RadoNorm
Managing risks from radon and NORM

Deliverable 5.2

Measurement protocol of air-exchange rate determination using tracer gas measuring technique

Work Package 5

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Executive Summary

Air exchange rate in a building is defined as a total volumetric airflow passing through the investigated volume of the building to outdoor air per unit of time. That is why it plays a crucial role in the behaviour of all gaseous mixtures and aerosol particles in indoor environment and mediates their transfer from the outside of buildings to their interiors and vice versa. Therefore, the air exchange rate is thus directly responsible for both thermal comfort and indoor air quality including behaviour of radon gas levels in measured homes and workplaces. A suitably performed simultaneous continuous or a passive integral measurement of volume radon activity and the air exchange rate in a measured building makes it possible to determine the temporal variability of a total radon entry rate into the internal volume of an investigated building or it's average value over the measured period. The knowledge simultaneously measuring both the total radon entry rate and the air exchange rate in an investigated building or workplace can then significantly help to decide on the effectiveness of the radon protection measure implemented or on the non-exceedance of the recommended reference radon level of 300 Bq/m^3.

The presented report provides standardised methodological guidance for use of a passive integral tracer gas technique for determining average air exchange in a building or a workplace based on many years of experience with the use of the method in SURO and obtained during this project, as well. The approach used involves the use of multiple tracer gases and thus allows not only the determination of average air exfiltration from individual zones of multi-storey buildings, but also the determination of average airflows between individual zones (floors).

The methodological procedure proposed is suitably supplemented by examples and procedures used in the SURO. An integral part of the validation and verification of the presented methodology were the results of a successful international comparison of the determination of average air exchange from 10 Czech buildings. The inter-comparison took place in March of 2025 and included results from both apartments and multi-storey family houses. The call for comparison was published on the official website of the RadoNorm project. Probably due to a uniqueness of direct and continuous measurement of the quantity air exchange rate in buildings on a larger scale, only a Swedish company PentIAQ applied to participate. Statistical evaluation of the comparison results showed that the mean difference between the SURO and PentIAQ results was not statistically significant for a significance level of α = 0.05 (95% confidence level). On average, the SURO measurement results were overestimated compared to the average PentIAQ measurement by approximately 6%.

The undeniable advantage of using this approach with passive integral tracer gas detectors is that they can be used on a large scale at a relatively affordable cost. The use of this technique is then also directly offered for validation and verification of numerical models of the air exchange rate calculation widely used especially in construction practice.

Dynamic range of measurement of indoor average air exchange rate using this methodology is ranging from 0.05 to 1.5 in units of (1/h) for the SURO equipment used. The overall uncertainties in the measurement of the average air exchange rate during a typical 1 - 4-week exposure in buildings are better than approximately 15% for an expansion factor of k=1.

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1. Introduction

1.1 Background

Air exchange rate in a building is defined as a total volumetric airflow passing through the investigated volume of the building to outdoor air per unit of time. That is why it plays a crucial role in the behaviour of all gaseous mixtures and aerosol particles in indoor environment and also mediates their transfer from the outside of buildings to their interiors and vice versa. Therefore, the air exchange rate is thus directly responsible for both thermal comfort and indoor air quality including behaviour of radon levels in measured homes and workplaces. A suitably performed simultaneous continuous or a passive integral measurement of volume radon activity and the air exchange rate in a measured building makes it possible to determine the temporal variability of a total radon entry rate into the internal volume of investigated building or it's an average value over the measured period [1].The knowledge of the total radon entry rate can then significantly help to decide on the effectiveness of the radon protection measure implemented or on the non-exceedance of the recommended reference radon level of 300 Bq/m^3 [2,3]. For this reason, SURO Prague has devoted a great deal of effort in recent years to the development and testing of an air change measurement system based on the use of tracer gases. The main goal was to develop a measuring system that would make its measurement relatively affordable and practically usable in apartments and workplaces on a wide scale. The result was a fully functional measurement system for the integral measurement of the average air exchange rate, which allows its measurement even in multi-storey buildings, divided into several measurement zones, over a period of several weeks. The developed measurement system thus allows to measure estimates not only of the so-called exfiltration air flows from the individual zones of the measured building to the outside environment, but also of average air flows between the individual zones of the measured building.

1.2 Current state in measurement of air exchange rate in buildings

Currently, following three approaches how the natural airflows can be estimated [4] exist:

-by means of modelling

-directly with use of anemometers or pressure transmitters

-indirectly with use tracer gas methods

Three modelling methods are used to model natural airflows: empirical and analytical models, and network models. Computational Fluid Dynamics (CFD) models: Empirical and analytical models assume homogeneity of all parameters inside the whole investigated building; required airflows are computed based on the knowledge of the indoor-outdoor temperature difference and pressure differences caused by wind. Network models (COMIS, CONTAM, MATHYS) are based on the resolution of Bernoulli equations. Zones are defined inside investigated building with homogenous parameters. Flow transfers between zones rely on pressure. The CFD models are the most used being based on Navier-Stokes equations resolution. Low natural airflow pressures prevent direct measurement of air velocity with instruments used to characterise mechanical airflow. Under natural conditions, the airflow meter could interfere with the unstable flow pattern that would result in a non-reliable measurement. Non-uniform air velocity fields along the window cross-section cause problems when using thermal anemometers or pressure transmitters. The above technical difficulties associated with the direct measurement of natural ventilation and the need to verify the models by measurement can be resolved by using methods based on appropriate injection and measurement of tracer gases used inside the building under investigation.

2. Scope

This measurement protocol provides a general guidance for determination of average air change rate in buildings consisting of N-measured zones using continuous tracer gas constant – stationary concentration method [4]. The general approach for the determination of the air exchange rate is illustrated by the SURO's specific technical equipment and its experience with selected tracer gases for buildings treated as a single zone (N=1) and three zones (N=3), respectively.

3. Terms and definitions

For the purposes of this report, the following terms and definitions based on International Standard ISO: EN – 12569/ 2013 [5] and the following apply:

3.1 Ventilation rate

- is total volume of air passing through the zone to the outdoor environment per unit of time, in (m^3/s) or (m^3/h).

3.2 Air exchange rate

- is total volume of air passing through the zone to the outdoor environment per unit of time, relative to the total volume of the measured zone, in (1/s) or (1/h).

3.3 Air exchange for N measured zones

- is total volume of air passing through the N measured zones to the outdoor environment per unit time, relative to the total volume of N measured zones, in (1/s) or (1/h).

3.4 Measured zone

- a space or multiple spaces where measured concentration of a tracer gas can be uniformly maintained. The measured zone in apartments or multi-storey family houses or buildings is usually each occupied room or each floor of a multi-storey house.

3.5 N measured zones

- represents N spaces where the concentration of each tracer gas used can be uniformly maintained.

3.6 Building

- for the purposes of this methodology, a building means: technically and structurally residential houses, houses, apartments, multi-storey family houses, work halls, public buildings, which include, but are not limited to, nurseries, schools, which are used generally for any kind of residence of persons most often for living, and working.

3.7 Family house

- for the purposes of this methodology it has a maximum of three separate apartments, a maximum of two above-ground and one underground floor and an attic. Single-family dwellings also include vacation cottages with a description number not excluded from the housing stock, used for recreation. A single-family house may be detached, semi-detached (sharing a portion of a perimeter wall with a single-family house on an adjacent lot), or terraced (at least three single-family houses abutting each other with a portion of a perimeter wall).

3.8 Apartment

- single-storey apartments with more than one living room represent for the purposes of this methodology single measurement zone (N=1).

3.9 Tracer gas

- is a gas that is highly miscible with air, has minimal adsorption and absorption properties to objects in buildings, has negligible background in the outdoor air of buildings, is acceptable in terms of health hazards, and is used to measure the air exchange rate. Measured volume (mass) concentration of a tracer gas is closely related to temperature and so the measured rooms should be well mixed.

3.10 Constant concentration method

- is the method by which the tracer gas concentration resulting from the continuous generation or injection of tracer gas into the measured zone(s) is obtained from the ventilation or air exchange rate.

4. Methodological procedure

To determine the average air exchange rate during the measurement period in buildings, this methodology uses a passive integral detection system based on the detection of suitably applied tracer gases injected into the measured zone or N-measured zones of a building with defined constant tracer gas entry rate. In the case of a building with one measured zone, a one type of tracer gas is used. In the case of a building with multiple measured zones, a different tracer gas is used in each measured zone. The difference between the known mass balance of the total tracer gas supply to the measured zone and its measured average mass concentration is then used to determine its removal, which is directly proportional to the average and time-weighted air exchange rate. An average mass concentration of the relevant tracer gas is determined from its mass trapped in the sorbent inside the detectors used and from the known sampling rate of detectors for the relevant tracer gas. The total mass of tracer gas trapped in the sorbent is determined by gas chromatography with an electron capture detector (ECD). Sampling of the detection system is by diffusion only. Due to requirement to achieve steady state tracer gas concentrations and a uniform field of tracer gas and air in each measurement zone, a measurement period of typically 1 to 4 weeks is selected. Mathematical description of the problem for N measured zones considered here and their solution for a typical number of measured zones N=1 and N=3 is then given in Appendix 1.

5. Measurement instruments

For purposes of this methodology, the necessary equipment includes, in particular:

- emission source for constant and defined injection (emission) of a tracer gas into the measurement zones,
- passive diffuse air samplers (detectors) for integral measurement of the mass concentration of tracer gases used in the measurement zones,
- analyser for selective determination of the mass of individual tracer gases in their mixture from the detector used,
- accurate scales for determination of the mass of tracer gas injected into the measurement zones,
- other ancillary equipment and facilities.

5.1 Tracer gas emission sources

This should be a suitable gas-tight capillary (e.g. glass or metal) containing the relevant liquid phase of the tracer gas, fitted with a diffusion membrane which controls the defined and constant evaporation of a tracer gas used from its liquid phase into the measured zone. The appropriate design of the total volume of the capillary and the diffusion membrane should ensure the necessary parameters of the emission, which is fundamentally influenced only by the ambient temperature. The sources used at the SURO are either all-glass or all-metal. They have their own identification numbers. For transport, distribution and use, suitable holders and transport packaging are used to prevent contamination of the integral detectors used during transport and to prevent them from breaking. In addition, SARTORIUS precision laboratory scales and TESTO type 174 H digital thermometers are used to check the stability of the diffusion evaporator and to select them for measurement.

5.1.1 Requirements for emission sources

1.1 The criterion for selecting of emission sources is the overall uncertainty in their mass emission rate denoted ***m*** in (mg/h) for a tracer gas used and a typically measured ambient temperature in the range (15 – 35) ^{o}C, which should not exceed 5%.

1.2 Before and after field use of the sources, and always for at least 10 days, all sources used shall be checked to ensure that their emission rate does not deviate from their nominal value as determined by the laboratory based on previous long-term measurements for the relevant ambient temperature range and a measurement period of at least 20 days.

1.3 The laboratory shall keep records of the emission rates of each source.

5.2 Air samplers

In principle, glass or all-metal tubes filled with a suitable, sorbent should be used for diffusion sampling of air with the appropriate tracer gas. Active sampling is also possible. The final design of the samplers should suit the evaluation unit used, which is a gas chromatograph for determining the mass amount of tracer used. Determination of the mass concentration of the relevant tracer gas according to this methodology is carried out by heating the sorbent in a chromatographic column, where the individual tracer gases are separated according to their retention times. The mass of the individual tracer gases in the measured samples is then determined from the internal calibration of the gas analyser used. For the SURO's purposes, all-metal thermo-desorption tubes from the company MARKES and, as suitable sorbents type Chromosorb 102 and Tenax are used.

5.2.1 Requirements for air samplers

1.1 Only air-samplers with the appropriate sorbent that have not undergone the maximum number of thermal cycles recommended by the sorbent manufacturer and are calibrated, conditioned and analysed according to a standard operating procedure based on the EN ISO 16017-2, which is outlined in Appendix 3, shall be used for measurements.

1.2 The dynamic ranges of the air samplers used to measure the mass amount of tracer gases absorbed on their sorbent without passing through the sorption column of the sampler used, denoted R_d in (ng), shall be determined with an overall uncertainty of less than 20 %, for example according to the working procedures in Appendix 3, with 95% confidence. This means that the lower and upper detection limits of R_d must be determined.

1.3 The sampling rate (uptake rate) denoted *U* in (ng/ppm min) of air samplers used for a sorbent and tracer gas used must be determined during the calibration measurements according to relation (8) given in Appendix 1. The exposure time for calibration and the ambient measurement conditions in terms of

temperature and relative humidity should be chosen with respect to those typical for the measurements under consideration.

5.3 Tracer gases

The main requirements for tracer gases are good mixing with air, negligible background in the measured zones, minimal adsorption to internal surfaces and sorption to internal materials, and health safety. Their selection is governed by the required detection properties and limits, the requirements for their resolution in the tracer gas mixture used in the field, the purchase price and shelf life in storage. The selection of suitable tracer gases is closely related to the type of sorbent used and the appropriate chromatographic column. Tracer gases on the PFT basis and their main physical properties used in the SURO are given in table 1. Rarely, tracers on Cl basis as TCE (CAS 79-01-6) and PCE (CAS 127-18-14) are used.

Table 1 – Physical properties of tracer gases used in the SURO

Trivial name	CAS number	Boiling point t_B (°C)	Density (g mL^{-1})	Purity (%)
Perfluoromethylcyclohexane (MCH)	355-02-2	76	1.788	97.6
Perfluoroethylcyclohexane (ECH)	335-21-7	101.7	1.829	95.6
Perfluoro-1.3-dimethylcyclohexane (MDC)	335-27-3	102	1.828	95.2
Perfluoro-1.3.5-trimethylcyclohexane (TMH)	374-76-5	127.4	1.888	97.5
Perfluoro-iso-propylcyclohexane (PCH)	423-02-9	130	1.894	90.8

5.4 Gas analyser

1.1 The type of analyser used, with a suitably selected chromatographic column and appropriate data acquisition software, must be capable of detecting and determining mass concentration of tracer gases used with the required accuracy and sufficient resolution, even when multiple tracer gases are used simultaneously during measurements in multiple zones of a single building.

1.2 In case of chromatographic evaluation of the mass concentrations an ECD (electron capture detector) detector is most often used.

1.3. A standard operating procedure for the analyser with a GC column and software (SW) used shall be developed and shall specify at least the following characteristics for each tracer gas used: precision, accuracy, selectivity, repeatability, minimum detectable mass concentrations measured and their dynamic range.

1.4 The standard operating procedure shall also include procedures for ensuring internal control and independent external controls measurement quality. The internal control of the entire chain (analyser-GC column- detector - SW) is most often provided by standards supplied by the manufacturer and the external control by means of an inter-laboratory comparison.

5.5 Other ancillary equipment

The following minimum ancillary equipment is recommended:

- TESTO 174H recorder with 8,000 records adjustable from 1 min to 24 hours for temperature and relative humidity measurements,
- laser range finders for determining the geometric volume of the measured zones,
- SARTORIUS precision digital laboratory scales with accuracy to tenths of milligrams for measuring and controlling tracer gas emissions from the used tracer gas emission sources,
- precision laboratory liquid phase tracer gas dispensers for filling emission sources from storage bottles with 5 µl resolution.

6. Handling of test samples

For the purpose of this methodology, we consider the indoor atmosphere of the measured zone of the buildings, which contains the time-varying mass concentration of tracer gases used to be measured, as test samples. Such a sample is uniquely related only to the measurement location and time. Sample measurements shall be carried out throughout the measurement period using air samplers located in the measured building zones.

7. Workflow

7.1 Planning and preparation of measurements

1.1 Depending on a number of zones, their volumes in a building to be measured and specified measurement time, the laboratory shall prepare the necessary number of following measuring equipment:

-suitable type of emission sources

-air samplers

-temperature recording meters (TESTO 174 H) and laser range finders for calculating the volume of the building to be measured (if a technical drawing is not available)

-working documentation needed to describe the measured situation, location of measuring instruments, etc. The minimum scope of the working documentation is given in Appendix 2.

1.2 The selection of a necessary tracer gas emission sources according to their emission rates and number is carried out according to sampling rates of the air samplers used which are determined by calibration (see previous text par. 5.2.1). It is also necessary to take into account the required measurement time, a volume of measured zones and a dynamic range of measured mass concentrations of the tracer gases used by the GC analyser.

1.3 Checking of tightening of the transport caps of the air samplers used.

1.4 Placement air samplers and tracer gas emission sources in separate shipping containers to prevent contamination of the air samplers during transportation.

7.2 Deployment of emission sources in a building

1.1 The smallest room in the measured zone of the building (excluding toilets and bathrooms) shall be equipped with one emission source with a suitable tracer gas. Sources with an emission rate k times higher than the sources located in the smallest room of the measurement zone shall be installed in rooms that differ from the smallest room by a volume factor k.

1.2 A source of tracer gas emissions is located in every room except toilets, bathrooms and technical rooms, which are usually always closed or abnormally ventilated.

1.3 For a building with N zones, N types of tracer gases are used. A single type of tracer gas shall always be used in each zone.

1.4 The sources shall be so located that the natural airflow in the rooms above them homogenises the mixture of tracer gas and air. They are ideally placed on surfaces at a distance of 1 – 2 m from the surrounding walls, i.e. on tables, hanging lamps. Practically, they should be placed up to 0.5 - 1.5 m above the ground on furniture, oriented with the source output in the centre of the measured room, away from direct sources of heat and cold and not on windowsills.

Due to the principle dependence of their emission on temperature, the entire time course of the temperature in the measured room, or at least the minimum and maximum temperature, should be recorded during the entire measurement.

1.5 The sources shall always be placed on opposite sides of the room to the positioned air samplers.

7.3 Deployment of air samplers in a building

1.1 Each measurement zone shall have at least two measurement points at its opposite ends. The samplers shall then always be placed in pairs at one measuring point. The distance of the sampler from the emission source should be at least 2 m. The use of multiple samplers in the measurement zone increases the accuracy and reduces the measurement uncertainty due to the inhomogeneity of the tracer atmosphere in the measurement zone.

1.2 The samplers shall be placed on furniture preferably at the same height as the sources but on the opposite side of the measured room from them and preferably in the geometric centre of the measured zone. Their distance from the walls should be a minimum of 2 cm and the orientation of their diffusion inlet should be towards the wall.

1.3 It is recommended that the samplers be not placed in direct heat and cold sources, in corridors, toilets, hallways and bathrooms.

NOTE: An example of the placement of tracer gas sources and air samplers in a house is given in Appendix 2.

7.4 Procedure for starting and ending measurements

1.1 The following data shall be entered and plotted on the worksheet according to the template listed in Appendix 2:

- identification of the owner and the building to be measured,
- date and time of the start of the measurement,
- a brief plan and description of the building layout indicating the location of the sources and air samplers, including their registration by their respective serial numbers, and the detectors used, if any sorbents,
- location of the temperature-recording instruments set to hourly records,
- the time delay between transport and the start of the measurement.

1.2 According to the principles described in a previous text of the chapter 7.2, first the emission sources and then the air samplers are deployed in a building to be measured and the start time of the measurement is recorded.

1.3 Start indoor temperature measurement of the measured zone with setting of an hourly thermometer record with recording or at least installation of a thermometer min/max.

1.4 When the measurement is complete, first collect all air samplers, seal them in their shipping containers, and record the time of the end of the measurement to the nearest tens of minutes. The

emission sources shall then be collected and placed in shipping containers in such a way as to ensure minimal contamination of the samplers during transport to the evaluation site. Finally, the rest of the equipment shall be collected.

7.5 Measurement time

1.1 For the purpose of this methodology and its further use, sequential 7-day screening or monthly integral measurements in buildings are considered that the required time criterion for minimum measurement time is met (see eq. (6) in Appendix 1).

7.6 Working records

1.1 All manual entries made on site for an investigated object, including the results of measurements of the necessary parameters for the calculation of the average air exchange rate (average emission rates from the sources used and the results of the air samplers used from the analyser) shall be archived in the worksheets for measured object both electronically and in paper form.

8. Validation and verification proposed methodology

To validate and verify the method, it is necessary to estimate its:

- identity confirmation and selectivity
- precision
- accuracy
- repeatability.

8.1 Identity confirmation and selectivity

Selective determination of tracer gases used, in sufficient measured concentrations to cover the required range of their measured changes in air without interference in multiple zones, can be achieved by a suitable evaluation procedure for a well-chosen sorbent type and chromatographic column with an appropriate analyser and SW. An example of a simplified standardised procedure implemented at the SURO for the sorbent Chromosorb 102 is then given in Appendix 3.

8.2 Accuracy

1.1 In general, the accuracy of the method, as the agreement between the result of the determination of the average air exchange by its use and the conventionally true value, is ensured by internal and external control.

1.2 The internal control of the method used at the SURO consists of a comparison with the conventional true method, which uses a defined determination of the air exchange in a SURO radon chamber [6] which is based on an accurate measurement of the volumetric airflow through a well-known volume of the chamber (48 m^3).

1.3 The external control of the method consists of a comparison with a relevant method commonly used by another laboratory, preferably an accredited one.

8.3 Precision

1.1 Based on multiple independent tests performed in the SURO radon chamber and mentioned in previous text of par. 8.2 the precision of the method was estimated as the maximum calculated standard

deviations normalised to the reference air exchange rate level set in the chamber separately for each of the sorbent and tracer gas used.

The results obtained then showed the independence of the determined standard deviation on the type of sorbent and tracer gas and its maximum value normalised to the respective reference air exchange rate level was about 9 %.

8.4 Repeatability

1.1 The results of the above independent tests carried out in the radon chamber of the SURO always under the same conditions showed a repeatability of the method better than 4%, independently of the type of sorbent and the type of tested tracer gas.

9. Measurement uncertainty

9.1 General approach for calculation

The actual procedure for calculating uncertainties of each individual input variable, that comes into play when calculating the average air exchange rate is based on the document [7] and the user manuals of the manufacturers of the individual measuring instruments used in this methodology. To estimate the expanded total uncertainty of the average air change measurement, denoted by U_c, one can write:

$$U_C = \quad k \sqrt{u_A^2 + u_B^2} \qquad (1)$$

k denotes expansion coefficient, which, assuming a normal distribution of the quantity to be determined, corresponding to a 95% confidence interval of coverage for k = 2.

u_A denotes uncertainties of type A, represented by the results of direct repeated measurements in particular:

- chromatographic determination of the absorbed amount of tracer gas used in the air samplers
- weighting of the pre- and post-exposure losses of tracer gases emission sources used to determine their total and average emission rate into the measured zone.

u_B denotes uncertainties of type B of the input parameters that are not subject to direct measurements. Type B uncertainties include the following:

- Uncertainty of the calibration standard for the chromatograph used to determine the total sorbent amount of the relevant tracer gas in the TD detector
- Uncertainty in the conventionally true value of the average air change used for calibration sampling rates of TD detectors
- Uncertainty of the effect of temperature on the emission of the tracer gas evolvers
- Uncertainty in the determination of the measured zone volume
- Uncertainty of sampling rates for air samplers given by calibration
- Uncertainty in the determination of the molar volume for a given tracer gas due to state changes of air pressure p and air temperature T.

An example of a partial uncertainty analysis to determine the total uncertainty in the estimate of the average air change rate using this methodology in case of a one investigated zone is given in Appendix 5. Due to the multiplicative nature of the model for calculating the average air exchange rate (see

Appendix 1), the following approach using the known relative standard uncertainties of the input variables is also advantageously used here [7].

To calculate the expanded total relative uncertainty of the measurement of the average air change estimate U_c /n, one can then write their propagation:

$$\left(\frac{U_c}{n}\right) = k \cdot \sqrt{\sum_{i=1}^{n}\left(\frac{\partial f}{nX_i}x_i\right)^2\Bigg|_{X_i}\left(\frac{u(x_i)}{x_i}\right)^2 + 2\sum_{j<k}^{n} r_{jk}\left(\frac{\partial f}{\partial nX_j}\right)\left(\frac{\partial f}{\partial nX_k}\right)\left(\frac{u(x_j)}{x_i}\right)\left(\frac{u(x_k)}{x_k}\right)} \qquad (2)$$

$\sum_{i=1}^{N}\left(\frac{\partial f(x_i)}{n\,X_i}\right)^2$ denotes relative sensitivity coefficients of the function: n = f *(x1, x2 ….. x_n)*

$X_1 = x_1, \ldots\ldots X_N = x_N$ denotes input variables X_i for calculation of the average air change ***n*** (see Appendix 1) and x_i their measured estimates

$\left(\frac{u(x_i)}{x_i}\right)^2$ denotes relative standard uncertainty of each individual variable x_i

A typical individual relative standard uncertainty of the SURO measurement system of average air exchange rate is given in table 6 of Appendix 4.

n denotes calculated average air exchange rate
r_{jk} denotes correlation coefficient between the *j-th* and *k-th* independent variable X_i,
k has the same meaning as in previous eq.(1)

Assuming the mutual independence of the input variables X_i and their estimates x_i appearing in the model for the calculation of the average air change (see Appendix 1) then $r_{ji} = 0$.

10. Quality control

This methodological procedure proposed in SURO, most of the sources that could negatively affect the quality of the results were analysed and preventive measures were taken to eliminate them or at least to limit their influence to an acceptable level. As part of the quality assurance process, SURO carries out internal and external checks both at the vertical level for the determination of the average air change rate and partial checks for the independent control of the entire evaluation chain, including the gas chromatography analyser used, according to a standard test procedure which is not part of this methodology and will vary according to the type of analyser used. A similar procedure is then recommended for all operators intending to use this methodology.

1.1 External control

- is assured by an independent comparison the SURO with a renowned laboratory. Last comparison was organized with renowned institution, National Brookhaven Laboratory NY U.S.A. in a 15 Czech houses. Recently, during March 2025 the comparison has been organized with the Swedish Lab. Pant IAQ from Uppsala in a 10 Czech houses.

1.2 Internal control

- is assured by repeated tests in the environment of the mentioned SURO radon chamber, which represents a single measurement zone with an adjustable and well-defined air exchange rate in the range of 0.1 - 2 (1/h) and freely adjustable ambient conditions for measuring temperature and relative humidity in a range similar to that in residential buildings.

11. Work safety

The handling of tracer gases, including their use for measurement and storage, is based on the generally binding safety precautions specified in the relevant Safety Data Sheets for a given tracer gas and on a legislative advice at national or international level. The average mass concentrations of individual tracer gases in the measured zones of buildings are at a level of no more than tenths of mg/m^3.

12. Conclusions

The presented report provides standardised methodological guidance for the use of a passive integral tracer gas technique for determining average air exchange in a building or a workplace based on many years of experience with use of the method in the SURO and obtained during this project, as well. The approach used involves the use of multiple tracer gases and thus allows not only the determination of average air exfiltration from individual zones of multi-storey buildings, but also the determination of average airflows between individual zones (floors, rooms).

The methodological procedure proposed is suitably supplemented by examples and procedures used in the SURO. An integral part of the validation and verification of the presented methodology are the results of a successful international comparison of the determination of average air exchange from 10 Czech buildings, which took place in March of this year and included results from both apartments and multi-storey family houses. Only the Swedish company PentIAQ AB from Uppsala provided its device and instructions needed for the comparison. The average agreement of the results from all the objects did not exceed acceptable 10 %. The results of the unpaired Two–sample t-test for the mean value used did not reject the null hypothesis that the mean difference between the SURO and the PentIAG is not statistically significant for a significance level of α = 0.05 (95% probability).

The undeniable advantage of using this approach with passive integral tracer gas detectors is that they can be used on a large scale at a relatively affordable cost. The use of this technique is then also directly offered for validation and verification of numerical models of ventilation calculation widely used especially in construction practice. The overall uncertainty in the measurement of average air changes during typical 1 to 4 week exposures in buildings is at an acceptable level of about 15 – 20 %.

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Appendix 1. Mathematical problem formulation

General continuity model for N measured zones

General mass continuity equation describing change of mass concentration $C_{ki}(t)$ (ng/m³) in time t in the zone $i \in \{1,2,\dots,N\}$ of the tracer gas type $k \in \{1,2,\dots,N\}$ can be written as follows [9]:

$$V_i \frac{dC_{ki}(t)}{dt} = m_{ki} + \sum_{j=1,j\neq i}^{N} R_{ji} C_{kj}(t) - C_{ki}(t) \sum_{j=1,j\neq i}^{N} R_{ij} - R_{ei} C_{ki}(t) \quad (1)$$

where

- $m_{ki} = 0$ if $k \neq i$ and m_{ii} denotes known, constant emission rate (ng h^{-1}) of a tracer k into a zone i
- R_{ji} denotes constant airflow (m^3 h^{-1}) from the j- th to the *i*-th zone (inter-zonal airflows)
- R_{ei} denotes constant airflow rate (m^3 h^{-1}) from the i –th zone to outdoor environment (exfiltration)
- V_i denotes volume of the zone i (m^3)
- $N + 1$ denotes outdoor.

Stationary concentration model for N-zones

1. The number of different used tracer gases must be equal to the number of measured zones and each zone type - j contains exactly one tracer gas type- k.

2. The following assumptions are met:

- The air in each measured zone must be well mixed and tracer gas should be emitted uniformly in the zone.
- All the measured zones are at steady state over the measurement period, which should usually be in the order of weeks.
- The used tracers should be emitted into each zone with a known and constant entry rate.
- The tracers used should not have a background in the outdoor air and should mix well with the air.
- The outdoor concentration of the tracers used should be negligible.

Then the equation (1) can be rewritten as follows:

$$m_{ki} + \sum_{j=1,j\neq i}^{N} R_{ji} C_{kj} - C_{ki} \sum_{j=1,j\neq i}^{N} R_{ij} - R_{ei} C_{ki} = 0. \quad (2)$$

Based on the analogy with the Kirchhoff's junction rule the knowledge of exfiltrations (R_{ei}) and the inter-zonal airflows (R_{Ii}) an infiltration rate into i –th zone from outdoor can be calculated as follows:

$$R_{Ii} = R_{ei} + \sum_{j,i=1}^{N} \left(R_{ij} - R_{ji}\right) \quad (3)$$

Time variable t is removed from the equation (2) since in the steady state the concentrations C_{ij} are constant.

Measured average concentration of the tracer type k in the $i-th$ zone can be calculated as follows:

$$C_{ki} = \frac{R_{dki}\ M_k\ p_i}{U_k \Delta T\ \ R\ T_i} \qquad (4)$$

where

R_{dki} denotes response of an air sample detector in (ng) used on tracer k in the zone i.
M_k denotes molecular mass (g mol^{-1}) of a tracer k.
p_i denotes atmospheric pressure (Pa) in zone i.
U_k denotes sampling rate (ng ppm^{-1} min^{-1}) of the tracer k used on a sorbent used in the air sampler estimated from calibration
ΔT denotes a total measurement (sampling) time (min).
R denotes universal gas constant (J K^{-1} mol^{-1}).
T_i denotes absolute temperature (K) in zone i.

The average air exchange rate of the multi-zone building n (h^{-1}) can be calculated as follows:

$$n = \frac{1}{V}\sum_{i=1}^{N} R_{ei} \qquad (5)$$

where

V denotes the total internal volume of the whole zone (m^3), $V = \sum V_i$.

Model for a single zone (N =1)

For case of a single-zone measured building, which in our case do mainly individual flats in apartment buildings realistically represent. We assume a well-mixed mixture of air with a tracer gas used that is injected into the zone with a constant and known emission rate m and stationary state is reached during a total measurement time interval ΔT. In addition, measurement time interval, ΔT meets following condition:

$$\Delta T >> \frac{c}{m} \qquad (6)$$

where

c, m denotes stepwise average measured tracer gas concentration during time interval ΔT and known emission rate of a tracer gas emission source used, respectively.

Considering equations (2), (4), (5) above-mentioned it is then possible to write for the average air exchange n in the zone during this time interval following relationship:

$$n = \frac{m}{c} \qquad (7)$$

All the symbols in eq. (7) are known from the previous text.

To calculate the average air exchange n over the time of its measurement ΔT, satisfying condition (6), the following can be written, taking into account the previous relations (4) and (7).

$$n = \frac{m\,.U\,.\Delta T.R.T}{R_d\,.V\,.p\,.M_w} \qquad (8)$$

All symbols in eq. (8) are known from the previous text.

Model for three zones N=3

The most common case use of the multi-tracer gas stationary concentration tracer gas method is the measurement of average air exchange rate in a multi-storey family house. A three-zonal approach of the general model described in equation (2) can be used in this case. The airflows schematics for a house that contains three investigated zones is illustrated in the Fig.1 considering exfiltration -R_{ei}, infiltration -R_{Ii} and average airflows between each zone -Rji. Assuming the model approach mentioned in previous section the average airflows during measurement time period from each compartment to outdoor environment can be described.

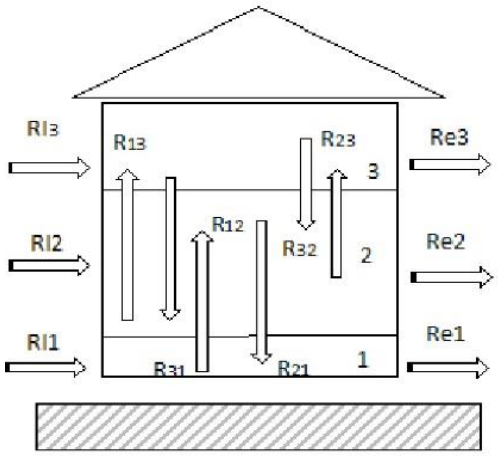

Figure 1 – Airflow schematics for a house with three well-mixed zones

The airflows between investigated zones R_{ji} can then be expressed and calculated from measured average concentrations of the k-th tracer in the j-th zone C_{kj} during measurement time ΔT and the known values of trace gas emission of the-k tracer into a relevant zone m_{ki} using equations (9)- (14). In this case, the sorbent used in the air samplers must be able to distinguish three different tracers in each measured zone using the gas analyser used. The necessary exfiltration rates shall be calculated according to eqs. (15-17). The eq. (5) in previous text shall be used to estimate investigated average air exchange rate between the building interior and outdoor. Additionally, considering eq. (3) in previous text infiltration into each investigated $i - th$ zone from outdoor can be estimated.

$$R_{21} = m_{11}(C_{21}C_{33} - C_{23}C_{31})\frac{1}{A} \quad (9)$$

$$R_{31} = m_{11}(C_{22}C_{31} - C_{21}C_{32})\frac{1}{A} \quad (10)$$

$$R_{12} = m_{22}(C_{12}C_{33} - C_{13}C_{32})\frac{1}{A} \quad (11)$$

$$R_{32} = m_{22}(C_{11}C_{32} - C_{12}C_{31})\frac{1}{A} \quad (12)$$

$$R_{13} = m_{33}(C_{13}C_{22} - C_{12}C_{23})\frac{1}{A} \quad (13)$$

$$R_{23} = m_{33}(C_{11}C_{23} - C_{13}C_{21})\frac{1}{A} \quad (14)$$

where

$$A = C_{11}(C_{22}C_{33} - C_{23}C_{32}) + C_{12}(C_{23}C_{31} - C_{21}C_{33}) + C_{13}(C_{21}C_{32} - C_{22}C_{31})$$

$$R_{e1} = R_{31}\frac{C_{23}}{C_{21}} + R_{21}\frac{C_{22}}{C_{21}} - R_{13} - R_{12} \quad (15)$$

$$R_{e2} = R_{32}\frac{C_{13}}{C_{12}} + R_{21}\frac{C_{11}}{C_{12}} - R_{23} - R_{21} \quad (16)$$

$$R_{e3} = R_{13}\frac{C_{11}}{C_{13}} + R_{21}\frac{C_{12}}{C_{13}} - R_{31} - R_{32} \quad (17)$$

Appendix 2. Deployment of tracer gas sources and air samplers in a building (an example)

1.1 Typically, in a single-storey (zone) “ranch”-type house without basement treated as a separate zone, two or three sources are placed in the living room (LR) – dining room (DR) – kitchen area (KITCH) and one in each of the bedrooms (see Fig. 2). The same type of source (denoted as GTS) is used in the entire zone.

1.2 Alternatively, the main floor of a “ranch”-type home can be divided into two zones, the family zone (living room - dining room - kitchen) and the bedroom zone (the bedrooms – BR, bathroom – BATH, and hall), each tagged with the appropriate number of the GTS but of different types. With a basement, the house then becomes a 3-zone study. An example of a real house comprising two or three zones (called “Colonial”) is shown on the Fig.3.

1.3 If the house has a basement, another GTS type should be used since it is a separate, but attached zone. For an open (unfinished) basement, one or two sources may be used; if it is divided into rooms, the sources should be deployed on a unit-volume basis. Ignoring the basement by not including any sources and samplers (denoted as CATS) or using sources of the same type as the main floor can result in errors in the determination of the living space air exchange rate.

1.3 In a two-storey house, one to four GTS sources of one type are deployed on the main floor (e.g. the living room, kitchen, family, and dining area) and one source of a second type in each bedroom upstairs. If the living area (1st and 2nd floors) is treated as a single zone, then sources of one type should be deployed on the main floor only. The stack effect will provide an essentially equal concentration upstairs without sources; the concentration should, however, be measured upstairs as well as on the main floor. During these tests, if possible, the doors to all rooms should remain open with the exception of the basement doorway that should be closed if that is its normal position.

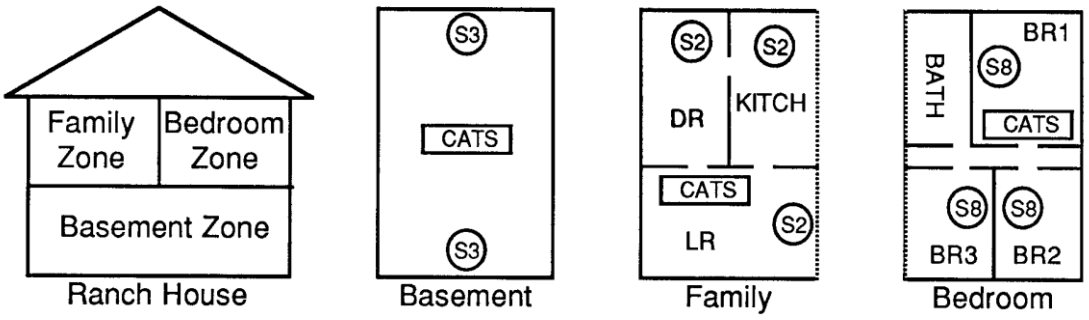

Figure 2 – One-storey house type “Ranch” with a basement

Basement Zone

Sources (S_i): Place two GTS sources (usually PCH) on opposite ends of the basement

(If an obstruction exists, place a source on either side of the obstruction)

Samplers: Place a pair of CATS in the centre of the basement or within the largest open area.

Family Zone

Sources: Place GTS sources (usually MDC) within the largest rooms

Samplers: Place a pair of CATS in the largest room.

Bedroom Zone

Sources: Place one GTS source (usually MCH) in each bedroom

Samplers: Place a pair of CATS in the largest bedroom in the zone.

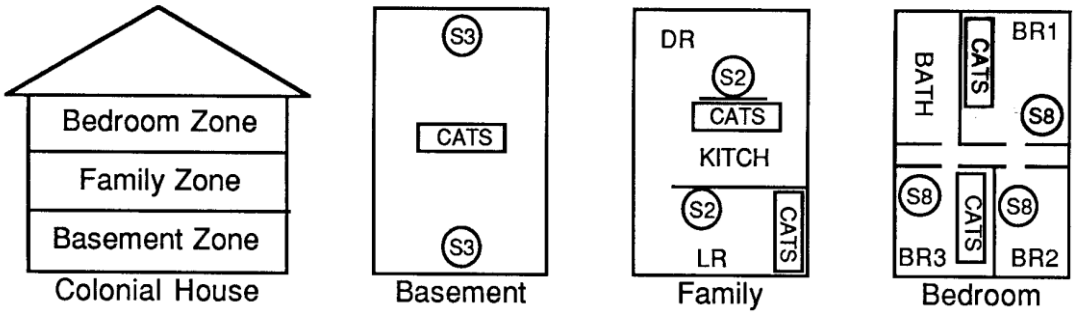

Figure 3 – Two-storey house type "Colonial" with a basement

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Basement Zone

Sources (S_i): Follow directions for "ranch" house

Samplers: Follow directions for "ranch" house.

Family Zone

Sources: Place two emission sources in the rooms at opposite ends of the zone

Samplers: Place two pairs of air-samplers in the two largest rooms in this zone, towards the centre but away from each other and the sources.

Bedroom Zone

Sources: Follow directions for "ranch" house

Samplers: Place two pairs of air -samplers in the two largest bedrooms within this zone.

Appendix 3. Working documentation

Measurement of air exchange in buildings using this technique and measurement methodology can be carried out either by a professional company or by the building owner according to instructions delivered by courier or post.

1.1 In the case of measurement by a professional company that is familiar with the principles of the use of measuring instruments, their placement and working with the technique, only the following is included in the work documentation:

-identification of the object and owner

-simple plan for dividing the building into the necessary measuring zones according to its nature (flat, multi-storey house)

-plan for the location of the measuring instruments and emission sources according to this methodology, including the exact identification of the measuring instruments and sources in the measuring zones

-plan for the appropriate measurement of the temperature of the internal geometric volume of each zone

-simple description of the condition of the building in terms of the tightness of its envelope (windows and outer envelope) is also appropriate

-date and time of the start and end of the measurement with an accuracy of about tens of minutes.

1.2 In case that the owner of the building takes the measurements, then the instructions for the measurements must include, in addition to the above mentioned:

-precise description of the measuring instruments (air samplers, sources) and the principles of their operation before and after their use

-detailed instructions for the placement of air sources and samplers in the zone. The number and location of which was agreed upon prior to the installation itself, based on a floor plan provided by the building owner to the measurement service provider

-the method of dispatch and the address of the supplier of the measuring service

-contact to a service provider

-if necessary, a questionnaire regarding a more detailed description of the building to be measured, its use according to the actual intention of the ventilation measurement.

1.3 The presented measurement methodology requires the completion of the following forms, examples of which are given in Tables 2–6:

- Type A: Object specification questionnaire.

- Type B: Volume / temperature measurement records.

- Type C: Deployment of tracer gas sources and air samplers used in a measurement zone.

Type A.

Table 2 – Object specification questionnaire

Age of building: □ older than 1950 □ 1950 – 1990 □ 1991 – 2000 □ 2001 - 2010 □ 2011 and newer	Adjustments after final building approval: yes / no □ outbuilding □ change of non-habitable space (e.g. cellar) to habitable □ reconstruction of structure in contact with earth (floors, basement walls) □ adjustments reducing energy performance of a building □ new tight windows □ insulation of a building envelope □ roof insulation □ change of heating system	
□ no cellar	□ partial cellar present	□ cellar present in a building
N° of floors below ground:	N° of habitable rooms below ground:	N° of floors above ground:
□ building on insulated ground floor (area under 1st floor with ventilation bores)		
□ building is on sloping ground/hillside (above ground walls are in contact with earth)		
Prevalent building material (indicate the part of building (floor, room), if the material is different): □ rock □ brick □ steel concrete □ slag concrete	□ expanded concrete blocks □ hollow ceramic bricks □ wood (frame house)	
Floor on ground type (indicate the floor n° when partial cellar is present): □ rammed earth, boards on slag subbase, dry rock or brick pavement □ concrete without hydroinsulation □ concrete with hydroinsulation □ concrete with hydroinsulation and thermal insulation		
Underground part of building □ porous layer of gravel / gravel sand under building □ thermal insulation filling under building □ building foundation includes perimeter insulation		

Building defects: □ cracks / fissures in above-ground structures (walls, ceilings) □ cracks / fissures in structures in contact with earth (floors, basement walls) □ elevated humidity of walls and / or floors □ hole in soil, dry wells, wells, etc.
Is building protected against radon? yes / no □ radon protection was installed during construction of building □ radon protection was installed later (after construction was finished) Radon protection principle: □ radon insulation □ natural / forced subsoil ventilation (draught) □ natural / forced air space ventilation in floor □ forced ventilation of air in rooms
Means of air ventilation in dwelling space: □ infiltration by windows (by a gap between casement and frame) □ by window ventilation slits or wall slits □ air inflow by ventilation slits, outflow by exhaust fan in bathrooms, kitchens, etc. □ local ventilation units with heat recuperation □ forced central ventilation with heat recuperation Is ground-coupled heat exchanger used for preheat of air inflow? yes / no
Means of heating: □ local (solid fuel source) with air outflow to chimney and inflow from room □ other local heating devices (heat storage stove, convector heater, etc.) □ central heating □ underfloor heating □ in living rooms □ only in bathrooms and toilets □ warm air heating

Type B:

Table 3 – Volume measurement records

Room	Floor	Dimensions [m]	Volume [m^3]

Record n°:

Date:

Name:

Building:

Measured by:

Signature / date:

Table 4 – Temperature measurement records

Room	**Floor**	**Date**	**Temp. [°C]**	**Time [hh:mm]**	**Temp. [°C]**	**Time [hh:mm]**	**Temp. [°C]**	**Time [hh:mm]**
			Morning		**Noon**		**Evening**	

Record n°:

Building:

Measured by:

Signature/ date:

Type C.

Record n°:

Date:

Building:

Table 5 – Air samplers used deployment in a house

Room No.	Floor	CATS sampler n°

Table 6 – Tracer gas emission sources used deployment in a house

Room	Floor	GTS source type (colour)	GTS number	Emission rate	Notes

Start of measurements:

End of measurements:

Exposure time:

Measured by:

Signature/date:

Appendix 4. Standard operating procedure for sorbent Chromosorb 102 according to EN ISO 16017-2

1.1 The diffusion air sampler was exposed for a known measurement time. Organic analyte vapours of the tracer gas migrate by diffusion through the sampler collection tube filled with sorbent and are captured by it. The captured analyte vapours in the sorption tube are then desorbed by heat and transported by a stream of inert carrier gas to a gas chromatograph equipped with a capillary column, an electron capture detector, and a flame ionisation detector for analysis.

1.2 Calibration of the analytical system used is carried out by injecting of the steam into the sorption tube. The sampling was carried out by placing a tube of Chromosorb102 (300 mg) sorbent for a defined period of time at the sampling point with one end sealed and the other end closed with a diffusion cap, only.

1.3 The Chromosorb102 sorbent was stabilized for 10 hours at 190 °C and a carrier gas flow rate of 100 ml.min^{-1} before use. It was then transferred to labelled sorption tubes (300 ± 2 mg) and conditioned for 2 hours at 220 °C and a carrier gas flow rate of 60 ml.min^{-1}. The samples were thermally desorbed from the sorbets on the ULTRA-UNITY equipment by. The gas chromatograph is equipped with a Rxi®-624Sil MS Restek capillary column (30 m, ID 0.25 mm, 1.4 µm). The temperature program of the method was as follows: 60 °C (5 min) to 120 °C (0 min) to 220 °C (5 min) with a heating rate of 5 °C.min^{-1} and from 120 °C 20 °C.min^{-1}. The ECD detector is heated to 300 °C, FID to 250 °C, flow path 190 °C. RANGE detectors - EDC 1, FID 0. The nitrogen flow rate through the capillary column was 0.7 ml.min^{-1} (velocity about 19 cm.s^{-1}) and pressure 59 kPa.

1.4 The following approval criteria were met during testing:

- If the tubes were not analysed within 8 hours after collection, they were stored in a hermetically sealed in an airtight box and sealed with PTFE seals.

- The sample was not exposed to high temperatures during transport to the laboratory.

- The recommended number of thermal cycles was not exceeded for the sorbent used.

- To ensure the purity of the sorbent prior to collection, Chromosorb102 was conditioned at 200 °C for 15 minutes at a carrier gas flow rate of 60 ml.min^{-1}. Sorbent tubes with less than 1% sorbent artefact content were used for the analysis.

The desorption efficiency was then greater than 98.5 % in all cases. Desorption efficiency is determined by comparing the chromatographic response of the analysis and the residue on repeated desorption of the tube.

1.5. The results of the measurements are reported with the measurement uncertainty expressed as an expanded uncertainty with an expansion coefficient of k=2, which for a normal distribution corresponds to a coverage probability of 95 %. The uncertainty quoted does not include sampling uncertainty and does not cover results below the limit of quantification.

NOTE: To ensure the functionality and suitability of the method used, a calibration method using the reference standard for chromatography TOL MIX-5 in methanol with CERTAN® capillary (each component 1000 ± 10 µg.ml^{-1}, ANALYTICA®, spol. s r.o.) was used. The defined amount of TOL MIX-5 was transferred to a 2379 ± 1 ml container using a calibrated Hamilton micro centrifuge (10 µl, 0,1 µl division). This gas mixture was tempered at 20 ± 0.5 °C and spiked with a Hamilton gas-tight micro centrifuge (1000 µl, 10 µl division) onto Chromosorb102 sorbent tubes.

Appendix 5. Calculation of uncertainty for measured average air exchange rate for cases a single and three measured zones

1.1 Example of calculation of relative expanded standard uncertainty of one measurement of average air exchange $\frac{U_c(n)}{n}$ for the case of one measured zone, when N=1.

Considering equation (1-2) given in the previous text of paragraph 10 and the input variables in equation (8) for calculating the average air exchange, given in Appendix 1, the total relative uncertainty of the air exchange rate can be calculated as follows:

$$\frac{U_c(n)}{n} = k\sqrt{u_{source}^2 + u_{sampl}^2 + u_{meas}^2} \qquad (18)$$

where

u source denotes the total relative uncertainty of the total emission of a tracer gas used injected into the measurement zone, which includes the sum of the relative uncertainties of the weighting of all tracer gas sources used before and after the exposure time ΔT and the relative uncertainty of volume measurement zone.

u sampl denotes the relative uncertainty of the sampling rate for air samplers used, which should be determined from the calibration using equation (8) given in the previous text of Appendix 1. If inhomogeneity of the measured zone is detected during the measurement using n samplers, it is necessary to add a relative standard deviation of the mean divided by the square root of the number of samplers (n-1) used.

$u$meas denotes the relative uncertainty due to analysis by means of gas chromatography analyser (reproducibility, drift, linearity, uncertainty of calibration).

After substituting the necessary input values from Table 7, given in the following text, into eq. (18), the typical total uncertainty in determining the average air exchange is approximately less than 20 % for k = 1, i.e. the conventional true value of the measured quantity lies within the specified range of values with a probability of approximately 68%.

NOTE: All calculations took into account negligible contributions from the relative standard uncertainties of the molecular weight of the used indicator gas M_w and the gas constant R. Furthermore, we assumed that the input quantities appearing in the used model in eq. (8) in the Appendix 1 are not correlated and therefore our result overestimates. Table 7 illustrates sources of a relative uncertainties type A, B [10], that contribute to the total relative uncertainty of the average air exchange rate estimated for the SURO measurement method used and for expansion coefficient k = 1.

Table 7 – Uncertainty budget for determination of a relative total uncertainty of air change rate for the method implemented in the SURO

Quantity	Source	type of uncertainty	$\frac{u(x_i)}{x_i}$ %
Calibration standard for GC	certificate	B	3
Emission rate of tracers m_{ki}	weighting error	A, B	5
	temperature dependence	B	
Sampling rate of the TD tubes U_k	self-calibration	A, B	11
Volume of measured compartment V	documentation	B	10
	direct measurement	A, B	
Temperature measurement T	data sheet of instrument	A, B	1
Barometric pressure measurement p	data sheet of used instrument	A, B	1
Repeatability of the analyser results	internal control	A	3
Linearity of used GC	data sheet of used instrument	B	3
Response of TD tubes R_{dki}	internal control	A	4
Universal gas constant R	tabulated	B	neglected
Tracer molecular weight M_w	tabulated	B	neglected

1.2 Example of calculation of relative expanded standard uncertainty of one measurement of average air exchange $\frac{U_c(n)}{n}$ for the case of three measured zones, when N=3.

Considering equations (1-2) given in the previous text of the paragraph 9 and the input variables in eqs.(2,4,5) for calculating the average air exchange, given in the Appendix 1, the total relative uncertainty of the air exchange rate can be calculated as follows:

$$\frac{u_c(n)}{n} = k\sqrt{\frac{u^2(n)}{n^2}} \quad (19)$$

$$u^2(n) = n^2\left(\frac{u^2(RE)}{RE^2} + \frac{u^2(V)}{V^2}\right) \quad (20)$$

where:

$$u^2(V) = V_1u^2(V_1) + V_2u^2(V_2) + V_3u^2(V_3) \quad (21)$$

$$u^2(RE) = (\mathrm{DRE})^T (\boldsymbol{VCR}) (DRE) \quad (22)$$

$(DRE)^T$ is a transposed vector to the vector (DRE) with components as follows:

$$(DRE) = \left(\frac{\partial RE}{\partial CC_1}, \frac{\partial RE}{\partial CC_2}, \frac{\partial RE}{\partial CC_3}, \frac{\partial RE}{\partial m_{11}}, \frac{\partial RE}{\partial m_{22}}, \frac{\partial RE}{\partial m_{33}}\right) \quad (23)$$

$(\boldsymbol{VCR})$ is matrix (6 x 6) as follows:

$$(\boldsymbol{VCR}) = \begin{bmatrix} x_{11}x_{12}x_{13} & 0 & 0 & 0 \\ x_{21}x_{22}x_{23} & 0 & 0 & 0 \\ x_{31}x_{32}x_{33} & 0 & 0 & 0 \\ 0\ 0\ 0 & (m_{11}s)^2 & 0 & 0 \\ 0\ 0\ 0 & 0 & (m_{22}s)^2 & 0 \\ 0\ 0\ 0 & 0 & 0 & (m_{33}s)^2 \end{bmatrix} \quad (24)$$

with matrix elements as follows:

$$X_{11} = \sum_{i=1}^{9}(C_i\ E)^2 \left(\frac{\partial CC_1}{\partial C_i}\right)$$

$$X_{22} = \sum_{i=1}^{9}(C_iE)^2 \left(\frac{\partial CC_2}{\partial C_i}\right)$$

$$X_{33} = \sum_{i=1}^{9}(C_iE)^2 \left(\frac{\partial CC_3}{\partial C_i}\right) \quad (25)$$

$$X_{12} = X_{21} = \sum_{i=1}^{9}(C_iE)^2 \left(\frac{\partial CC_1}{\partial C_i}\right)\left(\frac{\partial CC_2}{\partial C_i}\right)$$

$$X_{13} = X_{31} = \sum_{i=1}^{9}(C_iE)^2 \left(\frac{\partial CC_1}{\partial C_i}\right)\left(\frac{\partial CC_3}{\partial C_i}\right)$$

$$X_{32} = X_{23} = \sum_{i=1}^{9}(C_iE)^2 \left(\frac{\partial CC_2}{\partial C_i}\right)\left(\frac{\partial CC_3}{\partial C_i}\right) \quad (26)$$

where:

$V = \sum V_i$ denotes the known total volume of the whole zone comprising three individual sub-volumes $V1, V2, V3$ measured with their partial relative standard uncertainties $(\partial V_1, \partial V_2\ \partial V_3)$.

m_{ki} denotes the known total emission rates of the $k-th$ tracer gas source used into the i –th zone, $k = i$, i= 1,2,3.

$E = \frac{u(C)_{ki}}{c_{ki}}$ denotes known relative standard uncertainties of measured mass concentration of the $k-th$ tracer gas in the $i-th$ zone (see table 7 in previous text and eq. (5) in the previous Appendix 1).

$s = \frac{u(m_{ki})}{m_{ki}}$ denotes known relative standard uncertainty of the total mass emission rate of the $k-th$ tracer into $i-th$ zone, $k = i$=1, 2, 3 (see the table 7).

$RE = \sum Re_i$ denotes the total exfiltration from the building to outdoor estimated as sum of exfiltrations Re_i from the individual zones i=1, 2, 3.

Considering eqs. (10-17) from Appendix 1, the total exfiltration *RE* can be calculated by means of measured average mass concentrations of used $k-th$ tracer in the $i-th$ zone C_{ki} and known the total mass emission rate of the $k-th$ tracer into the $i-\ th$ zone m_{ki} ($i = k$ =1,2,3) as follows:

$$RE = Re_1+Re_2+Re_3 = m_{11}\,CC_1+ m_{22}CC_2 + m_{33}CC_3 \quad (27)$$

where:

$$CC_1 = (C_{22}\,C_{33}- C_{32}\,C_{23} - C_{21}C_{33}+ C_{31}C_{23}- C_{31}C_{22}+ C_{21}\,C_{32}) / \det A$$

$$CC_2 = (C_{11}\,C_{33}- C_{31}\,C_{13} - C_{12}C_{33}+ C_{32}C_{13}- C_{11}C_{32}+ C_{31}\,C_{12}) / \det A$$

$$CC_3 = (C_{11}\,C_{22}- C_{21}\,C_{12} - C_{22}C_{13}+ C_{12}C_{23}- C_{11}C_{23}+ C_{21}\,C_{13}) / \det A \quad (28)$$

$$\det A = [C_{11}(C_{22}C_{33}- C_{23}C_{32}) + C_{12}(C_{23}C_{31}-C_{21}C_{33}) + C_{13}(C_{21}C_{32}-C_{22}C_{31})] \quad (29)$$

1.3 Both Monte Carlo and Matrix inversion [11] approaches are used to calculate the average air exchange rate and its uncertainty in case of more measurement zones (N >1). The error propagation law using and Taylor series with only first derivatives is considered. All input variables are calculated as independent and, therefore, the error estimates are overestimated. Because the matrix inversions to calculate the air exchange rate is used, the experimental setup of each measurement is designed to ensure a positive and non-zero discriminant.

A typical results of measured average air exchange rate and partial airflows with their uncertainties for expansion factor k=1 in a multi-storey occupied building with the dwelling volume of 500 m^3 are illustrated in following table 8. The measurement was lasted for 3 weeks and tracer gases on both Cl and PFT base were used.

Table 8 – Typical results of measured exfiltrations and inter-zonal airflows including their uncertainties from a three-storey house estimated by the SURO method

Three-storey family house (V = 500 m³ t_{exp}= 3 weeks)						
Tracer type/sorbent	**Cl- base/ Tenax**			**PFT- base/Chromosorb 102**		
Airflow	R_d (m³/h)	$u(R_d)$ (m³ h⁻¹)	$u(R_d)/R_d$ (%)	R_d (m³/h)	$u(R_d)$ (m³ h⁻¹)	$u(R_d)/R_d$ (%)
R_{e1}	36	10.1	28.1	60	13.5	22.5
R_{e2}	107	23.4	21.9	105	23.1	22.0
R_{e3}	58.4	10.6	18.2	57.8	10.4	18.0
R_{21}	6.86	3.68	53.6	8.67	4.58	52.8
R_{31}	2.79	1.63	58.4	3.25	1.91	58.8
R_{12}	19.9	7.8	39.2	17.7	7.55	42.7
R_{32}	5.42	3.32	61.3	5.17	3.11	60.2
R_{13}	24	7.92	33.0	21.5	7.9	36.7
R_{23}	47.6	15	31.5	47.6	14.9	31.3
n	0.519	0.060	11.6	0.573	0.06	11.4

R_{ei} denotes exfiltration airflows from i –th zone (floor) in (m³/h)

R_{ji} denotes inter-zonal airflows between the three investigated zones (floors) in (m³/h)

$i = 1,2,3, j = 1,2,3, i \neq j.$

n denotes an average air exchange rate during measuring time.

Appendix 6. Inter-comparison of average air exchange rate organised in 10 Czech homes

The solution of this project also included a planned international comparison (IC) determination of average air exchange in a total of 10 Czech apartments and family houses. The goal of these measurements was to validate and verify the submitted SURO methodology by its comparing with a renowned relevant laboratory. Based on the call for comparison, which was published on the RadoNorm project website, a Swedish company PentIAQ from Uppsala, which performs measurements in buildings according to the ISO EN 16000-8 standard, applied [12].

After initial mutual communication and exchange of necessary input information about the measured objects and the used measuring technology, including its placement in the measured objects, approximately 3-week measurements were started in a total of 10 occupied objects in the Czech Republic in March of this year. All the objects were randomly selected. Five of them apartments of size 3-4+1 and the remaining five objects were multi-storey family houses.

The placement of the air samplers and emission sources in the measured buildings was carried out directly by their owners after they had been thoroughly briefed and received the necessary instructions on the placement and handling of the instruments. Both laboratories used perfluorocarbon-based tracer gases (PFTs) for the comparison. While the Swedish laboratory used only one type of tracer gas emission source and a one-air sampler in each measured room in the respective zone, then SURO used a pair of air samplers and a total of 4 types of PFT tracer gases in each measured room to refine the results.

The following two figures (4-5) show the air samplers (Fig. 4) and emission sources tracer gases (Fig.5) used by the SURO and the PentIAQ, respectively during the comparison.

Figure 4 – The SURO (left) and the PentIAQ air samplers used

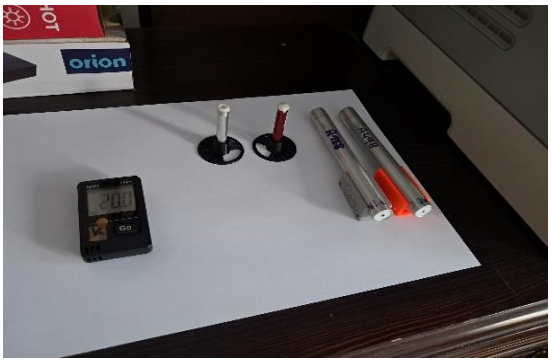

Figure 5 – The SURO (right) and the PentIAQ emission sources used

The results of the comparison are presented in tabular form in table 9 and graphically in Figure 6, as well. Table 9 shows the average air exchange rate value for each object (house) over the whole measurement period and its total uncertainty for the coefficient of expansion k=1 measured by both laboratories.

In the Figure 6, a comparison plot of the average air exchange rate values measured by the SURO from each object is presented, ordered by values in ascending order on the x-axis and paired by object with the corresponding average air exchange values measured by the PentIAQ on the y-axis. The total uncertainties of measured average air exchange rates measured by the PentIAQ for expansion factor k=1 are also listed there.

The following two groups (n_{A1} .... n_{A10}) ≈ N_A (μ_A,σ_A^2) and (n_{B1} .... n_{B10}) ≈ N_B ($\mu_{AB}\sigma_B^2$) are distributions of the average air exchange rates measured in the ten objects by the SURO and by the PentIAQ, respectively from the table 9. To decide which type of t-test to use to test whether the means of the two groups are equal, i.e. whether the null hypothesis: μ_A - μ_B =0, it was first necessary to test for both distributions:

- normality

- equality of their variances: $\sigma_A^2 = \sigma_B^2$

Results of using the Shapiro–Wilk test confirmed the logarithmic normal distribution of the both observed groups, and therefore further tests were performed with logarithmic values of n_{Ai}, n_{Bi}. Based on the achieved results of the F-tests, which demonstrated equality of variances of the both groups, the unpaired Two-sample t-test on the mean value was appropriately used. The results of the t-test showed that the null hypothesis tested could not be rejected and therefore the difference between the mean values of μ_A - μ_B was not statistically significant for a significance level of α = 0.05 (95% probability) The mean R ratio was calculated as R = $\frac{\mu_A}{\mu_B}$ = 1.06 with 95% confidence limit of R (1.17 - 0.98). In other words, the SURO results are on average overestimated by approximately 6%.

Table 9 – The results of inter-comparison for estimation the air change rate performed in 10 Czech houses.

Table of results				
Object: No./ type/ volume/zones	**SURO**		**PentIAQ**	
Quantity	n_A**(1 /h)**	$u(n_A)$ **(1/h)**	n_B**(1 /h)**	$u(n_B)$ **(1/h)**
1. (A)/219/1	0.352	0.043	0.330	0.030
2. (A)/240/1	0.604	0.076	0.470	0.033
3. (A)/167/1	0.320	0.044	0.420	0.076
4. (A)/199/1	0.240	0.035	0.390	0.039
5. (A)/130/1	0.277	0.038	0.300	0.012
6. (FH)/232/2	0.325	0.064	0.280	0.042
7. (FH)/457/3	0.428	0.096	0.240	0.274
8. (FH)/213/3	0.887	0.381	0.820	0.025
9. (FH)/380/2	0.235	0.054	0.230	0.035
10. (FH)/468/4	0.464	0.172	0.340	0.313

LEGEND:

A denotes measured object of type apartment

FH denotes measured object type family house

Volume denotes estimated internal volume of a measured object in m^3

Zone denotes the whole internal volume of the measured apartment or an each individual floor of the measured family house

n_A, n_B denotes the average air exchange rate in a building measured by the SURO or the PentIAQ, respectively in (1/h)

u_A, u_B denotes the total uncertainty of the measured average air exchange rate in a building estimated by the SURO and the PentIAQ, respectively in (1/h).

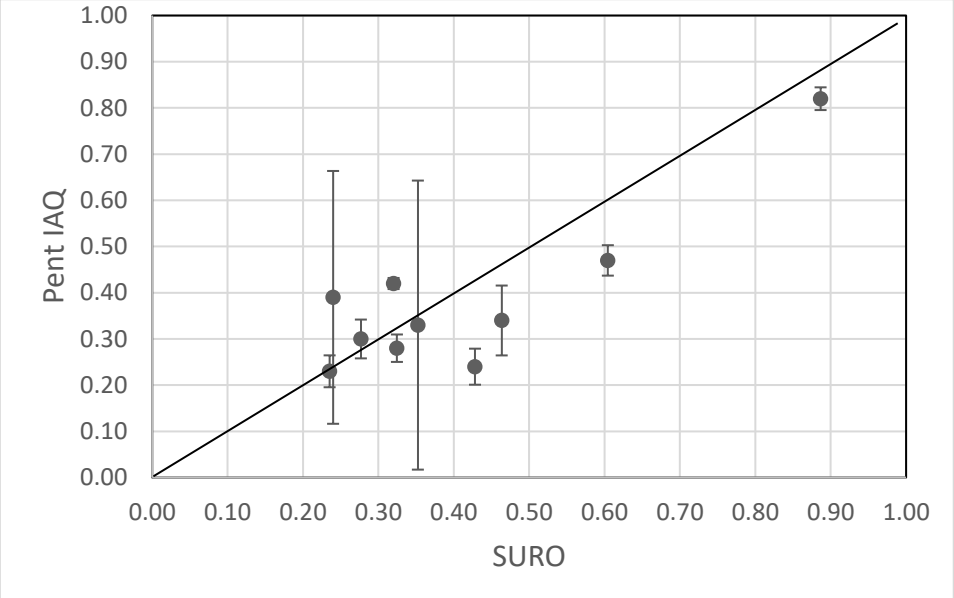

Figure 6 – The comparison plot of the average air exchange rate values measured in pairs by object in ascending order the SURO vs. the PentIAQ