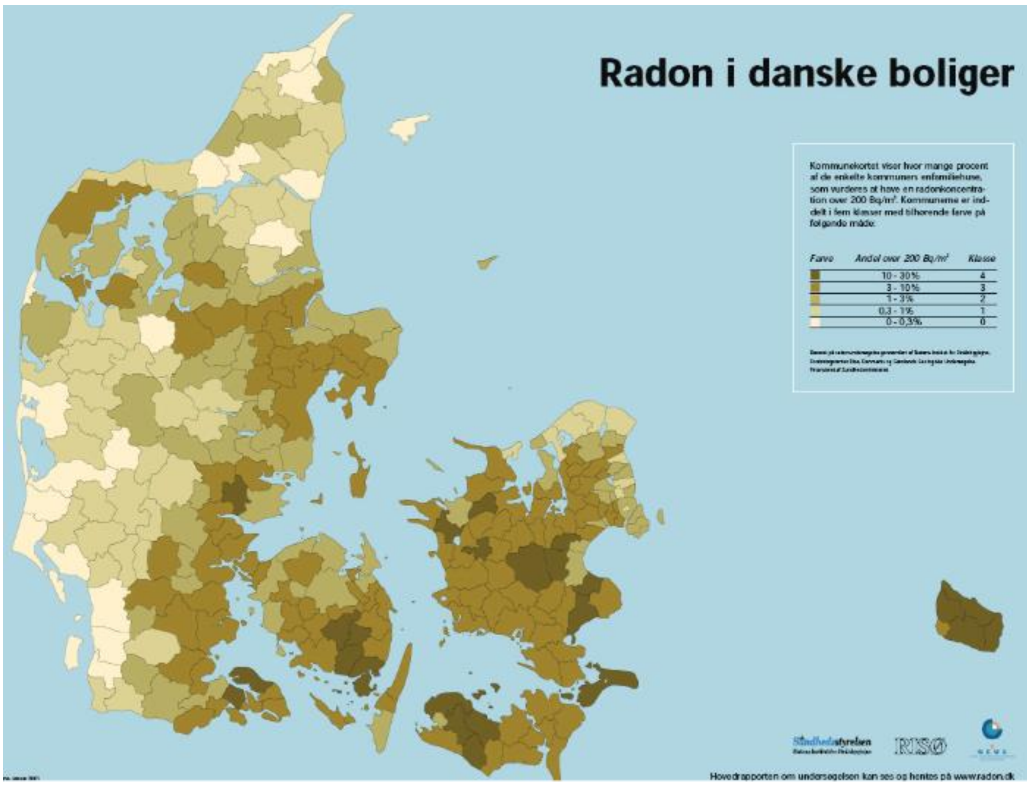
Indoor radon averages calculated at the municipal level (Dubois 2005).



Radon potential map using the vectorised contours of geological units (Dubois 2005).

Denmark

The National Institute of Radiation Hygiene used CR-39 SSNTD-s for the long term monitoring of indoor radon (Dubois 2005).



Percentages of houses above 200 Bq/m^3 based on municipalities (Dubois 2005).

Estonia

The Radiation Safety Department of Environmental Board utilizes CR-39 type SSNTD-s with the Radosys evaluation system for long time monitoring, has two Alphaguard P30s and an Atmos 12 DPX. The state owned Estonian Geological Survey conducts radon measurements in soil. Estonia also has several private companies offering radon measurements and measurement devices, such as the Ramon 2.2 (IAEA TC Project 9127). The Estonian Radiation Protection Centre used CR-39 type SSNTD-s for the monitoring of indoor radon (Dubois 2005). The Geological Survey of Estonia conducted a soil gas survey using Emanometer Markus-10 and Portable Gama Ray Spectrometer (GRS), Model GPS-21 (Dubois 2005). Estonia has radon risk maps including Rn concentration in soil, Preliminary Rn risk areas; Rn concentration in soil air by direct measurement with Markus 10 (recalculated to depth 1 m); Rn concentration in soil air calculated after U (^{226}Ra); U (^{226}Ra) concentration in soil; Th (^{232}Th) concentration in soil; K (^{40}K) concentration in soil; Natural radiation of soil).

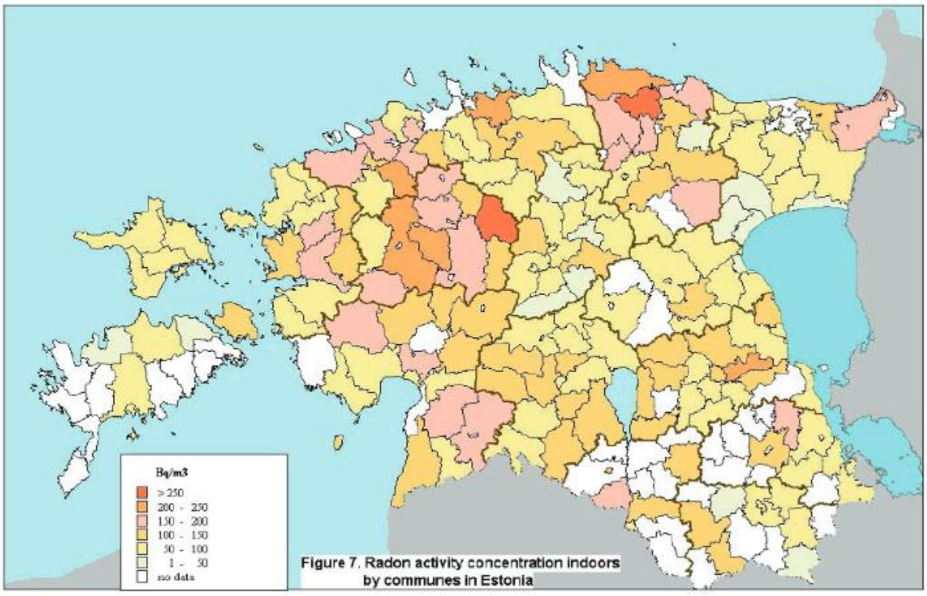
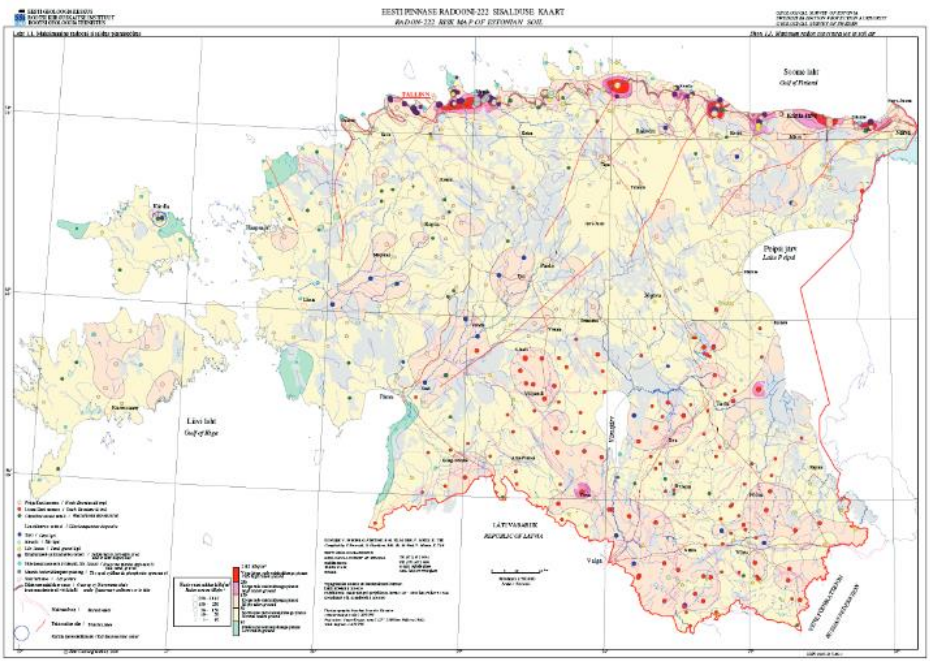


Figure 7. Radon activity concentration indoors by communes in Estonia

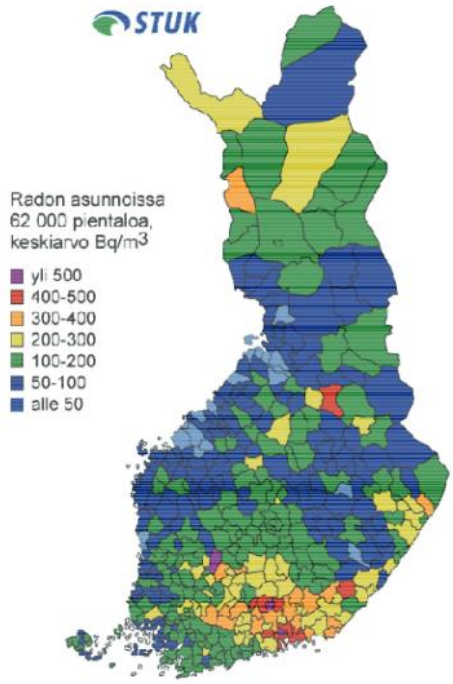
Indoor radon activity concentration by communes (Dubois 2005).



Map of maximum soil gas concentrations (Dubois 2005).

Finland

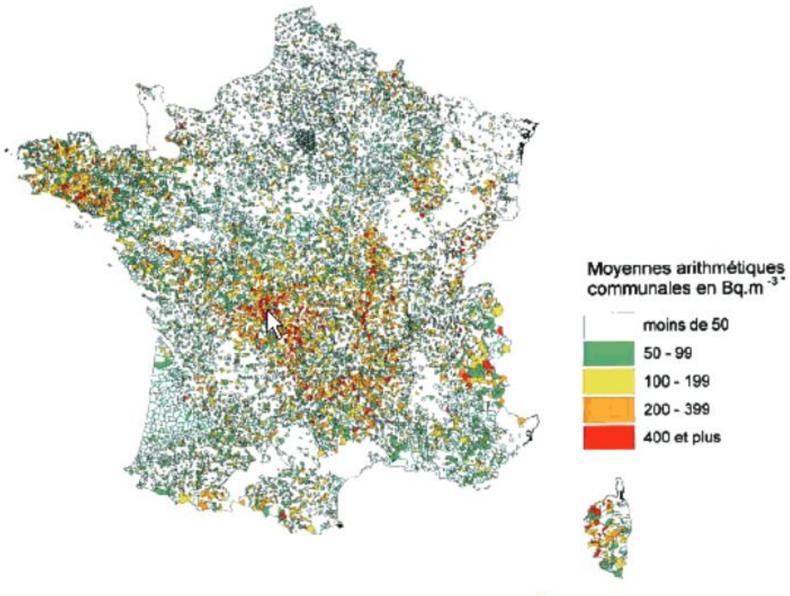
The Radiation and Nuclear Safety Contact point (STUK) conducted an indoor radon survey using Makrofol type track-etch detectors (Dubois 2005). Soil gas measurements for scientific purposes by radon-tight cans and Lucas cells were also reported (Dubois 2005). This type of activity is still ongoing and can be requested by homeowners as well (Valmari et al. 2014).



Indoor average annual radon concentration map by municipality (Dubois 2005).

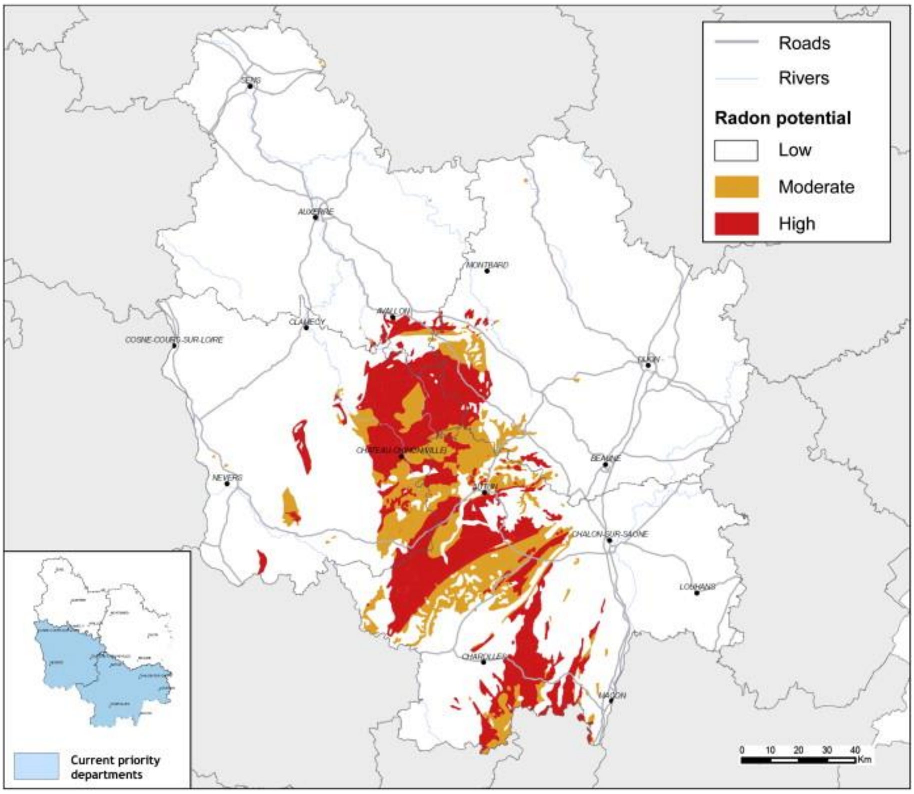
France

The Institute for Radiological Protection and Nuclear Safety (IRSN) used LR115 type track detectors for indoor radon measurements and maps were compiled both by grid pattern and by administrative boundaries, soil gas measurements were conducted using Lucas-cells (Dubois 2005).



Annual mean indoor radon concentration levels on a municipality basis (Dubois 2005).

As for radon potential mapping, a study utilized a set of geologic variables: geology, lithology, U content, fracturing (presence of faults), underground mines, and thermo-mineral sources as quantitative parameters (Ielsch et al. 2010). This was made necessary by the relative sparsity of the soil-gas data in France. The data was provided by previous geological and geochemical surveys, studies and databases, to compile the map they selected a 1.5 km^2 sized minimal object size and calculated the mean U content of the geological units based on the geological map of France (1:1,000,000, digital map). Then they took into account the various artefacts (mines, geological fractures, etc.) inside the geological units and constructed a map by compiling all considered layers together. For classifying the geogenic radon potential they used two quantitative scales, a more detailed 5 step and a more easily interpretable three step scale.



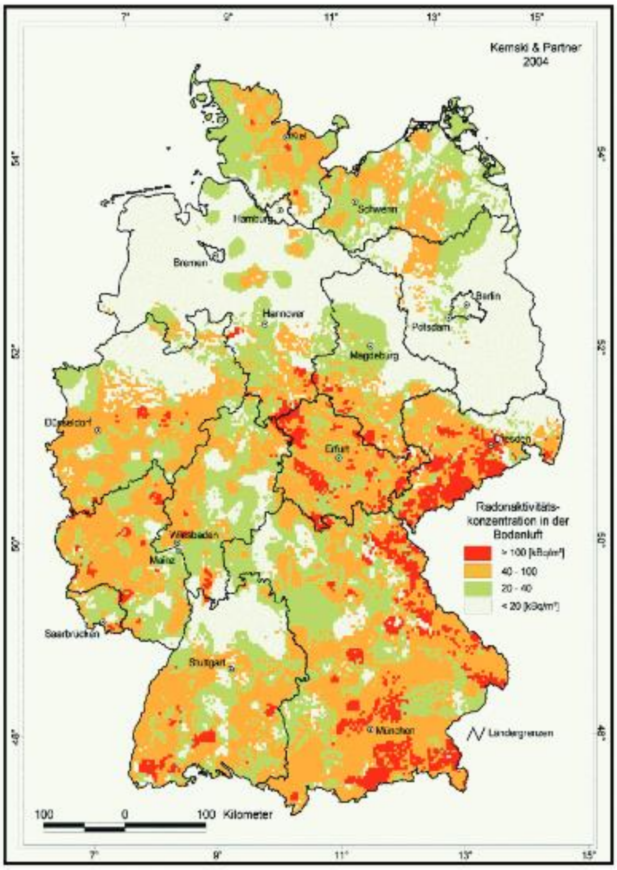
The geogenic radon potential map of Bourgogne (Ielsch et al. 2010).

Georgia

The Nuclear and Radiation Safety Department, Ministry of Environment and Natural Resources Protection of Georgia has access to various active devices, such as AlphaGUARD, RAD7, SISIE AND PPA-01M-03. Long term measurements are conducted by CR-39 type solid state nuclear track detectors or a variety of Electret ionisation chambers (IAEA TC Project 9127). Lucas cells and Radhome devices were also reported to be used (Dubois 2005).

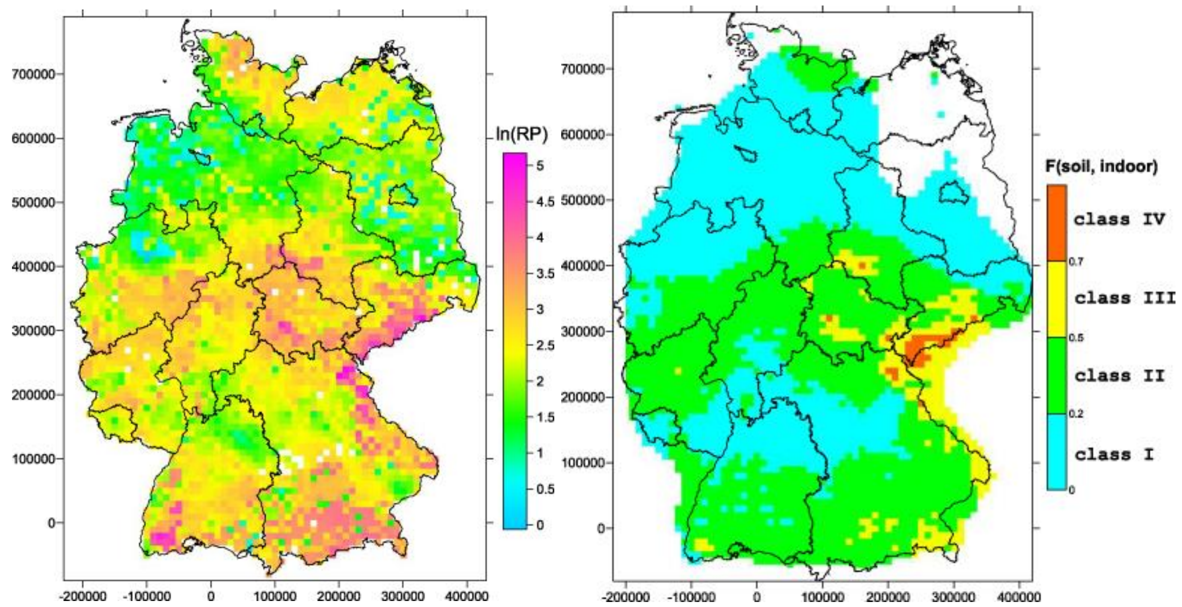
Germany

The Federal Office for Radiation Protection (BfS) reportedly used Makrofol type track-etch detectors, and activated charcoal detectors evaluated by either LSC or gamma-spectrometry. Soil gas-measurements were done by grab sampling and measurement using Lucas-cells (Dubois 2005). For the soil gas measurements, a measurement protocol using three 1 m deep boreholes in an equilateral triangle with sides approximately 3 m long. A steel probe would be sealed into the hole by an inflatable device, the surface air would be removed, the permeability measured, and two samples from each hole would be measured three times by Lucas cells. Means would be calculated by hole and the maximum would be used as the representative soil radon concentration. (Kemski et al. 2001, Gruber et al. 2013)



Soil-gas map of Germany by distance-weighted interpolation on a 3×3 km grid basis within geological units using GIS (Dubois 2005).

Newer maps have been compiled using a 10x10 km basis compatible with the joint European Atlas of Natural Radiation (EANR) project’s grid, which would be compatible with the European geogenic radon map (EGRM) and the European indoor radon map (EIRM). The ’Neznal-type’ radon potential was calculated and estimated using ordinary kriging, including geological classes as deterministic trend predictors, while after collocating the soil and indoor radon concentration and similar kriging techniques, the joint distribution of radon in soil and ground floor indoor radon was displayed as a copula using Sklar's theorem.



'Neznal-type' radon potential map (right) and joint distribution of radon in soil and ground floor indoor radon (left) (Gruber et al. 2013)

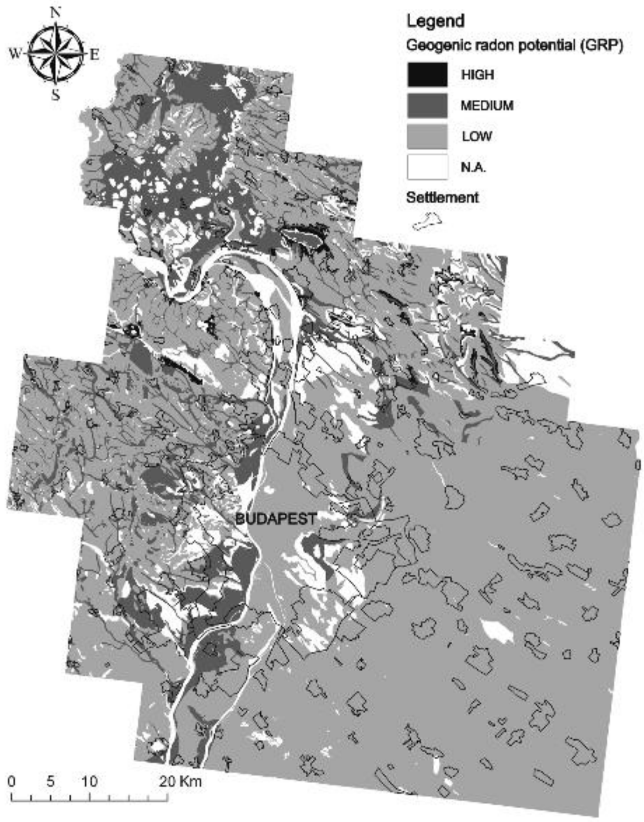
Greece

The Greek Atomic Energy Commission (GAEC) has access to CR-39 solid state nuclear track detectors, Electret ionization chambers as well as AlphaGUARD and SARAD type active devices (IAEA TC Project 9127). Other papers described the use of MPD radon dosimeters (using CR-39 chips inside) and active devices AlphaGUARD and Sarad EQF3023 (Nikolopoulos et al. 2002, Louizi et al. 2005)

Radon prone areas in Greece (Nikolopoulos et al. 2002)

Hungary

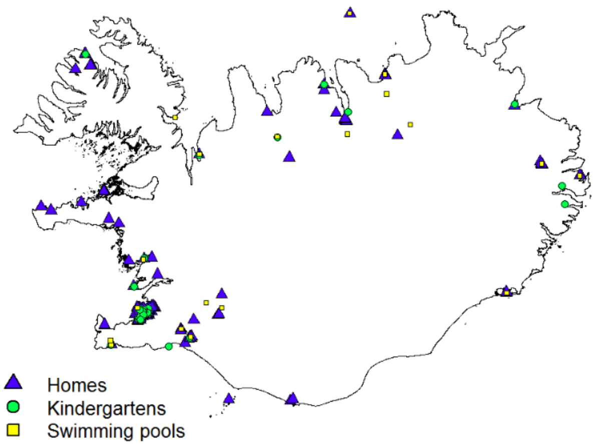
The National Research Institute for Radiobiology and Radiohygiene Frederic Joliot Curie (OSSKI) has access to electret detectors (E-PERM), CR-39 nuclear track detectors with the Radosys evaluation system, as well as a variety of active devices such as RAD-7 (Durridge Co.) AlphaGUARD (Genitron Inst.), Radim 2,-2P, -3, Pylon AB-5, RGM-3, SARAD, Dataqua and ATMOS 12 DPX (IAEA TC Project 9127). In case of Geogenic Radon Potential mapping a RAD7 Electronic Radon Detector has been reportedly used for soil radon gas measurements, while the soil gas permeability was measured by a Radon-JOK through the same probe. The 10 × 10 km grid suggested for the European indoor radon map was used to help in the uniform determination of the sampling points. The map was compiled using Triangular Irregular Network (TIN) interpolation and the median, upper quartile and internationally defined GRP limits (Szabó et al. 2014). The same area was later analysed by regression kriging (László et al. 2016).



Geogenic radon potential map of central Hungary (Szabó et al. 2014)

Iceland

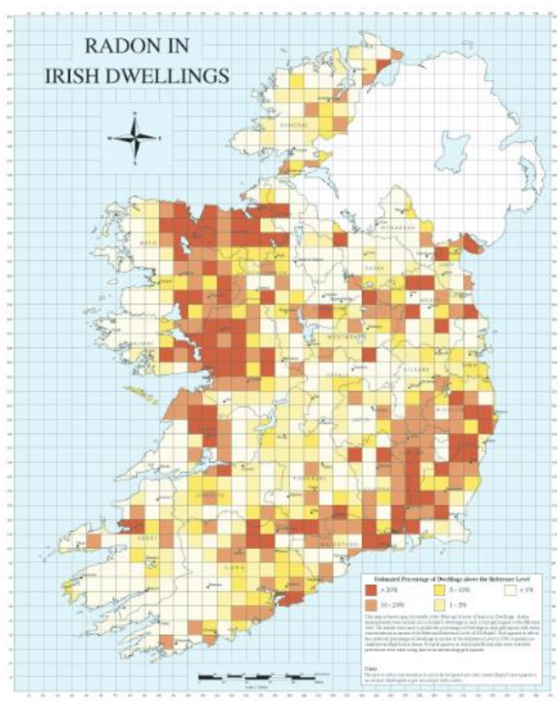
Iceland carried out a national survey of indoor radon using Radosys type CR-39 SSNTDs and the domestically developed Autoradon liquid scintillation system. The mean of the surveyed values was 13 Bq/m^3, the median 9 Bq/m^3, 95% of the results were below 40 Bq/m^3 and the highest value was 79 Bq/m^3 (Jónsson et al. 2016).



Points of measurement at the national survey of Iceland (Jónsson et al. 2016).

Ireland

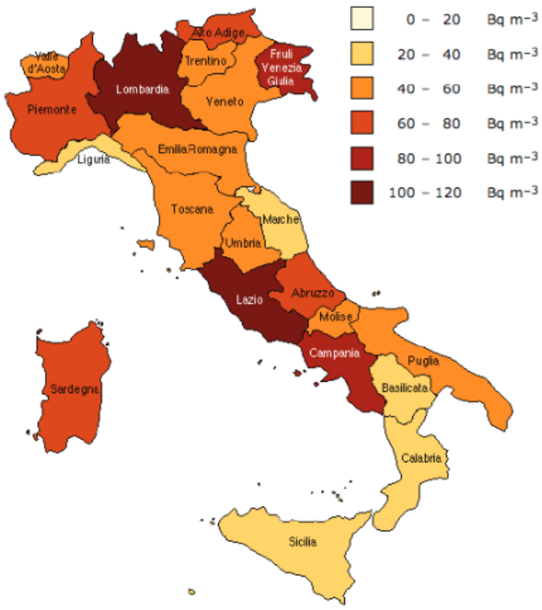
The Radiological Protection Institute of Ireland (RPII) used CR-39 type SSNTD-s for indoor radon monitoring (Dubois 2005).



Annual mean radon concentration values in Irish dwelling using a grid pattern (Dubois 2005).

Italy

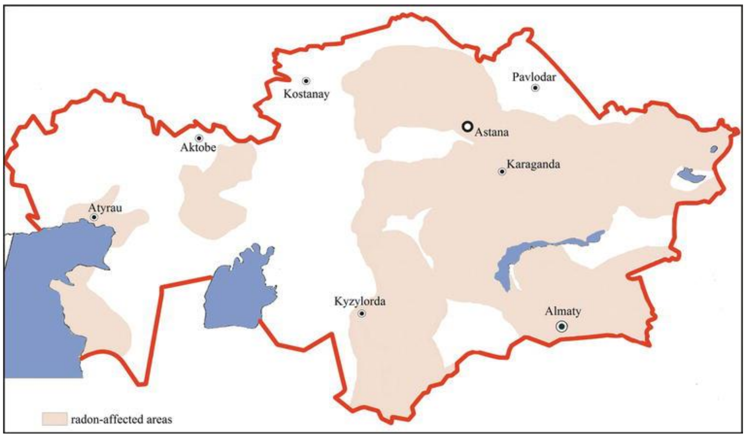
The Istituto Superiore di Sanità (ISS) (Italian National Institute of Health) used LR-115 type track-etch detectors for indoor radon monitoring (Dubois 2005). Radon measurements have been also conducted by CR-39 type SSNTD-s (Cafaro et al. 2014). Soil gas measurements using an active radon detector with a Lucas cell have been described as well as the use of “equivalent” uranium (eU) and average radium content in soil as proxies in the absence of soil gas data (Ciotoli et al. 2017).



Average annual radon concentration levels by region (Dubois 2005).

Kazakhstan

Kazahstan has access to many different types of devices, however the articles providing an overview on the radon situation are vague on the question of what type of devices are used (Bersimbaev and Bulgakova 2015, Bersimbaev and Bulgakova 2017). Other sources reported the use of Ramon-02, ALPHARAD and AlphaGUARD type active devices, as well as the use of CR-39 SSNTD-s with the Radosys system (Vladislav 2016).



Radon affected areas (Bersimbaev and Bulgakova 2017).

Kosovo

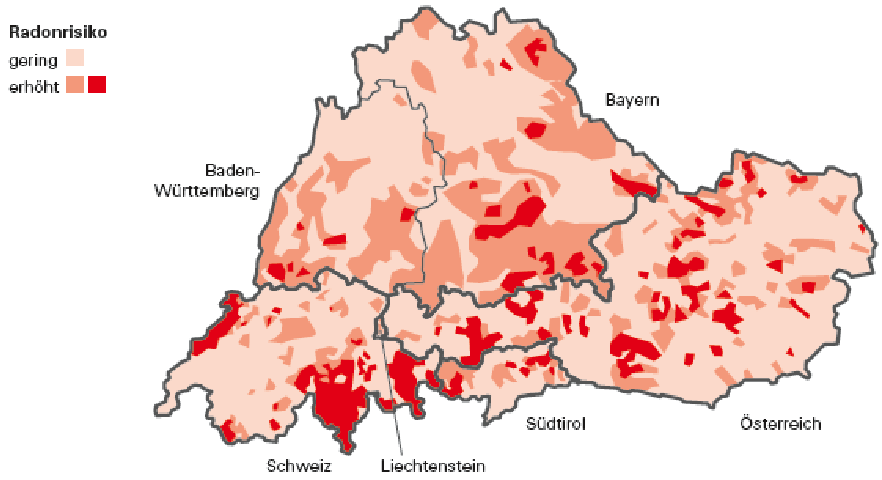
Surveys using Gammadata type CR-39 SSNTD-s were carried out in Kosovo for indoor radon measurements (Gulan 2017). In an other case TASTRAK type CR-39 detectors were used (Gulan et al. 2017). A CRM 510 type active device has also reportedly been used for monitoring radon in underground mines (Hodolli et al. 2015).

Latvia

The Environmental Quality Unit of the Ministry of Environment reported a few pieces of equipment for measurements in air, soil and water (radon activity concentration) (IAEA TC Project 9127). The Radiation Safety Centre reportedly used Electret Ion Chambers and Pulsed Ionization-Chambers (ATMOS-12, Gammadata Matteknik AB) for indoor radon monitoring. Soil gas measurements were carried out using Emanometer Markus-10 (Gammadata Matteknik AB) (Dubois 2005).

Liechtenstein

Liechtenstein seems to be covered by a cooperation between the Österreichische Agentur für Gesundheitund Ernährungssicherheit (AGES) Österreichische Fachstelle für Radon, the Bayerisches Landesamt für Umwelt Abteilung Strahlenschutz, the Ministerium für Umwelt, Klima und Energiewirtschaft Baden-Württemberg, the Amt der Oö. Landesregierung Abt. Umweltschutz / Strahlenschutz, the Landesagentur für Umwelt Bozen, and the Bundesamt für Gesundheit (BAG) Sektion Radiologische Risiken (BAG 2012).



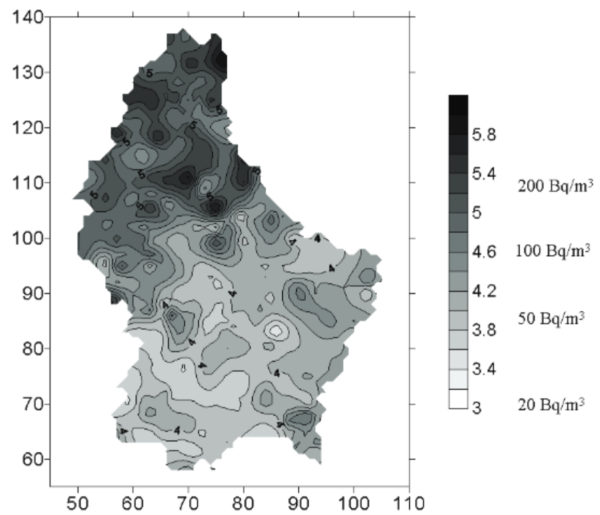
Radon risk area map published by the Bundesamt für Gesundheit (BAG 2012)

Lithuania

The Radiation Protection Centre of the Ministry of Health uses E-PERM electrets (IAEA TC Project 9127). Soil gas measurements were reported using Emanometer Markus-10 with Ortec Ultra Silicon detector (Dubois 2005).

Luxembourg

The Radioprotection Survey and the Laboratoire Physique des Radiations reportedly used Macrofol type track-etch detectors for indoor radon monitoring. Maps were compiled using SurferR and kriging techniques. Soil gas measurements were carried out by Lucas-cells (Dubois 2005).



Local annual radon concentration values by interpolating local median values (log-transformed) by ordinary kriging (Dubois 2005).

Macedonia (FYROM)

The Ionizing Radiation Department and Radioecology, Institute of Public Health applies CR-39 type SSNTD-s with the RadoSys evaluation system (IAEA TC Project 9127).

Malta

The Radiation Protection Board reportedly has access to track-etch detectors and AlphaGUARD detectors (Dubois 2005).

Moldova

The National Scientific-Applied Centre of Preventive Medicine (NSACPM) has Radonometer RTM 1688-2 and AlphaGUARD type active devices (IAEA TC Project 9127).

Monaco

A RAD7 type silicon semiconductor detector was reportedly used for studying the effects of radon loss in ^{226}Ra measurements (Scholten et al. 2013).

Montenegro

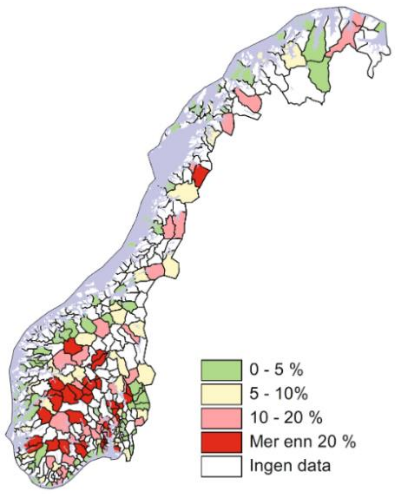
Montenegro has access to AlphaGUARD and RAD7 type active devices with various accessories included (IAEA TC Project 9127).

Netherlands

The National Institute for Public Health and the Environment and Laboratory for Radiation Research reportedly used KVI and FzK (Karlsruhe) type track-etch detectors. Top-soil measurements were carried out using HPGe detectors (Dubois 2005).

Norway

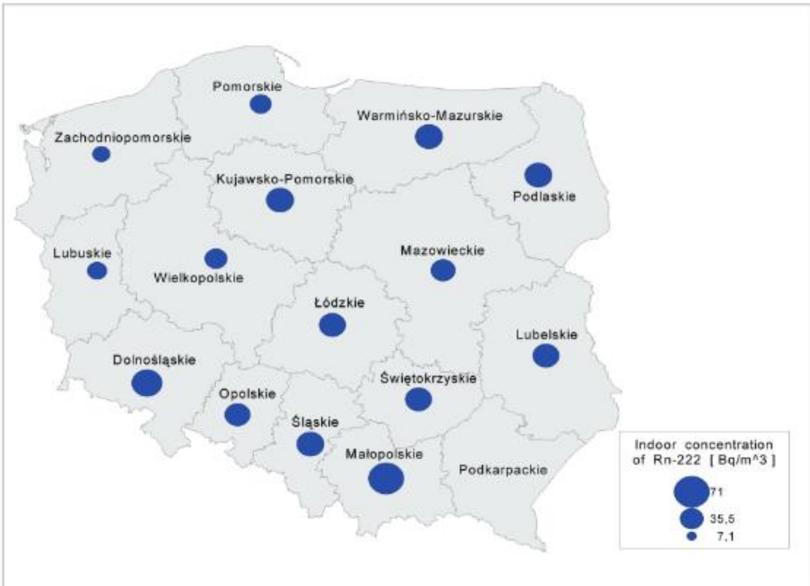
The Norwegian Radiation Protection Authority (NRPA) reportedly used CR-39 SSNTD-s for indoor radon measurements (Dubois 2005).



Estimation of the percentage of houses above 200 Bq/m3 by municipality (Dubois 2005).

Poland

The Central Laboratory for Radiological Protection reportedly used CR-39, LR-115 and charcoal for the monitoring of indoor radon. Soil gas measurements were carried out Lucas-cells and AlphaGUARD type active devices (Dubois 2005).

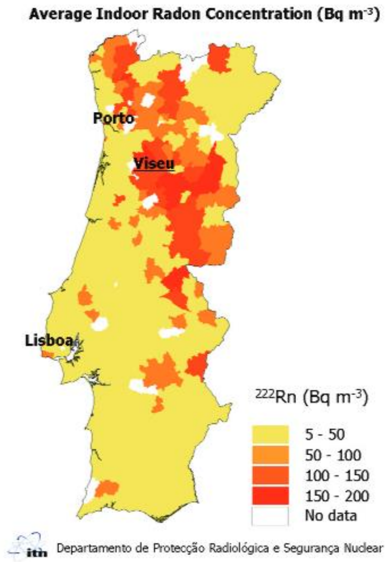


Local annual mean radon concentration values (Dubois 2005).

Portugal

The Instituto Tecnológico e Nuclear (ITN) reportedly used LR-115 II type track-etch devices for the monitoring of indoor radon, maps were prepared using administrative boundaries

(Dubois 2005). An AlphaGUARD Pro type active device was reportedly used for the study of radon exhalation (Pereira et al. 2017).



Local mean radon concentration values in dwellings (Dubois 2005).

Romania

The Nuclear Agency & Radioactive Waste (AN&DR) uses CR-39 type SSNTD-s with RadoSys-2000 type evaluation system (IAEA TC Project 9127). Previously air sampling on membrane filters was also reportedly used (Dubois 2005). Other sources reported the use of charcoal absorption with gamma spectrometry evaluation, LUK 3C utilizing Lucas-cell type scintillation devices and CR-39 type SSNTD-s for soil gas measurements (Cosma et al. 2014).

Russia

The Burnasyan Federal Medical Biophysical Center of the Federal Medical Biological Agency of Russia has more than 200 associated radiation monitoring labs and 7 Interregional radiological centres. Long term monitoring is done by LR-115 type track detectors, mid-term monitoring is conducted by using Charcoal or Electret ion chambers, and there are numerous domestic and international active devices (IAEA TC Project 9127). In addition to the national standards RAMON-01M and AlphaGUARD PQ 2000 PRO devices are used as secondary standards, and measurement devices are to be calibrated at least every 12 months (IAEA TC Project 9127).

Serbia

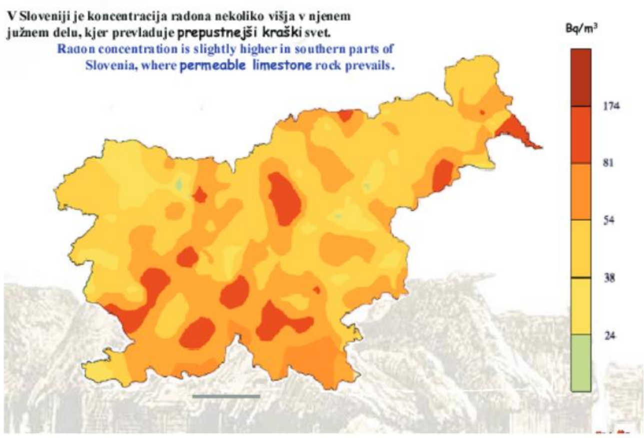
The Institute of Physics uses both domestic Electro-chemical etch track detectors and chemical etch SSNTD-s in various forms, such as UFO, RADUET, CR-39 ISS, and Rn/Tn progeny detectors. For short term measurements RAD7 devices and charcoal absorbers evaluated by gamma spectrometry are used (IAEA TC Project 9127).

Slovakia

The Slovak Medical University uses CR-39 type SSNTD-s chemical preetching, electrochemical etching and UANTIMET 520 image analyser type evaluation. For short term monitoring active coal evaluated by gamma spectrometry is used (IAEA TC Project 9127). Previously Lucas Cells were reportedly used for soil-gas monitoring (Dubois 2005).

Slovenia

The Slovenian Administration for Radiation Protection (SARP) uses SSNTD-s, Scintillation cells, various active devices as AlphaGUARD, RAD7, Radon Scout, Radim 5 as well as Working-level and equilibrium equivalent activity concentration meters (WLM-30, BWLM 2S, Doseman Pro, EQF 3020, RTM 1688-thoron) (IAEA TC Project 9127).

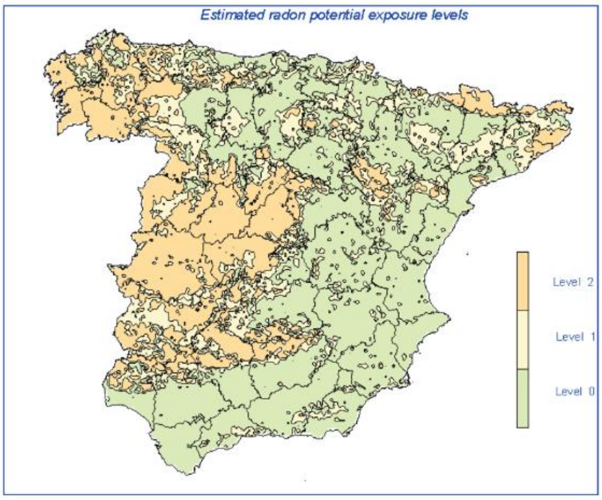


Map of indoor annual average radon concentration by interpolating the values on a grid with a resolution of 2 km × 2 km by universal kriging with linear drift (Dubois 2005).

Spain

The Consejo de Seguridad Nuclear reportedly has access to track-etch detectors, KfK detectors, charcoal detectors and Lucas-cells (Dubois 2005). A more recent measurement campaign was also described using a 10x10 km grid, external gamma measurements for selecting the high risk areas and CR-39 type SSNTD-s for the measurement of radon. (Sainz Sainz Fernandez et al 2017.)

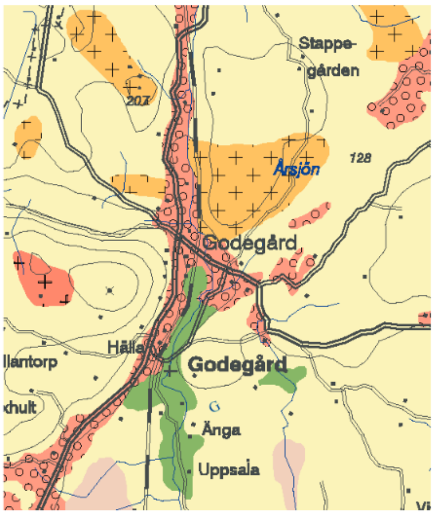
Category	Potential exposure to ^{222}Rn
0	Low (< 200 Bq/m^3)
1	Medium (200 - 400 Bq/m^3)
2	High (> 400 Bq/m^3)



Estimated annual mean indoor radon concentration values (Dubois 2005).

Sweden

The Swedish Radiation Protection Authority (SSI) reportedly used CR-39 SSNTD-s for the monitoring of indoor radon concentration while soil radon was measured by private companies. For the soil-gas measurements emanometers (Markus 10, Gammadata) and activated charcoal was reported to be used (Dubois 2005).



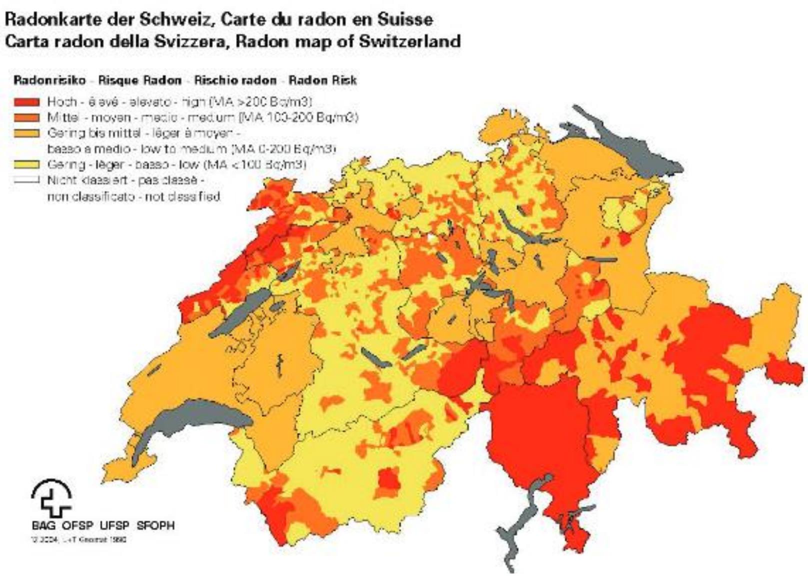
Example risk radon potential map High risk area (red), Probable high risk area (dark yellow), Normal risk area (light yellow), Low risk area (green) (Dubois 2005).

Classification of risk areas	Percentage of the Swedish surface	Types of ground	Technical building requirements
High risk	10 %	Uranium-rich granites, pegmatites and alum shale. Highly permeable soils, for example gravel and coarse sand. Radon concentration in soil gas >50 000 Bq/m^3	Radon safe construction, such as thicker, reinforced concrete foundation or ventilation below the foundation
Normal risk	70 %	Rocks and soil with low or normal U content and average permeability. Rn concentration in soil gas 10 000 - 50 000 Bq/m^3	Radon protective construction. No apparent fissures or leaks in the foundation
Low risk	20 %	Rocks with very low U content, for example limestone, sandstone and basic igneous and volcanic rocks. Soils with very low permeability, for example clay and silt or soils where the Rn gas concentration in the soil gas is < 10 000 Bq/m^3	Traditional

Summary of Swedish recommendations (Dubois 2005).

Switzerland

The Swiss Federal Office of Public Health (SFOPH) reportedly used track-etch detectors
and electrets for indoor radon monitoring (Dubois 2005).



Municipal annual mean radon concentration values (Dubois 2005).

Turkey

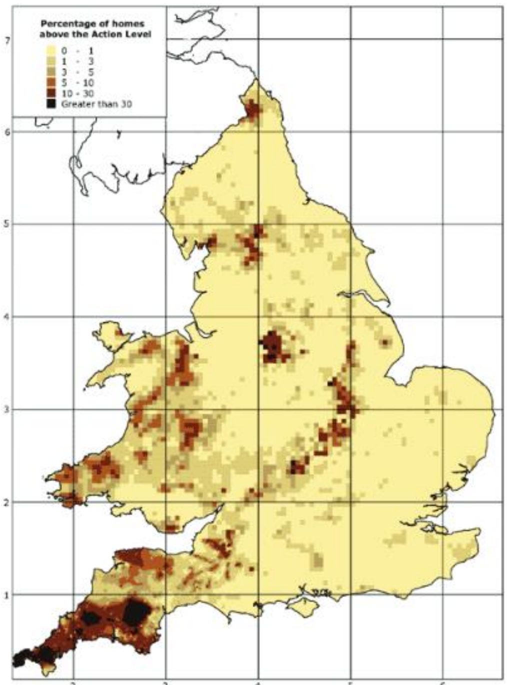
The Cekmece Nuclear Research and Training Centre, Turkish Atomic Energy Agency and the Cancer Control Department has active devices and uses CR-39s for long term monitoring (IAEA TC Project 9127).

Ukraine

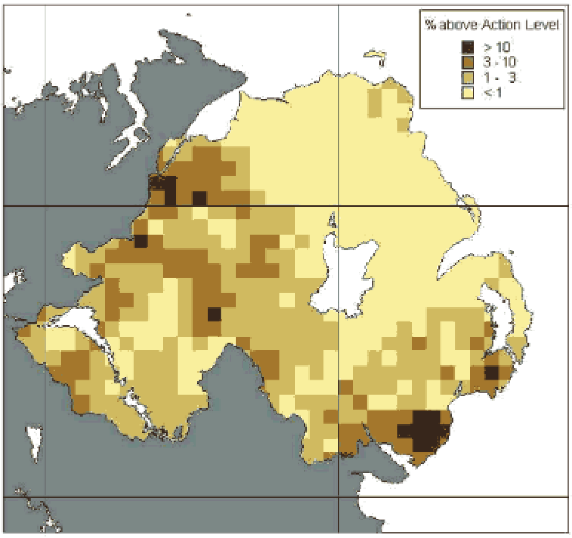
The Marzeev Institute of Hygiene and Medical Ecology at the Ukrainian Academy of Medical Sciences uses LR-115 track detectors and a light counter system (IAEA TC Project 9127).

United Kingdom (UK)

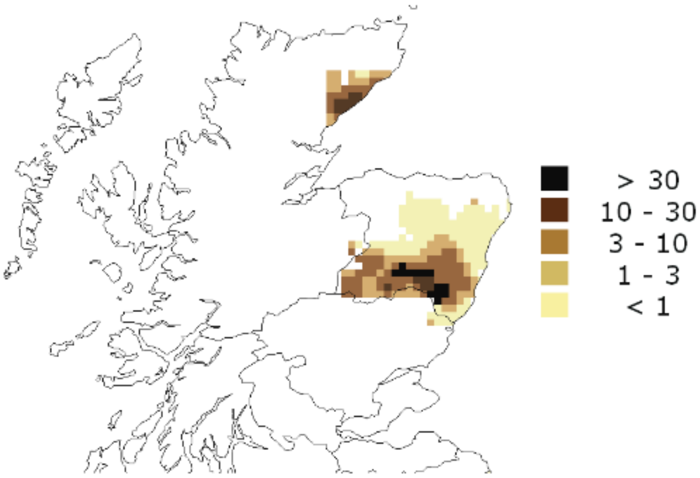
The Health Protection Agency (HPA) reportedly has access to track-etch detectors (NRPB/HPA, NET, Gammadata) used for indoor radon measurements. Maps were made by using local averages on a predefined grid with 5 km x 5 km cells, enhanced with higher measurement density areas with a resolution of 1 km (Dubois 2005). The use of Lucas-cells for soil gas measurements, as well as airborne gamma-surveys and XRF measurements of soil samples have been also described. The latter two were used to calculate uranium concentration in the topsoil, which was in turn linked to the radon concentrations (Appleton and Miles 2010).



Map of the percentage of homes above the action level in the UK and Wales (Dubois 2005).



Map of the percentage of homes above the action level in Northern Ireland (Dubois 2005).



Map of the percentage of homes above the action level in Scotland (Dubois 2005).

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Annex 7

Geogenic radon questionnaire, A3.2.2

Questionnaire on geogenic radon surveys (MetroRADON project)

Fields marked with * are mandatory.

Introduction

MetroRADON (16ENV10) is 3-years research project on metrology for radon monitoring granted by the European Metrology Programme for Innovation and Research (EMPIR), the main programme for European research on metrology.

The European Council Directive 2013/59/EURATOM (EU-BSS) laying down basic safety standards (BSS) for protection against the dangers arising from exposure to ionising radiation, evokes new challenges for the metrology of radon measurements and calibrations in Europe. For the first time, the exposure of the public caused by radon will be part of legal metrology in Europe. Since the EU-BSS stipulates that the EU Member States' level of relevant activity concentration shall not exceed 300 Bq/m3, new calibration procedures for existing commercial radon monitors with their limited counting statistics have to be developed.

The project will provide SI traceable metrological resources (calibration and measurement) for the monitoring of radon, which essentially facilitate the harmonised implementation of the new EU-BSS in Europe. It will contribute to the creation of metrological infrastructure for radon in Europe suitable for the requirements of the national radon action plan required by the new European Directive.

Follow the progress of the project at http://metroradon.eu/!

One of the specific objects is to compare existing radon measurement procedures in different European countries and use the results to optimise the consistency of indoor radon measurements across Europe.

For this purpose, a questionnaire was developed and is sent to all European countries. The scope of this questionnaire is to collect information to analyse and evaluate geogenic radon surveys in order

(i) to identify the rationale and methodologies used in Europe,

(ii) to identify the extent and possible sources of inconsistencies in the results of outdoor geogenic radon surveys and

(iii) to propose approaches to reduce inconsistencies and improve harmonisation of geogenic radon data.

We invite you to fill the questionnaire for your country or forward it to the persons, who can best answer these questions.

On behalf of the MetroRadon project consortium we thank you for your cooperation and help in obtaining these results that will help to improve radiation protection in Europe.

In the following sections:

- “you” is referred to your institution, not “personally”;
- geogenic radon survey includes all the possibilities: national and regional (“Region” could be: national; federal state; district; region which was suspected for high Rn levels,…).

Section 1. Information about respondent

* 1.1 Country, please select:

- Albania
- Andorra
- Armenia
- Austria
- Azerbaijan
- Belarus
- Belgium
- Bosnia and Herzegovina
- Bulgaria
- Croatia
- Cyprus
- Czech Republic
- Denmark
- Estonia
- Finland
- France
- Georgia
- Germany
- Greece
- Hungary
- Iceland
- Ireland
- Italy
- Kazakhstan
- Latvia
- Liechtenstein
- Lithuania
- Luxembourg
- Malta
- Monaco
- Montenegro
- Netherlands
- Norway
- Poland
- Portugal
- Republic of Moldova
- Romania
- Russian Federation
- San Marino
- Serbia
- Slovakia
- Slovenia
- Spain
- Sweden

- Switzerland
- The former Yugoslav Republic of Macedonia
- Turkey
- Ukraine
- United Kingdom

* 1.2 Name of the public authority / international organisation / organisation or company you represent:

1.3 Address of the public authority / international organisation / organisation or company you represent:

1.4 Full name (first and last name) of the individual respondent (The information you provide here is for administrative purposes only and will not be published):

1.5 Email address of the individual respondent (The information you provide here is for administrative purposes only and will not be published):

1.6 Your role in the organisation

- Management
- Professor
- Researcher
- Policy function
- Specialist/Expert
- Regulator
- Other

Please specify 'Other':

Section 2. Radon measurement in soil gas surveys

2.1 Have you carried out surveys of radon measurements in soil gas?

- Not planned
- Planned
- Ongoing
- Finished
- I don't know

2.2 Which motivation was behind your survey?

- Legal obligation

☐ Scientific interest
☐ Geogenic radon potential
☐ Other

2.3 Which sampling method have your used?

☐ Grab
☐ Time-integrated
☐ Continuous

2.4 At which depth have you sampled the soil gas?

[ ] cm

2.5 Which kind of detector and sampling mode have you used?

	Grab sampling	Continuos measurement	Time-integrated measurement
Track etch	○	○	○
Electret	○	○	○
Scintillation cell	○	○	○
Semiconductor	○	○	○
Ionization chamber	○	○	○
LSC	○	○	○
Charcoal	○	○	○
Other	○	○	○

Please specify 'Other':

[ ]

2.6 How many sampling points per measurement do you carry out to characterize a site (one or more than one)?

[ ]

2.7 Which is your definition of "site"?

[ ]

2.8 If in 2.6 you have performed more that 1 sampling point, which spatial configuration do you use for them (e.g. triangle, square, random)?

2.9 If in 2.6 you have performed more that 1 sampling point, which method do you use to report the output in the database (arithmetic mean, median, max..)?

2.10 Please provide the following information regarding the survey:

2.10a Total number of measurements

2.10b Area covered by the survey

km2

2.11 Have you performed permeability measurement together with the radon soil gas measurements?

- [ ] Yes
- [ ] No
- [ ] I don't know

2.12 Do you use any standard/guideline to perform radon measurements in soil gas?

- [ ] Yes
- [ ] No
- [ ] I don't know

2.13 Do you use any standard/guideline to perform measurements of soil permeability?

- [ ] Yes
- [ ] No
- [ ] I don't know

If 'Yes' in 2.12 and/or in 2.13, can you please provide us with a copy of standards/guidelines? (email going to giorgia.cinelli@ec.europa.eu)

Additional Information

Section 3. Radon exhalation rate surveys

3.1a Have you carried out surveys of radon exhalation rate from soil?

- [ ] Not planned
- [ ] Planned

- [ ] Ongoing
- [ ] Finished
- [ ] I don't know

3.1b Have you carried out surveys of radon exhalation rate from rock?

- [ ] Not planned
- [ ] Planned
- [ ] Ongoing
- [ ] Finished
- [ ] I don't know

3.2 Which method for measurement of radon exhalation from soil/rock have you used?

- [ ] Closed box, time resolved, slope of concentration *)
- [ ] Closed box, time resolved, saturation concentration
- [ ] Closed box, integral, short time
- [ ] Closed box, integral, longtime
- [ ] Near-surface concentration in air, “open box”
- [ ] 210Pb distribution in soil
- [ ] Other

Please specify 'Other':

*) Have you applied correction to limited box size (“back diffusion”) ?

- ( ) Yes
- ( ) No
- ( ) I don't know

3.3 Which kind of detector have you used?

- [ ] Track etch
- [ ] Charcoal
- [ ] Silicon detector+alpha spectrometry
- [ ] Electret
- [ ] Ionization chamber
- [ ] Other

Please specify 'Other':

3.4 How many measurements do you carry out to characterize a site/location?

3.5 Which is your definition of "site"?

3.6 What is the time between these measurements?

h

3.7 Which is the distance between these measurements?

cm

3.8 Please provide the following information regarding the survey:

3.8a Total number of measurements

3.8b Area covered by the survey

km2

3.9 Do you use any standard/guideline to perform radon exhalation rate?

- Yes
- No
- I don't know

If 'Yes' in 3.9, can you please provide us with a copy of standards/guidelines? (email going to giorgia.cinelli@ec.europa.eu)

Additional Information

Section 4. Radon in water

4.1 Have you carried out surveys of radon measurements in water?

- Not planned
- Planned
- Ongoing
- Finished
- I don't know

4.2 Which motivation was behind your survey?

- Legal obligation
- Scientific interest
- Geogenic radon potential

- [ ] Other

4.3 Which samples have you considered?

- [ ] Drinking water
- [ ] Ground water
- [ ] Surface water
- [ ] Thermal water
- [ ] Tap water
- [ ] Spring water
- [ ] Other

4.3 Please indicate the number of measurements you performed and which method have you used:

	Number of measurements	Method
Drinking water		
Ground water		
Surface water		
Thermal water		
Tap water		
Spring water		
Other		

4.4 Do you use any standard/guideline to perform radon measurements in water?

- ☐ Yes
- ☐ No
- ☐ I don't know

4.5 If 'Yes' in 4.4, can you please provide us with a copy of standards/guidelines? (email going to giorgia.cinelli@ec.europa.eu)

4.6 Did you analyse other nuclides than radon?

- ☐ Yes
- ☐ No
- ☐ I don't know

4.7 If Yes in 4.6, please indicate them:

Additional Information

Section 5. External gamma dose rate

5.1 Have you carried out surveys of gamma dose rate?

- ☐ Not planned
- ☐ Planned
- ☐ Ongoing
- ☐ Finished
- ☐ I don't know

5.2 Which motivation was behind your survey?

- ☐ Legal obligation
- ☐ Scientific interest
- ☐ Geogenic radon potential
- ☐ Background information
- ☐ Emergency preparedness and response
- ☐ Other

Please specify 'Other':

5.3 Do you provide your measurement data to the EURDEP system?

- ☐ Yes

- [ ] No
- [ ] I don't know

5.4 Which kind of detector have you used?

- [ ] HPGe
- [ ] NaI
- [ ] CZT
- [ ] LaBr3
- [ ] Ionization chamber
- [ ] Geiger Muller
- [ ] Proportional counter
- [ ] Passive detector

Please specify 'Other':

[ ]

5.5 At which height above ground have you performed the measurements, in general?

[ ] cm

5.6 Have you considered a proper distance from buildings, forest, or other obstacles to avoid their contributions?

- [ ] Yes
- [ ] No
- [ ] I don't know

5.7 As a rough estimate, which is the percentage of gamma dose rate measurement location which is conform to the standard protocol (probe located at a proper distance from buildings, forest, or other obstacles to avoid their contributions)?

[ ] %

5.8 At which height above ground have you performed the measurements?

[ ] cm

5.9 Have you subtracted the cosmic contribution?

- [ ] Yes
- [ ] No
- [ ] I don't know

5.10 Have you subtracted the intrinsic background of the instrument?

- [ ] Yes
- [ ] No
- [ ] I don't know

5.11 Please provide the following information regarding the survey:

5.11a Total number of measurements

5.11b Area covered by the survey

km2

5.12 Do you use any standard/guideline to perform external gamma dose rate measurements?

- [ ] Yes
- [ ] No
- [ ] I don't know

5.13 If 'Yes' in 5.12, can you please provide us with a copy of standards/guidelines? (email going to giorgia.cinelli@ec.europa.eu)

Additional information

Section 6. U concentration in soil/rock

6.1a Have you carried out surveys of U (eU) concentrations in soil/rock?

- [ ] Not planned
- [ ] Planned
- [ ] Ongoing
- [ ] Finished
- [ ] I don't know

6.1a Have you carried out surveys of 226Ra (eRa) concentrations in soil/rock?

- [ ] Not planned
- [ ] Planned
- [ ] Ongoing
- [ ] Finished
- [ ] I don't know

6.2 Which motivation was behind your survey?

- [ ] Legal obligation
- [ ] Scientific interest
- [ ] Geogenic radon potential
- [ ] Background information
- [ ] Mineral exploration
- [ ] Other

6.3 Which kind of sample have you considered?

- ☐ Top soil
- ☐ Sub soil
- ☐ Rock
- ☐ Other

Please specify 'Other':

6.4 Which method of measurement did you use?

6.5 Have you measured in the same sample other radionuclides/elements? Please list:

6.6 Please provide the following information regarding the survey:

6.6a Total number of measurements

6.6b Area covered by the survey

km2

6.7 Do you use any standard/guideline to measure U concentration in soil/rock?

- ☐ Yes
- ☐ No
- ☐ I don't know

6.8 If 'Yes' in 6.7, can you please provide us with a copy of standards/guidelines? (email going to giorgia.cinelli@ec.europa.eu)

Additional information

Section 7. Airborne

7.1 Have you carried out airborne surveys?

- ☐ Not planned
- ☐ Planned
- ☐ Ongoing

- [ ] Finished
- [ ] I don't know

7.2 Which data have you collected?

- [ ] Total gamma
- [ ] U
- [ ] Th
- [ ] K
- [ ] Other

Please specify 'Other':

7.3 Which fraction of territory covered (approx.)?

%

7.4 Which is the mean altitude of the survey?

m

7.5 Which is the mean line spacing of the survey?

m

7.6 Please indicate which kind of detector you have used

- [ ] HPGe
- [ ] NaI
- [ ] CZT
- [ ] LaBr3
- [ ] Other

Please specify 'Other':

7.7 Do you use any standard/guideline to perform airborne measurements?

- [ ] Yes
- [ ] No
- [ ] I don't know

7.8 If 'Yes' in 7.7, can you please provide us with a copy of standards/guidelines? (email going to giorgia.cinelli@ec.europa.eu)

Additional information

Other

Please indicate any database you have that can be helpful for characterizing geogenic radon potential/be available for multivariate geogenic mapping

- ☐ Soil gas permeability
- ☐ Soil grain size distribution
- ☐ Porosity
- ☐ Depth to rock
- ☐ Water recharge coefficient
- ☐ Organic matter
- ☐ Other

Please specify 'Other':

Annex 8

Report on Activity A3.2.3

MetroRADON PROJECT
Activity number A3.2.3: Evaluation of the existing ISO standards on the methodology of the radon concentration in soil gas measurement and the surface exhalation rate measurement (ISO 11665-7 and ISO 11665-11).

UC and IRSN evaluated the existing ISO standards EN ISO 11665-7 and ISO 11665-11 on the methodology of the Rn exhalation measurement and of radon concentration in soil gas measurement, in order to assess whether and how appropriate the methodologies in these standards are for use in the MetroRADON project particularly in Tasks 3.3, 3.4 and 4. The objectives of these tasks are the following :

- <u>Task 3.3: Intercomparisons of indoor radon and geogenic radon measurements under field conditions</u>

The aim of this task is to organise an intercomparison of indoor radon measurements and geogenic radon measurements (including radon exhalation rate) under field conditions. The partners, primarily those involved in WP1 and WP5, will test their devices under real conditions. The results from the direct comparison between different methodologies will help to identify physical reasons for possible inconsistencies, particularly related to sampling and measurement techniques. If necessary the results could be used in the activities in Task 3.4 on harmonisation, and to motivate development or improvements to standards.

- <u>Task 3.4: Development of options for harmonisation of indoor and geogenic radon data including practical examples</u>

The aim of this task is to test and propose options for harmonisation of indoor and geogenic radon data, by practical examples. Harmonisation can follow two different approaches. “Bottom-up” harmonisation intends to implement the same methodology to ensure consistency of results, while “top-down” harmonisation attempts to make existing results comparable and jointly interpretable, if the results are inconsistent due to different methodologies. While applying a standard method resulting from “bottom-up” harmonisation makes sense when starting new surveys or in the initial phase of an Rn action plan, it cannot be applied to existing results, in which case “top-down” harmonisation may be applicable. One example, which may prove relevant with regard to communicating the Rn problem to the public, is the lack of match between Rn priority areas across national borders. To assess the relevance of inconsistency and hence of harmonisation, the impact on stakeholders will be taken as a criterion.

- <u>Task 4: Radon priority areas</u>

The aim of this work package is to analyse and develop methodologies for the identification of radon priority areas and to investigate the relationships between indoor Rn concentration and quantities related to geogenic Rn (see WP3, Task 3.2).

1/ Measurement of radioactivity in the environment. Air: radon-222. Part 7: Accumulation method for estimating surface exhalation rate. (EN ISO 11665-7:2012).

1. Participants in Task 3.3 will be encouraged to use this ISO standard during the practical exercise at the laboratory of natural radiation located in Ciudad Rodrigo. Some participants may use their own procedures too, that may differ from the ISO standards. By doing this we will be in a good position to test the ISO standard against other methodologies to estimate the surface radon exhalation rate.

2. The approach used in Figure 1 of EN ISO 11665-7 (2012) is based on the lack of radon leakages. This is not easy to achieve in many cases, and the leakage of the accumulation container should be properly evaluated. Task 3.3 will help to evaluate this statement. It is an important factor since all the ISO standard is based on this assumption. A more general situation based on the analysis of the steady state situation could have to be considered. In this case it shall be needed to perform a non-linear fit of the growing curve representing the radon accumulation within the exhalation chamber. The loss of radon due to the problem of inadequate air-tightness of the accumulation container is cited in the section 9.2 “Influence parameters”.
3. Annex B is based on the linear approach using two methods to determine the radon concentration (continuous mode and diffusion mode). Annex C uses grab sampling method. Task 3.3 will provide important results to check methods described on these annexes since it is expected that participants will use more than one method. The linear approach shall be tested against the more general steady state method to determine the radon exhalation rate.
4. Some more specific comments:
    a. Page 17: The standard is applied to measure radon exhalation rates with a minimum value of 5 mBq m^{-2} s^{-1} which is equivalent to 18 Bq m^{-2} h^{-1} (this is another common way to express results of radon exhalation measurements). This is important to consider when measuring exhalation rates in building materials. (The numerical example provided in P. 17 provides a result 4.34 mBq m^{-2} s^{-1}, which is lower than the above mentioned minimum value.)
    b. Page 7: We remark two important aspects described here. First, the need of using an accumulation chamber as radon tight as possible. Second, the volume of this chamber should be large enough comparing with the volume of air samples.

2/ Measurement of radioactivity in the environment. Air: radon-222. Part 11: Test method for soil gas with sampling at depth. (ISO 11665-11:2016).

This ISO standard is very relevant for the aims expressed in Task 3.4. on the evaluation of parameters used to determine the geogenic radon potential. One of these parameters is the radon concentration in soil gas. Hence, to have a standardised method to evaluate this quantity is needed in order to compare different geogenic radon data in different regions (for instance country borders).

Subsection 6.2 “Sampling characteristics”: more information could be added to this paragraph. Since it is stated on the standard, radon in soil gas can change from point to point even in small areas. We find useful to refer to the ISO standard *ISO 10381-7:2005 Soil quality -- Sampling -- Part 7: Guidance on sampling of soil gas* to check the general requirements when taking soil samples.

1. Subsection 8.2: another parameter that may influence is the radon leakages when active sampling is in use. This phenomenon may lead to an underestimation of the radon concentration in the soil. This influence could be tested during task 3.3.
2. Subsection 8.3: task 3.3 of the project will contribute in terms of comparing different techniques to measure radon in soil gas. The planned inter-comparison exercise as described in A.3.3.3 already includes radon concentration in soil gas as a parameter to test on the exercise. In addition, the part of the system regarding the radon measuring device will be also tested on task 3.3. One of the requirements of the devices that will participate on this task will be to provide the calibration certificates.
3. Annex B mentions the need of using “perfectly sealed” systems to take the grab air samples. Some experiences showed that in practice, this cannot be always possible to fulfil since the whole measuring device may have radon leakages that appear on the joints of sampling

tubes for instance. Therefore, it could be interesting to develop a methodology that could describe how the radon leakages may be evaluated and the impact of such leakages on the uncertainty of the result. More experience feedback on this point could be provided during the task 3.3.

The two analysed ISO 11665-11 and ISO 11665-7 standards are essential for determining the radon in the soil that is the main source for radon in buildings. Also, they play an important role on the determination of the geogenic radon potential. This parameter may contribute to some of the points expressed in the Annex XVIII of the EURATOM BSS. So, tested methods and standards are necessary to compare values among territories.

3/ Conclusions

After reading the two ISO standards 11665-7 and 11665-11, we agree that they are well related to the Metroradon project. The work of task 3.3 might provide some relevant data to evaluate the methods and to give some elements for further revision of the standards.
One comment on the EN ISO 11665-7 could be sent to the ISO group: to give another example for the measurement of a radon exhalation rate above 5 $mBq.m^{-2}.s^{-1}$ (Annex B, B.5 Example) in order to be in the scope of the standard. Actually, the result of the current example is lower than the limit value given in the scope of the standard.

Annex 9

Report on Activity A3.2.4 –A3.2.5

3.2.4 and 3.2.5 Geogenic radon surveys

This document reports the results of the activities 3.2.4 and 3.2.5.

number	**Activity description**	**Partners (Lead in bold)**
A3.2.4	BfS and JRC will analyse the information collected in A3.2.1 and A3.2.2 on geogenic radon surveys and will identify and describe differences and possible inconsistencies. The impact and relevance of inconsistencies on stakeholders (the public, regulatory authorities, etc.) will be assessed. If relevant inconsistencies are identified, then it is likely that there will be a repercussion on the country or region involved in the survey, even if QA compliance is given. This may trigger the need for "top-down" harmonisation of existing data. In this activity, the rationale and techniques for harmonisation will be assessed, whilst further elaboration including case studies, where applicable, will be the subject of Task 3.4.	**BfS, JRC**
A3.2.5	Based on information from A3.2.1-A3.2.4, BfS, VINS, AGES and JRC will compile a report about geogenic radon surveys in Europe including their strategies, methodologies employed, inconsistencies in the results, potential methodologies to harmonise data and reduce inconsistencies, the potential to use radon surveys to develop geogenic radon map (Article 103, EU-BSS) and approaches to assist member states to implement the EU-BSS (mapping, providing information about radon exposure to the public, preventive measures etc.).	**BfS, VINS, AGES, JRC**

The report is structured as:

3.2.4.1 Evaluation of the literature report (A3.2.1) and the questionnaires (A3.2.2)

a) Literature report

b) Questionnaire design

c) Participation

3.2.4.2 Soil radon and permeability

a) Participants

b) Survey sizes and coverage

c) Definition of "sampling point"

d) Sampling and measurement methods

e) Measurement of permeability

3.2.4.1 Evaluation of the literature report (A3.2.1) and the questionnaires (A3.2.2)

a) Literature report

Literature has been summarized in a report by Szücs et al. (2018). The report shows the diversity of measurement methodology in several aspects:

- Definition and estimation of the GRP; this concerns the actual definition and covariates and proxies used to estimate it;
- Sampling design: depth, spatial scheme, areal coverage;
- Sampling and measurement methodology: instrumentation:
- Evaluation and displaying the results as maps: post maps, class maps, interpolated maps.

b) Questionnaire design

The questionnaire intended to collect information about surveys of geogenic radon; this includes Rn concentrations in soil gas and water, radon exhalation from the ground, concerning Rn proper, and for covariates (predictors, proxies) of geogenic Rn: U concentration in the ground, airborne gamma ray surveys and ambient dose rate surveys.

Basic information was wanted about methodology (sample acquisition and measurement) and spatial design, next to rather administrative questions.

c) Participation

Institutions from 19 European Countries out of nominally 50 responded to the invitation to fill the questionnaire. This includes 15 EU Member States (Austria, Belgium, Bulgaria, Croatia, Czech Republic, Finland, Germany, Italy, Lithuania, Netherlands, Portugal, Romania, Spain, Sweden and GB (still counted as EU)) and 4 non-EU countries (Norway, Serbia, Switzerland and Ukraine). From several countries, more than one institution responded. If no response from a country was received, it does not mean that no geogenic Rn surveys had been performed, as known from literature. A summary is shown in Table 1.

The information reflects what has been communicated by the institutions which participated in the questionnaire; other institutions that were active in the field may not have responded, therefore the information may not be exhaustive for the country. (For example, for Germany, the 2 reportedly finished soil Rn surveys refer to the national and the regional Saxonian one. Several more regional surveys are currently under way or have already been finished, but the respective institutions did not respond.) Additionally, reported surveys may have been regional ones, i.e. not covering the entire country. For details, including more in-depth technical descriptions and references to relevant documents, see the table <Content_Export_GeogenicRadonSurveys_MetroRADON_Geogenic_20180904.xls> in the annex.

Table 1: Contributors to the questionnaire on geogenic surveys. For the ISO codes see annex. The figures denote the number of participating institutions in that country. Status (around Sept. 2018): fin – finished; on – ongoing; (not) pl. – (not) planned. If no number is given: only 1 institute responded in that country. "fin.+pl.", etc. – one survey finished, another planned by the same institution.

ISO code	Soil Radon	Radon exhalation	Radon in water	Geochem-istry	Aero-gamma	ADR
AD						
AL						
AM						
AT	fin.	not pl.	fin.+pl.	fin.		fin.
AZ						
BA						
BE	2 fin., 1 on.	3: not pl.	1 fin., 2 on.	1 fin, 2 not pl.	2 fin.	2 fin., 1 on.
BG	pl.	not pl.	on.	not pl.	not pl.	not pl.
BY						
CH	not pl.	not pl.	not pl.	not pl.	not pl.	not pl.
CY						
CZ	1 fin., 2 on.	2 fin.	fin.	fin.	not pl.	fin.
DE	2 fin.	1 fin., 1 not pl	1 not pl.	2 not pl.	1 not pl.	1 fin.
DK						
EE						
ES	on.+plan.					
FI	fin.	fin.	fin.	fin.	not pl.	fin.
FR						
GE						
GR						
HR	on.	not pl.	fin.+on.			
HU						
IE						
IS						
IT	1 fin., 2 on., 1 not pl.	1 fin., 1 pl., 1 not pl.	3 on., 1 pl.	3 on, 1 not pl.	2 on., 1 not pl.	3 on., 1 pl.
KZ						
LI						
LT	on	not pl.	on.	fin.		on.
LU						
LV						
MC						
MD						
ME						

MK						
MT						
NL	not pl.		fin.	not pl.	not pl.	fin.
NO	1 fin., 1 not pl		2 fin., 1 on.		1 on.	1 on.
PL						
PT	on.	on	on	on	not pl.	fin.
RO	fin.+on.	pl.	fin.+on.	pl.	not pl.	fin.
RS	on.	on.	on.	on.	on	on.
RU						
SE	fin.	not pl.	on.	on.	on.	on.
SI						
SK						
SM						
TK						
UA	on.	on.	pl.	on.	on.	on.
GB	not pl.	not pl.	not pl.	not pl.	not pl.	fin.
VA						

Remark: In the following, the term “sample” will be used frequently. The term is used here in the sense of physical sample (a volume of soil, a borehole, e dose rate measurement, etc.), not in the statistical sense, where it denotes a set of physical samples, i.e. a statistical draw from a population.

3.2.4.2 Soil radon and permeability

a) Participants

Table 2 summarizes replies about soil radon and permeability surveys. An additional column indicates whether information about soil Rn surveys is available in literature, see separate document <Report on geogenic radon potential in Europe.docx> prepared by BFKH, located in in the MetroRn repository.

Table 2: Contributors to the questionnaire about soil radon and soil permeability. For the ISO codes see annex. The land areas have been taken from https://en.wikipedia.org/wiki/List_of_countries_and_dependencies_by_area . Last column: Y = additional information available in the literature. n.a. – not available.

ISO code	# respon-ding institu-tions	# data	area covered	country land area	% covered	per km² covered	per km² country	status	perm ?	from lit?
AD										
AL										
AM										
AT	1	300	200	82445	0.24	1.50E+00	3.64E-03	fin.	Y	
AZ										
BA										
BE	3	5117	30000	30278	100	1.71E-01	1.69E-01	fin., on.	part	
BG	1	n.a.						pl.	Y	
BY										
CH	1							not pl.	.	
CY										
CZ	3	350000	79000	77247	100	4.43	4.53	fin., on.	Y	
DE	2	4716	357000	348672	100	1.32E-02	1.35E-02	fin.	Y	
DK										
EE										
ES	1	518	5321	498980	1.1	9.74E-02	1.04E-03	on, pl.	Y	
FI	1							fin	n.a.	
FR										
GE										
GR										
HR	1							on.	Y	
HU										Y
IE										
IS										
IT	4	3120	245	294140	0.083	1.27E+01	1.06E-02	fin.+on.	part	
KZ										
LI										
LT	1	210	70	62680	0.11	3.00E+00	3.35E-03	on.	N	
LU										Y
LV										Y
MC										
MD										
ME										
MK										
MT										
NL	1							not pl.		
NO	2	21	10	304282	0.0033	2.10E+00	6.90E-05	fin.	n.a.	

PL										Y
PT	1	2000		92212				on.	N	
RO	1	3100	75000	231291	32	4.13E-02	1.34E-02	on.	part	
RS	1							on.	N	
RU										
SE	1	1500						fin.	N	
SI										
SK										Y
SM										
TK										
UA	1	3000	10	579300	0.0017	3.00E+02	5.18E-03	on.	Y	
GB	1							not pl.		
VA										

b) Survey sizes and coverage

Participants were asked for areas covered by the surveys. This figure is thought to represent the size of administrative regions or otherwise defined areas (not specified) which had been sampled.

Countries with complete coverage are Belgium, the Czech Republic and Germany, with 0.17, 4.5 and 0.014 samples per km^2, respectively (printed red in Table 2). The high value of CZ does not reflect the density of measurement *sites*, but of individual boreholes. Each site consists of typically 15 samples. The estimated number of sites is about 20000, which leads to a density about 0.26 sites per km^2, still world record. In other countries, only parts have been sampled, so that the sampling density per land area is not informative. However, in the sampled areas, sampling densities can be quite high. Probably this reflects local surveys performed for specific purposes.

The figures in the table should be understood as preliminary and representing the status around end-2018, as surveys are ongoing in many countries.

c) Definition of "sampling point"

A particularly interesting finding is the diversity of what is understood as sampling site or "point". The question is relevant with respect to the area for which the result could be thought as representing an estimated mean.

The questions in the questionnaire were the following:

(2.7) Which is your definition of "site"?

(2.6) How many sampling points per measurement do carry out to characterize a site (one or more than one)?

(2.8) If in 2.6 you have performed more than 1 sampling point, which spatial configuration do you use for them (e.g. triangle, square, random)?

(2.9) If in 2.6 you have performed more than 1 sampling point, which method do you use to report the output in the database (arithmetic mean, median, max…)?

The questions may have not been formulated sufficiently clearly and be linguistically awkward; but most participants seem to be aware of the problem underlying these questions. The natural spatial variability is accounted for by taking several samples according some sampling scheme, mostly random or regular along a square, triangular or linear design. Preferred statistics are the AM and the maximum. The latter makes sense because of the specific error distribution of usual methods of soil gas measurement. Uncertainty due to counting statistic is usually negligible against the error considered most important related to the sampling procedure: the measured value can only be *lower* than the true value, since error is caused by leakage of “clean” outdoor air into the soil air to be measured. Therefore, taking the maximum tentatively minimizes this source of error.

The “estimation support”, i.e. the area to which the measurement result is assigned, or to which it is supposed to be representative, varies strongly between participants: the area can be as large as a 10 km × 10 km grid cell or a geologically defined fraction of it, down to areas of building sites or small triangles.

A summary is given in Table 3. The number of samples (usually boreholes) affects precision of the result while the sampling pattern, representativeness i.e. accuracy within the estimation support.

The actual choice of a sampling pattern is probably less critical. A regular scheme (e.g. along a square grid) can be problematic only if it coincides with a geological pattern of the similar regularity, but this can be expected to occur only rarely. The problem of random schemes is that they are rarely truly random, but rather representing random walks of sampling staff, which are prone to unintended preferential sampling.

Remarkably, no participant has reported only 1 measurement per site. (But 9 participants did not reply to this group of questions.)

The choice of the latter however makes a crucial difference between the methods and affects comparability. The subject is discussed further in section 3.2.4.3 below.

Table 3: Sampling designs for measuring radon in soil gas.number - number of individual bore holes per sample location; statistic - evaluation of the individual results.

country	geometry	number	statistic
AT	triangle around or line across defined meas. point; size=?	3	AM,max
BE	rand at point (=?) in 1x1km² grid square	2-3	max
BG	construction site in RPA (legal); square sampling grid	10	AM, max, min
CZ	construction site, regular grid (legal)	typically 15	3.quartile
DE	triangle, 5 m side	3	max
ES	lithostrat. unit within 10x10km² grid cell	2	AM, Med
IT-1	"study area", rand. or square scheme	5	AM,GM
IT-2	triangle (size=?)	3	AM,max
LT	diagonal of 10x10m² square	3	AM

NO	Triangle (size=?) of ADR meas. points; within triangle 2 points separated 50cm	2	AM
PT	Geological outcrop or building site; acc. gamma survey or transect across faults	3 to about 1 per $4m^2$	Med
RO	$10x10km^2$ grid cells, rnd within	3	AM,GM,min,max,CV
SE	2 points <15m apart; rnd where possible	2	all data
UA	$1 km^2$, square scheme	30	AM,max

d) Sampling and measurement methods

The most common sampling depth appears to be 80 cm, followed by 100 cm (Figure 1).

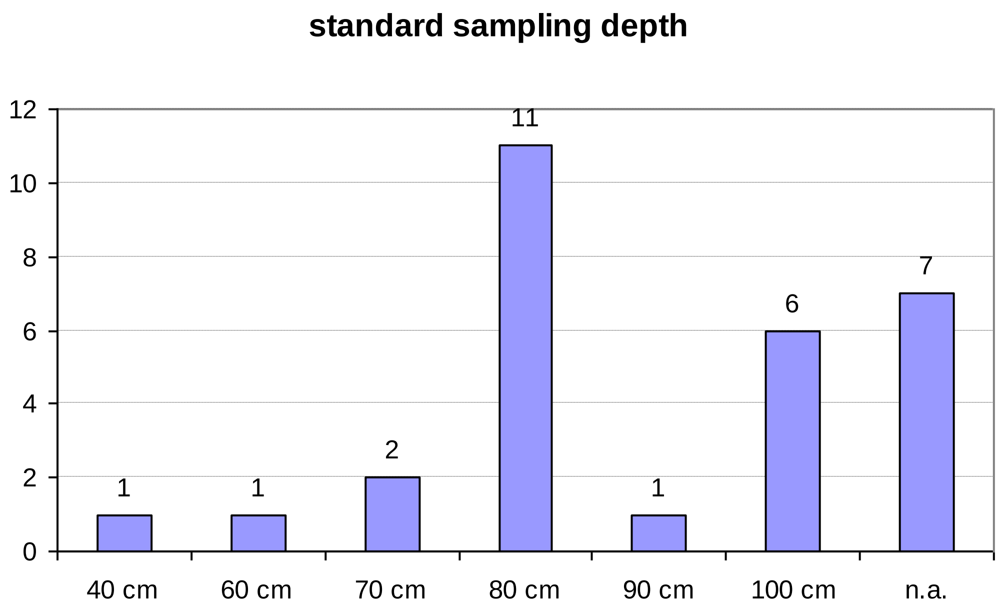


Figure 1: Standard sampling depths for soil radon measurement

It should be reminded that – depending on soil type – equilibrium concentration in soil gas is attained in greater depth (see sec. 3.2.4.3a). The questionnaire did not ask for whether depth correction has be applied to the measurement result, to compensate for radon loss through the surface (or dilution by “clean” outside air) for shallow depth sampling.

Sampling acquisition is mostly done by grab sampling; continuous measurements seem to serve mostly scientific purposes, e.g. assessment of temporal variability. Time-integrated measurements with TE detectors were reported twice, probably referring to the “buried detector” method.

For counting, most use scintillation cells (Lucas cells: Radon v.o.s. RM2 , Mi.am MR1), some ionization chambers (e.g. Alphaguard) and a few, semiconductors (e.g. Rad 7, Markus 10, Atmos 12). The latter two can be operated in (quasi-) continuous mode.

Of those participants who indicated that they follow a particular protocol, most cited the Czech protocol (Neznal et al. 2004, Barnet et al. 2008, http://www.radon.eu/ca2.html), some ISO 11665-11.

e) Measurement of permeability

54% of respondents (altogether 22 institutions) that reported geogenic Rn surveys also measured permeability parallel to all or parts of the soil Rn measurements, Figure 2.

The availability of soil Rn for exhalation from the ground surface or for infiltration into buildings also depends on the efficiency of its transport in the ground. Rn availability is often quantified by the geogenic radon potential (GRP) (see WP4, task 4.2). Transport is mainly controlled by ground permeability, which is therefore being measured in situ or assessed otherwise. Figure 2 summarizes the replies to the question about whether permeability has been measured alongside soil Rn concentration.

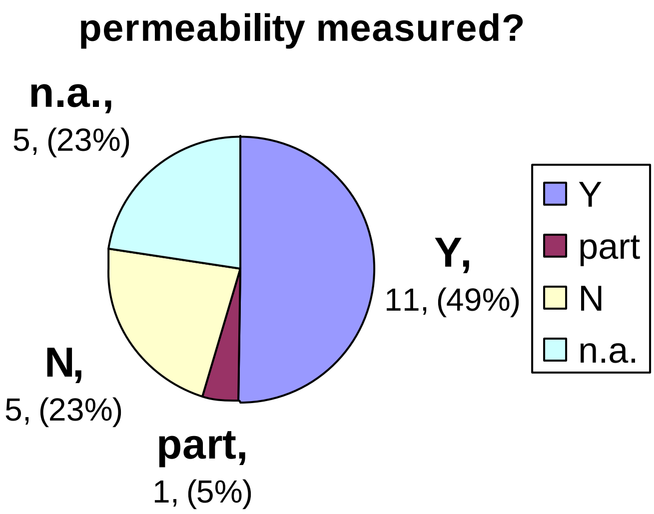


Figure 2: Permeability measurements

3.2.4.3 Differences and inconsistencies in soil Rn methodology

a) Depth dependence

In single-layered soil, the stationary solution of the 1D-diffusion-advection equation with concentration equal 0 on the surface (i.e., C(z=-0)<<C_0), reads

$$C(z) = C_0(1-\exp(-\alpha z))$$

$$\alpha = -\frac{v}{2D} + \sqrt{\frac{v^2}{4D^2} + \frac{\lambda}{D}}$$

C(z) – concentration depth z (z counted positive downwards), C_0 – equilibrium concentration, v – advection velocity from Darcy law, D – diffusion constant, λ - ^{222}Rn decay constant. (Among many, Clouvas et al. 2017; Nazaroff 1992)

$C_0=C_{Ra}\ \varepsilon\ \rho/por$ (C_{Ra} – ^{226}Ra concentration assumed homogeneous, ε - emanation coefficient, ρ - bulk density, por – porosity)

D = D(air)·por;

$v = \frac{k}{\mu}\nabla p$; k - permeability, μ - dynamic viscosity of air, ∇p - pressure gradient (Pa/m); laminar flow assumed (low Reynolds number; may be violated for higher ∇p).

Solutions for different parameters are shown in Figure 3; C_0 is set to 1.

Material parameters used are λ(^{222}Rn)=1.1e-6 s^{-1}; D(air) = 1.2e-5 m²/s; μ = 1.8e-5 Pa s (value for 15°C; applicable for about 10 - 20°) and Table 4.

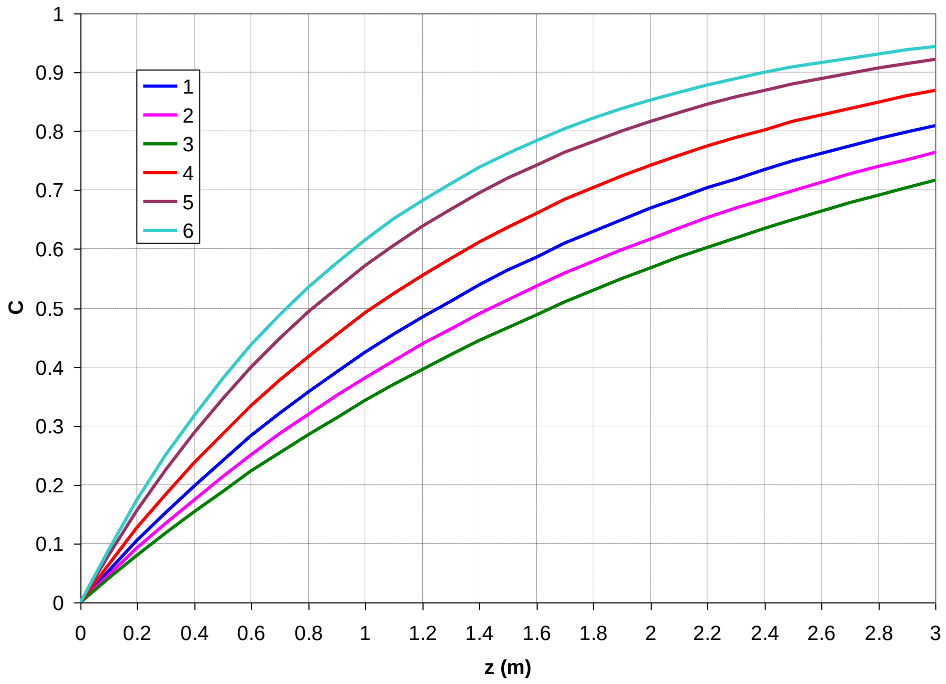


Figure 3: Radon profiles in soil for different migration parameters (Table 4)

Table 4: parameters of the 6 soil radon profiles shown in Figure 3. z95 - saturation depth: C(z95)=0.95; C0.8/1m: ratio between concentrations in 0.8 and 1 m soil depth.

	1	2	3	4	5	6
por	0.3	0.3	0.3	0.2	0.1	0.1
k (m²)	1.00E-11	1.00E-11	1.00E-11	1.00E-12	1.00E-12	1.00E-14
∇p (Pa/m)	0	1	2	0	5	0
D (m²/s)	3.60E-06	3.60E-06	3.60E-06	2.40E-06	1.20E-06	1.20E-06
v (m/s)	0	5.56E-07	1.11E-06	0	2.78E-07	0

z95 (m)	5.42	6.23	7.14	4.42	3.53	3.13
C0.8/1m	0.78	0.78	0.77	0.80	0.81	0.82
C(1m)	0.42	0.38	0.34	0.49	0.57	0.62

The advective term plays a role only for high permeability (lg(k) > ca. 10^{-12}) and high pressure gradients; otherwise the diffusion term $\lambda/D \approx 1$ is dominant. Saturation depth is several meters, not attainable with usual sampling equipment. For the examples shown, the ratio C(0.8 m) / C(1 m) ≈ 0.8, little depending on the profile shapes.

2D solutions reflecting the modification of the pressure field by the presence of a building have been shown by Jiránek (2010). For a discussion of multi-layered soil, see e.g. Yakovleva and Parovnik (2010).

Consequence for definition of the GRP

The main problem seems to consist in that in a realistic sampling depth (0.7 - 1 m), SRC is only between 25% and 65% of the equilibrium concentration $C_0=C(\infty)$. The ratio is specific to the site (per soil material; main parameter: porosity; permeability is important only if the advective component is high) and to the circumstances of measurement (per pressure gradient and porosity and permeability via humidity). Therefore, the empirical GRP as defined by the Neznal formula (Neznal et al. 2004),

GRP(empir) = SRC (certain depth) / (-lg k -10)

is no reasonable estimate of the "ideal" $GRP(\infty) = C_0 / (-\lg k - 10)$.

One can argue that the empirical GRP, derived from observation in low depth, reflects better availability near the surface, in view that soils are almost never vertically homogeneous, and that therefore SRC in greater depth may not be relevant to Rn availability near the surface.

On the other hand, it cannot be expected that the empirical GRP, calculated from SCR in shallow depth, is numerically consistent with the formally same quantity, calculated from C_0, where the latter is determined as $C_{Ra}\ \varepsilon\ \rho$/por. Again on the other hand, the latter quantity is ill-defined for vertically heterogeneous soil. Replacing its constituents, C_{Ra}, etc., by means over the soil column, would yield a kind of mean C_0 whose meaning and relevance for the GRP is unclear.

The matter should be discussed further in future work.

It seems that the different sampling depths used in different protocols (e.g., Germany: 1 m, Czech Republic: 0.7-0.8 m) are of minor difficulty, in comparison, since they can be normalized by factors which are little dependent on soil physical parameters (Table 4).

b) Sampling "point"

Sampling geometry and pattern depend on the purpose of a survey. For example, in the Czech Republic, every building ground has to be characterized for its RP by law. Therefore, one attempts a sampling scheme which one thinks yields an unbiased mean value. On the other hand, if the purpose is regional mapping, as in Germany, one tries to generate reliable "point" samples whose locations are chosen according to the variability of the physical process that controls soil Rn concentration or the GRP, i.e. according geological units.

However, the subject of this section is the sampling pattern on a site, which is regarded a point relative to the domain, but not the distribution of these points within the domain. As a reminder, here is a short account on regional mapping:

If relying on “point” samples, where “point” denotes a sampling area much smaller than the domain which shall be surveyed, most seem to assume spatial continuity of soil Rn. More specifically, the assumption is,

a) that if the sample has been taken according to rules, it fairly represents a temporal mean of the measurand on that point; this may be critical if the ground, in a chosen sampling depth, is subject to high temporal variability.

b) that Tobler’s First Law is applicable, i.e. “everything is related to everything else, but near things are more related than distant things” (Tobler 1970). In particular, this means that observations can be interpolated by geostatistical means. Hence, observed “point” values can be transformed into area values, that is, means over given areas (so-called block estimates) or to estimates on other points.

Practice has shown that this is indeed true, although autocorrelation (which is the quantitative criterion) of spatial Rn fields is sometimes poor. However, many examples show that mapping geogenic Rn based on “point” samples is viable.

At this point, one should remind the difference of design and model based approaches. In the first case, one strives to generate samples (in statistical sense, i.e. a set of physical samples) in an area such that they represent a wanted statistic unbiased, usually the mean, more generally the value which is attributed to the area. The wanted mean is simply the arithmetic mean of the individual sample values. Its standard deviation (or standard error SE) is estimated as $SD/\sqrt{n}$, n - sample size; neglecting possible autocorrelation of the sampled quantity.

For the model based approach, the condition of representativeness is more relaxed. A spatial model is derived from the data and possibly additional information, so that the investigated quantity can be modelled as response surface. The mean of an area (so-called block estimate) is the integral over it, usually approximated by the sum over regular grid nodes within.

The following applies to sampling of a site or "point" and to regional sampling likewise. Different sampling patterns are shown in Figure 4. The polygon may represent a site and the crosses the actual physical samples, or a domain, in which case the crosses are the sites. Regular patterns (A and B) can lead to misestimation if the pattern happens to coincide with an (unknown) natural periodic pattern. This problem is rare in spatial sampling, but frequent in sampling time series. Graph D shows a pure random pattern, here one must expect clusters and the opposite, i.e. empty areas. C is a mixture of regular and random, in that points are randomly placed within regular cells. E represents a random walk, constrained by the sampling path lying within the domain and returning to the entrance point. Alleged random patterns are often in fact random walk paths. It can take relatively long time until a random walk path fills a domain more or less uniformly. F is a preferential pattern, in this case the samples were preferentially placed along the border of the domain. At the one hand it ensures that the domain is well covered (no empty corners like in D and E), but representativeness is questionable.

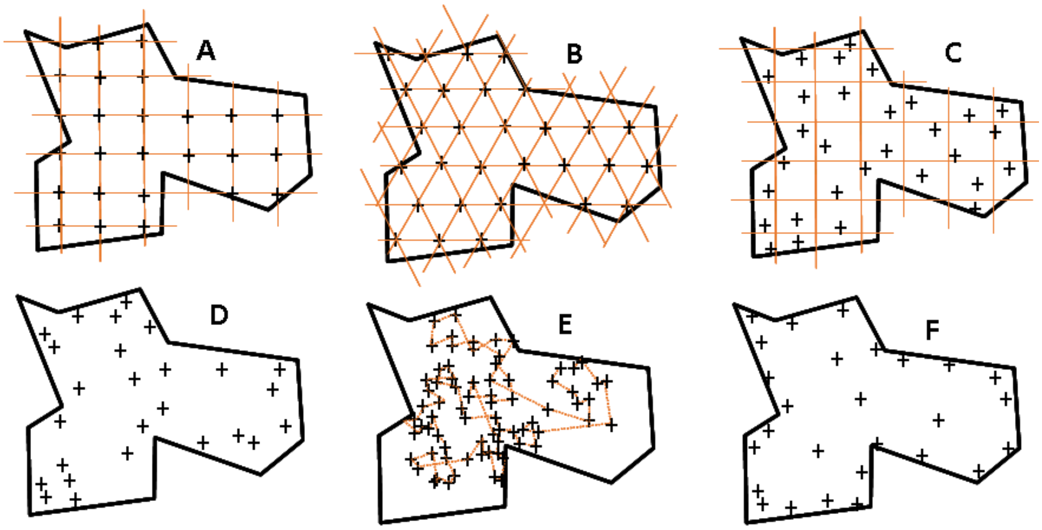


Figure 4: Sampling patterns (see text). A – regular quadratic grid; B – regular hexagonal grid; C – stratified random; D – random; E – constrained random walk; F – preferential.

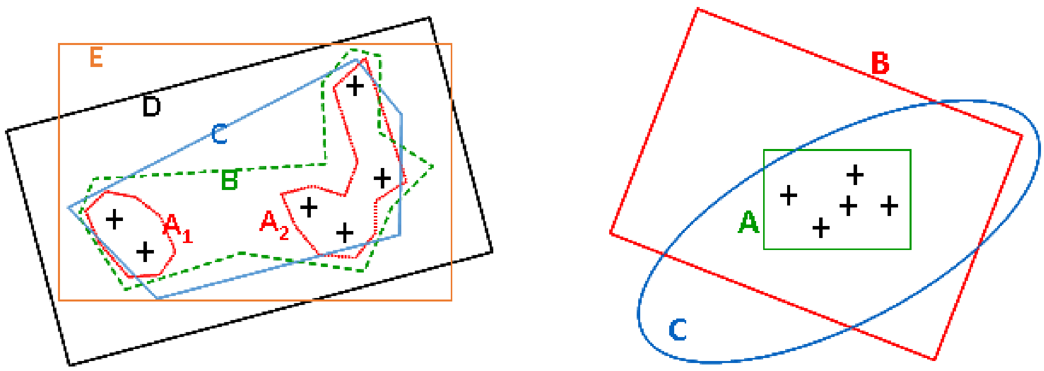


Figure 5: Sampling patterns (see text)

Figure 5 shows two sampling problems:

Left graph: given sampling points (+), which is the domain for which these points stand? A (broken into two parts), B, C, D and E are prima vista equally plausible.

Right graph: If the sample is considered representative for A – is it also for B and C? Or under which conditions? Or quantitatively: if the sample is believed to represent the mean of A accurately (no bias) with certain precision (standard error), which error must one assume for the value considered as mean over B or C?

These questions are quite difficult to answer, but evidently the problem can have practical impact. Statistically, it depends on stationarity of the true (unknown) quantity (understood as random field) within a domain and its spatial autocorrelation function. For both, usually previous knowledge is required.

Probably the subject should be further explored in more depth in the future.

Example

The matter shall be illustrated on an example. We ask: if a mean (AM) is calculated from data (physical samples) taken from an area, how representative is it with respect to a larger area (situation of Figure 5). As data, we take a survey of terrestrial ADR performed in a part of E Germany (Will et al. 1997; 2003), consisting of a sample of size 7101 (i.e. this number of measurements), as shown in Figure 6.

We select a number (N) of random points (x_i) in the domain, define a circle of radius r_1 around each point, forming areas $B(x_i; r_1)$. In each area we compute the $AM_{1,i}$ of ADR. Next, we draw a larger circle ($r_2>r_1$) around each x_i, forming $B(x_i; r_2)$, and compute the $AM_{2,i}$. (The circles are selected so that they lie within the domain in order to avoid border effects. $r_1=0$ means that $B(x;r_1)$ is the value of point x itself.)

The question is: how representative is $AM_{1,i}$ of $AM_{2,i}$?

To this end, calculate two statistics (among others possible):

$$rss(r_1, r_2) := \sqrt{[(1/N) \sum (1 - AM_{1,i}/AM_{2,i})^2]} \text{ and}$$

$$r^2(r_1, r_2) := \text{Pearson corr}^2 (AM_{1,i}, AM_{2,i}).$$

As expected, in general, the rss increases and the r^2 decreases with increasing difference between r_1 and r_2, i.e. the less $B(x;r_1)$ represents $B(x;r_2)$. The results are shown in Figure 7 (upper row) for rss and r^2, and scatter plots between $AM(x,r_1)$ and $AM(x,r_2)$, in the lower row.

From the left scatter plot one notes that single points ($r_1=0$) can be quite un-representative for an area 10 km around them, which is not surprising. The blue graphs in the upper row show that – equally not surprising – the correlation decreases (uncertainty of x as estimate of $B(x,r_2)$ increases) with increasing r_2 around x. Evidently, for small difference between r_1 and r_2, rss is low and r^2 high.

The rss levels in at about r_2=40 - 50 km, which reflects the correlation length of about 50 km.

The lesson is that the uncertainty of a value assigned to the mean over an area is not only the standard error (or another measure of uncertainty or confidence) calculated from the sample. Instead, it also depends on which area it is supposed to serve as the estimated mean. In Figure 5, the mean over the sample (denoted by the n crosses) is an estimate of the unknown true mean over all possible areas (denoted by different shapes), but its uncertainty is different in all cases.

One may put,

$$SE^2(\text{total}) = SD^2/n + unc^2(\text{shape}),$$

Where the latter component is independent of the sample, but dependent only on the shapes of the areas B_1 (which may be the points themselves) and B_2, for which the mean is meant to be an estimate. Unfortunately, this component is difficult to quantify, in general, but may relevantly contribute to the uncertainty budget.

In geostatistical reasoning, this component may be derived by averaging the block-semivariances $\gamma(B(x,r_1), x_i)$ over $x_i \in B_2$.

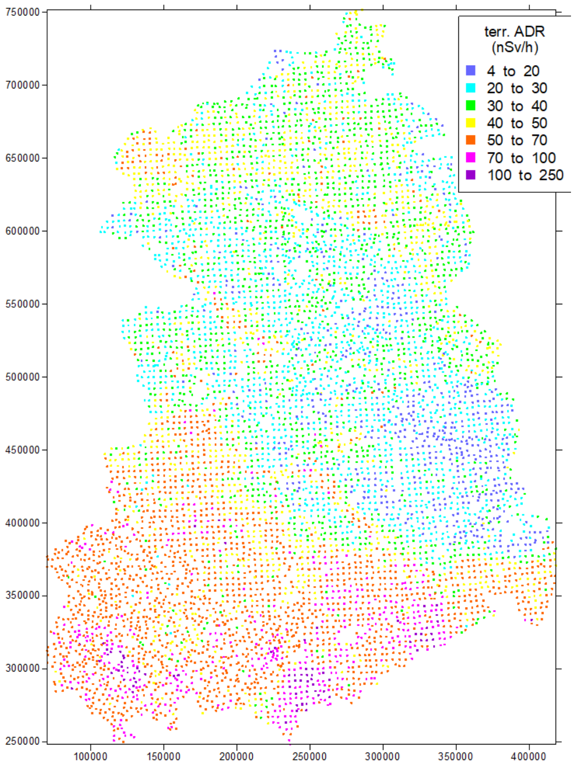
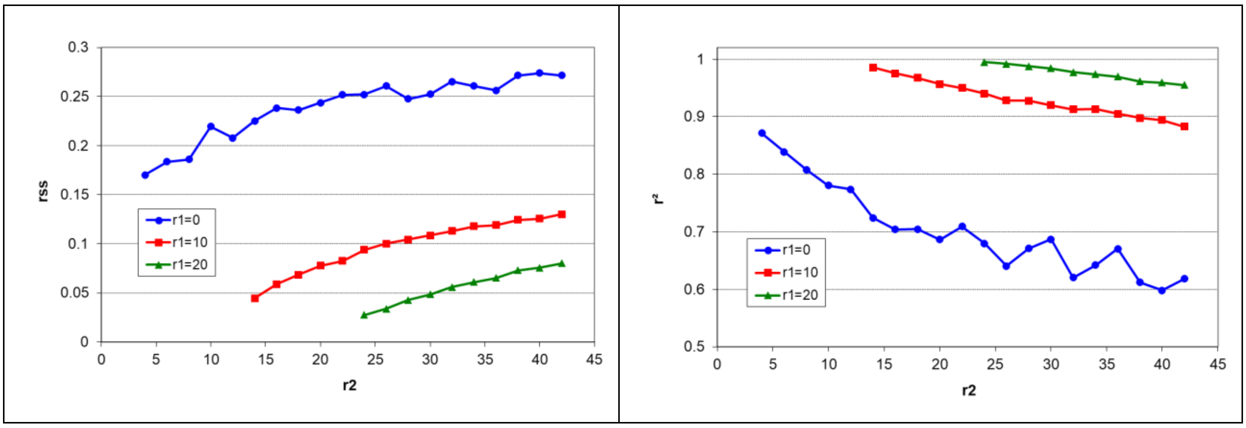


Figure 6: ADR data from a survey used in the example.



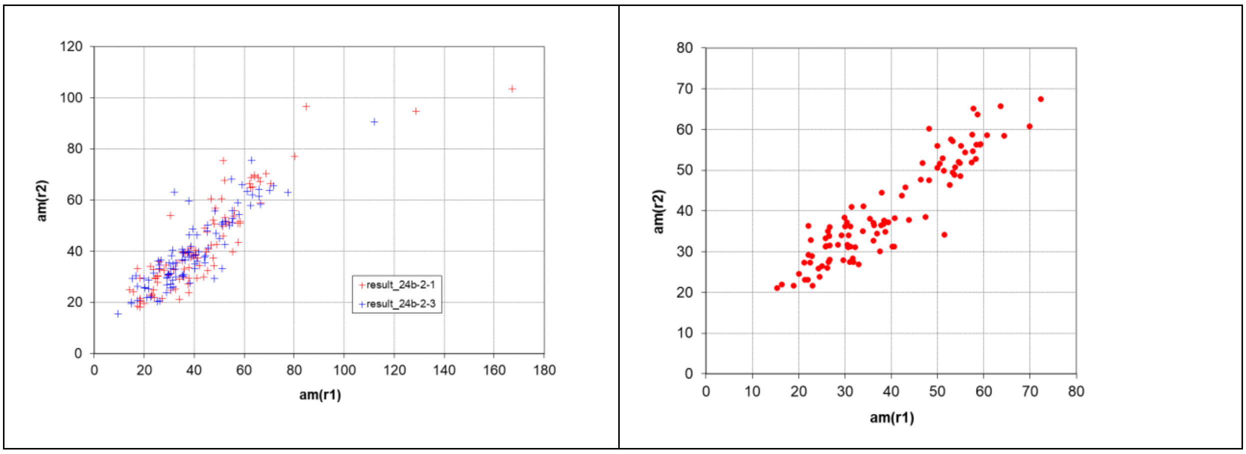


Figure 7: Upper row: statistics rss(r_1,r_2) and r²(r_1,r_2) for three different radiuses r_1 in dependence of r_2>r_1. In both cases, N=1000.
Lower row: Scatter plots of AM(x;r_2) vs. AM(x;r_1): Left: r_1=0, r_2=10 (two random realizations with N=100, distinguished by blue and red crosses); right: r_1=6, r_2=40 (one realization, N=100). All radiuses in km.

<u>Consequence</u>

When reporting soil Rn values, attention should be given to indicating for which area a value is thought representative. More precisely, the uncertainty of the reported value it should be estimated with respect to a hypothetical mean over a target area, in addition to the measurement uncertainty.

This first, spatial uncertainty component is little known so far. Further research on this topic is suggested.

c) Statistic of measured values on a site

Table 3, last column, shows that different statistics are used as value which is attributed to a site. Most common are the AM and the maximum; notably in the Czech Republic, the 3rd quartile is used. As explained in section 3.2.4.2c, the rationale of using the maximum or high quantiles lies in the error distribution of soil Rn sampling. Also the wish to generate conservative estimates may play a role. As GM and median < AM, using these statistics may not be conservative.

However, the different approaches are a source of disharmony between data. Evidently, attributing maxima to a site leads to higher estimates than doing so with AMs.

It has been shown by field experiments and by simulation that the German and Czech protocols of SRC sampling and measurement (maximum of 3 measurements and 3rd quartile of ≥15 measurements, respectively) yield compatible results (Neznal et al. 2004; Bossew 2012).

3.2.4.4 Radon surface exhalation

Most questionnaire participants use the closed box method (some correcting for the finite box size) and analyze the slope and/or the saturation value of Rn concentration per time function. One institute uses the method of excess/depleted-^{210}Pb in upper soil layers. Also in one case, TE detectors 10 cm above surface were used for long-term exhalation assessment on waste piles.

For counting, 2 participants each indicated using electrets and Si semiconductors.

3.2.4.5 Radon in water

Ground water absorbs geogenic Rn and can transport it over considerable distance. Therefore, Rn in ground and well water is a consequence of geogenic Rn, and one of its indicators. Investigations of Rn in ground water often serve hydrological and tectonic studies. In these, Rn is use as a tracer of transport processes.

Many questionnaire participants indicated that the purpose of measuring Rn in water is legal obligation, because consumption of Rn with drinking water contributes to exposure and radiological burden. Some use it as complement to assess geogenic Rn.

Sampled media are drinking and tap water; also ground water and spring water; a few named surface and thermal waters.

a) Participants, number of measurements, motivation

Many of the institutions that participated in the questionnaire indicated that they measure Rn in water. Motivation is mostly legal obligation (ensuring safety of drinking water), scientific interest (not specified - possibly hydrological tracer studies) and support for Rn studies (may coincide with tracer studies).

Table 5: Responses to questions concerning Rn in water. # ground, etc: number of measurements of Rn in ground water, etc.; Motivation: code see Figure 8; Method: code see Table 6.

ISO code	# respon-ding institu-tions	motiv	status	# ground	# well	# surface	# thermal	# tap	# drinking	method
AD										
AL										
AM										
AT	1	1,2	pl., fin.	100	50				250	1,2
AZ										
BA										
BE	2	1,2	on, fin.	50					100	1
BG	1	1	on						1	3
BY										
CH	1		not pl.							
CY										
CZ	2	1	on, 0	10000						

DE	2	1	not pl, 0	912					510	1
DK										
EE										
ES										
FI	1	0	fin.							
FR										
GE										
GR										
HR	1	2	on, fin.				(*)	100s	<100***	4
HU										
IE										
IS										
IT	4	1,2,4	3 on, fin.		130	5	10	544	446	2,3,6,7
KZ										
LI										
LT	1	1.2	on	190					220	7
LU										
LV										
MC										
MD										
ME										
MK										
MT										
NL	1	1	fin	dozens					dozens	7
NO	2	2,4	on, fin.						(**)	1
PL										
PT	1	1,2	on							
RO	1	2,4	on, fin.	2500	300	300	250	450	1500	6,1
RS	1	2	on	~ 50			~ 50		>100	5
RU										
SE	1	0	on		~700				2000	
SI										
SK										
SM										
TK										
UA	1	2,4	plan.	8		7				
GB	1		not pl.							
VA										

(*) The Croatian participant replied that almost all thermal waters are being monitored.

(**) One Norwegian participant said that about 4000 drinking / ground / tap water samples had been measured.

(***) Croatia: bottled drinking water

b) Sample types

The question in the questionnaire was not entirely clear: Drinking water can be of any other source; so replies in the questionnaire are probably redundant to some degree.

Most mentioned sample types are ground and drinking water (16 and 15, respectively), followed by tap water (9), spring and thermal water (5) and surface water (4). This appears to reflect the radiological importance and concerning ground water, its importance as indicator of geogenic Rn and as tracer in hydro-geological studies. One participant measures Rn in bottled drinking water. Since bottles are stored over periods usually much longer than the half life of ^{222}Rn (3.7 d), Rn in bottled water can almost only have its origin in ^{222}Ra in the water.

c) Measurement methods

Table 6 summarizes how often various measurement methods are mentioned in the questionnaire. Most common is LSC, followed by gamma spectrometry (sometimes in combination with emanometry and extraction). Two institutes each use Alphaguard and Rad-7 for measuring Rn in water (methods provided by these instruments). Many refer to ISO standards, which means that an approved method is used, probably mostly LSC.

Most participants indicated that they indeed keep with standards for determining Rn in water.

Table 6: Methods of measurement of Rn in water.

code	method	number of mentions
1	LSC	15
2	gamma spectrometry	6
3	emanometry	4
4	Alphaguard	1 institution
5	Rad 7	1 institution
6	extraction	2
7	reference to ISO 13164-3, -4	8

Many participants indicated that except Rn, also U, ^{226}Ra, ^{210}Pb,Po, Th and progenies and ^{40}K are measured, as well as gross-α and -β.

3.2.4.6 Ambient dose rate

Ambient dose rate (ADR) is easy to measure. It is being surveyed and continuously monitored by networks of probes in most European countries. Reasons for surveys are mineral exploration (because ADR points to certain geological structures) and fallout mapping. Continuous monitoring is performed as part of warning against nuclear pollution. After the Chernobyl accident (26 April 1986), monitoring networks have been installed in all EU Member States and beyond. They serve the monitoring needs of the countries and in most cases, contribute the data to the EURDEP system, run by the Joint Research Centre (JRC) of the European Commission, https://remap.jrc.ec.europa.eu/ . At the time of the Chernobyl accident, only one national monitoring network was operational, namely in Austria, consisting of about 335 automatic stations. Its performance which allowed very fast assessment of the extent and the dynamic of the contamination, was a convincing argument for such monitoring, although the systems are certainly not cheap. However - fortunately - since Chernobyl there was no case of contamination in Europe which would have generated detectable ADR. The networks still continuously record ADR, which apart from residual radiation from global and Chernobyl fallout, mainly consists of natural terrestrial and cosmic radiation. The data are stored and the idea arose to use the information to study natural environmental radiation (e.g., Bossew et al. 2017).

ADR is given in physical dose rate (nGy/h) or ambient dose equivalent rate (nSv/h) which accounts for the biological effect. (Metrological details e.g. in the European Atlas of Natural Radiation, chapter 4, EC 2019) Sources of ADR are visualized in Figure 8.

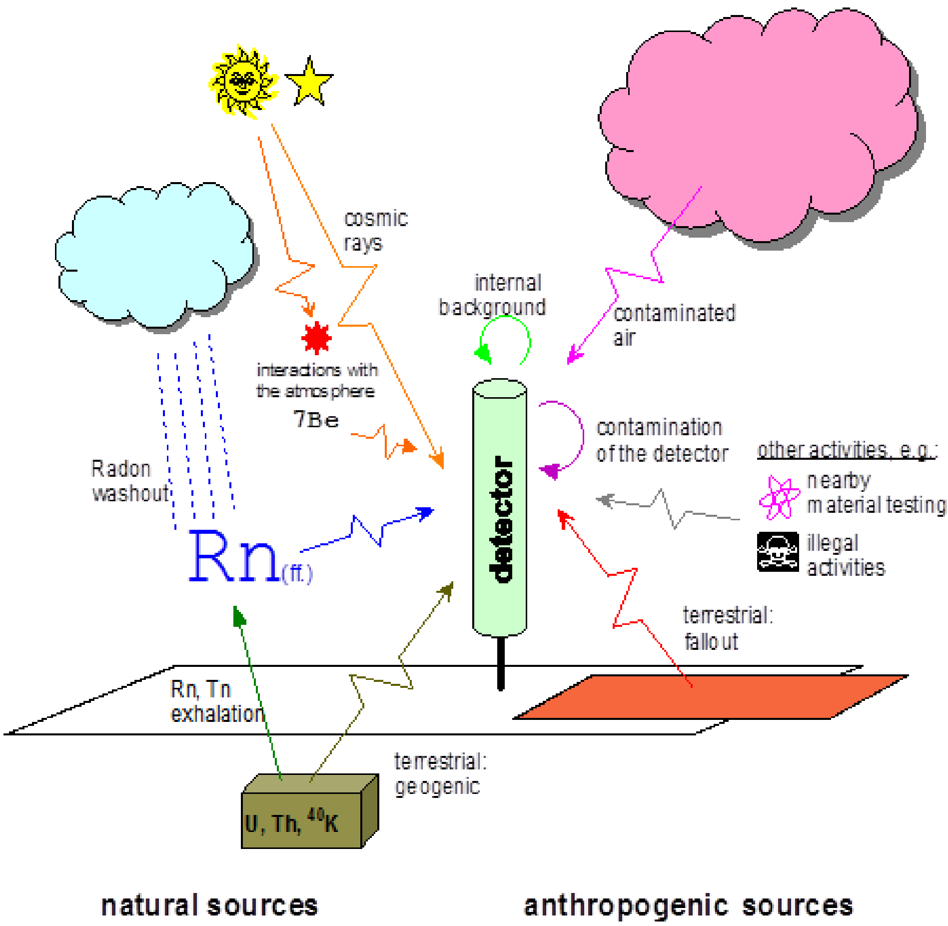


Figure 8: Contributions to the dose rate recorded by a detector. (Graph taken from the AIRDOS report).

The reason why ADR is considered relevant in geogenic Rn study, lies in its function as proxy to geogenic Rn, as visualized in Figure 9. This relationship has indeed been used for estimation of Rn priority areas in Spain (Quindos Poncela et al. 2004; Garcia-Talavera et al. 2013; WP4 section 4.1.1.5.4). Another example how to explore the relationship for RPA estimation has been given in Bossew (2015). However, given the many covariates which also contribute to both ADR and GRP (Figure 9), the statistical correlation between the two is not very strong, but "blurred" by the presence of these "noise factors" or "nuisance variables" https://en.wikipedia.org/wiki/Nuisance_variable). "Noise" and "nuisance" has to be understood with respect to the relationship of interest. Managing situations with the presence of such factors is a challenging statistical discipline, however beyond the scope of this section.

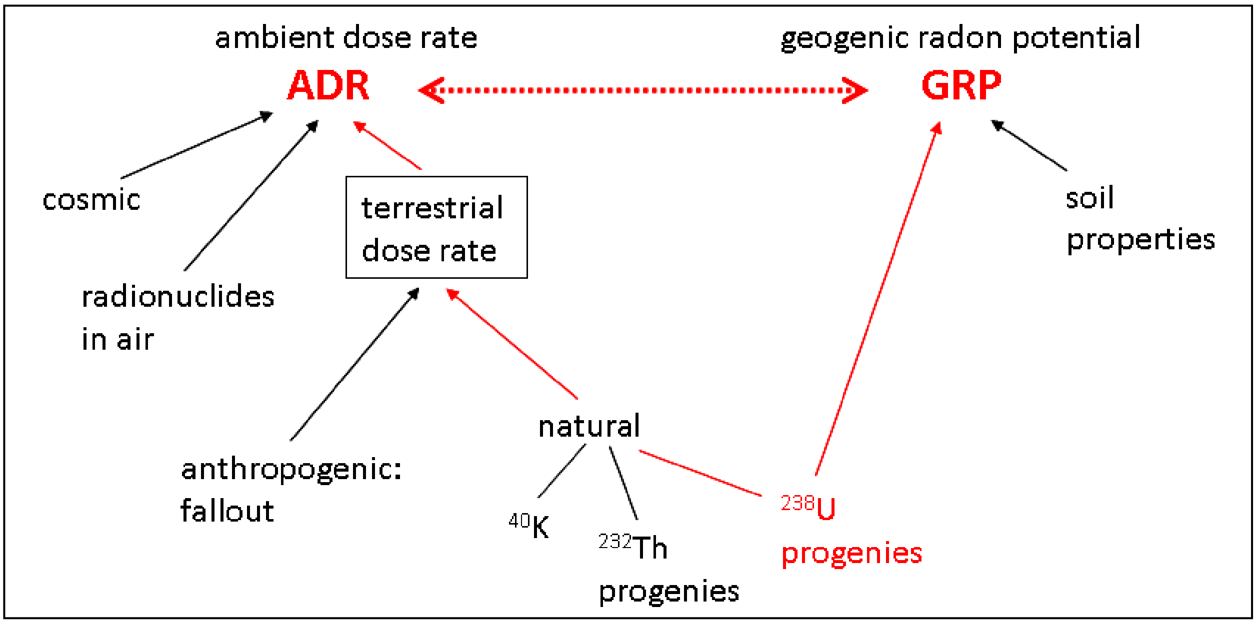


Figure 9: Proxy relationship between ambient dose rate and geogenic radon potential

a) Participants

As shown in Table 7, many of the institutions which responded to the questionnaire, also performed ADR surveys.

From 13 countries institutions replied that they performed surveys; out on these, in 5 countries, 100% coverage was achieved, and >80% in two more countries.

Table 7: Responses to questions concerning ambient dose rate (ADR): participants, survey coverage and motivation. Column "EURDEP": participation in the EURDEP network (see b)

ISO code	# resp. inst.	# data	area covered	country land area	% covered	per km² covered	per km² country	status	motivation	EURDEP?
AD										
AL										
AM										

AT	1	1000	20000	82445	24	5.00E-02	1.21E-02	fin.	2,3	N
AZ										
BA										
BE	3	200	30000	30278	100	6.67E-03	6.61E-03	fin.; 0; on.	1,2,3,5 ; 0	Y; Y; 0
BG	1							no plan		
BY										
CH	1							no plan		
CY										
CZ	3	20000	79000	77247	100	2.53E-01	2.59E-01	on; 0; 0	0; 1; 0	0
DE	2	7101	150000	348672	~ 43	~4.7E-02	2.04E-02	fin.; 0	1,2,5 ; 0	N, 0
DK										
EE										
ES				498980	100					
FI	1							fin.	2	0
FR										
GE										
GR										
HR	1									
HU										
IE										
IS										
IT	4	1500429	28675	294140	10	5.23E+01	5.10E+00	3 on.,1 plan.	1,2,3,4,5	N; N; Y; Y
KZ										
LI										
LT	1	650	65300	62680	100	9.95E-03	1.04E-02	on.	1,2,3,4.5,6	Y
LU										
LV										
MC										
MD										
ME										
MK										
MT										
NE	1	1049	36500	41528	88	2.87E-02	2.53E-02	fin.	2	N
NO	3	2133	385200	304282	100	5.54E-03	7.01E-03	on.	5	N; N; Y
PL										
PT	1	1000		92212				fin.	6	N
RO	1	1200	75100	231291	32	1.60E-02	5.19E-03	fin.	2,3	N
RS	1							on.	1,2,5	0
RU										
SE	1							on.	4	N
SI										
SK										
SM										
TK										
UA	1	3000	10	579300	0.002	3.00E+02	5.18E-03	on.	2,3,5	0
GB	1	3100	200000	244820	82	1.55E-02	1.27E-02	fin.	3	0
VA										

b) Motivation; EURDEP participation

Interestingly, the most cited motif for performing ADR surveys is scientific interest, followed by emergency preparedness (Figure 10). It seems that in these cases, early warning networks are addressed.

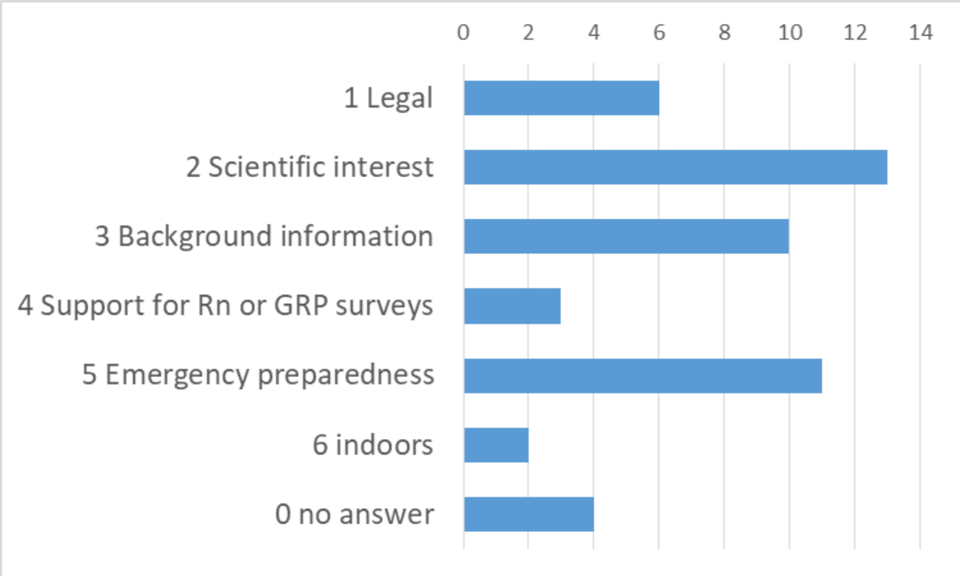


Figure 10: Motivation to perform ADR surveys. Since several answers are possible, the sum exceeds the number of participants.

There is clear association between those who indicate emergency preparedness and those who supply the data to EURDEP, p(no association)=0.012 by Fisher's exact test on the contingency table, Table 8 . This result points to a misleading formulation in the questionnaire: it seems that some participants interpreted ADR monitoring networks (which in most cases do send their data to EURDEP) as ADR surveys, which was not the intention of the questionnaire. Instead, a long-term mean or typical BG local value was targeted, i.e. without influence of short-term fluctuations or change points, whose detection is indeed the purpose of emergency monitoring.

In at least one case, however, such typical values were the purpose of a survey, at the same time motivated by emergency preparedness (the German survey Will et al. 1997; 2003): the rationale is to enable detecting increased ADR by nuclear fallout, independent of radionuclide analysis of soil samples or in situ-gamma spectrometry. Since these are not dynamic values, they are not supplied to EURDEP.

Table 8: Contingency table for association between motivation = emergency preparedness and supply of data to EURDEP. not-Y: answer is different from Y, i.e. including no answer.

motiv. = emergency response → supply data to EURDEP ↓	Y	not-Y

Y	6	0
not-Y	5	10

c) Type of detector

For scintillators, mostly NaI(Tl) is used. Sweden indicated the additional use of BGO scintillators. The indication of using a $LaBr_3$ detector in one German survey in the questionnaire was a mistake that has been corrected here.

According Table 9, most popular seem to be GM counters, followed by scintillators and ionization chambers.

Table 9: Technical details of ADR measurement. “geometry”, “height”, “% conform std.”: see below d); “cosmic subtr.” and “BG subtr.”: see below e). – ‘0’: unknown or no answer, expect in column “% conform. std.”, where this is denoted by ‘n’.

ISO code	detector	geometry	height (cm)	% conform std.	cosmic subtr.	BG subtr.
AD						
AL						
AM						
AT	Prop	0	100	n	N	0
AZ						
BA						
BE	GM; GM; 0	Y; Y; 0	100: 100; 0	80; 85; n	Y; Y; 0	Y; Y; 0
BG						
BY						
CH						
CY						
CZ	GM; 0; 0	N; 0; 0	100; 0; 0	90; n; n	N; 0; 0	N; 0; 0
DE	Scint; 0	Y; 0	100; 0	100; n	Y; 0	Y; 0
DK						
EE						
ES						
FI			0			
FR						
GE						
GR						
HR						
HU						
IE						
IS						
IT	Ion, GM, Scint, HPGe	Y	3x 100; 200	100; 100; 30; n	Y; Y; N; part	Y; Y; Y; 0
KZ						
LI						

LT	passive	N	150	n	N	Y
LU						
LV						
MC						
MD						
ME						
MK						
MT						
NE	Ion	Y	100	100	Y	Y
NO	GM,GM,Scint	Y; N; N	2x 100; 250	100; 10	Y; N	Y; 0
PL						
PT	Scint	n.a.	100			
RO	GM, Prop	part. Y	100	1	N	N
RS	GM, Scint,HPGe		100	100	Y	Y
RU						
SE	Scint	Y	0	n	N	Y
SI						
SK						
SM						
TK						
UA	GM, Ion	Y	100	5	N	N
GB	GM, passive	Y	100	100	Y	Y
VA						

d) Measurement geometry

While ADR measurement itself is simple, achieving comparability of ADR, acquired with different protocols, is not. This concerns the geometrical setup of the measurement system, i.e. its position relative to the environment which it is supposed to characterize, and the way how data are evaluated (section e).

As an informal standard in the community, as standard the following situation has been defined as follows:

- An infinitely large plane natural ground such as a meadow; infinite means a radius of 100 m and plane, no sinks and hills, and not inclined. Mounting on roofs or parking areas is not according to standard;
- Soil typical for the region;
- Detector mounted about 1 m above ground (since often detectors are elongated in shape and mounted vertically, an exact height is difficult to define);
- No buildings, trees, roads, water bodies in the vicinity, typically a few 10 meters.

Evidently, this is achievable only rarely. As minimal requirement, a distance of at least 10 m is considered appropriate between detector and any object which may alter the photon flux. For contamination concentrated near the surface (fallout), a larger radius is required: the closer the source to the surface, the larger the radius around the detector, from within which most radiation originates. For literature and details, see e.g. Bossew et al. (2017).

In the questionnaire, the questions about geometry, measurement height and percent conformity were motivated by checking whether participants would find these problems relevant for operating their detectors and for interpretation of results.

d1) Geometry of the measurement site

This concerns the location of a detector in its environment, e.g. planarity and micro-topography of the ground, vicinity to buildings, vegetation, roads or water bodies, etc.. The ideal setup is of course not achievable, thus any real-world detector setup is inevitably a compromise, for better or worse.

In countries with large parts characterized by rugged terrain and mountainous topography (typically Austria), conformity with standard geometry is evidently more difficult to achieve than in comparatively flat countries.

It appears that most respondents, but still less than half (45%) of the participants, do care about measurement geometry. Almost the same number indicated that they do not know whether this factor is considered or did not answer the question.

d2) Measurement height

The terrestrial ADR depends on the height above ground in which it is measured. The reason is absorption of geogenic gamma rays in air and in the ground. Dependence on altitude is roughly falling-exponential; however it depends on source geometry - close to surface as typical for fallout, or more or less homogeneous over the soil column, as often approximately the case for natural radionuclides - and gamma ray energy spectrum of the source. For real sources, for which a very complex mixture of gamma ray energies is typical, and heterogeneous sources, it is practically impossible to give the height dependence function analytically.

For pure surface fallout, the *unscattered* photon flux decreases like $\sim E_1(h\ \mu_a(E))$, while for a source homogeneously distributed in the soil column, the dependence is $\sim E_2(h\ \mu_a(E))$; E_1 and E_2 - the exponential integrals of first and second kinds, $\mu_a(E)$ - linear attenuation coefficients in air, dependent on gamma ray energy. Considering the *Compton scattered* flux which adds substantially to the ADR and realistic source distributions in the ground makes ADR analytically nearly intractable.

Therefore as a standard, measurement 1 m above surface has been established. This cannot be realized easily in many cases: in regions with deep snow in winter (e.g. Finland, mountains in Central Europe), monitors are often mounted higher than 1 m. As a result, while well serving the original purpose to warn against increases of ADR due to nuclear events, i.e. *relative* information about the dynamic of ADR, monitors mounted in different heights above ground yield *absolute* results which are difficult to compare between stations. This is among the reasons, why some effort is required to use data from stations belonging to early warning networks for estimation of the terrestrial radiation background. See also Bossew et al. (2017) and chapter 4 of the European Atlas of Natural Radiation (EC,2019) for further discussion.

The questionnaire revealed (Table 9) that most responding institutions apply the standard measurement height of 1 m above ground, but not all. (Erroneously, the question appeared twice in the questionnaire.)

d3) Conformity with standards

As self-assessment, most participants who answered to this question, indicated a high degree of conformity, most 100%, a few between 80-90%.

e) Standardization of measured values

As shown in Figure 8, ADR is composed of several components. Some institutions choose to report only the terrestrial one (plus eventual airborne radiation), subtracting the internal background and cosmic radiations.

The replies show that there is no uniformity in reporting ADR values, concerning treatment of internal BG and cosmic radiation.

e1) Internal background

Internal BG (also called intrinsic BG or self-effect) is characteristic for different types of detectors, but it also varies slightly between individual instruments of the same type and manufacturer (so-called component spread; the German term *Exemplarstreuung*, literally dispersion between exemplars of the same model, seems to have no authoritative English equivalent). Since it does not matter much for the original purpose of the monitoring systems, viz. radiological early warning, some institutions did not bother much about exact characterization. However, most of the respondents to the questionnaire did care about internal BG, as indicated by ticking YES to the question whether internal BG has been subtracted.

On the other hand, nearly the same number of participants indicated that they do not know or did not respond to this question.

e2) Cosmic radiation

ADR monitors are differently sensitive to secondary cosmic radiation (mainly muons). Again, for their purpose as early warning systems, this does not matter; but if one attempts gaining comparable information on terrestrial gamma radiation as proxy to the GRP, it does.

More participants replied that that they do not subtract cosmic dose rate, than those who do.

3.2.4.7 Geochemical surveys

Uranium concentration in the ground, or more precisely, the concentration of its progeny ^{226}Ra, is the source of geogenic Rn. (^{238}U and ^{226}Ra are not necessarily in equilibrium, because of different chemical properties of these elements which render them differently subject to environmental transport processes. Therefore Ra may be enriched or depleted relative to U.) (Figure 11)

^{238}U and ^{226}Ra are therefore considered important predictors to the GRP. A number of studies has demonstrated statistical correlation between U/Ra and the GRP (WP4, section 4.2.1.4+5) and U concentration in soil may also serve as RPA predictor. However, as Figure 11 shows, the pathway from U to Rn available for exhalation is controlled by a number of factors related to chemical milieu, mineralogy and soil physics. Therefore, correlation between U and GRP may be weak.

This was the reason why geochemical surveys were included in the questionnaire on geogenic Rn.

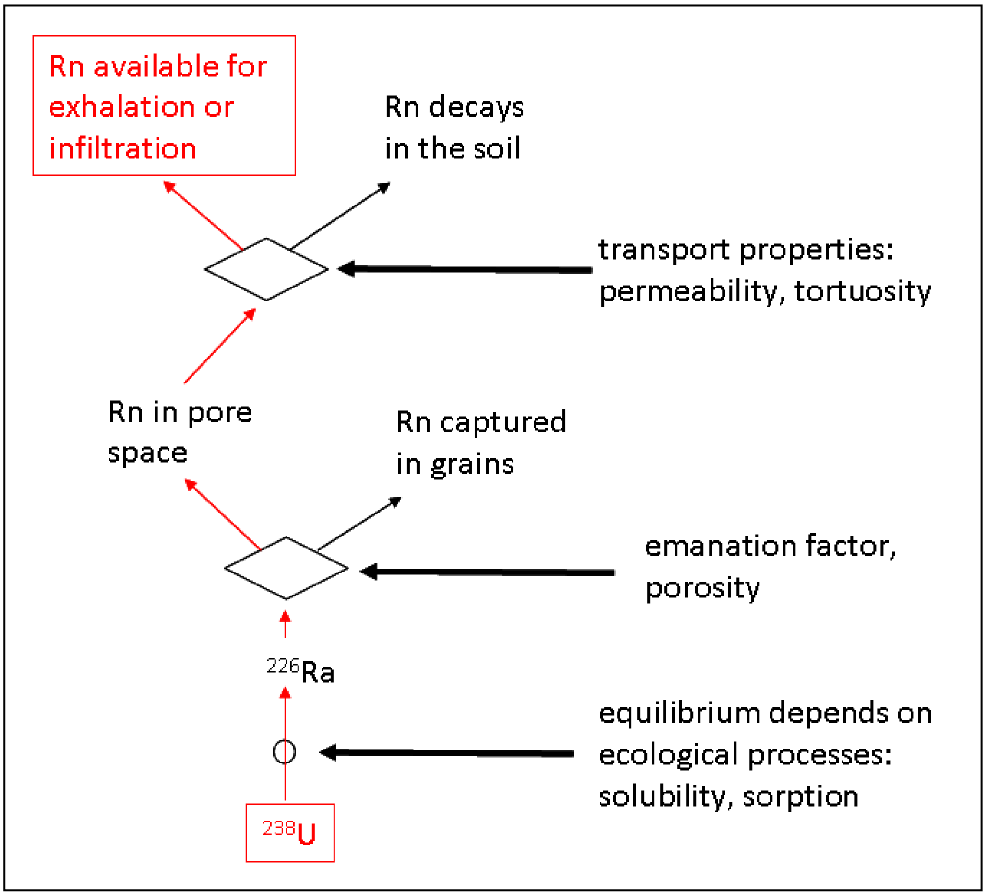


Figure 11: Pathway from ^{238}U to ^{222}Rn available for exhalation

a) Participants and motivation

Responding questionnaire participants, coverage, motivation and media sampled are summarized in Table 10.

Table 10: Participants who performed geochemical surveys, their motivations and technical details. For motivation, see section 3.2.4.6b; additionally category 7: mineral exploration.

ISO code	# resp. inst.	# data	area covered	% cov.	per km² covered	per km² country	status	motiv.	sanple
AD									
AL									
AM									

AT	1	100	200	24	5.00E-01	1.21E-03	fin.	2	top soil
AZ									
BA									
BE	3	92	18000	59	5.11E-03	3.04E-03	fin.,no plan; no plan	2	sub soil
BG	1						no plan		
BY									
CH	1						no plan		
CY									
CZ	3	200	79000	100	2.53E-03	2.59E-03	fin., fin., 0	4	
DE	2						no plan; fin.		
DK									
EE									
ES									
FI	1						fin.		
FR									
GE									
GR									
HR	1						0		
HU									
IE									
IS									
IT	4	417	25415	8.6	1.64E-02	1.42E-03	on, on, no plan,0	2,4	top soil, sub soil, rock
KZ									
LI									
LT	3	1530	65300	100	2.34E-02	2.44E-02	fin	2,3	soil profile
LU									
LV									
MC									
MD									
ME									
MK									
MT									
NL	1						no plan		
NO	3	6000	385200	100	1.56E-02	1.97E-02	on, 0, 0	2,4,7	rock
PL									
PT	1	650					on	2,4	top soil, rock
RO	1	23					plan	2	top soil
RS	1						on	1,2	top soil, rock
RU									
SE	1	50000	300000	60	1.67E-01	1.00E-01	on	3,4,7	top soil, sub soil, rock
SI									
SK									
SM									
TK									
UA	1	3000	10	0.002	3.00E+02	5.18E-03	on	2,3,4,7	top soil, sub soil, rock
GB	1						no plan		
VA									

As motivation for performing geochemical surveys, scientific interest was indicated in the first place, followed by support for Rn and GRP studies.

b) Sample type

Most respondents indicated top soil, followed by rock and sub soil, several of them all types. One (Lithuania) indicated analysis of soil profiles, which is certainly the most informative method, but also the most laborious one.

Although in most cases, soil is chemically derived from underlying rock, U, and in particular, Ra concentrations are not necessarily the same due to possible differentiation processes. This may lead to harmonization problems between geochemical surveys.

Stream sediments, which are also common in geochemical surveys, have not been mentioned by any participant.

c) Measurement

Measurement method is not included in Table 10. (See annexed detailed tables.) Most respondents indicate gamma spectrometry (most HPGe, also NaI), which we interpret as laboratory based analysis of samples. One participant indicates ICP-MS. However, some quote in situ gamma spectrometry (Lithuania) and hand-held gamma spectrometry (Sweden) (detectors not specified), from which can be concluded that also in situ surveys are included in the list. It has to be kept in mind that ^{226}Ra concentration inferred from in-situ or airborne assay (see next chapter) relies on measuring the gamma ray flux of ^{226}Ra progenies (^{214}Pb, Bi) and include assumptions about distribution in soil and physical properties of the soil. Therefore, results acquired by remote sensing (in situ gamma close to the ground, aerogamma) do not necessarily conform to sample-based results. ^{238}U and ^{226}Ra measured by remote sensing are often denoted by eU and eRa.

3.2.4.8 Airborne gamma ray spectrometry (AGRS)

Historically, this technique has been developed for regional mineral exploration, in particular search for uranium resources. Much literature is available about the technique. For a summary and bibliography, see chapter 4 of the European Atlas of Natural Radiation (EC,2019).

The subject has been addressed in the questionnaire, because AGRS surveys could be a valuable source for GRP estimation, although this has not been investigated systematically so far, to our knowledge.

Table 11: Technical details about airborne gamma ray spectrometry, as applied in some European countries.

ISO code	# responding institutions	% covered	status	altitude (m)	spacing (m)	detector
AD						
AL						
AM						
AT	1					
AZ						
BA						
BE	3	100,100	fin., fin.,0			NaI, NaI
BG	1		no plan			
BY						
CH	1		no plan			
CY						
CZ	3		no plan, 0, 0			
DE	2		no plan, 0			
DK						
EE						
ES						
FI	1		no plan			
FR						
GE						
GR						
HR						
HU						
IE						
IS						
IT	4	5	on, on, no plan, 0	600, 200		HPGe, HPGe
KZ						
LI						
LT	1		plan			
LU						
LV						
MC						
MD						
ME						
MK						
MT						
NL	1		no plan			
NO	3	50	on,0,0	80	200	NaI

PL						
PT			no plan			
RO	1		no plan			
RS	1		on			NaI, HPGe
RU						
SE	1	85	on	60	200	NaI
SI						
SK						
SM						
TK						
UA	1	30	on	50	1000	0
GB	1		no plan			
VA						

Detectors used are traditionally NaI scintillators because of their high sensitivity. However, for the last decade or so, also semiconductor detectors became more common, because today highly sensitive HPGe are available which have much higher energy resolution than NaI based systems.

It seems that new alternatives such as $LaBr_3$, $CeBr_3$, BGO (scinitillators), CZT (semiconductors) and others have not yet become common for the purpose.

Flight altitude and spacing determines the spatial resolution of the resulting data. Clearly, resolution increases with lower flight altitude and narrower spacing between flight lines, but so do also costs.

Institutions from the Czech Republic indicated no AGRS surveys; however, as early as in the late 1940s, then Czechoslovakia performed extensive AGRS surveys in the search for uranium resources. The data also entered the Czech ADR map.

3.2.4.9 Relevance for stakeholders

a) Geogenic radon

Geogenic radon surveys can support or partly replace indoor Rn surveys for estimating radon priority areas (RPA). The reason is that geographical variability of indoor Rn concentration is importantly controlled by the one of geogenic radon. However, from the questionnaire it could be concluded that most institutions that measure geogenic radon do this out of scientific interest. In three countries it is done due to legal obligation. (Notably in the Czech Republic this has been required since the early 1990s on grounds of new buildings.)

Stakeholders are:

1. Administrations and authorities as land use planners, which are responsible to establish reliable rules for Rn prevention, mitigation and remediation;

2. The property industry (including public investment) that wants to rely on classification of an area in terms of Rn hazard, because of development costs and property prices;
3. The building industry which has to calculate construction costs and make adequate provisions for construction;
4. Users of buildings – residents, enterprises and public users (from schools to administrations) alike – who want to trust that decisions have been correct according state of knowledge; in the end these are the stakeholders who are primarily affected by the radon hazard.

b) Radon in water

Water is the most important of all food. The need for regulation against pollutants is therefore evident; this includes radon.

The relevant QA issue is therefore, ensuring compliance with regulation. Concerned stakeholders are:

1. Drinking water suppliers (public or private) which have to guarantee compliance of their commodity to regulation;
2. Controlling authorities which have to verify compliance;
3. Consumers, i.e. the public, who righty want good quality drinking water. QA by 1. and 2. is therefore a matter of being trusted by the consumers.

c) Other media

Radon exhalation, dose rate and geochemical surveys play a supportive role in assessment of the geogenic Rn hazard. (For other purposes, they may be the primary target quantities.)

d) General stakeholders

Regarding all media, concerned stakeholders are obviously those who perform the measurements on which assessments are based, including supply of instruments, which are subject to metrological QA in a classical sense. Consequently, also those who verify that QA standards are respected, i.e. metrological authorities, are stakeholders:

1. Developers of standards on scientific and technical level, mostly radioprotection institutes, universities and other research institutions;
2. Legislators who transpose them into law;
3. Metrological institutes, (a) providing the technical means for validation and QC and (b) actually doing it (issues discussed in WP1, 2 and 5);
4. Companies that develop and supply measurement instruments and/or evaluate the results at various aggregation levels (from raw count numbers to results that can be communicated, including information about uncertainty and detection limit).

3.2.4.10 Possibility of harmonization

a) Geogenic radon

1. The dependence of soil Rn concentration on sampling depth is of concern. To some extent, this can be corrected mathematically, but bottom-up harmonization would be preferable (i.e. standardized sampling depth). On the other hand, however, the achievable sampling depth may be technically limited in shallow soil. A further problem is that the depth zone in soil which is relevant for the generation of Rn that exhales from the surface, or infiltrates into a building, is not necessarily located in the same depth in all instances; in contrary, it can be expected to be very different between sites. This question certainly needs further discussion. Generally, one would assume:
   - for surveys, methodology should be standardized, for the sake of comparability of results;
   - for building site assessment: the methodology should be adapted to the purpose, i.e. optimizing construction, and therefore adjusted to the site-specific situation.
2. Experiments should be performed which clarify the relation between soil Rn concentration measured by grab sampling (which yields a temporal point value) and by long-term integrated measurement (buried detector). Both methods have pros and cons which have not been sufficiently discussed so far.
3. The influence of estimation support (the area to which the reported value refers) becomes relevant if statistics of the quantity are shown. The larger the area and the higher the number of samples which define a site, the “smoother”, i.e. lower statistical dispersion and the lower the occurrence probability of extremes. This becomes relevant if statistics shall be compared between surveys, and if the result shall serve to generate maps.
4. GRP: If an in-situ GRP is applied composed of soil Rn concentration and permeability, such as for the popular Neznal-GRP, both soil Rn measurement and permeability determination methodologies contribute to possible discrepancy between results.
5. A possible alternative is under discussion, namely a possible “synthetic” GRP, built of *calculated* instead of in situ measured values. For the Rn concentration in soil, one may think on using the equilibrium concentration $C(\infty)=C_0$ and for permeability, long-term means calculated via soil models. Input data would come from regional or Europe-wide databases.
   The advantage is independence of small-scale local fluctuation and of temporal variability; the disadvantage consists in that this data represent spatial aggregates with possible low resolution, thus missing local phenomena.
6. ADR: The ADR is an easy to measure quantity, but harmonization is complicated. This was the experience of the AIRDOS project of the JRC, whose objective was understanding the methodically caused differences between ADR measurement data supplied to EURDEP by different networks, and their possible post-hoc harmonization. Even after about 15 years of effort, this target could not been fully achieved, because for many networks, the

necessary method-related parameters are not available. To some extent, this can also be expected for ADR surveys addressed in the questionnaire.

b) Radon in water

Details in chapter 6 of the European Atlas of Natural Radiation (EC, 2019).

c) Ambient dose rate

Harmonization of ADR measurements acquired with different real-time systems and protocols is a long standing task. It has been subject of the AIRDOS project performed by the JRC in the mid 2000s. Shortly, one distinguishes between bottom-up and top-down harmonization: in the former case, all participants use the same instruments and protocols, while in the second case, different procedures are harmonized a posteriori, applying models derived from physical knowledge of the differences. Obviously, bottom-up harmonization is unrealistic. The problem of top-down harmonization is that, although the physical principles and harmonization procedures are well known, the necessary parameters are not. This concerns for example internal BG or response to secondary cosmic radiation of monitors, and site geometry of the monitoring stations.

Since providing this information requires some effort, but is not considered relevant by many authorities that operate the systems for different objectives (radiological early warning), ADR harmonization will probably remain on the agenda unresolved.

3.2.4.11 Geogenic radon maps

Few countries have so far produced geogenic Rn maps with more than local coverage. It seems that the situation will not improve in near future. But even provided better European coverage, top-down harmonization remains a problem (cf. 3.2.8.4.a bullet 4).

The most promising alternatives, at current knowledge, seem to be bottom-up or synthetic maps (3.2.8.4.a bullet 5). The two options are:

- GRP from datasets as outlined, either as Neznal-type GRP (most popular) or as dimension-reduced quantity built from many predictors e.g. by PCA;
- A geogenic radon hazard index GRHI, which is a combination of relevant geogenic predictors and proxies, but tailored such as to serve as optimal predictor of indoor Rn concentration. See WP4, A.4.3.4)

3.2.4.12 Relevance for quality assurance

As far as can be concluded from the literature review and the questionnaires, the following are among issues relevant for QA:

a) Soil radon

Temporal variability is a sensitive topic for grab samples; this can be mitigated by sticking to sampling protocols which define sampling depth and weather and soil conditions, for which sampling is advised or discouraged.

b) Radon in water

Ensuring compliance with regulation implies generation of representative values which only allow meaningful comparison with reference level. This implies developing sampling protocols; as can be concluded from the questionnaire, protocols tailored for this purpose are already widely used.

3.2.4.13 Conclusions

Relatively much information is available on the status of geogenic Rn surveys in European countries, as well as about methodology.

On the other hand, not many countries have embarked into geogenic Rn surveys; therefore European coverage is poor. Again on the other hand, surveys and data sets about quantities are available in many countries, which can serve as predictors (U concentration) or proxies (ADR) of the GRP.

So far, the data have been exploited for generating European wide geogenic Rn map only in experimental trials. As expounded in WP4, section 4.3.4, current work seems more focused on developing a geogenic Rn hazard index (GRHI) which relies on Europe wide available data bases (such as for geology and geochemistry), rather than on assembling regional un-harmonized datasets. However, this discussion is ongoing.

Regarding methodical harmonization of geogenic quantities, a few issues have been identified, section 3.2.4.10. The problems can be solved, but in some cases require further experiments and partly development of procedures for harmonization.

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Annex:

ISO codes of European countries (https://en.wikipedia.org/wiki/List_of_ISO_3166_country_codes); black / blue: EU / non-EU countries; GB was EU Member State at the time of writing (mid. 2019)

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ISO code	country
AD	Andorra
AL	Albania
AM	Armenia
AT	Austria
AZ	Azerbaijan
BA	Bosnia and Herzegovina
BE	Belgium
BG	Bulgaria
BY	Belarus
CH	Switzerland
CY	Cyprus
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GB	United Kingdom
GE	Georgia
GR	Greece
HR	Croatia
HU	Hungary
IE	Ireland
IS	Iceland
IT	Italy
KZ	Kazakhstan
LI	Liechtenstein
LT	Lithuania
LU	Luxembourg

LV	Latvia
MC	Monaco
MD	Republic of Moldova
ME	Montenegro
MK	North Macedonia
MT	Malta
NE	Netherlands
NO	Norway
PL	Poland
PT	Portugal
RO	Romania
RS	Serbia
RU	Russian Federation
SE	Sweden
SI	Slovenia
SK	Slovakia
SM	San Marino
TK	Turkey
UA	Ukraine
VA	Vatican