Results of the 2019 International Comparison of Radon/Thoron and Radon Short-lived Decay Product Measurement Instruments at the NRPI Prague

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ABSTRACT

During the 9th International Conference on Protection against Radon at Home and at Work held in September 2019 in Prague, the 5th international comparison of radon/thoron and radon short-lived decay products measurement instruments was organized by and held at the Division of the Natural Sources of Irradiation of the National Radiation Protection Institute (NRPI, SÚRO v.v.i.) in Prague.

The main goal of these international comparisons was primarily to assist participants in their accreditation process. In addition, the instruments were tested in radon atmosphere under special conditions, which can strongly affect their responses. For these tests the parameters as humidity, aerosol concentration, aerosol size distribution were varied so that the measurement conditions more corresponded to the real situation occurring in houses or workplaces.

The NRPI radon calibration facility based on a big (45 m^3) radon and a small (150 dm^3) radon/thoron chambers and relevant measurement standards allow to compare the measurement ability of all the existing types of radon/thoron and radon decay product measurement instruments (spot, passive integral detectors and, continuous monitors) with the NRPI reference instruments traceable to national standards.

The NRPI declares results with the combined standard uncertainty (k=1) of the activity concentration better than 5 % (in range 1-10 kBq/m^3) for ^{222}Rn in air , better than 10 % (in range 1-10 kBq/m^3) for ^{220}Rn in air and the same uncertainty also for radon and thoron mixtures. In addition, the NRPI declares uncertainty (k=1) better than 10 % (in range 1-10 kBq/m^3) for equivalent equilibrium radon concentration (EEC) and better than 15 % for unattached fraction of EEC (f_p).

In total, 13 laboratories from nine countries took part in this international comparison. They submitted 14 continuous monitors, six passive integral systems for radon measurements and one continuous monitor for measurement of radon short-lived decay products (EEC) in the walk- in radon chamber. Additionally, a unique continuous radon/thoron diffusion monitor and two radon/thoron discriminative integral systems based on solid state alpha track detectors (SSNTD) and electrets ion chamber (EIC), respectively were submitted for separate measurement of ^{222}Rn/^{220}Rn activity concentration in their mixtures carried out in the small NRPI radon/thoron chamber.

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Both radon and thoron and primarily their short-lived decay products are the largest contributors to the radiation dose from inhalation of the natural radionuclides at homes and at workplaces. While passive integral detectors are frequently used for wide-range surveys of radon/thoron activity concentration in homes, continuous monitors are usually used both during special radon diagnostic measurements performed in homes and as the key instruments in the scope of relevant QA/QC programmes for radon/thoron and their short-lived progeny measurement.

The Division of the Natural Sources of Irradiation of the NRPI plays the key role in the Czech National Radon Programme. Within its scope a lot of special radon diagnostic measurements are carried out. They are focused on investigation and location of the radon pathway into a house, quantification of radon entry rate into a house and dose assessment [1,2].

For this reason besides the routine measurements of ^{222}Rn activity concentration and equilibrium factor F, the NRPI also provides measurements of special quantities such as unattached fraction of EEC (f_p), air exchange rate, aerosol size distribution, air flow rates and thoron activity concentration.

In order to guarantee the quality of these measurements, the internal NRPI QA/QC programme for relevant instruments was established. Currently, the Division of the Natural Sources of Irradiation is accredited by the Czech National Accreditation body according to the ČSN EN ISO/IEC 17020:2008 to perform radon measurements in a house. The QA/QC programme and radon calibration facility enable to assure quality measurements for all the types of measurement instruments (spot, passive integral, continuous) for quantities as follows:

- ^{222}Rn activity concentration in air
- ^{220}Rn activity concentration in air
- mixture of ^{222}Rn /^{220}Rn
- equivalent equilibrium ^{222}Rn or ^{220}Rn concentration (EEC)
- unattached fraction for ^{222}Rn or ^{220}Rn decay products (f_p)

The programme is based on the traceability of reference instruments to national standards and on the independent comparisons of the NRPI reference instruments with measurement standards of the renowned laboratories. The crucial role in the programme plays the both radon chambers [3,4,5,6,7] and HPGe gamma ray spectrometry system.

During the 9th International Conference on Protection against Radon at Home and at Work held in September 2019 at Prague, the 5th international comparison of radon/thoron and radon short-lived decay products measurement instruments was organized by and held at the Division of the Natural Sources of Irradiation of the NRPI. The main goal of these international comparisons was primarily to help participants in their accreditation process. In addition, the instruments were tested in radon atmosphere under special conditions, which can strongly affect their responses. For these tests the parameters as humidity, aerosol concentration, aerosol size distribution were varied so that the measurement conditions more corresponded to the real situation occurring in houses or workplaces.

In total, 13 laboratories from nine countries took part in this international comparison. They submitted 14 continuous monitors, six passive integral systems for radon measurements and one continuous monitor for measurement of radon short-lived decay products (EEC) in the walk- in radon chamber. Additionally, a unique continuous radon/thoron diffusion monitor and two radon/thoron discriminative integral systems based on solid state alpha track detectors (SSNTD) and electrets ion chamber (EIC), respectively were submitted for separate measurement of ^{222}Rn/^{220}Rn activity concentration in their mixtures carried out in the small NRPI radon/thoron chamber.

1 MEASUREMENT FACILITY

I. The walk-in NRPI radon chamber

The chamber is a 48 m^3 in volume, with airlock. It allows the following quantities to be adjusted, held stable, monitored and recorded:

- ^{222}Rn concentration in air
- equivalent equilibrium ^{222}Rn /^{220}Rn activity concentration in air (EEC),
- unattached fraction of ^{222}Rn /^{220}Rn decay products (f_p)
- air exchange rate (ACH)
- air temperature and its relative humidity
- monodisperse/poly-disperse aerosol concentration, size distribution ranging from about 100 nm up to 3µm prepared from liquid NaCl or solid carnauba wax generator

^{222}Rn

The chamber inner atmosphere concentration can be adjusted and kept stable from about 200 Bq/m^3 up to 100 kBq/m^3. The stable steady state of radon concentration is reached by means of known, constant and adjustable radon entry rate to the chamber and defined, stable and measured ACH. The required magnitude of radon entry rate can be easy reached and changed depending on the use of a various activity solid state ^{226}Ra/^{222}Rn flow through sources. These sources are certificated by their manufacturer the Czech Metrology Institute (ČMI) on their ^{226}Ra activity and corresponding ^{222}Rn emanation power.
During any exposure in the chamber, the radon concentration is continuously monitored using reference monitors type AlphaGUARD or/and type RAD7 placed in the chamber. Additionally, the chamber inner atmosphere is usually sampled twice a day with reference scintillation cells type NY.
The final NRPI reference value is calculated from response of the used reference continuous monitor corrected to the results obtained from the NY scintillation cells. The NY cells were originally calibrated by means of the NRPI primary radon standard based on pulsing ion chambers [3, 5]. Newly, the cells were recalibrated by means of a new NRPI radon standard based in principle on properties of used solid state ^{226}Ra/^{222}Rn flow through sources. The sources are certified at the ČMI on their production rate of ^{222} Rn with the total uncertainty better than 1.5 % (k=1).
In order to avoid effects of an absolute humidity to responses used reference instruments (RAD7, NY scintillation cells) we use a proper desiccant during sampling. The influence of primary radon decay products during sampling was eliminated using of a special 3D 0.45 µm nylon filter.
All the NRPI reference radon gas instruments were successfully compared with the renowned laboratories as the Physikalisch Technische Bundesanstalt (PTB) Braunschweig (Germany), the BfS Berlin (Germany) and the Authorized Metrological Centre SUJCHBO Kamenna (Czech Republic).
With respect to primary calibration uncertainties about 3% (k=1) of the NRPI reference instruments, the relative combined standard uncertainty (k=1) can be estimated better than 5% for testing radon concentration about 9 kBq/m^3

Air exchange rate (ACH)
The air exchange rate in the chamber can be easily adjusted, changed and kept stable in the range from 0.05 h^{-1} to 2 h^{-1} by means of the chamber built-in ventilation system. The ACH can be continuously measured by means of the tracer gas method [2] based on stable and defined tracer entry rate into the chamber. As a tracer gas we use N_2O or SF_6. The relative combined standard uncertainty of ACH could be estimated better than 5% (k=1).

Equivalent equilibrium radon gas activity concentration (EEC) and f_p
For this international comparison, a continuous monitor of unattached and attached activity of each radon short-lived decay products Fritra4 was used for measurement both EEC and f_p.
The monitor Fritra4 was calibrated for EEC and f_p against the NRPI reference radon daughter products measurement instrument (NRPI-RRDPMI) based on one grab samplings simultaneously through the diffusion screen on the Millipore 0.8µm filter type AA placed behind the screen [3,4]. The activity of each decay product collected on both the screen and the filtr was determined by means of alpha and HPGe gamma ray spectrometry calibrated using ČMI standards.
Additionally, the reference monitor Fritra 4 was compared with relevant standards of the PTB, the BfS and the SUJCHBO with agreement up to 5% .
For independent assessment of f_p and equilibrium factor F we adopted following two approaches based on the application of the Inversion method of the Jacobi-Porstendörfer room model [4,7] and on measurement of aerosol size distribution and aerosol concentration [8].
To obtain high values of the equilibrium factor F and corresponding low values of f_p, which are related to high aerosol concentration, the carnauba wax aerosol generator was used. On the other hand, to produce simultaneously low equilibrium factor F and high values of f_p an electrostatic aerosol precipitator including fan was applied.
Having in mind primary calibration uncertainty EEC better than 8% (k=1) for monitor Fritra4 and its counting statistics better than 5% during adjusted and stable testing levels of EEC, then the relative combined standard uncertainty of measured reference EEC in the chamber can be estimated better than 10% (k=1).
Taking into account the results of the comparative measurements of f_p carried out with the monitor Fritra4 at the PTB [4], counting statistics and calibration uncertainty of the monitor derived from the calibration obtained by the NRPI RRDPMI instrument [3], values f_p uncertainty was estimated about 15% (k=1) .

Total aerosol concentration and size distribution in the chamber
The total aerosol concentration and particle size distribution ranging from 5 nm to 1100 nm were measured by means of an aerosol measurement instrument SMPS+C (Grimm, Germany) comprising CPC (ultrafine particle counter) and DMA (Differential mobility particle analyser). Due to possibility to measure total aerosol concentration and dynamic range of aerosol diameters in the chamber the instrument provided input data for an independent estimation of f_p in the chamber [8].

Exposure conditions
Temperature and relative humidity in the chamber was measured and controlled during the exposure. Temperature was controlled by means of heating and cooling system JDK^{Tm} (CZ) and relative humidity by means of the device Hygrotest HG 600 PHT (TESTO). The aerosol generator based on carnauba wax produced particles of the regular spherical shape in total aerosol concentration (***Z***) of the order 10^4 p./cm^3. The aerosol size distribution could be represented by geometric mean (GM) GM = (100-150) nm with corresponding GSD = 1.5.

The list of measured and controlled parameters in the big radon chamber is summarized in the Table 1.

II. The small NRPI radon/thoron chamber

The chamber is a 150 dm^3 stainless steel cylindrical vessel with approximately 80 cm height and 45 cm in diameter without an external thermal isolation. The chamber shell has built-in one multi-pin and five bushings for gas inlet/outlet. The bushings allow using of HV power supply devices, e.g. for monitors of internal atmosphere parameters, inside the vessel. The bushings with closing taps allow the chamber filling with gas mixture prepared in an external radon/thoron source and sampling of the internal atmosphere by an external device. The two wire shelves built-in the chamber allows to create two levels which can be independently moved up or down.

^{222}Rn/^{220}Rn concentration

Required ^{222}Rn/^{220}Rn activity concentration inside the chamber was adjusted by means of flow through ^{226}Ra/^{222}Rn source placed outside of the chamber and by ^{228}Th/^{220}Rn emanation source fixed on the inside wall of the chamber, whereas both sources are characterised by well-known stable radon/thoron production. The flow through radon source was coupled to a stable pump and a precision flowmeter, which together ensured atmosphere with a stable, well-defined ^{222}Rn/^{220}Rn activity concentration.
The ^{222}Rn/^{220}Rn activity concentration was continuously monitored and recorded by means of a reference monitor RAD7, which was externally connected, through the DRYSTIK, to the chamber. This monitor enables to distinguish radon/thoron activity concentrations in the mixture. The monitor was calibrated (last in 2012) on the primary thoron atmosphere at the PTB and then was periodically checked at the NRPI using ^{226}Ra/^{222}Rn and ^{228}Th//^{220}Rn flow through sources certified by the ČMI.

Homogeneity of the chamber internal atmosphere

Generally, the homogeneity was assured by means of using two fans placed inside the chamber, the first small one (of input power about 1 W) was fixed closely to thoron source to ensure its high emanation, the second 50 W fan was used for mixing of the whole chamber volume.
Homogeneity was checked by three RAD7 monitors, whereas the atmosphere was sampled from top, centre and bottom of the chamber. This test has been done in a separated study. Additionally, the homogeneity was also checked with use of a large number of a radon/thoron discriminative electret ion chambers.

Uncertainty

Concerning the uncertainty of radon activity concentration, the source production for used ^{226}Ra/^{222}Rn source was certified by their producer (ČMI) with uncertainty up to 1.6 %. In the case of thoron, the source production of the used ^{228}Th source was based on the NRPI HPGe gamma ray spectrometry measurement results [6] with uncertainty up to 5%. The next significant components of the uncertainty were derived from the determination of the air flow rate through the radon source, volume of atmosphere in the radon chamber filled with devices (free volume for gas), homogeneity and radon concentration in the inflow air used for the radon flow through source.
Then, the combined uncertainty of each measured value of radon and thoron concentration in their mixture can be estimated for k=1, better than 5% for radon and 10% for thoron, respectively.

Exposure conditions
In the chamber, just two parameters, temperature and relative humidity were continuously measured and recorded by means of a transducer TESTO 174H.

2 MEASUREMENT INSTRUMENTS

In total, 13 laboratories from nine countries took part in this international comparison. They submitted 14 continuous monitors, 6 passive integral systems for radon measurements and one continuous monitor for measurement of radon short-lived decay products (EEC) in the big radon chamber.
Additionally, a one unique radon/thoron diffusion continuous monitor and two radon/thoron discriminative integral systems based on solid state alpha track detectors (SSNTD) and electrets ion chambers (EIC), respectively were submitted for separately measurement of radon/thoron in their mixture performed in the small radon/thoron chamber.
The six SSNTD and four radon EIC of the E- perm system were exposed in the mixture of radon/thoron in the small chamber to estimate only radon activity concentration. Each submitted passive integral system included more than one set of the solid state alpha track detectors or electrets.
The review of institutes and instruments participating in the international comparison is shown in Tables 2-3. The review of instruments sorted according to their identification numbers (ID) and type of the exposures in more details is shown in the Tables 4 -5. Since radon/thoron diffusion monitor Scout is a relatively new and unique instrument, a separate paragraph was devoted to present its results. Therefore, it was excluded in the Table 5.

3 EXPOSURES

In accordance with the main goal of the international comparison the following scenarios were performed and evaluated in the NRPI chambers:

- Scenarios A_1,A_2: The exposure of continuous monitors and passive integral systems for measurement of radon concentration, EEC or/and f_p in the big chamber under two different exposure conditions differing in values of equilibrium factor F and f_p for radon and its short-lived decay products.
- Scenarios B_1,B_2: The exposure of passive continuous monitors and integral systems in defined radon/ thoron mixture in the small chamber under two different exposure conditions differing only in ratios of radon and thoron activity concentrations.

I. Exposure in the big radon chamber (A_1, A_2 scenarios)
Prior to the installation of all the instruments, steady-state radon concentration and defined exposure conditions were set up in the chamber. Radon concentration was continuously monitored and recorded by means of the NRPI reference monitor AlphaGUARD set to hourly records.
In addition, twice a day, the chamber inner atmosphere was sampled into the NRPI reference scintillation cells type NY. Simultaneously, each two hours, also EEC and f_p were monitored

by means of the NRPI reference continuous monitor Fritra4. Besides that, twice a day, the chamber inner atmosphere was sampled by means of the one-grab samplings through the diffusion screen mounted in front of the Millipore 0.8µm, AA filter This measurement was done to estimate unattached and attached activity of each short-lived radon decay product f_p and EEC.

In order to check the influence of equilibrium factor F and f_p on the response of tested instruments the aerosol concentration was changed by means of the chamber accessories. To increase the aerosol concentration and at the same time to increase factor F we injected a solid spherical aerosol from the carnauba wax aerosol generator. On the other hand, to reduce factor F and to increase f_p we used the electrostatic air cleaner TRION.

During injection of aerosols, the aerosol concentration ***Z*** and the aerosol size distribution were characterised in "the steady state" by GM= 200 nm, GSD =1,8, ***Z*** = 7500 p/cm^3. After reduction of the aerosols concentration the chamber inner atmosphere was characterised by the steady state values of ***Z***= 500 p/cm^3, GM= 90 nm, GSD =2,1. With respect to character of tested instruments and considering that the stability of the affecting factors f_p and equilibrium factor F, the following two time periods of scenarios A_1 and A_2 was selected:

For continuous monitors
scenario A_1: 16.9.2019/22:00 - 18.9.2019/14:00
scenario A_2: 19.9.2019/03:00 - 20.9. 2019/08:00

For integral passive detectors
scenario A_1: 16.9.2019/16:00 - 18.9.2019/14:49
scenario A_2: 18.9.2019/15:00 - 20.9. 2019/09:00

Time variations of radon concentration, equilibrium factor F and f_p during selected time periods can be seen from Fig.1. The relevant conditions are summarized in Table 6.

II. Exposure in the small radon/thoron chamber (scenarios B_1, B_2)

Prior to install of all the compared instruments in the chamber, the ^{228}Th/^{220}Rn emanation source was properly placed on the chamber wall. Then the chamber built-in ventilation system was switched - ON and the chamber was immediately closed. After that the ^{226}Ra/^{222}Rn source, stable pump, precise flow meter Defender type 530 (S.K.C. U.S.A.) and the reference continuous monitor RAD7 were externally connected to the chamber, the exposure was started. This experimental set up allowed easy to create steady state ^{222}Rn/^{220}Rn concentration in the chamber in a short time (several minutes) after installation of all the compared instruments.

The inner chamber temperature followed an external laboratory temperature about 23.5 ^{o}C, the inner relative air humidity varied from 35% up to 45%.

With respect to character of measurement instruments and quality of provided results the following two time periods of the scenarios B_1 and $B_{2,}$ differing in ratios of radon/thoron concentrations were selected:

For continuous monitor
scenario B_1: 16.9.2019/16:00 - 17.9.2019/13:00
scenario B_2: 18.9.2019/15:00 - 20.9. 2019/07:00

For integral passive detectors
scenario B_1: 16.9.2019/13:00 - 18.9.2019/09:12
scenario B_2: 18.9.2019/12:32 - 20.9. 2019/07:30

The time variation for both radon and thoron during selected time periods is illustrated in Fig.2.

4 LOGISTICAL ARRANGEMENT

Each participant was informed about the dynamic range of relevant exposures planned during this international comparison in advance. One was also asked to provide results in terms of all measured records from every used continuous monitor and in terms of measured time exposure integral and corresponding standard deviation from every exposed passive detector or continuous monitor.
Serial numbers of all the monitors and each of the submitted passive detectors were also required. After the end of all the exposures all the monitors and detectors including passive transit detectors were returned to the participating laboratories for evaluation of results.

5 DATA TREATMENT

The results for all the monitors were obtained by comparing their data with the reference monitor's data. This fact should be considered while interpreting the results. Although the experiments were designed in such a way that the reference values were supposed to be as close to real values as possible there can still be some differences. Formally, the correct interpretation is that there was (or was not) found the significant difference between data from a monitor and data from the reference monitor.
Besides residual statistical errors the uncertainty of the reference values was increased by an additional uncertainty that represents possible deviation of the mean value of the reference monitor from the real value (this uncertainty is for instance caused by uncertainty in calibration).
This uncertainty represents possible bias, hence the error is shared across all the reference monitor's continuous measurements in the each scenario. The value of this additional uncertainty depends on the scenario (A_1, A_2, B_1, B_2), measured quantity (radon, thoron) and type of the reference monitor (AlphaGuard, RAD7). See Table 7.
This additional uncertainty was only considered for the reference monitors. It can happen that statistical test shows a significant difference from the reference monitor but at the same time the difference is tolerable for a given monitor (for instance it is within range given by additional uncertainty for a given monitor). While interpreting the result where the tests showed significant difference, the severity of a difference should always be assessed with respect to requirement for a given monitor.
The data analysis was done in R software [9]. Across all the scenarios A_1, A_2, B_1, B_2 the same methods for data analysis was used. They only differed in variables that were used to calculate the results. Hence in the following section the mathematical formulas are only described for scenarios A_1 and A_2. While summarising the results of statistical testing usual value of the test level of 5% was assumed.

A. Scenarios: A_1 and A_2

1. Continuous monitors

For the analysis only the subset of data - where quantities that could possibly affect the results were stable (factor F, f_p) - was considered. Mainly the beginning of the investigated time periods was removed. Time periods considered during the analysis are listed at beginning of Section 3.

In both scenarios the following two null hypotheses were tested for each monitor separately:

- The first null hypothesis was hypothesis if a tested monitor measured the data in the same shape as the reference monitor. The term “same shape” is considered as the same pattern of dependence of measured values on time. The difference in mean values is not considered while testing the hypothesis. In the following text this hypothesis is called as “same shape of temporal variations as reference values.”
- The second null hypothesis was hypothesis if there was no difference between mean value of a monitor and the mean value of the reference monitor.

It means that a monitor can differ in shape and it can also be biased from the reference monitor. Applied approach can for instance distinguish cases where a monitor had relatively small bias but at the same time the measured values have different shape from the reference monitor.

Data from some monitors were collected in shorter intervals than 60 minutes (for instance 10 minutes). Further measurements for some monitors were not collected every hour but in different times. To make a graphical representation clearer and to make application of some methods easier the individual measurement for each monitor were averaged to be on hourly basis and the measurements were assigned to hours closest to the actual time of measurements.

Test of the same shape of temporal variation as reference values

To test whether a tested monitor in each investigated time period produced data in the same shape (but not necessary with the same mean value) as the reference monitor the regression F-test of sub-model was used. The shape of measured data was approximated by a linear combination of natural cubic splines with 4 degrees of freedom for the reference and for a tested monitor (intercept not included in the natural cubic base). It was tested whether the data for both monitors together can be described by the model where the coefficients for natural cubic splines base are the same for both monitors (intercept can be different for both monitors). In statistical terminology it was tested whether there is a significant interaction between monitor and natural cubic spline base. Rejecting hypothesis (e.g. p-value < 5%) means there is significant difference in shape. Note that the test is approximate since the variances of residual errors can differ for both monitors. But it was not expected that this would strongly affect the statistical results. The weighted regression was therefore not used. Also because of often unrealistic reported residual uncertainties weighting could affect the results more than no weighting.

Test of the difference between mean value of a monitor and mean value of the reference monitor

To test if there was a difference between the overall mean value of the reference monitor and overall mean value of a tested monitor test based on modified Z-statistics calculated from pair differences, (EQ01), was used.

$$Z = \frac{|X|}{\sqrt{\sigma_X^2 + \sigma_0^2}} \quad \text{(EQ01)}$$

where X is average of differences between measurements for a tested monitor and for the reference monitor, i.e. the average of $X_i = M_i - R_i,\ i = 1, \dots, n,$ where M_i, R_i are values from a tested monitor and the reference monitor and n denotes number of hourly measurements during given period. Parameter σ_X^2 is the estimate of variance of X (variance of the average), i.e. $\sigma_X^2 = \frac{1}{n(n-1)} \sum_{i=1}^{n} (X_i - \overline{X_n})^2$, where $\overline{X_\mathrm{n}}$ is average of X_i. Finally, $\sigma_0 = u\overline{R_n}$ is the standard deviation for the additional uncertainty. Symbol $\overline{R_n}$ denotes the average of the reference values during given period. Parameter u denotes the value of additional uncertainty from Table 7.

In the both scenarios A_1 and A_2 is $u = 0.03$. Z-statistics follows approximatively normal distribution. The test yields a p-value. If p-value < 5% we reject the hypothesis that overall mean values for a tested monitor and the reference monitor are the same. Note that the mean value of the reference monitor during scenarios A_1 and A_2 was changing with time and hence using the overall average could lead to oversimplified, imprecise or even incorrect results. In particular, it can happen when there was significant difference between the shape of a monitor and the reference monitor. If there was no significant difference between the shapes of a monitor and the reference monitor the test yield reasonable results.

Ratio of overall means

In order to quantify observed difference between the reference monitor and a monitor overall mean values we define r - ratio as follows:

$$r = \frac{M}{R} \quad \text{(EQ02)}$$

where M is average of a monitor values over given period
R is average of the reference monitor over given period.

Variance of variable r is approximated, using Taylor's formula, as:

$$\mathrm{var}(r) = \frac{M^2}{R^2} \left(\left(\frac{\sigma_M}{M} \right)^2 + \left(\frac{\sigma_R}{R} \right)^2 \right) \quad \text{(EQ03)}$$

where σ_M is the estimate of standard deviation of M.
σ_R is the estimate of standard deviation of R.

The approximate 95% confidence interval for ratio of the two means (r) is constructed adopting the Fieller's theorem [10] in a usual way as $r \pm 2\sqrt{\mathrm{var}(r)}$. The results can also be affected by different shapes of functions with measured values hence similar thoughts as in the section "Test of the difference between mean value of monitors and mean value of the reference monitor" holds here. Further, for higher values of standard deviations the Fieller's formula is very approximate and thus in cases when 95% interval is not in coincidence with the result of test of the difference of overall means the result of the latter is preferred.

2. Integral detection systems

All the compared integral detection systems of each institution included usually more exposed track detectors or electret ion chambers. They were installed and removed at approximatively equal times. The reference values for scenarios A_1, A_2 were calculated as the average of values from the reference monitor that were recorded during investigated time period in time between installation and removal of the monitors. While the temporal variations of measured values cannot be tested for integral systems, the approach for the rest of data treatment is a very similar to that for continuous monitors.

As it was mentioned in the previous sections, since the mean value of the reference monitor changes with time, the results are approximate, only.

Note that the statistical results are based on reported values of uncertainty by participants. If these values are overestimated a significant difference could not be shown even in cases when the actual difference is high.

Test of the difference between measured value of a tested monitor and the mean value of the reference monitor

The test is based on equation (EQ01), where $X = M - R$ is the difference between a tested monitor (M) and the reference value (R). Value of σ_X^2 is calculated as $\sigma_X^2 = \sigma_{R0}^2 + \sigma_M^2$ where σ_{R0}^2 is estimate of variance of the average R (see previous sections for details) and σ_M is a standard deviation for a tested monitor value M reported by a participant together with measured value. Parameter σ_0, $\sigma_0 = uR$, denotes the standard deviation for the additional uncertainty. Parameter u denotes the additional uncertainty from Table 7. It holds that $u = 0.03$ in both scenarios A_1 and A_2.

Ratio of overall means

The approach for continuous monitor was used. Variables M, R and the parameters σ_M, σ_0 in equation (EQ03) have the same meaning as in the previous section. The variance σ_R^2 in the equation is calculated as $\sigma_R^2 = \sigma_{R0}^2 + \sigma_0^2$.

B. Scenarios B_1 and B_2

1. Integral detection systems

The results from all the integral detection systems exposed during these scenarios were treated for both radon and thoron exactly in the same way as those obtained from the integral detection systems exposed during the scenarios A_1, A_2 . Reference values were calculated from time periods corresponding to exposure time of exposed integral detection systems in the chamber. See the beginning of Section 3.

Since radon and thoron gas activity concentration in the chamber could be considered as stable in time (the mean value substantially did not change with time) the statistical results are relatively precise.

Note that the statistical results are based on reported values of uncertainty by participants. If these values are overestimated a significant difference could not be shown even in cases when the difference is high.

2. Continuous monitors

The data from only one continuous monitor exposed during these investigated periods was analysed (both for radon and thoron) in the same way as the data from all the continuous monitor exposed during investigated periods A_1, A_2. The time period considered for the analysis can be seen at the beginning of Section 3.

The reason for shortened time period B_1 is mainly because for the rest of the period the data were not provided to us. Further, some measurements at the beginning of the periods during scenarios B_1 and B_2 were removed since they differed from the rest of the data and they have relatively high impact on results (possible outliers).

C. Other statistics tools used during the analysis

For some hypothesis Welch Two Sample t-test was used. It compares the mean values of the populations with different variances, [12]. This test was mainly used to test if there was a difference between two types of monitors.

To test whether the mean value of data from a tested continuous monitor is dependent on time (suffers from a seasonal variation) the regression F-test of submodel is used. We test whether the model with only intercept term describes data statistically equally well as a model where dependence on time is approximated by linear combination of natural cubic spline base (for our purpose 4 or 5 degrees of freedom describe the data well). This test was used to test whether the continuous reference monitor data depends on time.

To test whether values are homogenous (i.e. their differences are caused only by measurement error) the Cochran's test for heterogeneity is used, see [11]. This test was used the test hypothesis if values from some set of monitors are homogenous.

D. Other diagnostics tools

Funnel plot

The funnel plot is defined as a scatterplot of standard deviations of values (e.g. standard deviations of the means for continuous monitors or reported uncertainty for integral systems) vs. values (e.g. the average for continuous monitors or measured value for integral systems). Additionally, the line with grand mean and lines with grand mean ± standard deviations of means are plotted. These lines form a cone. About 95% of points (monitors) should lie inside this cone if no heterogeneity between monitors occurs. Points near the apex are "state of the art" results, points far from the apex in the direction of y-axis means results with high measurements error (uncertainty), points on the left or on the right side of the plot means biased results (because of heterogeneity).

Grand mean was calculated as a weighted average of individual values for all the monitors. The weights are composed of the uncertainty of measured values together with a heterogeneity of values and are estimated using restricted maximum likelihood model for meta-analysis, [11]. Using this model also the heterogeneity among measured values for different monitors can be tested.

Box plot

The box-plots results compare distributions of measured radon gas concentrations between continuous monitors. The bold horizontal line in the box represents median, the ends of the box are the first and third quartiles. The narrow horizontal line represents the mean. Whiskers sprouting from the two ends of the box represent the sample lowest and highest observations which are in the distance of 1.5 times the interquartile range (IQR) from the box. Data which

are further than 1.5 times IQR from the box are represented by a dot and can be considered as outliers.
The box length IQR gives an indication of the sample variability. A symmetric boxplot suggests that the data has an asymmetric distribution. Dotted lines delimit distance ± 5 % and ± 20 % from the reference mean value.

Forest plot
Forest plot provides similar graphical information as the funnel plot. It represents measured values together with 95% confidence interval (calculated using standard deviation of the measured values). Further it shows grand mean estimated using restricted maximum likelihood model for meta-analysis, [11]. This estimated takes possible heterogeneity of values into account. Additional information was added in the plot as red lines showing reference mean and reference mean plus minus 5% and 20%.

RESULTS AND DISCUSSION

No serial numbers of monitors and no association between results for specific monitor and an institute are provided in this report. To provide potentially useful information, the labels for monitors were encoded in the format X/Y/Z,
where

- X is the identification number of participant (institute),
- Y is identification number of the monitor,
- Z denotes the type of monitor.

Each participant receives a key to be able to identify their monitors. Note that for scenarios A_1, A_2 the reference values for radon activity concentration are obtained from the reference NRPI continuous monitor AlphaGuard. It can possible cause that participants with the same type of monitor are potentially favoured in the comparison. It should be considered while interpreting the results.

Beside the random error fluctuations of the reference monitor, the addition uncertainty of the main reference value is considered. See the “Data treatment” section and its first paragraphs for more details. This additional uncertainty is not considered for participants’ monitor. This fact also should be considered while interpreting the results – it can possibly happen that a test suggests significant difference from the reference values but the difference falls within tolerable range for a given monitor type.

Continuous monitors A_1
Figs. 3 and 4 show data from continuous radon monitors during scenario A_1. Data from monitors 4/1/RADIM3A, 7/1/RADIM3AT, 7/2/RADIM3AT were far from the reference (and the average of remaining monitors). These monitors have also very different shape of temporal variations than the reference monitor. The reference values significantly ($p < 10^{-9}$, see section other statistics tools) depend on time during the investigated period. They fluctuate from approximatively 8500 Bq/m^3 to 10200 Bq/m^3.
See Table 8 for results. Nine of 14 monitors had significantly different shape of temporal variations than the reference monitor. Monitor 7/5/RAD7 had slightly different shape from reference monitor only at the beginning of the period – the monitor there recorded higher

values than the reference monitor, at the remaining part the monitor produced lower values but there it followed the shape of the reference monitor. The higher values at the beginning and the lower values at the remaining part are the reason why the overall bias is low. Monitor 5/1/RSC differs mainly approximatively in the middle of the period A1 where it produced higher values. Monitors 6/1/TERA and 6/2/TERA are relatively far (higher values) from the reference values at the beginning of the period A_1, then they are both closer to the reference values. Monitor 6/1/TERA then recorder lower values that caused that its overall bias was very small. These biased TERA monitors were from one institute. The other two TERA monitors produced substantially better results. Monitor 5/1/RSC differed mainly in the middle of the period A_1.
Five of 14 monitors recorded very different values from the reference monitors. The averages or the remaining monitors was not further than 5% from the average of the reference monitor. See Fig. 5 for boxplot. Note that the height of the boxes in the boxplot is largely caused by temporal variations of the mean value and not by measurement error.
Despite the possibility of measurement of equilibrium factor F and f_p, no results for the both scenarios A_1, A_2 was provided to analysis, because the only one submitted continuous monitor did not start.

Continuous monitors A_2
Fig. 6 shows data from continuous radon monitors during scenario A_2. Fig 7 shows more detailed view of the measured data. Data from monitors 4/1/RADIM3A, 7/1/RADIM3AT, 7/2/RADIM3AT, 8/1/TERA and 8/2/TERA were again very far from the reference (and the average of the remaining monitors). Further, monitor 3/1/AG recorded values exhibited unusual variability (Fig. 6.), therefore the data from this monitor were not analysed.
During scenario A_2 the experiment was more stable (in sense that radon mean values did not suffer from high temporal variation) than in the period A_1. But the dependence of reference values on the time was still significant (p-value < 10^{-6}). Further behaviour of all the monitors except 3/1/AG were also more stable. There was no initialization period as in the period of the scenario A_1 where recorded values from some monitor started to approach the reference values.
The results are similar to results for period of scenario A_1. See Table 9 where the results are summarized. The difference in shape of temporal variations is not as noticeable as in A_1. Four (two RADIMs. two TERAs) of 14 monitors had different shape of temporal variations than the reference monitor.
Five of 14 monitors (three RADIMs and two TERAs) were biased with respect to the reference monitor. Similarly to A_1 the difference between their mean values and the mean value of the reference monitor were high.
The overall mean of all the remaining monitors stayed close to the mean of the reference monitor. See Fig. 8 for boxplot. Note that the height of the boxes in the boxplot is largely caused by temporal variations of the mean value and not by measurement error.

Passive integral systems A_1
There were total 14 integral systems. All the values were close to the reference mean. None of the difference exceeded 10% of the reference value and none of the monitor recorded significantly different value than the reference value. Table 10 summarises the results. See Fig. 9 to a graphical representation of the data.
The integral systems are only divided into two categories EIC and SSNTD. There were eight SSNTD monitors and six EIC monitors. No significant difference was found between the

mean of SSNTD (9637 Bq/m^3) and the mean of EIC (9255 Bq/m^3) data (p = 7.6%, Welch Two Sample t-test).

Passive integral systems A_2

There were total 19 integral systems (six EIC and 13 SSNTD). The heterogeneity was higher than in A_1 but the difference was significant for only one system (p = 1%). All the systems except one fall within range of ± 10% from the reference value. The p-values for two systems were close to 5%. Table 11 summarises the results. See Fig. 10 to a graphical representation of the data.

There was significant difference between the mean of SSNTD (9331 Bq/m^3) and the mean of EIC (10304 Bq/m^3) data (p = 0.005, Welch Two Sample t-test). The mean (and also variance) for EIC is strongly affected by one far from reference value (3/4/EIC). If this value is removed the mean is 10100 Bq/m^3 and the difference is still significant (p = 0.0009, Welch Two Sample t-test).

Passive integral systems B_1

Radon

There were only provided data from seven (two SSNTD, five EIC) radon integral detector systems for period B_1. Radon values from the reference monitor RAD7 during this period could be considered as stable. See Fig. 11 where the values from the reference monitor are shown. Note that while interpreting the image relatively small range of y-axis should be considered.

One of the seven exposed integral systems recorded significantly different value than the reference value. Remaining monitors fell within range of 90% – 114% of the reference value. The results are summarised in Table 12. Fig. 12 shows the forest and funnel plot for the recorded values.

Thoron

There were only data from five (two SSNTD, three EIC) thoron integral detector systems available. Thoron concentrations from the reference monitor (RAD7) during this period can be considered as stable. See Fig. 11.

Although two integral systems measured values about 165% of the reference values no significant difference was found. Data from these two monitors were provided with very high uncertainty. This high uncertainty can be seen in the forest and funnel plots in Fig. 13. The results are summarised in Table 13.

Passive integral systems B_2

Radon

There were provided data from 13 (eight SSNTD, five EIC) radon integral detector systems for period B_2. Radon data from the reference monitor (RAD7) during this period can be considered as stable. See Fig. 14 for radon data from the reference monitor.

Five integral systems measured significantly different values than is the reference value. Some of these values were not further than other (not significantly different) values. The reason for this is mainly because these values were reported with lower uncertainty than the remaining values.

The measured values ranged from 66% to 144% of the reference value. The results are summarised in Table 14. Fig. 15 shows the forest and funnel plot for the recorded values. See the relatively high heterogeneity of the measured data. The heterogeneity is significant ($p = 0.0002$, Cochran's test for heterogeneity).

Thoron

There were only data from five integral systems (two SSNTD, three EIC) available for the analysis. Thoron data from the reference monitor RAD7 during this period can be considered as stable. Fig. 14 shows data from the thoron reference monitor.

One value (about 165% of the reference value) was significantly different from the reference value. Another value of approximatively 150% of the reference value was not significantly different from the reference value due high reported uncertainty. Remaining three values were close to the reference value. The data are shown in Fig. 16.

Continuous monitor B_1 and B_2

Radon and thoron data for the Scout monitor together with the data from the reference monitor RAD7 are shown in Fig. 11 and Fig. 14.

The data provided to us for scenario B_1 only covered about 50% of investigated time period. The reason why the remaining data were excluded is unknown to us. At the beginning and also at the end of this shortened interval the data were not consistent with the remaining radon data. Their values were much lower that it would be expected. Since these data had big leverage on the statistical results for B_1 they were omitted for purpose of the analysis. See the beginning of Section 3 for the time interval considered during the analysis. For the similar reason the few data points for B2 at the beginning and at the end of the period were also removed.

The results are summarised in Table 16. The difference in shape visible in Fig. 11 for radon was statistically significant. For scenarios B_2 there was not statistically significant different shape from the reference monitor. The overall means for radon are close to the reference value. The difference is less than 3%.

The thoron data from the tested monitor were almost two times higher than the reference values. Despite the additional uncertainty of 10% for the bias of the reference values, the differences were still very statistically significant.

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TABLES AND FIGURES

Table 1. The list of measured and controlled parameters in the NRPI big radon chamber

Parameter	Control	Measurement
Temperature	SW- JDK- cooler/ heater	Continuous measurement- Hygrotest HG 600 PHT
Humidity	SW - (de) humidifier	Continuous measurement- Hygrotest HG 600 PHT
Aerosol concentration	- solid - carnauba wax aerosol generator TRION elst. precipitator - TOPAS SLG 250 liquid NaCl aerosol generator	Continuous measurement- SMPS +C (Ultrafine CPC
Aerosol size distribution	- solid aerosol: GM (0.1 -0.3) μm GSD = 1.8 - liquid aerosol: GM (0.4 - 2)μm GSD = 1.15	Continuous measurement- SMPS +C (Differential mobility analyzer)
Air exchange rate (ACH)	Chamber ventilation system	Continuous monitor of tracer gases (CO, N_2O, SF_6)
Radon concentration	^{226}Ra/^{222}Rn flow through sources and defined ACH in the chamber	Continuous monitor AlphaGUARD PQ 2000 Pro. RAD7 one grab-sampling to scintillation cells NY
Radon decay product concentrations	Used aerosol generator ACH elst. precipitator fans	Continuous monitor Fritra 4 and one-grab samplings on the Millipore 0.8 μm filters type AA. through diffusion screen, α/γ spectrometric evaluation method
Unattached+ attached fraction	as for radon decay product concentration	Continuous monitor Fritra 4 and one-grab samplings on the Millipore 0.8 μm filters type AA. through diffusion screen , α/γ spectrometric evaluation method aerosol method - SMPS +C

Table 2. The list of participants

Institution	Contact Person	E - mail:	Country
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Table 3. The list of measurement instruments

Order	Instrument serial.number	Measured Quantity	Instrument Type	Scenario	Total nu. of SSNTD or EIC
1	RAD 7_ 3713	^{222}Rn	CM	$A_1 + A_2$	
2	AlphaGUARD PQ 2000_ EF-528	^{222}Rn	CM- REF.	$A_1 + A_2$	
3	AlphaGUARD PQ 2000_ EF-1914	^{222}Rn	CM	$A_1 + A_2$	
4	AlphaGUARD PQ 2000 PRO _ EF-1522	^{222}Rn	CM	$A_1 + A_2$	
5	Electrets RM-1_ EIC RM 200 R	^{222}Rn	passive	$A_1 + A_2$	6 pcs.
6	Electrets RM-1_ EIC RM 200 R/T	$^{222}Rn/ ^{220}Rn$	passive	$B_1 + B_2$	6 pairs - RT
7	RAD 7_ 1976	$^{222}Rn/ ^{220}Rn$	CM - REF.	$B_1 + B_2$	
8	Fritra 4 _ J.P. 01	EEC/ fp	CM - R	$A_1 + A_2$	
9	AlphaGUARD DF-2000_ AG 000115	^{222}Rn	CM	$A_1 + A_2$	
10	AlphaGUARD PQ 2000 PRO _ EF-2219	^{222}Rn	CM	$A_1 + A_2$	
11	AlphaGUARD DF-2000_ AG 000050	^{222}Rn	CM	$A_1 + A_2$	
12	Radim 3A_ 18001	^{222}Rn	CM	$A_1 + A_2$	
13	Radim 3AT_ 19002	^{222}Rn	CM	$A_1 + A_2$	
14	Radim 3AT_ 19003	^{222}Rn	CM	$A_1 + A_2$	
15	TESLA probe TSR_19031	^{222}Rn	CM	$A_1 + A_2$	
16	TESLA probe TSR_19038	^{222}Rn	CM	$A_1 + A_2$	
17	TESLA probe TSR_17084	^{222}Rn	CM	$A_1 + A_2$	
18	TESLA probe TSR_17085	^{222}Rn	CM	$A_1 + A_2$	
19	Radon Scout Professional_ RSC 00596	^{222}Rn	CM	$A_1 + A_2$	
20	Thoron Diffusion -Scout _ TSC 00001	$^{222}Rn/ ^{220}Rn$	CM	$B_1 + B_2$	

21	BWLM 2S_ 139	EEC/ fp	CM	$A_1 + A_2$	FAILED
22	SSNTD-CR39_ GM Scientific	^{222}Rn	passive	$A_1 + A_2$	15 pcs.
23	E- perm _ EIC: SCH	^{222}Rn	passive	$A_1 + A_2$	6 pcs.
24	E- perm _ EIC: L-oo CH	^{222}Rn	passive	$B_1 + B_2$	4 pcs.
25	SSNTD-CR39_ RSKS	^{222}Rn	passive	A_2	6 pcs.
26	SSNTD-CR39_ RSKS	^{222}Rn	passive	B_2	6 pcs.
27	SSNTD-CR39_ Duotrak R/T	^{222}Rn/ ^{220}Rn	passive	$B_1 + B_2$	4 pairs - RT

CM means continuous monitors
RT means a relevant radon/thoron pairs of discriminative chambers for electrets and SSNTD, respectively
REF. means the NRPI reference instrument
The meaning of all the rest symbols is obvious from the previous text.

Table 4. ID of all the instruments exposed during scenarios A_1, A_2

Instrument ID	Order	S/N.	Instr. Type	Exp. Type
REF	REF	EF528	CM	A_1+A_2
1/1/AG	11	AG000050	CM	A_1+A_2
2/1/AG	10	EF-2219	CM	A_1+A_2
3/1/AG	9	AG000115	CM	A_1+A_2
4/1/RADIM3A	12	18001	CM	A_1+A_2
5/1/RSC	19	RSC00596	CM	A_1+A_2
6/1/TERA	17	TSR17084	CM	A_1+A_2
6/2/TERA	18	TSR17085	CM	A_1+A_2
7/1/RADIM3AT	13	19002	CM	A_1+A_2
7/2/RADIM3AT	14	19003	CM	A_1+A_2
7/3/AG	3	EF1522	CM	A_1+A_2
7/4/AG	4	EF1914	CM	A_1+A_2
7/5/RAD7	1	3713	CM	A_1+A_2
8/1/TERA	15	TSR19038	CM	A_1+A_2
8/2/TERA	16	TSR19031	CM	A_1+A_2
1/1/SSNTD	22	509-90006	SSNTD	A_1
1/2/SSNTD	22	509-90007	SSNTD	A_1
1/3/SSNTD	22	509-90008	SSNTD	A_1
1/4/SSNTD	22	509-90009	SSNTD	A_1
1/5/SSNTD	22	509-90010	SSNTD	A_1
1/6/SSNTD	22	509-90011	SSNTD	A_1
1/7/SSNTD	22	509-90012	SSNTD	A_1
1/8/SSNTD	22	509-90013	SSNTD	A_1
3/1/EIC	23	LX-3541	EIC	A_1
3/2/EIC	23	LX-3756	EIC	A_1
3/3/EIC	23	LX-3542	EIC	A_1
4/1/EIC	5	0208-15	EIC	A_1
4/2/EIC	5	0021-04	EIC	A_1

4/3/EIC	5	LX-3542	EIC	A_1
1/9/SSNTD	22	509-90014	SSNTD	A_2
1/10/SSNTD	22	509-90015	SSNTD	A_2
1/11/SSNTD	22	509-90016	SSNTD	A_2
1/12/SSNTD	22	509-90017	SSNTD	A_2
1/13/SSNTD	22	509-90018	SSNTD	A_2
1/14/SSNTD	22	509-90019	SSNTD	A_2
1/15/SSNTD	22	509-90020	SSNTD	A_2
2/1/SSNTD	25	4F6321	SSNTD	A_2
2/2/SSNTD	25	4F6407	SSNTD	A_2
2/3/SSNTD	25	4F6270	SSNTD	A_2
2/4/SSNTD	25	4F6328	SSNTD	A_2
2/5/SSNTD	25	4G0700	SSNTD	A_2
2/6/SSNTD	25	4F6772	SSNTD	A_2
3/4/EIC	23	LX-3779	EIC	A_2
3/5/EIC	23	LX-3797	EIC	A_2
3/6/EIC	23	LX-3675	EIC	A_2
4/4/EIC	5	0352-03	EIC	A_2
4/5/EIC	5	1007-93	EIC	A_2
4/6/EIC	5	1424-96	EIC	A_2

The numbers in the column titled Order matches to those listed in the previous Table 3
S/N. in case of the passive detection systems corresponds to number of used electrets in the EIC or to number of used each track detector.

Table 5. ID of all the instruments exposed during scenarios B_1,B_2

Instrument ID	Order	S/N.	Instr. Type	Quantity	Exp. Type
2/3/SSNTD	27	263021-8	SSNTD	^{222}Rn	B1
2/4/SSNTD	27	942997-8	SSNTD	^{222}Rn	B1
3/1/EIC	24	SLF-477	EIC	^{222}Rn	B1
3/2/EIC	24	SLF-793	EIC	^{222}Rn	B1
4/1/EIC	6	0176-15	EIC	^{222}Rn	B1
4/3/EIC	6	0008-04	EIC	^{222}Rn	B1
4/5/EIC	6	1164-95	EIC	^{222}Rn	B1
1/1/SSNTD	26	4G0552	SSNTD	^{222}Rn	B2
1/2/SSNTD	26	4F6627	SSNTD	^{222}Rn	B2
1/3/SSNTD	26	4G0682	SSNTD	^{222}Rn	B2
1/4/SSNTD	26	4F6211	SSNTD	^{222}Rn	B2
1/5/SSNTD	26	4F6421	SSNTD	^{222}Rn	B2
1/6/SSNTD	26	4F7037	SSNTD	^{222}Rn	B2
2/9/SSNTD	27	279945-0	SSNTD	^{222}Rn	B2
2/10/SSNTD	27	343722-5	SSNTD	^{222}Rn	B2
3/3/EIC	24	SLF-368	EIC	^{222}Rn	B2
3/4/EIC	24	SLF-257	EIC	^{222}Rn	B2
4/7/EIC	6	0217-15	EIC	^{222}Rn	B2

4/9/EIC	6	1418-96	EIC	^{222}Rn	B2
4/11/EIC	6	443-01	EIC	^{222}Rn	B2
2/5/SSNTD	27	660470-6	SSNTD	^{220}Rn	B1
2/6/SSNTD	27	465386-1	SSNTD	^{220}Rn	B1
4/2/EIC	6	2744-95	EIC	^{220}Rn	B1
4/4/EIC	6	1100-03	EIC	^{220}Rn	B1
4/6/EIC	6	391-98	EIC	^{220}Rn	B1
2/11/SSNTD	27	465610-4	SSNTD	^{220}Rn	B2
2/12/SSNTD	27	465362-2	SSNTD	^{220}Rn	B2
4/8/EIC	6	2987-95	EIC	^{220}Rn	B2
4/10/EIC	6	2304-94	EIC	^{220}Rn	B2
4/12/EIC	6	912-96	EIC	^{220}Rn	B2

The meaning of all symbols in this table is the same as in the previous Table 4

Table 6. Exposure conditions during scenarios A_1, A_2

Scenario/ Time Period	Instruments		F (-)	f_p (-)	RH (%)	T (^{o}C)
A1	CM					
16.9. 22:00 - 18.9. 14:00		MIN.	0.45	0.058	11.2	28.1
		MAX	0.54	0.081	19.2	28.1
		MEDIAN	0.50	0.067	16.2	28.1
		1.Q	0.48	0.063	12.2	28.1
		3.Q	0.52	0.071	18.2	28.1
A2	CM					
19.9. 03:00 - 20.9. 8:00		MIN.	0.04	0.769	39.5	27.1
		MAX	0.06	0.995	42.5	27.8
		MEDIAN	0.04	0.876	10.2	27.1
		1.Q	0.04	0.833	9.2	27.1
		3.Q	0.05	0.895	41.8	27.6
		IQR	0.01	0.062	1.8	0.28
A1	SSNTD/EIC					
16.9. 16:00 - 18.9. 14:49		MIN.	0.18	0.058	42.3	27.9
		MAX	0.54	0.352	50.8	28.6
		MEDIAN	0.49	0.067	48.0	28.5
		1.Q	0.48	0.063	43.7	28.5
		3.Q	0.52	0.073	49.8	28.5
		IQR	0.04	0.009	6.1	0.0
A2	SSNTD/EIC					
18.9. 15:00 - 20.9. 9:00		MIN.	0.04	0.061	39.5	27.1
		MAX	0.54	0.995	42.5	28.3
		MEDIAN	0.05	0.841	41.5	27.6
		1.Q	0.04	0.567	40.8	27.4
		3.Q	0.09	0.877	41.8	27.8
		IQR	0.05	0.310	1.0	0.3

F means equilibrium factor

f_p means unattached part of EEC

RH means relative air humidity

T means ambient air temperature

MIN./MAX. means minimum / maximum

MEDIAN means median of values

1.Q. 3.Q means 1th and 3rd quartile of values

The meaning of all the rest values in the table is obvious from previous text.

Table 7. Additional relative uncertainty assumed for the mean value of the reference monitor

Scenario:	**A_1 + A_2**	**B_1 + B_2 radon**	**B_1 + B_2 thoron**
Uncertainty for the mean value:	5%	5%	10%

Table 8. The results for continuous monitors during A_1

ID	average	different shape p [1]	bias	Z [2]	P [3]	ratio R	R LB [4]	R UB [5]
REF	9541							
7/5/RAD7	9395	0.005	-146	-0.50	0.614	0.98	0.92	1.05
7/3/AG	9361	0.731	-180	-0.62	0.533	0.98	0.92	1.04
7/4/AG	9431	0.404	-110	-0.38	0.705	0.99	0.93	1.05
3/1/AG	9738	0.201	197	0.68	0.498	1.02	0.96	1.09
2/1/AG	9550	0.256	9	0.03	0.974	1.00	0.94	1.06
1/1/AG	9995	0.232	454	1.58	0.115	1.05	0.98	1.11
4/1/RADIM3A	5753	<1e-9	-3788	-12.93	<1e-9	0.60	0.56	0.64
7/1/RADIM3AT	6312	<1e-9	-3228	-10.83	<1e-9	0.66	0.62	0.70
7/2/RADIM3AT	6912	<1e-9	-2628	-8.89	<1e-9	0.72	0.68	0.77
8/1/TERA	13098	<1e-9	3557	11.20	<1e-9	1.37	1.28	1.46
8/2/TERA	12798	<1e-9	3257	10.76	<1e-9	1.34	1.25	1.43
6/1/TERA	9683	<1e-9	142	0.48	0.633	1.01	0.95	1.08
6/2/TERA	9887	<1e-9	346	1.17	0.243	1.04	0.97	1.10
5/1/RSC	9841	0.010	300	1.03	0.304	1.03	0.96	1.10

[1] p value of the test of different shape of temporal variations described in section Test of the same shape of temporal variation as reference values.

[2], [3] Z-statistic and p-value for test based on (EQ01).

[4], [5] lower and upper bound of confidence interval for ratio (EQ02).

Table 9. The results for continuous monitors during A_2

ID	average	different shape p [1]	bias	Z [2]	P [3]	ratio R	R LB [4]	R UB [5]
REF	9515							
7/5/RAD7	9265	0.671	-250	-0.87	0.387	0.97	0.91	1.03
7/3/AG	9340	0.828	-175	-0.61	0.544	0.98	0.92	1.04
7/4/AG	9404	0.964	-111	-0.39	0.700	0.99	0.93	1.05
3/1/AG								
2/1/AG	9519	0.463	4	0.02	0.988	1.00	0.94	1.06
1/1/AG	9862	0.916	347	1.21	0.228	1.04	0.97	1.10
4/1/RADIM3A	6301	<1e-3	-3214	-11.06	<1e-9	0.66	0.62	0.70
7/1/RADIM3AT	6845	0.043	-2670	-9.29	<1e-9	0.72	0.68	0.76
7/2/RADIM3AT	7226	0.267	-2289	-7.96	<1e-9	0.76	0.71	0.81
8/1/TERA	11815	0.012	2300	7.84	<1e-9	1.24	1.16	1.32
8/2/TERA	12162	0.016	2647	8.92	<1e-9	1.28	1.20	1.36
6/1/TERA	9441	0.148	-74	-0.25	0.799	0.99	0.93	1.05
6/2/TERA	9403	0.854	-112	-0.39	0.700	0.99	0.93	1.05
5/1/RSC	9559	0.274	44	0.15	0.879	1.00	0.94	1.07

[1] p value of the test of different shape of temporal variations described in section Test of the same shape of temporal variation as reference values.
[2], [3] Z-statistic and p-value for test based on (EQ01).
[4], [5] lower and upper bound of confidence interval for ratio (EQ02).

Table 10. The results for integral systems during A_1

ID	radon	Sd [1]	bias	Z [2]	P [3]	ratio R	R LB [4]	R UB [5]
REF	9499							
1/1/SSNTD	9771	647	272	0.38	0.702	1.03	0.88	1.18
1/2/SSNTD	8938	609	-561	-0.83	0.407	0.94	0.80	1.08
1/3/SSNTD	9759	650	260	0.36	0.715	1.03	0.88	1.18
1/4/SSNTD	9508	635	9	0.01	0.990	1.00	0.86	1.15
1/5/SSNTD	9994	659	495	0.69	0.493	1.05	0.90	1.20
1/6/SSNTD	9534	631	34	0.05	0.960	1.00	0.86	1.15
1/7/SSNTD	9854	647	354	0.50	0.618	1.04	0.89	1.18
1/8/SSNTD	9740	641	240	0.34	0.733	1.03	0.88	1.17
3/1/EIC	8662	442	-838	-1.58	0.114	0.91	0.81	1.02
3/2/EIC	9166	467	-333	-0.60	0.546	0.96	0.85	1.08
3/3/EIC	9586	489	86	0.15	0.879	1.01	0.89	1.13
4/1/EIC	9055	474	-444	-0.80	0.426	0.95	0.84	1.07
4/2/EIC	9357	490	-142	-0.25	0.804	0.99	0.87	1.10
4/3/EIC	9703	498	204	0.35	0.725	1.02	0.90	1.14

[1] value calculated from uncertainty data provided by each participant.
[2], [3] Z-statistic and p-value for test based on (EQ01).
[4], [5] lower and upper bound of confidence interval for ratio (EQ02).

Table 11 The results for integral systems during A_2.

ID	radon	Sd [1]	bias	Z [2]	P [3]	R	R LB [4]	R UB [5]
REF	9475							
1/9/SSNTD	9142	638	-333	-0.48	0.634	0.96	0.82	1.11
1/10/SSNTD	9020	631	-455	-0.66	0.512	0.95	0.81	1.09
1/11/SSNTD	8970	629	-506	-0.73	0.465	0.95	0.80	1.09
1/12/SSNTD	9627	661	152	0.21	0.833	1.02	0.87	1.17
1/13/SSNTD	10257	691	782	1.04	0.296	1.08	0.93	1.24
1/14/SSNTD	9055	633	-420	-0.60	0.546	0.96	0.81	1.10
1/15/SSNTD	9582	663	107	0.15	0.882	1.01	0.86	1.16
2/1/SSNTD	8819	177	-656	-1.94	0.052	0.93	0.86	1.00
2/2/SSNTD	9796	206	321	0.91	0.365	1.03	0.96	1.11
2/3/SSNTD	9687	206	212	0.60	0.550	1.02	0.95	1.10
2/4/SSNTD	9073	209	-402	-1.13	0.259	0.96	0.89	1.03
2/5/SSNTD	8791	200	-684	-1.95	0.051	0.93	0.86	1.00
2/6/SSNTD	9479	201	4	0.01	0.992	1.00	0.93	1.07
3/4/EIC	11323	577	1848	2.86	0.004	1.20	1.06	1.33
3/5/EIC	10113	516	638	1.08	0.280	1.07	0.94	1.19
3/6/EIC	10225	521	750	1.26	0.208	1.08	0.95	1.20
4/4/EIC	10454	624	979	1.42	0.154	1.10	0.96	1.25
4/5/EIC	10005	616	530	0.78	0.436	1.06	0.91	1.20
4/6/EIC	9704	505	229	0.39	0.693	1.02	0.90	1.15

[1] value calculated from uncertainty data provided by each participant.
[2], [3] Z-statistic and p-value for test based on (EQ01).
[4], [5] lower and upper bound of confidence interval for ratio (EQ02).

Table 12. The results for radon integral systems during B_1

ID	radon	Sd [1]	bias	Z [2]	P [3]	R	R LB [4]	R UB [5]
REF	9562							
2/3/SSNTD	10208	635	646	0.81	0.417	1.07	0.90	1.23
2/4/SSNTD	10435	658	873	1.07	0.283	1.09	0.92	1.26
3/1/EIC	10888	599	1326	1.73	0.084	1.14	0.97	1.30
3/2/EIC	12086	665	2524	3.08	0.002	1.26	1.08	1.45
4/1/EIC	8865	541	-697	-0.96	0.335	0.93	0.78	1.07
4/3/EIC	8608	525	-954	-1.34	0.180	0.90	0.76	1.04
4/5/EIC	8801	537	-761	-1.06	0.290	0.92	0.78	1.06

[1] value calculated from uncertainty data provided by each participant.
[2], [3] Z-statistic and p-value for test based on (EQ01).
[4], [5] lower and upper bound of confidence interval for ratio (EQ02).

Table 13. The results for thoron integral systems during B_1

ID	thoron	Sd [1]	bias	Z [2]	P [3]	R	R LB [4]	R UB [5]
REF	5209							
2/5/SSNTD	8529	2178	3321	1.48	0.138	1.64	0.76	2.52
2/6/SSNTD	8665	2155	3457	1.56	0.119	1.66	0.79	2.54
4/2/EIC	4761	433	-448	-0.66	0.509	0.91	0.67	1.16
4/4/EIC	4538	413	-671	-1.01	0.314	0.87	0.64	1.10
4/6/EIC	5510	501	301	0.42	0.677	1.06	0.78	1.34

[1] value calculated from uncertainty data provided by each participant.
[2], [3] Z-statistic and p-value for test based on (EQ01).
[4], [5] lower and upper bound of confidence interval for ratio (EQ02).

Table 14. The results for radon integral systems during B_2

ID	radon	Sd [1]	bias	Z [2]	P [3]	R	R LB [4]	R UB [5]
REF	3921							
1/1/SSNTD	3095	161	-826	-3.25	0.001	0.79	0.68	0.90
1/2/SSNTD	3486	164	-436	-1.70	0.089	0.89	0.77	1.01
1/3/SSNTD	2570	324	-1352	-3.57	<1e-4	0.66	0.48	0.83
1/4/SSNTD	3570	159	-351	-1.39	0.166	0.91	0.79	1.03
1/5/SSNTD	3448	179	-473	-1.78	0.075	0.88	0.76	1.00
1/6/SSNTD	2753	207	-1168	-4.09	<1e-4	0.70	0.58	0.83
2/9/SSNTD	4500	320	579	1.54	0.123	1.15	0.95	1.34
2/10/SSNTD	4545	320	624	1.66	0.097	1.16	0.96	1.36
3/3/EIC	5767	317	1846	4.94	<1e-4	1.47	1.26	1.69
3/4/EIC	5395	297	1474	4.14	<1e-4	1.38	1.17	1.58
4/7/EIC	3605	292	-316	-0.90	0.370	0.92	0.75	1.09
4/9/EIC	3859	313	-62	-0.17	0.866	0.98	0.80	1.17
4/11/EIC	4344	352	423	1.05	0.294	1.11	0.90	1.31

[1] value calculated from uncertainty data provided by each participant.
[2], [3] Z-statistic and p-value for test based on (EQ01).
[4], [5] lower and upper bound of confidence interval for ratio (EQ02).

Table 15. The results for thoron integral systems during B_2

ID	thoron	Sd [1]	bias	Z [2]	P [3]	R	R LB [4]	R UB [5]
REF	4992							
2/11/SSNTD	7409	1205	2417	1.85	0.064	1.48	0.93	2.04
2/12/SSNTD	8250	1230	3258	2.45	0.014	1.65	1.07	2.23
4/8/EIC	5350	487	358	0.51	0.608	1.07	0.79	1.36
4/10/EIC	5007	456	14	0.02	0.983	1.00	0.74	1.27
4/12/EIC	4915	447	-78	-0.12	0.908	0.98	0.72	1.25

[1] value calculated from uncertainty data provided by each participant.

[2], [3] Z-statistic and p-value for test based on (EQ01).

[4], [5] lower and upper bound of confidence interval for ratio (EQ02).

Table 16. The results for continuous monitor during B_1 and B_2

Scenario	quantity	average	REF mean	bias	N [6]	different shape p [1]	Z [2]	P [3]	R	R LB [4]	R UB [5]
B1	radon	9968	9670	298	22	0.034	0.60	0.547	1.03	0.93	1.13
B1	thoron	9701	5242	4460	22	0.051	14.05	<1e-9	1.85	1.48	2.22
B2	radon	4012	3917	95	41	0.220	0.47	0.638	1.02	0.92	1.13
B2	thoron	9907	5002	4905	41	0.112	18.07	<1e-9	1.98	1.59	2.37

[1] p value of the test of different shape of temporal variations described in section Test of the same shape of temporal variation as reference values.

[2], [3] Z-statistic and p-value for test based on (EQ01).

[4], [5] lower and upper bound of confidence interval for ratio (EQ02)

[6] number of observations.

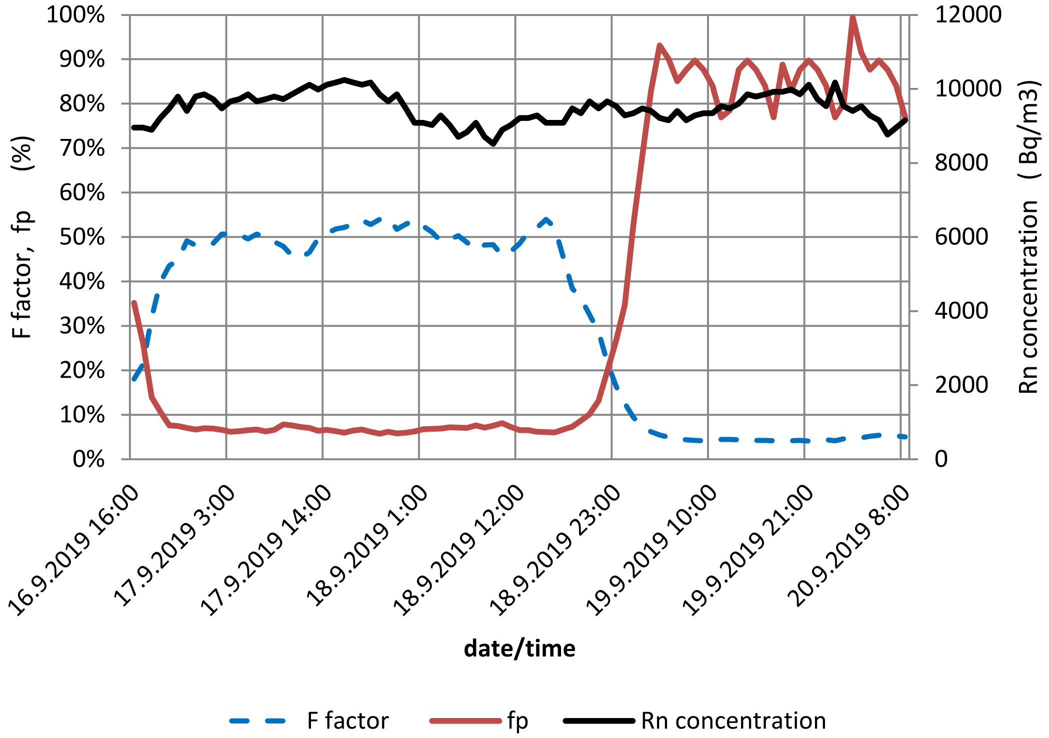


Fig.1 Time variation of radon concentration, equilibrium factor F and f_p from the beginning of A_1 to the end of A_2 exposure

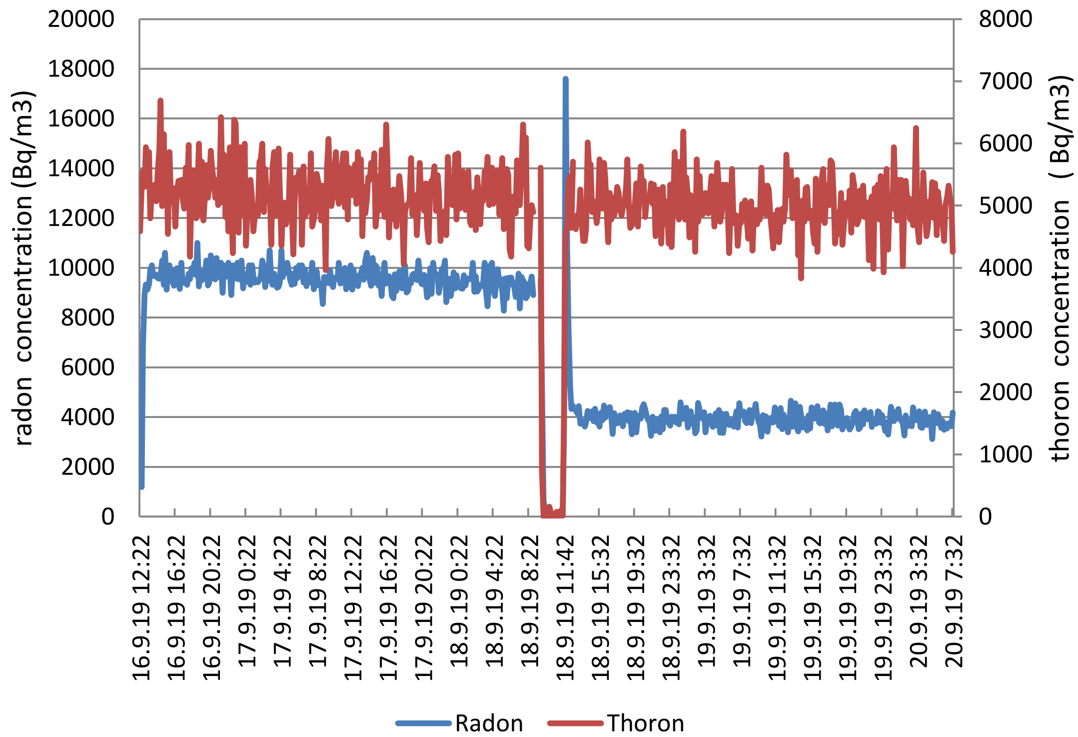
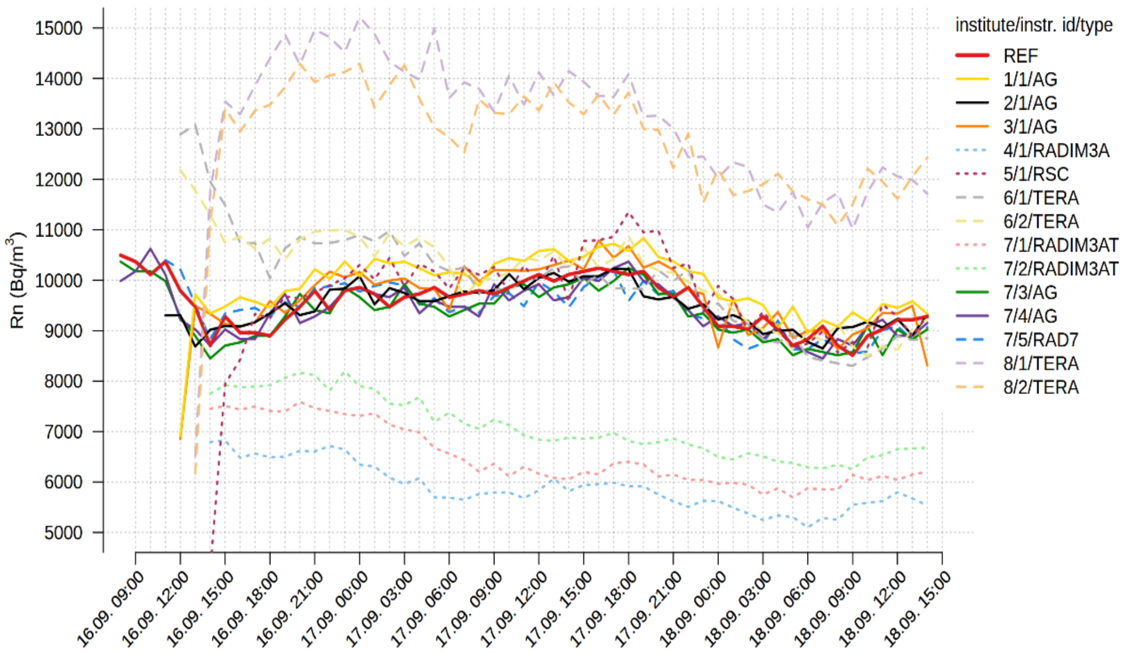


Fig.2 Time variations of radon and thoron concentration from the beginning of B_1 to the end of B_2 exposure.



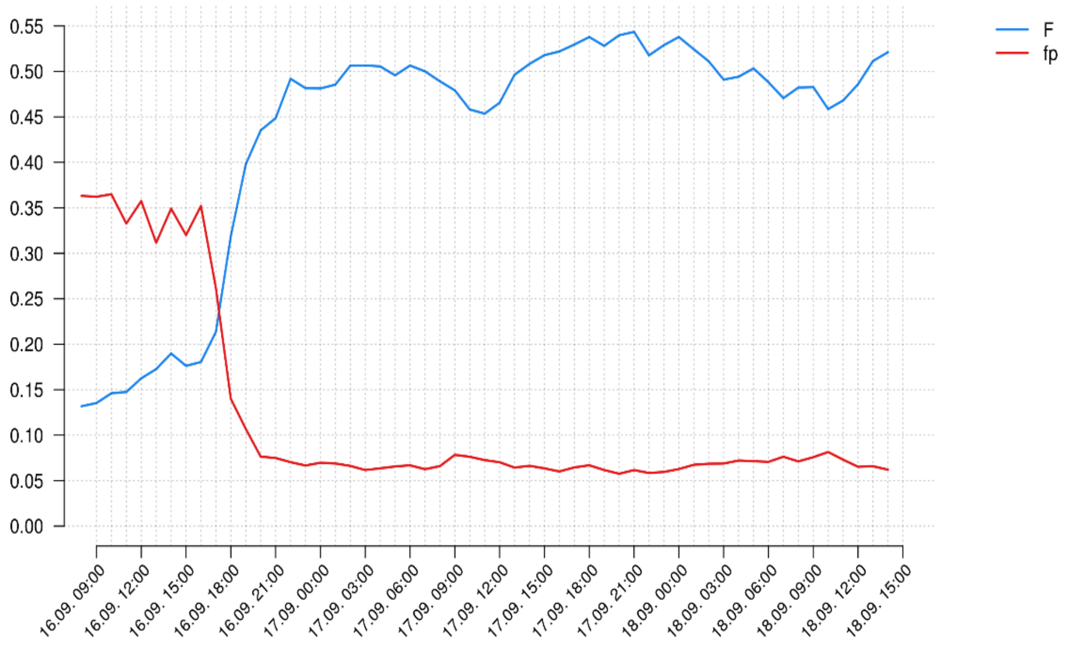


Fig. 3 Top panel – data from all radon continuous monitors during A_1. Bottom panel – factor F and f_p during A_1. Note that not all the data that are shown in the figures are not used for the analysis.

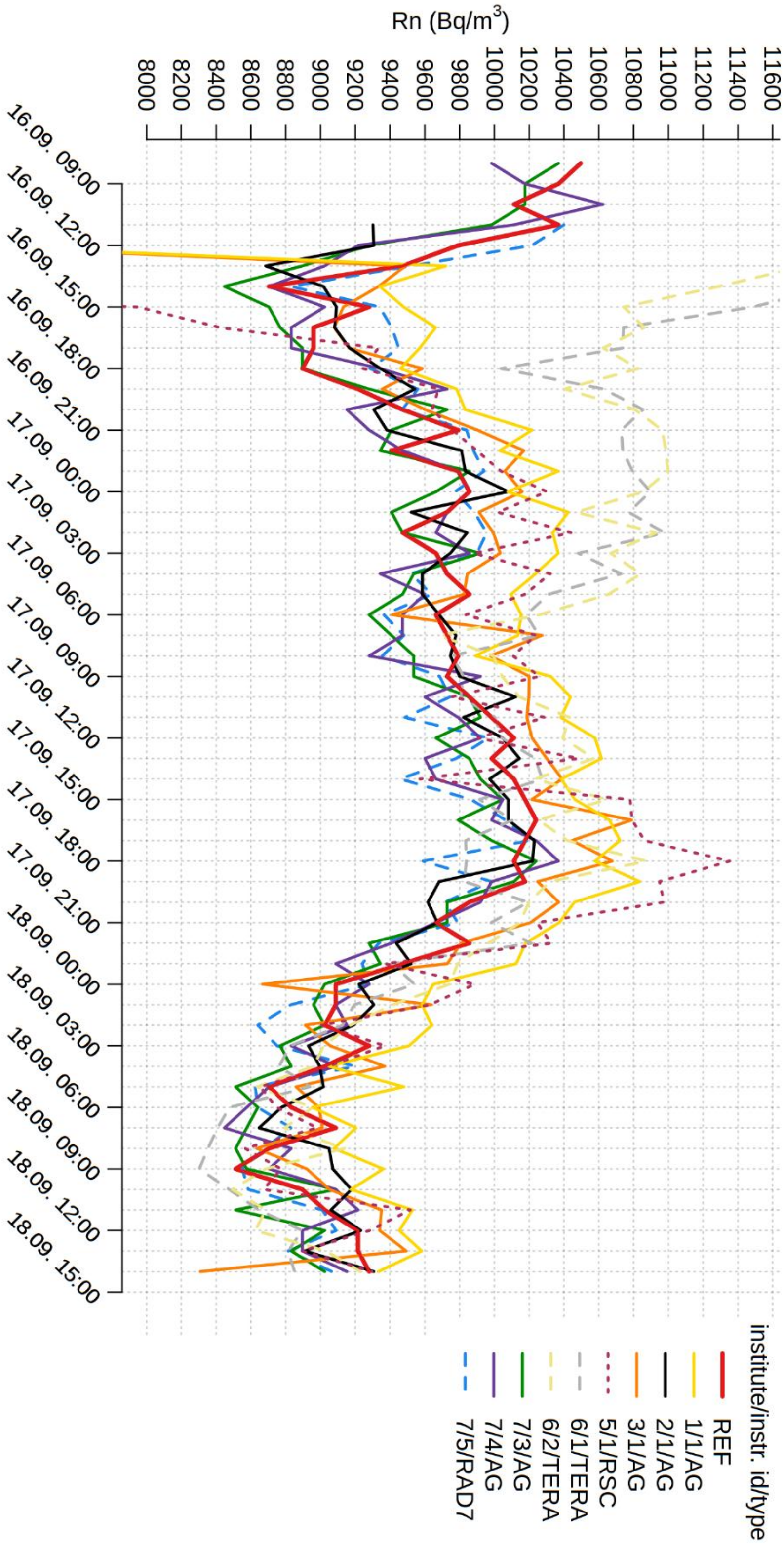


Fig. 4 Data from radon monitors during A_1 in more detailed view (some monitors far from the reference monitor are excluded).

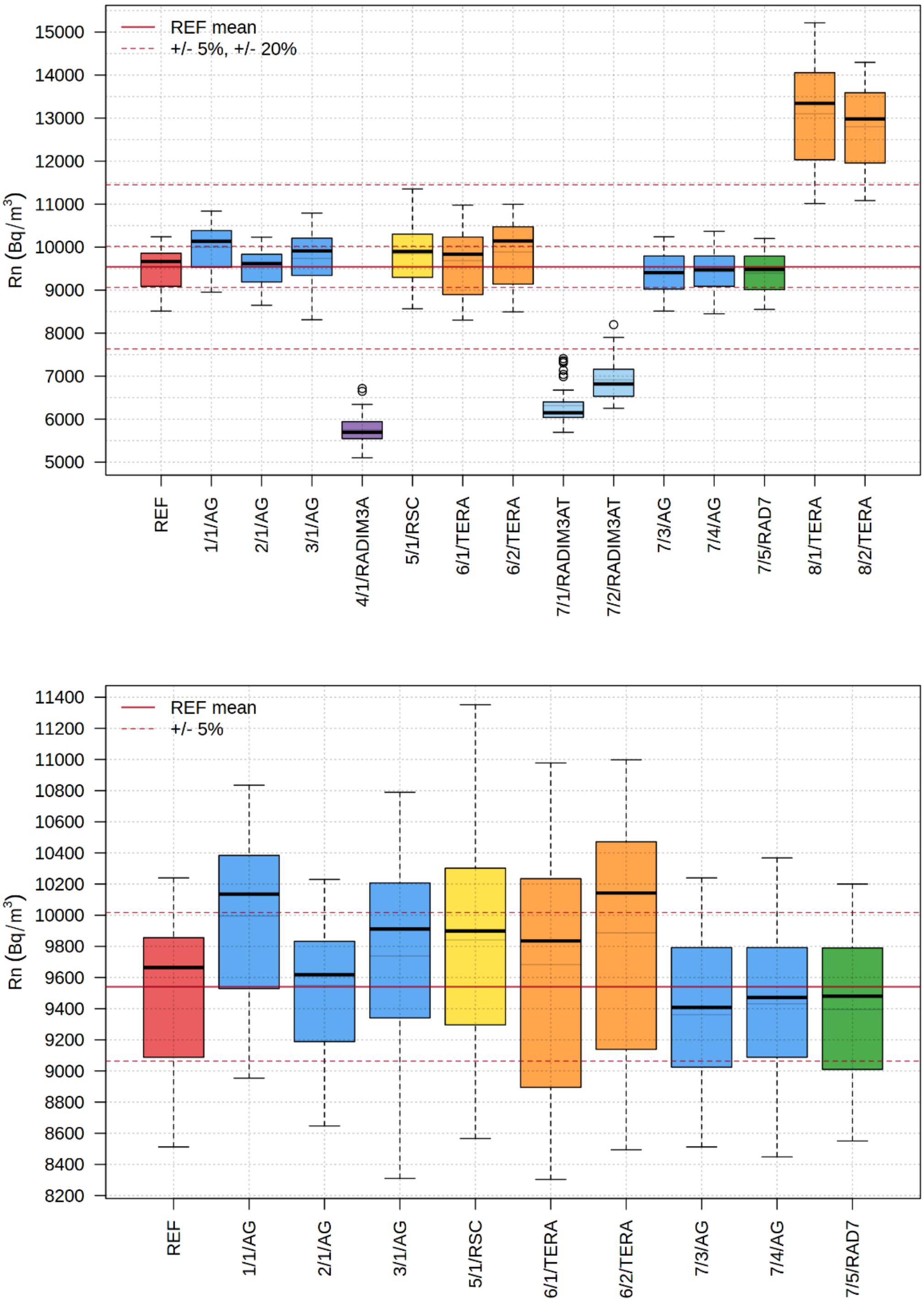


Fig. 5 Boxplot representing data from continuous monitors for A_1. Top panel shows all monitors, the bottom panel shows the same without five outlying monitors. Colours represent different types of monitors.

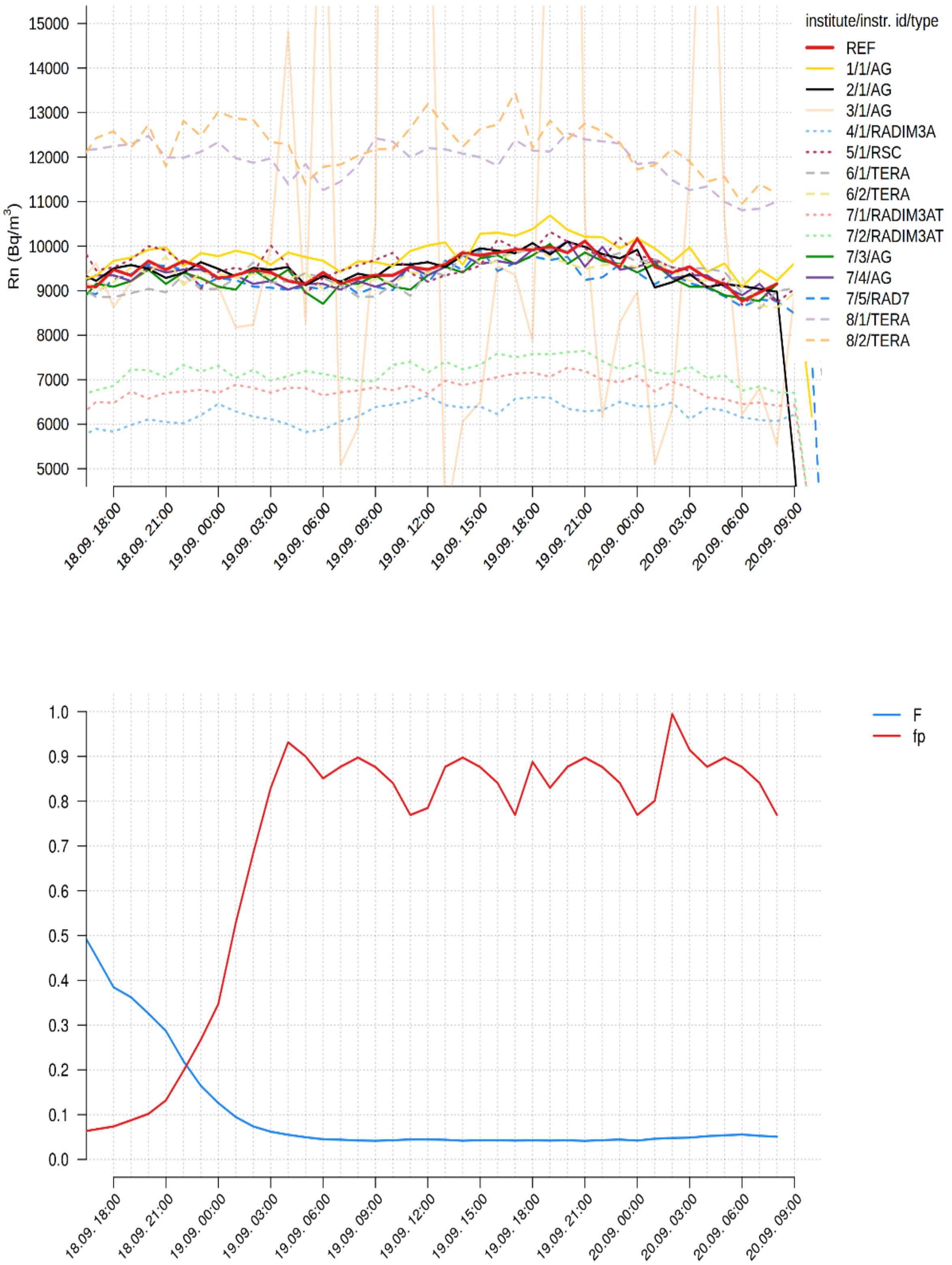


Fig. 6 Top panel – data from all radon continuous monitors during A_2. Bottom panel – factor F and f_p during A_2.

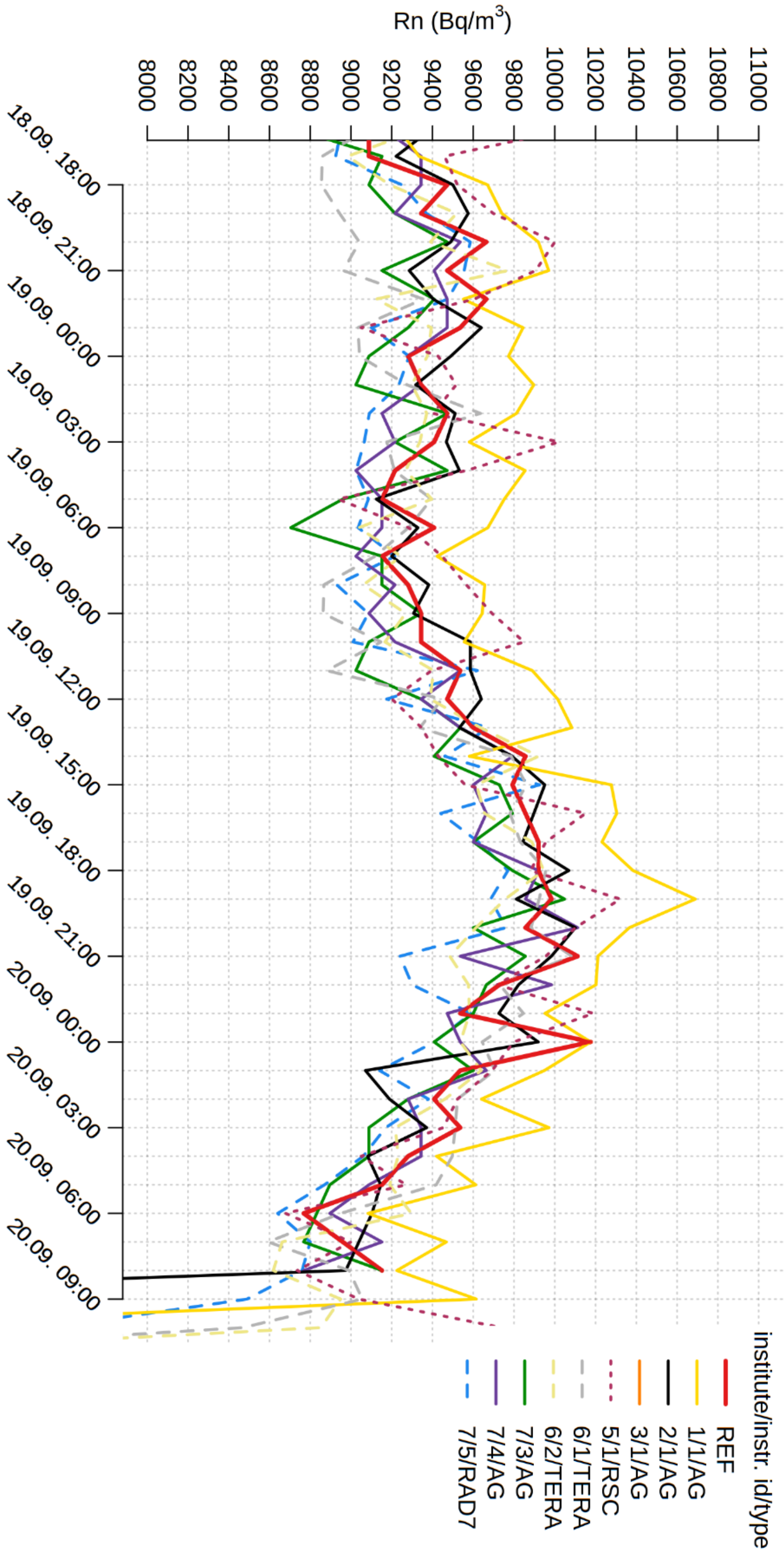


Fig. 7 Data from radon monitors during A_2 in more detailed view (some monitors far from the reference monitor are excluded).

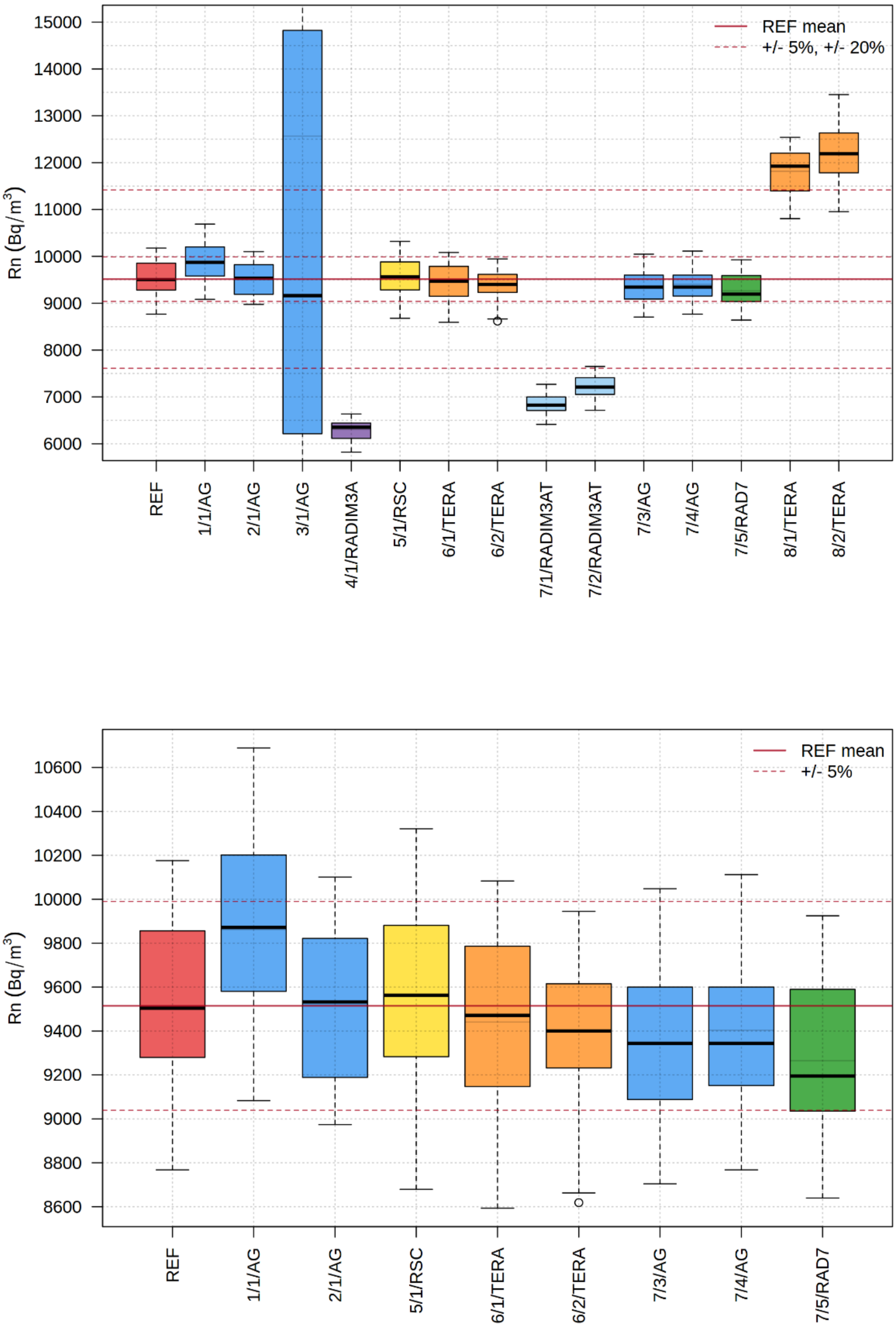


Fig. 8 Boxplot representing data from continuous monitors during A_2. Top panel show all monitors, the bottom panel shows the same data without five outlying monitors. Colours represent different types of monitors.

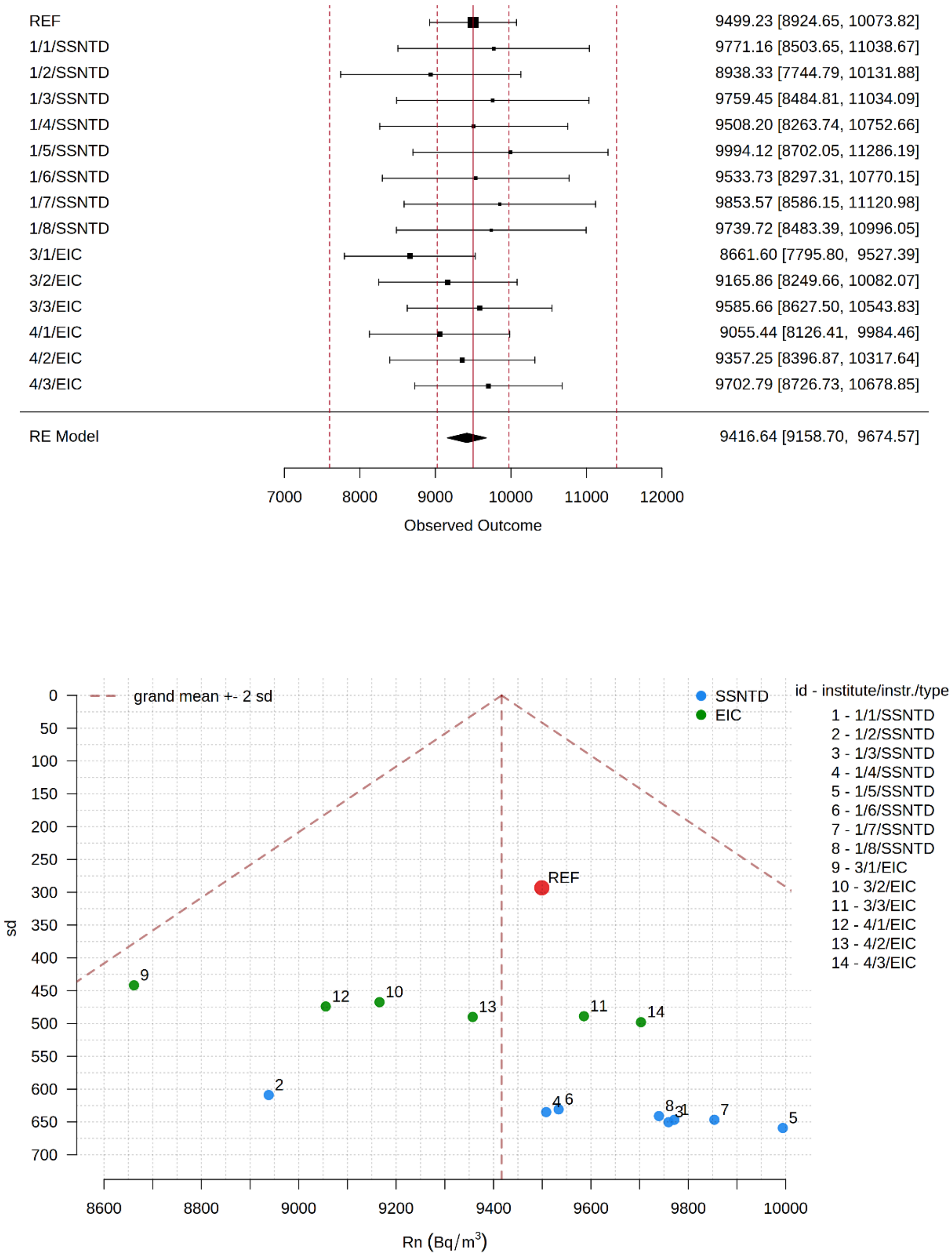


Fig. 9 Results for integral systems during A_1. Top panel - forest plot. Red lines represent the reference mean together with ±5%. 20%. Bottom panel – funnel plot.

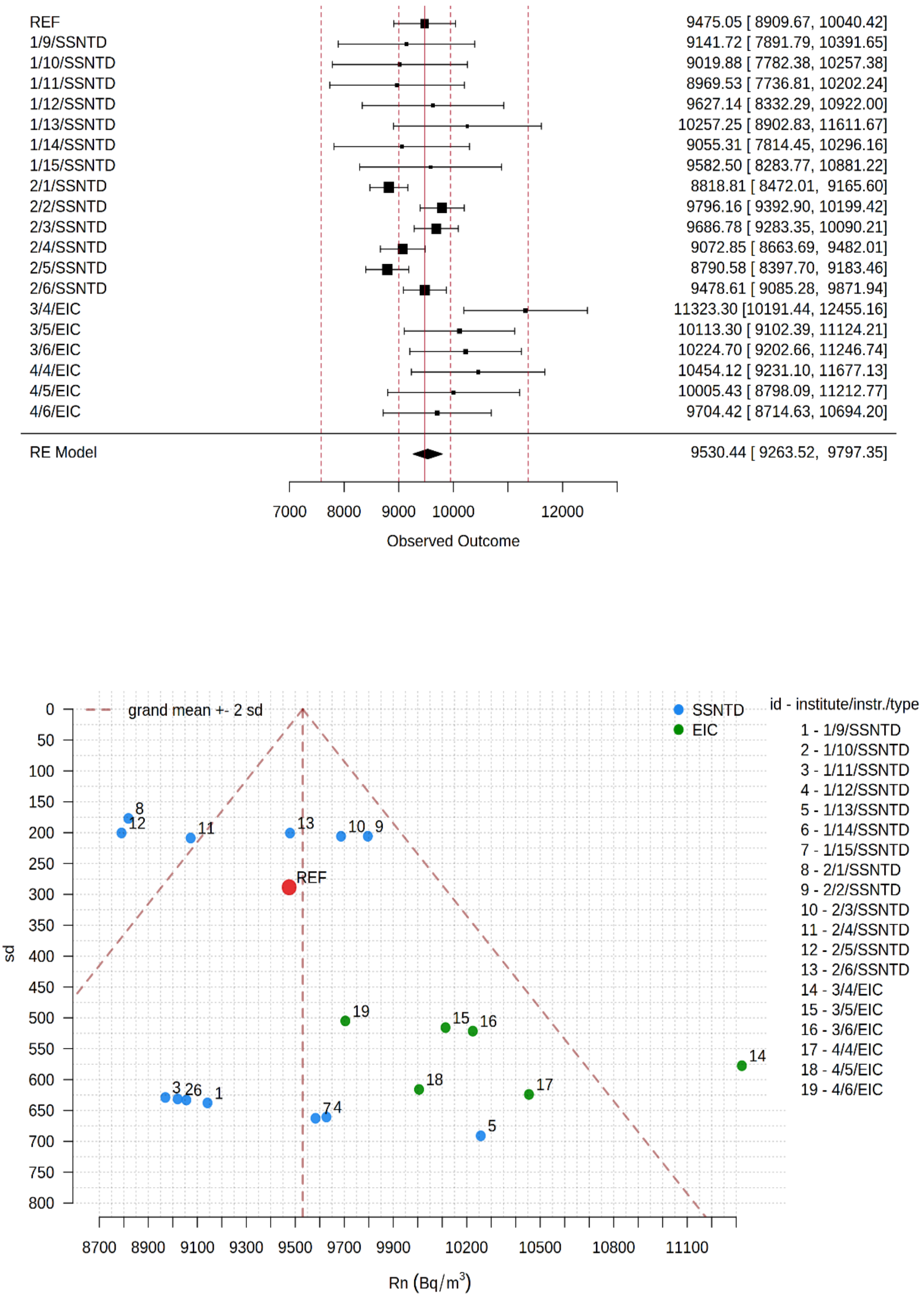
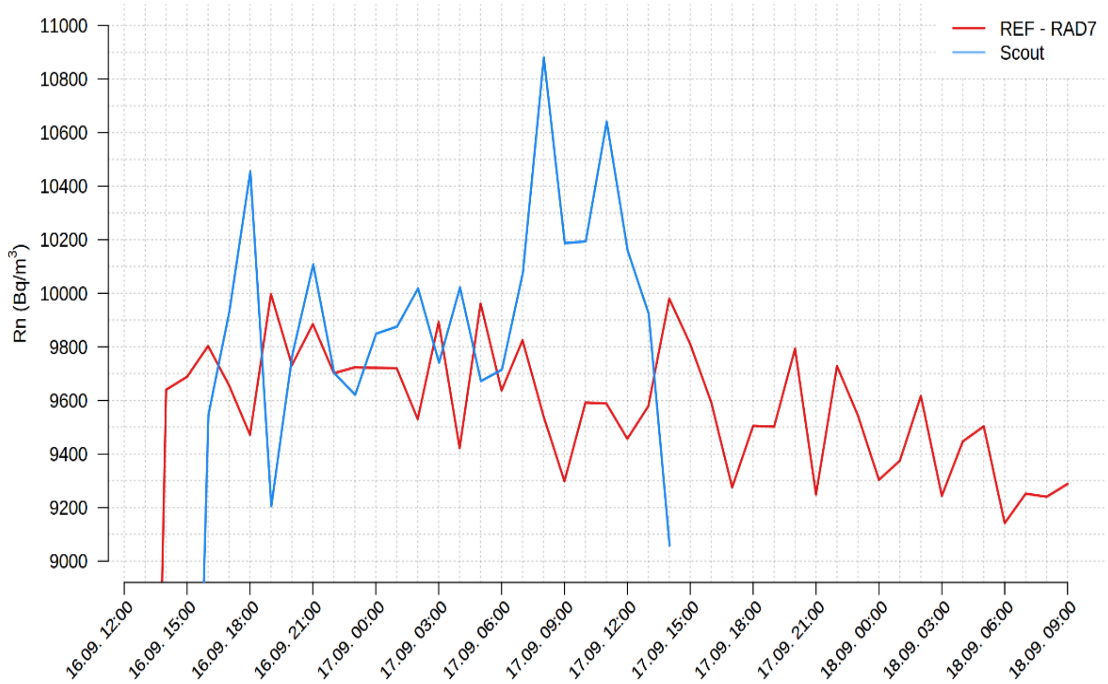


Fig. 10 Results for integral systems during A_2. Top panel - forest plot. Red lines represent the reference mean together with ±5%, 20%. Bottom panel – funnel plot.



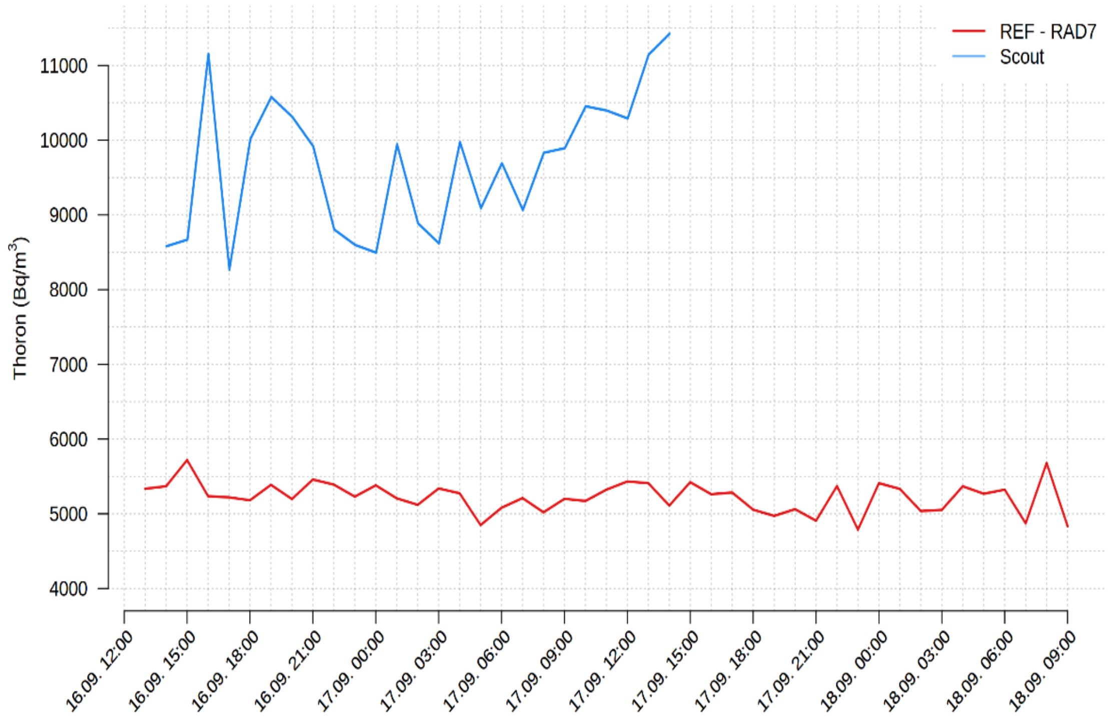


Fig. 11 Radon (top panel) and thoron (bottom panel) concentration during B_1 for the reference RAD7 monitor and the participant's Scout monitor.

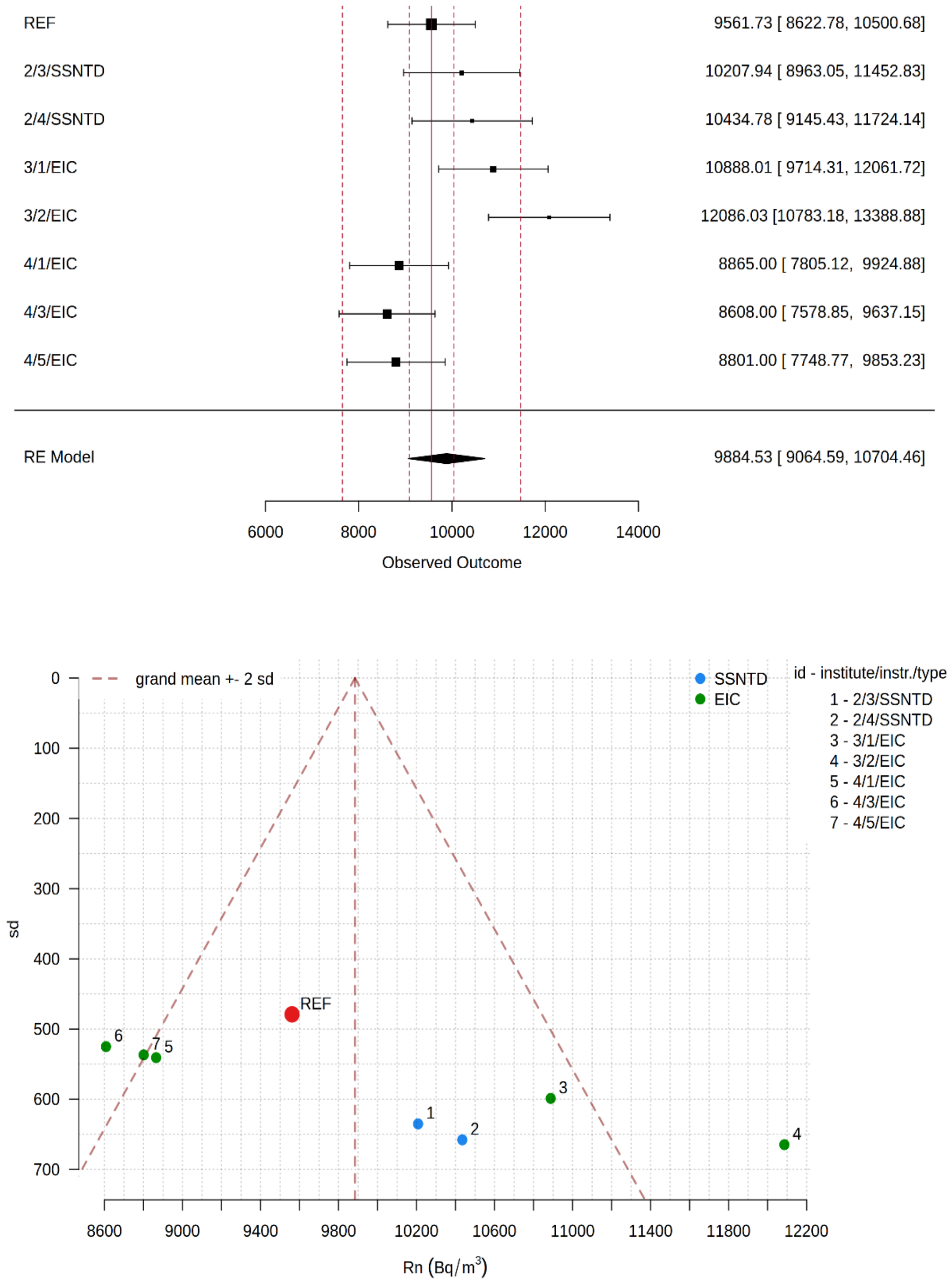


Fig. 12. Results for radon integral systems during B_1. Top panel - forest plot. Red lines represent the reference mean together with ±5%, 20%. Bottom panel – funnel plot.

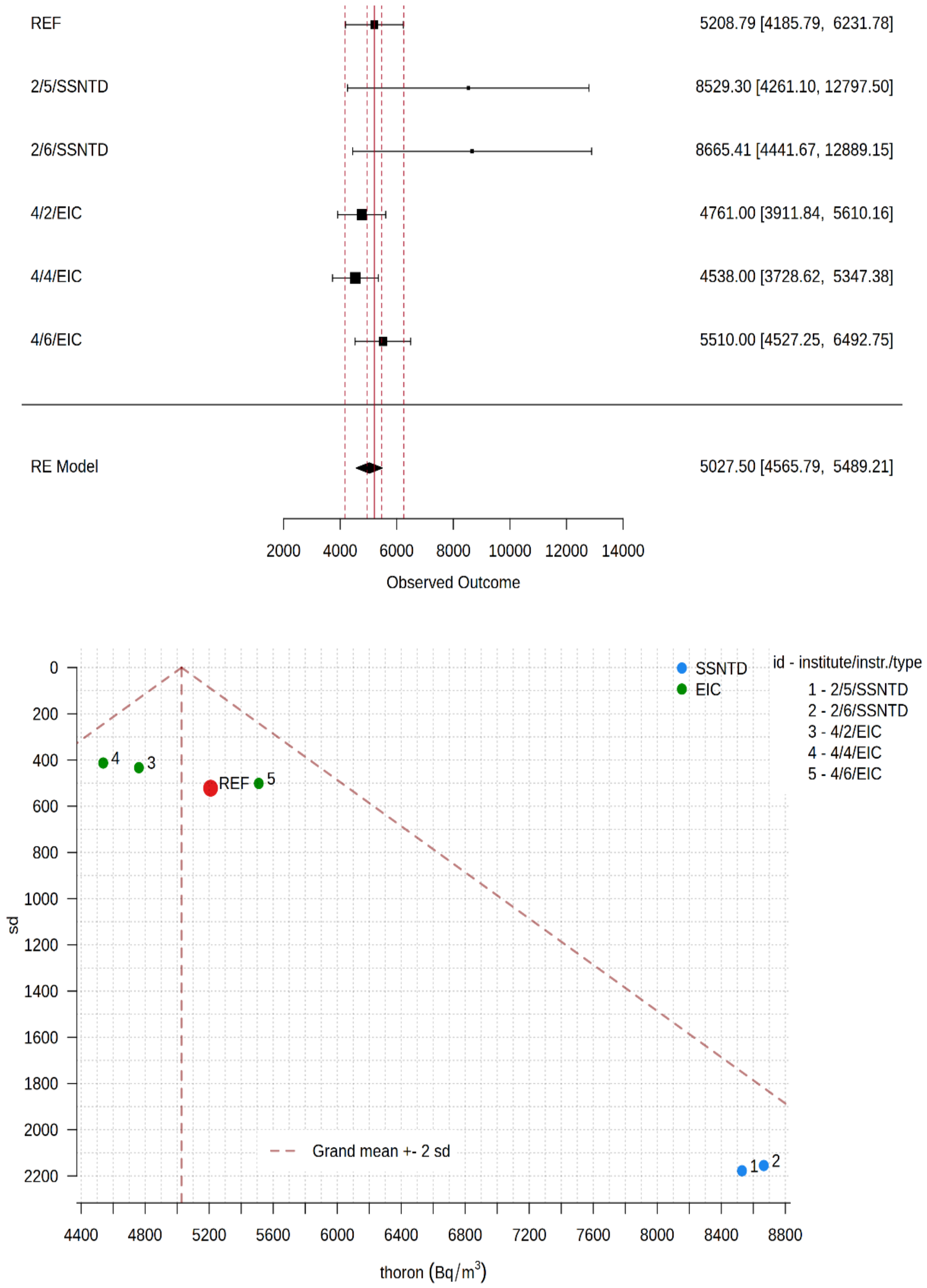


Fig. 13 Results for thoron integral systems during B_1. Top panel - forest plot. Red lines represent the reference mean together with ±5%, 20%. Bottom panel – funnel plot.

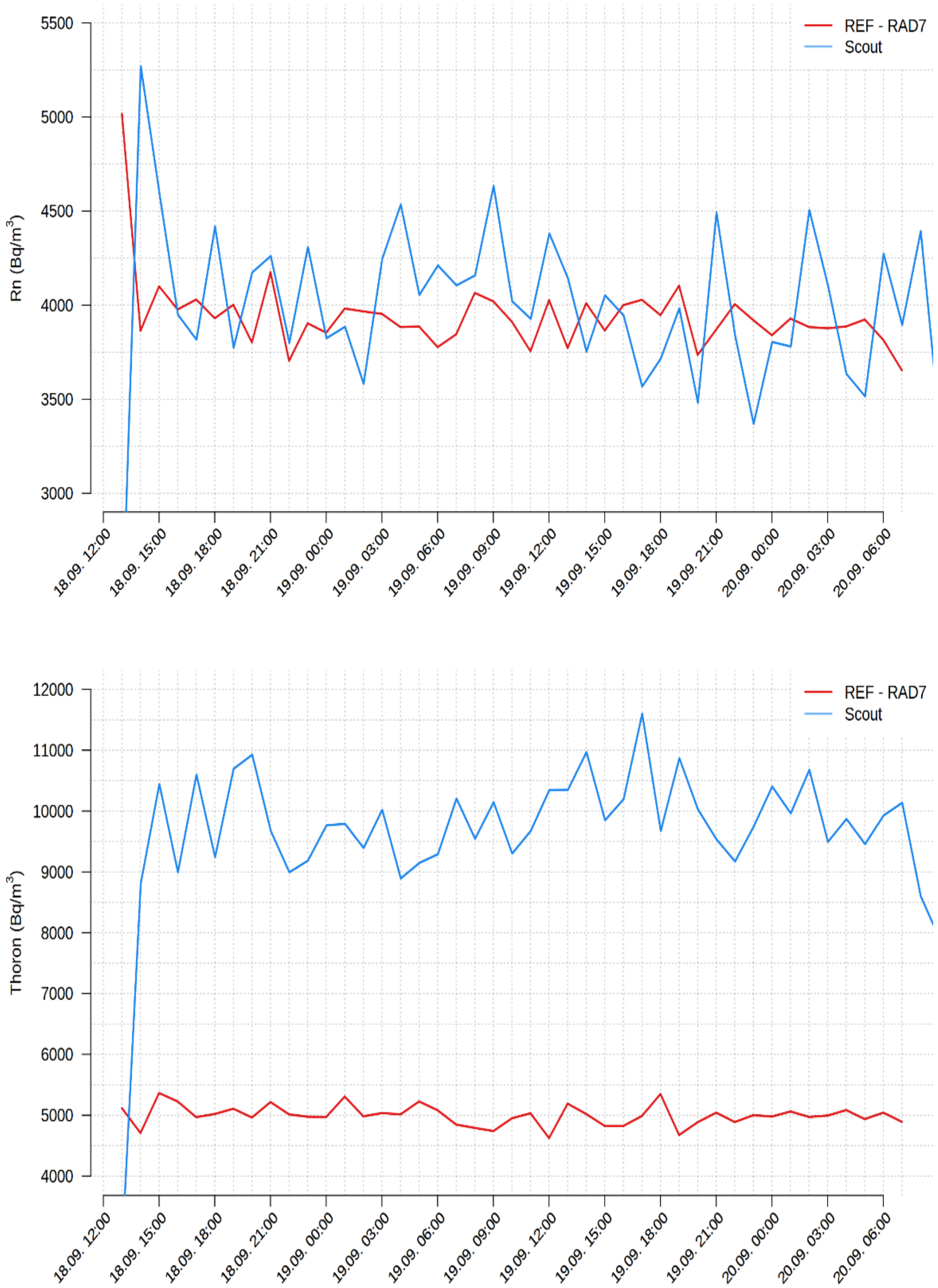


Fig. 14 Radon (top panel) and thoron (bottom panel) concentration during B_2 for the reference RAD7 monitor and the participant's Scout monitor.

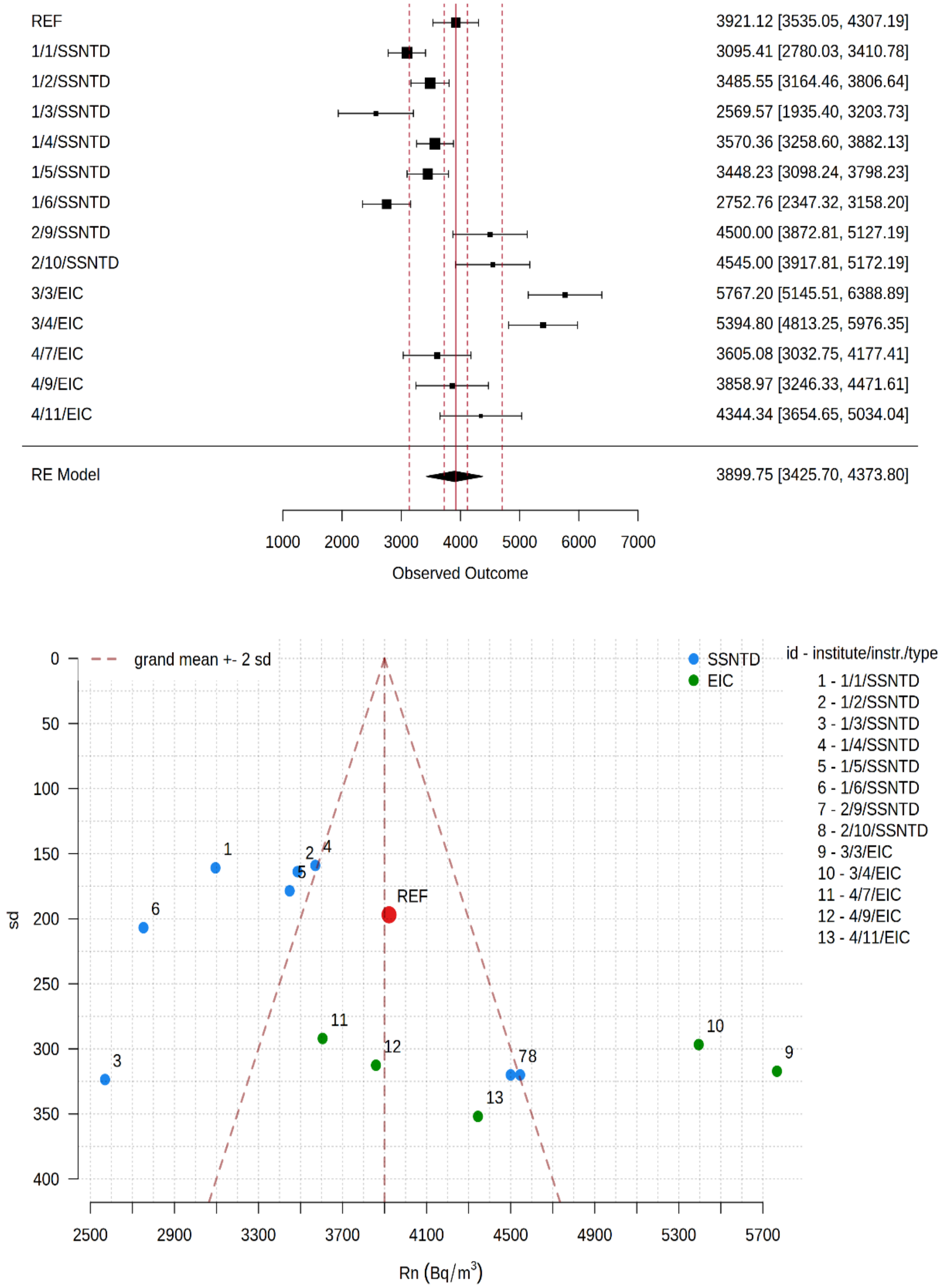


Fig. 15 Results for radon integral systems during B_2. Top panel - forest plot. Red lines represent the reference mean together with ± 5%, 20%. Bottom panel – funnel plot.

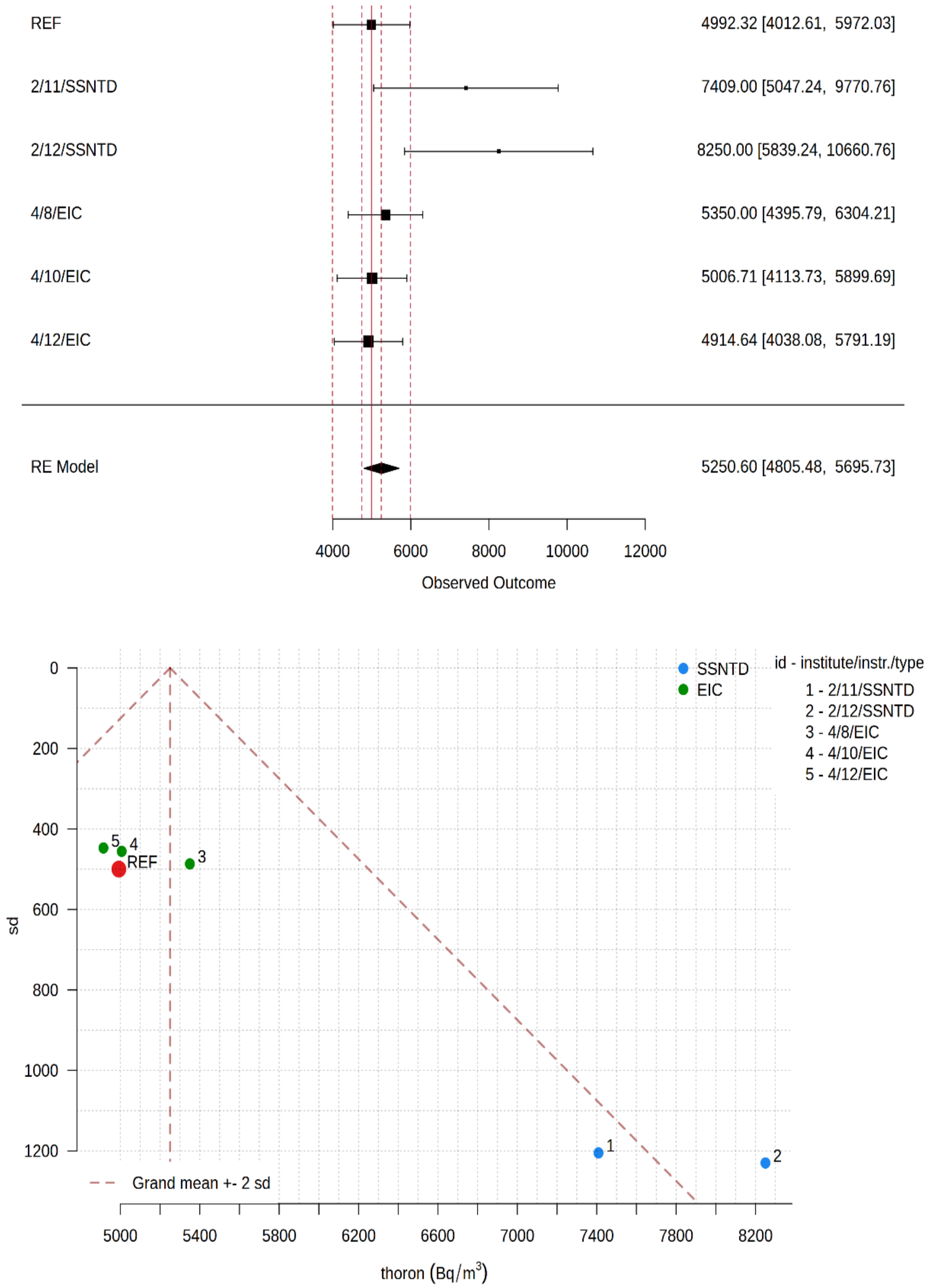


Fig.16 Results for thoron integral systems during B_2. Top panel - forest plot. Red lines represent the reference mean together with ± 5%, 20%. Bottom panel – funnel plot.