Measurement of radon
Content of this block

- Purpose of measurement
- What to measure
- QA & QC
- Influencing quantities
- Measurement protocols
DISCLAIMER

Neither the presenter nor the IAEA endorses the use of any of the commercially available radon detectors presented here.

This presentation aims to give the widest overview of measurement techniques, protocols and devices etc.
In this presentation:
222Rn is referred as *radon*
220Rn is referred as *thoron*
Measurement protocol is understood as a set of requirements and procedures aiming to collect reliable data on activity concentration of radon gas or radon progenies.
Motivation for radon measurement

Components of annual effective doses of general public caused by natural radiation sources based on UNSCEAR, 2008

- Terrestrial radiation: 0.48 mSv/y
- Cosmic radiation: 0.39 mSv/y
- Radon inhalation (thoron and their progeny included): 1.26 mSv/y
- Food, etc. (ingestion): 0.29 mSv/y

Worldwide average Total: 2.4 mSv/y
Dose assessment

Dose assessment (procedure to obtain the effective dose received by individual)

- Complex problem, simplifications necessary
  Personal dosimeters?

- Continuous measurement of radon in all inhabited rooms +
  timesheet with presence of people?

- Year average of radon activity concentration in the most frequently used rooms (usually bedroom, living room or kitchen) – the most usual way
Legal framework

Requirements on protection of public against exposure to radon are predominantly expressed in a form of radon activity concentration, not as a effective dose.

Radon measurement is used to verify the quality of the environment where people live and work.

Need of clearly defined set of rules how should be the data collected and how to interpret them = measurement protocol.
Introduction - Purpose of measurement

- Device/detector and measurement protocol is chosen in accordance with the intended purpose of the measurement
  - Passive detectors + Long term measurement = Enough time to get average radon concentration for reasonable price
  - Radon diagnostics takes time and a lot of effort from experienced people, but can avoid expensive and never-ending sealing of cracks and holes in the waterproofing membrane
  - Measurement for real estate selling/buying process is usually short term in unoccupied dwelling = indicative measurement to find out if there is “a problem” or not

Key message 1: The purpose of the measurement should be clearly stated before the measurement is started.
Introduction - Purpose of measurement

• Duration of measurement
  • Grab sampling (spot sampling) –
    • one or repeated readings of immediate concentration at a place
  • Short-term measurement – days up to 1 month
    • Fast access to results
    • More sensitive to measurement conditions (e.g. ventilation rate), meteorological conditions (e.g. wind speed, indoor/outdoor temperature)
    • The recommended minimum duration of measurement of indoor radon concentration is 7 days to cover the basic behaviour pattern of inhabitants
  • Long-term measurement – 1 month up to 1 year
    • Long time to get desired values
    • Detectors are not under control (possible displacement, destruction, etc. → cheap detectors are preferred)
    • The longer the measurement is, the more is the average value representing the real situation
Variation of radon concentration within 1 year, seasonal variation, daily variation

Source: SURO v.v.i
Measurement protocols - content

• What to measure
  • The main source of health risk are radon progenies but radon gas is easier to be measured.

• Where to measure
  • Depends on the purpose of measurement. Usually, the purpose is to find out whether radon concentrations are above certain level in areas occupied by humans → habitable rooms
  • Simultaneous measurements in at least 2 rooms is recommended

• Duration of measurement
  • Radon concentration variation needs to be taken into account → at least 7 days, preferred 1 year

• Detector position
  • Any position that can be considered representative of the average radon concentration
  • Detectors should not be exposed to direct sunshine, draught; nor closed in a drawer or to other influencing factors as required by manufacturer
Measurement protocols – content

- Accompanying measurements
  - Any quantity influencing detector response should be measured (e.g. gamma dose rate for electrets)
  - Temperature, pressure, humidity are helpful in explaining the development of radon concentrations measured continuously.
  - Meteorological parameters are useful for radon diagnosis
- Period of measurement
  - Heating season is preferred for short term measurements even if it could lead to overestimation of the annual average
- QA/QC
  - To guarantee and adequate measurement quality
- Measurement results evaluation and Reporting
  - How are the measurement result handled
  - What are the minimum requirements on the content of the report
Measurement devices

<table>
<thead>
<tr>
<th>DETECTOR TYPE</th>
<th>PASSIVE / ACTIVE</th>
<th>TYPICAL SAMPLING PERIOD</th>
<th>COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activated Charcoal Detector</td>
<td>Passive</td>
<td>1 – 7 days</td>
<td>low</td>
</tr>
<tr>
<td>Alpha-track Detector</td>
<td>Passive</td>
<td>1 - 12 months</td>
<td>low</td>
</tr>
<tr>
<td>Electret Ion Chamber</td>
<td>Passive</td>
<td>2 days - 1 year</td>
<td>medium</td>
</tr>
<tr>
<td>Continuous Radon Monitor</td>
<td>Active</td>
<td>1 hour – 1 year</td>
<td>high</td>
</tr>
</tbody>
</table>

- The type of detector should be carefully selected since it influences the cost of measurement per dwelling and therefore the cost of a radon programme on a national level.
- Radon measurements in homes are easy to perform, but need to be based on standardized (e.g. national) protocols to ensure accurate and consistent measurements.

--- WHO, Handbook on Indoor Radon ---
Education, training courses

- Training courses for professionals are key instruments to develop and improve practices.
- They should be linked with development of regulation and communication to the public.
- Courses could be ended with examination which could be considered as an element for accreditation of actors. In this case, course organization should be approved by authorities: content, duration, examination level. Content is generally more consistent and duration is longer, with better attendance and efficiency.

Source: The RADPAR Recommendations
Education, training courses

• Based on experience in different countries, a good efficiency has been observed in courses associating practical examples and exercises (case studies) to theory.

• It seems not to be appropriated to have common course on specialized radon measurement and building protection, because professional competences are different. On the other hand, if a course deals only with radon measurement or building protection, it is needed to have an overview on the other topic because they are linked.

• For all courses, it is needed to present a basic knowledge on risk assessment and regulation.

Source: The RADPAR Recommendations
PURPOSE OF MEASUREMENT
Purpose of measurement - situations

- verification of radon concentration in newly built house
- measurement before renovation/modification of existing dwelling
- measurement after renovation/modification of existing dwelling
- verification after radon corrective action in existing dwelling
- dwelling rental process (to provide the dweller with information on radon level)
- purely individual interest of inhabitant/owner
- selling/buying process (to provide the buyer with information on radon level)
- other measurements required/recommended by regulation
- public measurement campaign/survey
- national radon survey

- measurement of radon in soil gas on building site
- measurement of radon in water
Groups

- Indoor air quality
  - assessment of residential exposure
  - quality of the building itself
- Assessment of a building site
  - Radon in soil
- Source location and quantification
  - Radon diagnosis
- Mapping
  - Combination of different types of measurement and statistical analysis
Indoor air quality

- Assessment of residential exposure
  - In what radon concentration do the people live?
  - Different user conditions may lead to different radon concentrations in a single building.

- Radon survey (national, local)
- Compliance with requirements of law on radiation protection (workplaces, building with high occupancy factor e.g. kindergartens)
- Decision to decrease the radon concentration indoors (dwellings)

- Long term measurement under standard conditions is recommended
- Short term if quick results are desired
Indoor air quality

Initial short term measurement

- $C_{Rn} < RL$
  - Consider follow-up measurement in future
- $RL < C_{Rn} < \text{limit}^*$
  - Perform a long term measurement
- $C_{Rn} > \text{limit}^*$
  - Perform radon diagnosis and corrective action

Consider corrective action

- $C_{Rn} > RL$
  - Consider corrective action
- $C_{Rn} < RL$
  - Consider follow-up measurement in future

RL = reference level  $C_{Rn}$ = radon activity concentration  * if defined
Indoor air quality

- Quality of a building
  - Was the protection against radon ingress designed properly? Was the building built in high quality?
  - Independent on user conditions = characteristic of a particular building (house). One user may have low radon concentration, the other very high.

- Short term measurements possible, radon diagnosis
- Closed conditions
- Measurement of air exchange rate (connection to user conditions)
MEASUREMENT TECHNIQUES
Measurement techniques - introduction

• Classification of detection
  • Most methods: alpha particles
  • Some methods: gamma emissions
  • Only a few: beta particles

• Objectives of Measurement
  • Radon
  • Radon progeny
    • Individual radon progeny concentration
    • Potential alpha energy concentration (Working Level)
    • Particle size
Classification of time resolution

- **Grab-sample (spot-sampling) technique**
  - The radioactive content of discrete samples of air taken over a short time at a single point is analyzed

- **Continuous technique**
  - Designed to provide information on the time dependence of concentrations

- **Integrating technique**
  - Provide a single concentration determination, generally averaged over a period of a few days to a year
This classification depends on whether energy is supplied during air sampling or not.

Active method
- An air pump is used for sampling
- Usually used for short-term measurements of radon and its progeny.
- Can provide time variation in concentration.

Passive method
- Samples are taken without a pump – diffusion or deposition.
- Suitable for assessment of radon exposures for a long time scale.
- Can provide only average radon concentrations over a long term.

In between are some of the active monitors using diffusion of radon to the detection chamber (then suitable only for radon gas measurement) and data are stored into the internal memory of the device.
How to select from detectors/monitors?

• Define what parameters are important for your measurement based on the purpose of measurement
  • Sensitivity of the detector (counts per unit radon activity)
  • Time resolution (minutes, hours, days)
  • Spectrometric capabilities of the detector
  • Stability of results under different conditions (radon/thoron interference, stability of signal in high relative humidity)
  • Operating ranges
  • Stability of background
  • Data storage and data processing, connectivity
  • Energy consumption, batteries
  • Size, weight, robustness of the case
  • Cost
Measurement procedure – general provisions

- Measurement location selections;
- Detector preparation and installation;
- Recording the location, date and time of the installation of the device in the worksheet;
- Exposure period - performing the sampling (passive or active) of an air sample representative of the atmosphere under investigation;
- Exposure termination and detectors collection;
- Recording the date and time of the removal of detectors;
- In-situ or laboratory analysis – detectors processing (e.g. SSNTD etching or other chemical treatment; EIC voltage reading; continuous radon monitors data retrieving)
- Raw data evaluation – scanning the detector under an optical microscope and counting the number of etched tracks; analysis of data from radon monitors
- The average radon activity concentration assessment by calculation; measurement uncertainty assessment;
- Final report
QUALITY ASSURANCE AND CONTROL
Introduction

QA (Quality Assurance)
• The set of planned and systematic actions put in place at specified stages of the radon measurement process to ensure confidence and accuracy of the measurement results.

QC (Quality Control)
• The quality checks carried out within the radon measurement laboratory as part of the overall quality assurance system.

Quality assurance and quality control measures are strongly recommended to assure the reliability of radon measurements.

--- WHO, Handbook on Indoor Radon ---
Quality assurance

• QA is a broad concept that includes all matters that individually or collectively influence the quality of measurement.

• The implementation of QA standards and guidelines to ensure confidence in the measurement results are strongly recommended.

• All entities (individuals, businesses, government agencies, etc.) providing measurement services should establish and maintain quality assurance programmes.
Quality assurance plan

• At the heart of a quality assurance programme is the QA plan, which includes:
  • Written standard operating procedures
  • Written procedures for attaining quality assurance objectives and a system for recording and monitoring the results of QC measurements.

• Minimum detectable concentration:
  • Any entity performing radon measurements should calculate and include the minimum detectable concentration (MDC) for its measurement system in its QA plan and report it with the radon measurement results.
Calibration of detector

- Individual for a device (active monitor) or for a batch (lot) of passive detectors.
- Exposure of detectors to the standard atmosphere under known conditions to obtain a calibration factor (factor converting the detector response to the true value).
- Detector is calibrated as received to the calibration laboratory, if any part of the detector which may influence the response to radon (measured entity), new lot of SSNTD foils, new readout microscope etc. is used, the calibration should be renewed.
- The detector should be used under conditions to which it was calibrated (extreme conditions of high humidity, high ratio of attached fraction etc. may increase the measurement uncertainty).
- The calibration should be repeated – based on the recommendation of manufacturer and requirements of licensing and certifying agencies – each year or semi-annually.
Calibration – example NIRS, SSNTD

Time variation of radon concentration, temperature and relative humidity in the radon chamber during an exposure test

Radon concentration was measured by a pulse-type ionization chamber (AlphaGUARD), which was calibrated by Physikalisch-Technische Bundesanstalt (PTB), Germany.
Calibration – example SURO, active monitors

Time variation of radon concentration in the radon chamber during an exposure test – active radon monitors. Radon concentration was measured by AlphaGUARD, which was calibrated by PTB, Germany.
Calibration of detector

• A statement or certificate of calibrations is then issued containing following information:
  • the condition of the monitor “as received” including any physical damage and settings of discriminator, voltage, background and calibration factor as necessary;
  • the measured background;
  • the measured response to the reference atmosphere;
  • the settings of the discriminator, voltage, background and calibration factor, “as calibrated”;
  • the date the calibration was performed, and
  • the name and signature of the person responsible for the calibration.

• The device is the labelled with sticker saying that this device has been calibrated, expiry date of the calibration and calibration factor
Background measurement

- **Active detectors**
  - Over the time, the atoms of $^{210}$Pb accumulates in the detector → the activity of alpha emitting $^{210}$Po is increasing and the background of the detector is increasing.
  - Repeated measurement of detector background every $\frac{1}{2}$ year or in shorter time periods if necessary.
  - The measurements of detector background should be recorded.

- **Passive detectors**
  - Laboratory background measurements
    - The inherent background of laboratory equipment which is used to analyse the detectors must be measured and subtracted from the response of detectors used in field.
    - Background measurements are also used in establishing of detection limit and MDC.
  - Field background measurement
    - “field blanks” – detectors which are handled in the same manner as those for field measurement but are not exposed to ambient atmosphere or are stored in low-radon atmosphere.
Intercomparison exercises

- Entities performing radon measurements should participate periodically in inter-laboratory comparison exercises.
- The usual way how the intercomparison measurement is organised is that the detectors are sent by the tested entity to the testing laboratory. Once the detectors are exposed, the testing laboratory return the detectors back for evaluation. Each tested entity reports its values to the testing laboratory which issues a report comparing the participants’ results with the true value(s).
- The testing laboratory should be traceable to the primary standard.
- Usually, the measurement is carried out at different radon levels, different relative humidity and aerosol spectra (size distribution, unattached fraction).
## Where are the intercomparisons organised?

### Examples of laboratories providing intercomparison measurements

<table>
<thead>
<tr>
<th>Laboratory</th>
<th>Cost</th>
<th>Detectors</th>
<th>Atmosphere</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIRS, Japan</td>
<td>free</td>
<td>Passive</td>
<td>Radon</td>
<td>Upon request</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Active</td>
<td>Thoron</td>
<td></td>
</tr>
<tr>
<td>Public Health England (former NRPB), UK</td>
<td>£280 per set of detectors</td>
<td>Passive</td>
<td>Radon</td>
<td>Each Autumn</td>
</tr>
<tr>
<td>Federal Office for Radiation Protection, Berlin, Germany</td>
<td>free</td>
<td>Passive</td>
<td>Radon</td>
<td>Every year (Feb – Apr)</td>
</tr>
<tr>
<td>PTB, Germany</td>
<td>EUR 650</td>
<td>Passive</td>
<td>Radon</td>
<td>Upon request</td>
</tr>
<tr>
<td>SURO, CZ</td>
<td>Upon request</td>
<td>Passive</td>
<td>Radon</td>
<td>Upon request</td>
</tr>
<tr>
<td>SUJCHBO, CZ</td>
<td>Upon request</td>
<td>Passive</td>
<td>Radon</td>
<td>Upon request</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Active</td>
<td>Thoron</td>
<td></td>
</tr>
</tbody>
</table>
International intercomparisons of integrating radon detectors in the NIRS radon chamber

Miroslaw Janik a,b, Shinji Tokonami a,*, Tibor Kovács c, Norbert Kávási a, Chutima Kranrod a,d, Atsuyuki Sorimachi a, Hiroyuki Takahashi a, Nobuyuki Miyahara a, Tetsuo Ishikawa a

a National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage-ku, Chiba 263-8555, Japan
b Institute of Nuclear Physics PAN, al. Radzikowskiego 152, 31-342 Krakow, Poland
c University of Pannonia, Egyetem u. 10, 8200 Veszprem, Hungary
d Chulalongkorn University, Department of Nuclear Technology, Bangkok, Thailand

ARTICLE INFO

Article history:
Received 29 May 2008
Received in revised form 4 March 2009
Accepted 4 March 2009

Keywords:
Radon
Intercomparison
Quality assurance
Radon chamber
Radon detectors

ABSTRACT

An international intercomparison of integrating detectors was conducted at NIRS (National Institute of Radiological Science, Japan) with a 24.4 m³ inner volume walk-in radon chamber that has systems to control radon concentration, temperature and humidity.

During the first intercomparison (05.2007) four groups participated from four countries and for the second intercomparison (10.2007) 17 participants were involved from 11 countries.

Most of detectors are in good agreement with each other when compared to the radon level provided by the radon chamber. It appeared that the 70% of detectors are unified within the 20% margin of uncertainty.

© 2009 Elsevier Ltd. All rights reserved.
International intercomparison experiments of passive 222Rn/220Rn detectors in NIRS chambers
70% of results were in a good agreement with the reference value of radon concentration in the radon chamber.

Fig. 5. Detector results with measurement uncertainty of radon exposure for all detectors during all experiments with percentage deviation of 20% from the reference value of the radon concentration.
Intercomparison exercises in field

- Detectors (active, passive) are usually used in field not under standard laboratory conditions.
- Intercomparison under field conditions are occasionally organized also. The problem is “the true value”.

IAEA
Quality control

- Duplicate measurements – two or more radon detectors at the same place and the relative percent difference among the set is monitored.
- Field blanks – set of detectors accompanying the exposed detectors to check whether the expected background level is in expected limits.
INFLUENCING QUANTITIES
Directly influencing quantities

- Thoron
  - Alpha track detectors (some)
  - Continuous radon monitors (some)
- Gama dose rate
  - Ionization chambers in current mode
  - Electret ion chambers
- Aerosol concentration, spectra
  - Influence on equilibrium factor $\rightarrow$ radon/thoron progenies measurement
- Humidity
  - High RH and low temperature $\rightarrow$ condensation of water
  - Drop in the collection efficiency
Thoron influence in detail

Spatial distribution of radon and thoron concentrations in a house with gypsum wall (under static condition)

- **Gypsum wall**
- **Radon detectors**

Radon concentrations:
- $^{226}\text{Ra}$: $163\pm5$ Bq/kg
- $^{232}\text{Th}$: $522\pm15$ Bq/kg
- $^{40}\text{K}$: $31\pm14$ Bq/kg

Thoron concentrations:
- Radon: constant
- Thoron: exponentially decreased

Source: S. Tokonami, Radiation Protection Dosimetry Vol 141/4, 2010
Overestimation of radon concentration

- Thoron signal interfere with radon signal which may lead to overestimation of radon concentration if they are placed near the wall (indoor thoron source).
- Observed Radon conc. = Actual Radon conc. + Relative Sensitivity(Thoron) x Thoron conc.
  - For example, when actual radon conc. and detected thoron conc. are 100 Bq/m$^3$, respectively, radon concentration observed by Radtrak (Tn sensitivity 0.68) is estimated to be 168 Bq/m$^3$.

→ Check with the manufacturer and/or laboratory the sensitivity of used detector to thoron.
## Relative sensitivities of passive radon detectors

<table>
<thead>
<tr>
<th>Measuring device</th>
<th>Relative sensitivity</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>RADUET (Low Diffusion)</td>
<td>1</td>
<td>0.02</td>
</tr>
<tr>
<td>RADUET (High Diffusion)</td>
<td>1</td>
<td>0.90</td>
</tr>
<tr>
<td>Ordinary RADOPOT (Low diffusion)</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>Modified RADOPOT (High diffusion)</td>
<td>1</td>
<td>0.59</td>
</tr>
<tr>
<td>KfK monitor&lt;sup&gt;a&lt;/sup&gt; (Germany)</td>
<td>1</td>
<td>0.78</td>
</tr>
<tr>
<td>Radtrak&lt;sup&gt;b&lt;/sup&gt; (USA)</td>
<td>1</td>
<td>0.68</td>
</tr>
<tr>
<td>NRPB/SSI (UK, Ireland, Sweden)</td>
<td>1</td>
<td>0.05</td>
</tr>
<tr>
<td>E-ERM (USA)</td>
<td>1</td>
<td>0.03</td>
</tr>
<tr>
<td>ISS monitor (Italy)</td>
<td>1</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>RamaRn (Czech Republic)</td>
<td>1</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Pill bottle monitor (Canada)</td>
<td>1</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Aerosol spectra

- Equilibrium factor F
  - extreme values may influence response of some detectors – bare SSNTD

- Effective dose calculation – unattached fraction
  - The ratio of unattached fraction is important due to the deposition pattern in respiratory tract and its high dose conversion factor

Absorbed dose in bronchial epithelial cells per unit exposure (EEC) to radon.
Source: Report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly, 2000, Annex B, Fig. XIV.
User conditions

- Ventilation and heating habits differ family to family (age, employed/retired) and are expected to be different based on the purpose of the building or room (office, storeroom, school/kindergarten, etc.)

![Graph showing radon concentration in kindergarten](source: SURO v.v.i)
Influence of user conditions on indoor radon

Radon concentration (Bq/m³)

Night, closed windows

Morning, opened windows

Back home, cooking, windows and doors partly opened and closed again

Weekend out of the house, closed windows

At work, closed windows

Arrival back home, windows and doors partly opened

Source: SURO v.v.i
Indirectly influencing quantities

- Construction of the house
  - Building material type
  - Type of substructure (transfer factor from soil to house)
- Soil parameters
  - Soil permeability
  - Water content
- Meteorological condition
  - Strong wind \( \rightarrow \) under-pressure zones in house
  - Heavy rains \( \rightarrow \) (soil permeability) \( \rightarrow \) groundwater horizon \( \rightarrow \) radon source cut off
  - Direct sun hitting one part of the house (windows with large area \( \rightarrow \) local increase of temperature indoors)
Description of measurement techniques for long-term measurement

INDOOR MEASUREMENT
Measurement protocols

- **What to measure**
  - The main source of health risk are radon progenies but radon gas is easier to be measured.

- **Where to measure**
  - Depends on the purpose of measurement. Usually, the purpose is to find out whether radon concentrations are above certain level in areas occupied by humans → habitable rooms.
  - Simultaneous measurements in at least 2 rooms is recommended.

- **Duration of measurement**
  - Radon concentration variation needs to be taken into account → at least 7 days, preferred 1 year.

- **Detector position**
  - Any position that can be considered representative of the average radon concentration.
  - Detectors should not be exposed to direct sunshine, draught; nor closed in a drawer.
Measurement protocols

• Accompanying measurements
  • Any quantity influencing detector response should be measured (e.g. gamma dose rate for electrets)
  • Temperature, pressure, humidity are helpful in explaining the development of radon concentrations measured continuously.
  • Meteorological parameters are useful for radon diagnosis

• Period of measurement
  • Heating season is preferred for short term measurements even if it could lead to overestimation of the annual average

• QA/QC
  • To guarantee and adequate measurement quality

• Measurement results evaluation and Reporting
  • How are the measurement result handled
  • What are the minimum requirements on the content of the report
Measurement protocols - conditions

- User conditions
  - no limitations applied
- Conservative approach
  - closed room conditions application to avoid false positive conclusions
- Residential behaviour control
  - methodology requirements on minimal buoyancy induced pressure difference to ensure the convective radon entry into buildings in case of short-term measurement performance
- Two/three steps methodology
  - short-term screening measurement followed by long-term measurement in case of mean indoor radon exceeding the pre-set level (reference level);
  - If the reference level is exceeded for long-term measurement → radon diagnosis
LONG TERM MEASUREMENT FOR RADON SURVEY
Population-weighted survey

- Aim of this survey:
  - to determine the radon exposure distribution of the population,
  - to estimate the average exposure and the percentage of dwellings exceeding reference levels.
- Measured homes have to be representative of the total building stock → random selection.
- Representativeness can be achieved by choosing homes at random from a complete list of the residential dwellings (e.g. houses and flats, list of inhabitants) in the country.
- It is important to obtain statistical advice - many biases can distort the results.
Radon survey in buildings with public access

• If the survey in dwellings is not possible for different reasons, the buildings with public access can be used for the 1st step of radon survey.

• Primary schools and kindergartens should be primarily selected rather than hospitals
  • Usually easy to access through municipality
  • Positive public perception of the measurement (protection of children)
  • Classrooms are occupied with predictable pattern BUT nights, weekends and holidays the building is unoccupied → the average radon concentration for the whole exposure period may be higher than during occupation

• Hospitals has very specific user conditions, ventilation rate is higher than in usual dwelling and cellar or storage rooms are not appropriate to describe the exposure of public.
Population-weighted survey – issues to be considered

- Random selection of households
- Sample size
- Monitored rooms
- Number of detectors per household
- Duration of measurement (seasonal variation and correction factors)
- Detector type
- Detector placement
- Contacting householder, detector deployment and collection
- Measurement protocol
- Questionnaire
- Quality assurance
- Data analysis
- National database
Sample

- Simple sample
  - Random sample from the list of all dwellings or inhabitants
  - Deviations from randomness are causing biases – measurement only for volunteers, high number of refusals
- Stratified sample – Multistage sampling
  - Target population is partitioned into separated groups (strata)
  - Distribution of sampled units is then under control in the group
- Sample size depends on
  - Bias and uncertainty that is acceptable (larger sample may somehow decrease the bias and uncertainty)
  - Population of the country
    → usually hundreds to several thousands of dwellings are measured
Dwellings and householders

It is equivalent to consider housing units or the householders as the target population of the survey (all inhabitants are exposed to about the same radon concentration). Choice depends on the availability of complete lists from which the sample units could be randomly selected (complete list of inhabitants often easier to have than of dwellings)
Randomness and completeness

Need a sample which is representative of the population exposure → select a random sample of dwellings (or inhabitants) from a complete list.

If not (e.g. sample of volunteers, large number of refusals to participate) then bias.

For practical reasons often surrogate of complete list used (e.g. list of telephone numbers) → need to check representativeness (e.g. compare certain parameters with last census).
Sample Size

If possible large sample size → reduces probability of bias due to non-representative sample and increases precision

Depends basically on country population (and available resources)

Usually several hundreds to several thousands of dwellings
Variation of radon concentration within 1 year, seasonal variation, daily variation
Duration of measurement

- Variation of radon concentration is high → the duration of measurement should be preferably 12 months; two consecutive 6-month measurement to cover the seasonal variation can be also used (depends on type of the detector, budget etc.). A 6-month which covers equal parts of both winter and summer season is often a good compromise.

- Short term measurements ~ 1(2) months are not recommended due to high probability of under or overestimation of the exposure BUT if necessary then it is recommended to carry out the measurement in the period of the heating season.
Seasonal variation and correction factors

- Represents collective variation of radon
- Seasonal correction factors should be derived nationally or even better on local level
- It is not recommended to use seasonal correction factors derived in other countries due to different occupancy pattern, way of building construction, contribution of different radon sources
- Can be used for short term measurements

Recent publications showed that:
- The variation of house-to-house behaviour and year-on-year variation in radon concentration is too wide from the norm and the application of seasonal correction factors to short term measurements may confuse the interpretation
- Applying seasonal correction factors to 3 months measurement can bring only relatively small improvements in the accuracy of estimates of annual mean
Monitored rooms - number of detectors per dwelling

- Measurement in inhabited rooms only (→ radon exposure of inhabitants), such as bedroom and living room (kitchen)
- The number of detectors per house/flat should be decided – the recommended number of detectors per dwelling is at least 2 (to reduce the impact of detector losses, measurement error, etc.)
- Decision should be taken on:
  - The measurement in single and multi-storey flats → The distribution of detectors across the storeys should be clear before the survey begins – if the aim of the survey is to estimate the population exposure, at least one room per floor level should be monitored, basement can be used but not for estimation of population exposure (higher values can be expected and not representing the real exposure scenario)
Detector type

- **Alpha track detectors** (LR115tII, CR-39) in a diffusion chamber
  - Cheap, gamma insensitive, easy to operate, human curiosity resistant
  - Sensitivity to thoron should be known (ask the supplier for this information)
  - Available on the market for long time

- **Electret detectors**
  - Moderate cost, also available for long-term measurement
  - Sensitive to gamma radiation → the requirement of additional measurement

- **Active monitor** could also be used, but they are preferred to be used for detailed measurements and when the knowledge of development of radon concentration in time is required, devices are rather expensive

- **Activated charcoal detectors** are NOT suitable for the purpose of long term measurement = NOT suitable for radon survey

- **Grab sampling** (spot measurement) is NOT suitable for radon survey

- Each of the detector should have unique code for identification; this code should be clearly visible → measurement protocol
Detector placement

- Radon gas is usually quite homogenously distributed in a room (the exception is single very strong source of radon).
- The detector has to be placed in an inhabited room (typically bedroom or living room).
- Due to the duration of radon measurement (months) it is recommended to use the most convenient places – top of the wardrobe, bookcase – but the detector should remain sufficiently exposed to the ambient air.
- The clear information on the positioning of detector(s) in the room should be provided to the house owner or to the person who is deploying the detectors.
- The positioning should be meet the requirements of detector supplier (e.g. distance from wall, source of heat etc.)
Deployment and collection of detectors

Contact and Deployment

- Basic information on radon survey should be provided to the householder and in media if possible
- Detector may be sent by post directly to the house owner or the third party can be used to deploy detectors (e.g., fire brigade, police, civil servants, interviewers)
- In any case, provision of written clear instructions with sketch or photo of required positioning in the room together with the measurement protocol and questionnaire is very important.
- Each of the measurement kit (assuming one kit per dwelling) should include a measurement protocol collecting at least basic information about the address, contact details of the house owner, position of each of the detectors in the house (detector code, room, floor).

Collection

- The way of collection may to some extent influence the return rate of the detectors
- Pre-paid envelope for house owner or House owner pays for the detector return
- Third party is used to collect the deployed detectors
The aim of the questionnaire is to collect additional information about the building (house – age, prevailing building material), its inhabitants (e.g. ventilation habits), water source (if it is expected that water can be with higher content of uranium/radium/radon)

- Questions related to radon awareness could be included as well
- The questionnaire shall be kept short (one page)
- Questions shall be short and very clear
- Multiple choice questions are preferable
- The questionnaires should be repeatedly tested and improved before using in a survey and the testing should include members of different social groups
- It is recommended to prepare the questionnaire OCR-readable
Easy to fill and read out form 1st page is collecting information on:

- Name and family name of the inhabitant (user),
- Full address of the building where the measurement is carried out and contact telephone,
- Source of water (well water or public water supplier),
- Type of building (family house, school, kindergarten etc.)
- Number of habitable rooms in the house by floor levels
2nd page is collecting information on:

- the type of the room (kitchen, bedroom, ...),
- name of the room, floor in which is the room located,
- prevailing ventilation habit (high, low, medium), tightness of windows, prevailing building material (stone, bricks, ...), year of construction of the building,
- number of detector, date of beginning of exposure
**Measurement protocol**
Includes data like start and end of measurement, type of measured room (bedroom, living room, etc.), floor level, detector-ID

**Questionnaire**
For building characteristics, building material etc.

![Image of questionnaire form]

<table>
<thead>
<tr>
<th>Bezeichnung des Raumes</th>
<th>Stockwerk</th>
<th>Ist der Raum erdberührt?</th>
<th>Serien-Nummer der Radionuklitoren</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCHLAFZIMMER</td>
<td>KINDERZIMMER</td>
<td>Kellergeschoß</td>
<td>Ja</td>
</tr>
<tr>
<td>WOHNZIMMER</td>
<td>(WOHN-)KÜCHE</td>
<td>Erdgeschoß</td>
<td>NFIN</td>
</tr>
<tr>
<td>ESSZIMMER</td>
<td></td>
<td>1. Stock</td>
<td></td>
</tr>
</tbody>
</table>

*RAUM 1*

<table>
<thead>
<tr>
<th>Bezeichnung des Raumes</th>
<th>Stockwerk</th>
<th>Ist der Raum erdberührt?</th>
<th>Serien-Nummer der Radionuklitoren</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCHLAFZIMMER</td>
<td>KINDERZIMMER</td>
<td>Kellergeschoß</td>
<td>Ja</td>
</tr>
<tr>
<td>WOHNZIMMER</td>
<td>(WOHN-)KÜCHE</td>
<td>Erdgeschoß</td>
<td></td>
</tr>
<tr>
<td>ESSZIMMER</td>
<td></td>
<td>1. Stock</td>
<td></td>
</tr>
</tbody>
</table>

*RAUM 2*

*Bezeichnung des Raumes:* Kindergarten

*Stockwerk:* Kellergeschoß

*Ist der Raum erdberührt?* Ja

*Serien-Nummer der Radionuklitoren:* NFIN

*Eikette vom Aluminumbeutel hier einkleben*

**Bemerkungen:**
Quality assurance

- Quality assurance and quality control measures are strongly recommended to assure the reliability of radon measurements.
- The responsibility for QA/QC falls on the provider of the detectors. The operational guideline/standard operation procedure issued by provider must be followed.
- It is recommended to use one type of detector, one laboratory or provider of detectors for the entire survey
  - Different systems and different measurement protocols may cause problems with standardization of results
Data processing

• Check the representativeness
  • due to refuses to participate in measurement and detectors losses it is necessary to check the representativeness of final set of results.

• Log-normality test
  • the frequency distribution of radon concentration tends to have a log-normal shape
  • the log-normality (normality of the logarithms) should be tested before further analysis by chi-square or Kolmogorov test

• Sampling scheme
  • simple sampling → no weighting for results from particular dwellings
  • complex sampling schemes (stratified sampling) – the parameters have to be calculated separately for each stratum and then be combined in a proper way.
Data processing

- Parameters of the survey
  - If the frequency distribution of radon concentrations has or tends to have log-normal shape, then the distribution can be described by geometric mean (GM) and geometric standard deviation (GSD).
  - Based on the knowledge of GM and GSD it is possible to estimate the number of dwellings above any reference level (action level or limit).
National database

- To store results from radon measurements on national level
- Radon database is an important tool for National radon action plan (planning, evaluation)
- Questions to solve:
  - Who will enter the results in to the database – everyone incl. private companies? national laboratories only? – obligation should be introduced in relevant regulation.
  - Who will have access to the database – national authority only? municipalities?
  - Consider carefully what information should be stored in the database – only results of radon measurements? To get a real benefit of the radon database information from the questionnaire on building characteristics etc., information on corrective actions (type, cost, radon concentration before/after), information on preventive measures (type, cost, radon concentration should be also collected for further analysis.
  - Consider confidentiality of (some) data?
Who should get the results?

• How to present the results to the homeowner – official protocol with results
• Ownership of the results and confidentiality
• Be prepared on how to deal with dwellings with high (elevated) radon concentrations → civil engineers should be involved in radon issue from early beginning!
SHORT TERM MEASUREMENT - EXAMPLES
Data collection - What needs to be recorded in and about the house?

- Information related to measurements carried out inside a building that needs to be recorded in a measurement protocol/report:
  - building characteristics and building site description (full address, contact person);
  - sampling location identification (basement, ground floor, upper floor) + simple floor plan sketch;
  - individual sampling points – detectors installation;
  - exposure time;
  - results of previous measurement;
  - radon prevention measures or corrective actions description if any installed and how they are operated;

- Measurement conditions:
  - occupants’ lifestyle (regular ventilation, heating operation etc.);
  - ventilation characteristics;
  - outdoor and indoor climatic conditions during exposure;
  - influencing factors identification and evaluation (e.g. gamma dose rate).

IAEA
# Indoor radon measurement worksheet and report

## Worksheet – building characteristics (site description)

<table>
<thead>
<tr>
<th>Type of building</th>
<th>Address</th>
<th>Cadastral (land-registered) area</th>
<th>Building site number</th>
</tr>
</thead>
<tbody>
<tr>
<td>(family house, apartment block, school, kindergarten ...)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Owner** (contact person – name, contact details (tel./ e-mail))

### Building characteristics and site description

- New built house / existing building year of construction
- Number of floors Underground floors Above ground floors
- Building site information/terrain features Building layout
- **Cellar extent** (full scale, partial)
- Floors in a contact with soil; connection to upper floors (open stairs, separate entrance etc...)

**Type of building materials**

**Water supply** (public water pipeline, drilled well)

### Facts important from radiation protection point of view (radon preventive or remediation measures)

- HVAC system description (type, operational mode)
- Description of passive and active elements of radon protective measures (radon-proof membrane installation, active/passive soil depressurization systems operation etc...)

## Measurement

### Results of previous investigation (e.g. radon potential of building site)

- *Type of measurement according to the indoor radon measurement methodology*
- Building
- **Occupied/unoccupied**
- **Type of exposure**
- **Exposure time**
  - User defined/ controlled/ reference
  - Start of measurement
  - End of measurement

### Detection equipment

| Measuring device serial number | Calibration certificate number |

## Measurement conditions

### Weather conditions

*Indoor and outdoor temperature, air humidity, atmospheric pressure fluctuations, extreme climatic effects occurrence, wind speed, precipitation*

### Residential habits

*(number of occupants, staying time, ventilation regime)*

## Additional observation and comments

Measure to be undertaken to control the ventilation régime and residents behavior

## Operator identification

<table>
<thead>
<tr>
<th>Name</th>
<th>Signature</th>
</tr>
</thead>
</table>
Indoor radon measurement worksheet

- Electret detectors (CR is using pair of electrets as a certified radon monitoring device)
- Obligatory gamma dose rate measurement at the measurement position – compensation of drop of voltage.

Worksheet
Indoor radon concentration measurement (electret ion chamber system RM1)

<table>
<thead>
<tr>
<th>Sheet number/</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

Date/time:
Building identification:

Start of measurement:  End of measurement:  Exposure time (hours):

<table>
<thead>
<tr>
<th>Measurement location</th>
<th>Floors</th>
<th>Electret No.</th>
<th>$U_p$ [V]</th>
<th>$U_k$ [V]</th>
<th>$D$ [µGy.h$^{-1}$]</th>
<th>$C_v$ [Bq.m$^{-3}$]</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Electret reader:  serial number
Etalon voltage check reading:
Type of ionization chamber:
Operator:
Signature:
Indoor radon measurement protocol - ISO

New drafts:

ISO 11665-10: Determination of diffusion coefficient in waterproof materials using activity concentration measurement

ISO 11665-11: Test method for soil gas with sampling at depth

### Table 2 — Characteristics of the measurement methods described in ISO 11665

<table>
<thead>
<tr>
<th>Measurement method</th>
<th>Sampling</th>
<th>Detection</th>
<th>SSNTD</th>
<th>Electret</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Characteristic</td>
<td>Type</td>
<td>Ionization chamber</td>
<td>Alpha spectroscopy</td>
</tr>
<tr>
<td>Spot</td>
<td>Grab</td>
<td></td>
<td>ISO 11665-6</td>
<td>ISO 11665-3&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td>Continuous</td>
<td>Active</td>
<td>Continuous</td>
<td>ISO 11665-5</td>
<td>ISO 11665-5</td>
</tr>
<tr>
<td>Integrated short-term</td>
<td>Continuous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated long-term</td>
<td>Continuous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous</td>
<td>Passive</td>
<td>Continuous</td>
<td>ISO 11665-5</td>
<td>ISO 11665-5</td>
</tr>
<tr>
<td>Integrated short-term</td>
<td>Continuous</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Integrated long-term</td>
<td>Continuous</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<sup>a</sup> Measurement method: radon decay products.
<sup>b</sup> Measurement method: exhalation rate.

Source: ISO 11665-1
### Indoor radon measurement protocol

**Annex C, ISO 11665-1**

**Example of test report**

<table>
<thead>
<tr>
<th>Identification</th>
<th>Reference to the relevant part of ISO 11665</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purpose of measurement</td>
<td></td>
</tr>
<tr>
<td>Measurement method</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sampling</th>
<th>Identification of the sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling characteristics</td>
<td>Passive – active</td>
</tr>
<tr>
<td>Date and time</td>
<td>day/month/year hour:minute</td>
</tr>
<tr>
<td>start</td>
<td></td>
</tr>
<tr>
<td>end</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sampling duration</th>
<th>day/month/year hour:minute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location – place</td>
<td>country/administrative region</td>
</tr>
<tr>
<td></td>
<td>commune/named locality</td>
</tr>
<tr>
<td></td>
<td>postcode</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Indoor location</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Building characteristics</td>
<td></td>
</tr>
<tr>
<td>basement</td>
<td>yes – no (If yes, type of ground)</td>
</tr>
<tr>
<td>crawl space</td>
<td>yes – no</td>
</tr>
<tr>
<td>construction on earthen platform</td>
<td>yes – no</td>
</tr>
<tr>
<td>construction date</td>
<td>pre-1945 – post-1945 – etc.</td>
</tr>
<tr>
<td>building material</td>
<td>breeze blocks – rubble stones – bricks – etc.</td>
</tr>
<tr>
<td>ventilation</td>
<td>natural – mechanical</td>
</tr>
<tr>
<td>types of finish coat</td>
<td>floors: tiles – parquet – etc.</td>
</tr>
<tr>
<td></td>
<td>walls: plaster – paint – wallpaper – etc.</td>
</tr>
<tr>
<td>type of heating</td>
<td>ceilings: plaster – paint – wallpaper – etc.</td>
</tr>
<tr>
<td></td>
<td>geothermal – heat-exchanger – etc.</td>
</tr>
</tbody>
</table>

| Outdoor location |  |
| Ground characteristics |  |
| ground type | plant formation – etc. |

| TEST RESULTS |  |
| Measurement duration |  |
| Parameter measured | Activity concentration or PAEC |
| Result ± uncertainty (units) |  |

| COMPLEMENTARY INFORMATION |  |
| Decision threshold |  |
| Detection limit |  |
Description of measurement techniques for

SOIL MEASUREMENT
Radon concentration in soil gas

- **Grab sampling**
- Continuous measurement
- Integral measurement
- Crucial part of the measurement is sampling
  - Important to avoid leakages around the probe
  - Do not sample high volumes in short time – the capacity of the soil gas is not unlimited
  - Sampling depth – enough deep to avoid disturbances due to dilution of soil gas by atmospheric air
- Measurement of soil permeability
  - To accompany radon concentration in soil gas to create more realistic picture
- Sufficient number of sampling points to cover the surface area of interest (sampling grid 10x10 m for large areas, single family house 15 sampling points)
Measurement protocol - CR example

1. Sampling probe is hammered down in to sampling depth - 80 cm

2. Sampling probe is hammered down in to sampling depth - 80 cm

3. The tip is pushed out using long punch wire to form sampling volume

4. Soil gas with radon is sampled with syringe

5. Soil gas is transferred in to measuring chamber

Radon is present in soil gas

Source of photos: Radon v.o.s.
Example: Procedure for radon measurements (standard)

Grab sampling method:
1. The ionization chamber is dried and cleaned from radon progeny (e.g. wipe with ethanol).
2. The background of the chamber is measured as the ionization current of empty chamber.
3. The air sample is transferred to the chamber:
   • Using the air pump to ensure that the entire volume of the chamber is replaced by the sampled air
   • The pump is used to decrease the pressure in the chamber and the air sample taken of known volume in transferred to the chamber by under pressure.
4. After the chamber is sealed the chamber should be allowed to reach radioactive equilibrium between radon and its progeny (approx. 3.5 h)
5. Measure the ionization current, apply calibration factor to get the radon concentration.
6. The chamber should be cleaned up with radon-free gas to avoid further contamination of inner surface.
Description of measurement techniques for

RADON IN WATER
Measurement techniques used for radon in water

- Liquid scintillation counters
  - Mixing water sample with scintillation cocktail
  - For high radon concentrations
- Gamma spectrometry
  - Direct measurement of water sample using HPGe via radon progenies
  - Measurement after sampling – radon activity concentration
  - Measurement of sealed water sample at least after 30 day from sampling – indirect assessment of 226Ra content via radon progenies while radon is in secular equilibrium with radium
- Gas extraction
  - Water is bubbled to release radon which is then captured and measured using a radon gas detector (Si diode, Lucas cell, ion chambers …)
  - Air (gas) which is bubbled through water must have low intrinsic radon activity
Description of measurement techniques for RADON DIAGNOSIS
Radon diagnosis

- Can be used for:
  - indoor radon sources identification and quantification;
  - radon entry pathways analysis;
  - short-term measurement results validation
- Qualitative and quantitative analysis of radon entry pathways - blower door method and air exchange rate assessment using tracer gas application as the interrelation of radon entry rate and air exchange rate has been identified as a key area of interest for further investigation
- Methods independent on human activities and weather conditions
  - radon entry rate and air-exchange rate assessment
  - sophisticated experimental methods
  - high cost; short-term investigation; high qualified experts needed
Radon diagnosis – standard operational procedures

- **Radon sources** identification and quantification (subsoil, building materials, water supply etc.)
- Radon potential quantification of a building site (radon concentration and soil permeability measurement)
- Qualitative and quantitative analysis of radon entry pathways (simultaneous *continuous indoor and soil gas radon measurement*, *blower door test*, *infrared imagery* etc.)
- **Independent air exchange rate** assessment (air infiltration, exfiltration evaluation, weather conditions monitoring) – tracer gas method
- Air sampling from selected locations suspected as potential radon sources (leakages, concrete slab cracks, joints, technological penetrations within the building structure elements etc.)
- Analysis of indoor radon transport and distribution for the different parts of the building
- **Visual inspection** of buildings with regard to relevant physical properties of individual elements of building structures (fabric and components air tightness classification, individual locations selection for subsequent detailed radon entry analysis)
Radon diagnosis specific operating procedures

- **Radon dominant source oriented procedures**
  - building material as a main source of indoor radon – gamma dose rate mapping; in-situ gamma spectrometry or building materials samples laboratory analysis
  - different radon entry rate behavior (relatively stable radon exhalation rate from building materials; no significant pressure field effect regarding the radon supply)
  - constant radon entry rate approximation can be assumed

- **Mechanically ventilated buildings** – forced type of ventilation (specific modes of HVAC systems operation)
  - passive and low energy consumption houses
  - well defined and controlled pressure field conditions (over pressurizing, under pressurizing, balanced (equal pressure) systems
  - homogeneous pressure field within the single pressure zone building

- **Naturally ventilated buildings**
  - types of ventilation – main driven forces
  - design characteristics – low-energy requirements; building details (macro vs. micro scale)
  - the building site parameters; shielding effects – terrain features; structures in the vicinity of the building
  - details of a window type
Naturally ventilated buildings – radon entry dynamics

- Natural ventilation driving forces (infiltration and exfiltration)
  - stack effect (buoyancy driven ventilation)
    airflow caused by pressure difference due to air density differences – magnitude of the airflow is determined by the pressure difference and building opening characteristics
    - building layout – pressure zones distribution – different radon entry rate pattern
    - neutral pressure level position – internal and external pressures balanced
    interior heat sources distribution – role of floor heating systems; local and central heating systems; solar radiation effects; glazing
  - wind driven ventilation
    - two important factors - wind speed and wind direction
    - the pressure difference dramatically varies with building geometry and location of the building (highly protected vs. highly exposed buildings)
  - combined buoyancy-wind driven ventilation
    - very complex evaluation – not many simplified methods available

- Thermal mass effect and thermal performance
  - building characteristics describing the storing of heating or cooling energy
  - thermal conductivity and capacity influencing airflow patterns across the building envelope and within the building itself – impact on ventilation performance and radon entry rate dynamics (peak shifting)
Simultaneous continuous measurement of radon concentration in the different parts of a single family house (the indoor radon dynamics study)

Source: SURO v.v.i
Continuous measurement of radon concentration

In the cellar as a result of the different ventilation operation modes (the indoor radon dynamics study)

Source: SURO v.v.i
Blower door test (qualitative and quantitative methods of radon diagnosis)

Source: SURO v.v.i
Infrared images of a selected leakage for different blower door operating modes

Natural state

\( dp = 17 \text{Pa} \)

\( dp = 30 \text{Pa} \)

\( dp = 50 \text{Pa} \)

Source: SURO v.v.i
Radon diagnosis photo documentation and sketch of revealed transport path

Source: SURO v.v.i
Thank you for your attention