Implementing soil radon detectors for long term continuous monitoring

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Abstract

The employment of different instruments for radon continuous measurements within the Italian Radon mOnitoring Network (IRON), mostly INGV, Algade AER and Airthings Corentium instruments, requires a uniform characterization and calibration protocol for the results to be comparable in a rigorous way. A 56 L stainless steel radon chamber with a sensitivity of 0.95 ± 0.01 Bq m^{-3} per pulse h^{-1} has been used and validation of Algade AER, Airthings Corentium and Durridge RAD7 radon monitors equipped with solid-state detectors operated at different absolute humidity values has been performed, extending their operative range. Robustness to atmospheric electromagnetic phenomena of INGV and Algade AER instruments has been investigated and, for the former instrument, improved.

Keywords

Soil radon; long term continuous monitoring; lucas cell vs solid-state detectors; calibration; electrical shielding

1. Introduction

Radon detectors are employed in a wide range of applications, from environmental safety and public health to Earth sciences studies, especially in the frame of volcanic surveillance and seismic monitoring. The Istituto Nazionale di Geofisica e Vulcanologia in Italy (INGV) hosts the Radionuclide Laboratory where radon instrumentation devoted to all the above applications is managed, set up and developed. In the last years, INGV implemented the Italian Radon mOnitoring Network (IRON), a new nationwide permanent network for near real-time measurements of soil radon emissions in Italy (Cannelli, 2017; Cannelli et al., 2018). Presently IRON consists of 36 stations covering the whole Italian peninsula and represents one of the few examples worldwide of such a network (in terms of covered area, time series length and total number of stations).

The employment of different instruments within a same network, used for discrete or continuous radon measurements, requires a unified calibration protocol and the certification of their robustness to variable environmental conditions, so that results are comparable in a rigorous way.

Therefore, the manuscript is aimed at *i*) the fulfilment of the above stated requirements, also testing and improving, if necessary, the instrument electrical shielding and *ii*) the validation of the behaviour of radon monitors equipped with solid-state detectors operated at high absolute humidity values, thus extending their operative range and employing possibilities. A radon chamber available at the INGV Radionuclide Laboratory has been used, calibrated by intercomparison as described in De Simone et al., 2016.

As a matter of fact, monitors equipped with a scintillation cell are not influenced by absolute humidity, consequently only their calibration and linearity have been assessed. Differently, the response of radon monitors employing semiconductor detectors needs to be corrected as a function of absolute humidity (Chu and Hopke, 1988; Hopke, 1989; Roca et al., 2004; Tuccimei et al., 2006; De Simone et al., 2016), especially if electrostatic collection of the short-lived radon daughters takes place and/or big sized detection volumes are adopted. Water molecules cause the neutralization of radon progenies, reducing the detector efficiency (wall attachment, thin water film onto the detector and, for electrostatic chambers, reduced collection).

Corrections can vary for every instrument also because their temperature, humidity and pressure sensors (when available) are used, consequently also their conditions may affect the monitor characterization.

2. Materials and methods

A list of radon monitors available at INGV laboratories and/or employed at remote sites follows.

2.1 INGV proprietary instrument

Most IRON stations adopt a high sensitivity proprietary instrument employing an alpha scintillation detector (a Lucas Cell), consisting of a flask, whose inner wall is coated with silver-activated zinc sulphide (ZnS). It integrates a front-end electronics for pulse shaping. Radon enters the detector by diffusion through an inlet filter that traps radon daughters. For 500 mL scintillating flasks (Algade©), sensitivity is typically in the range 0.24-0.28 Bq m^{-3} per pulse h^{-1}, while minimum detectable concentration is 3-6 Bq m^{-3}. The instrument is powered by a 12V lead-acid battery, which is charged by a power supply connected to 220V mains or to a solar panel, depending on installation types. Radon measurements are performed by counting the radon decay signals within an adjustable acquisition time; in old models they are stored locally in the front-end electronics memory and can be downloaded through a serial interface. In recent models a new acquisition system with remote transmission based on the open-source Arduino platform (https://www.arduino.cc/) has been implemented; this low-cost, low-power data acquisition device can provide both local storage on a flash memory and real-time data transmission via the Global System for Mobile Communications (GSM) network (Cannelli et al., 2018).

2.2 Algade AER

Algade AER Plus (http://www.algade.com/) is a small sized commercial solid-state radon detector, providing also local storage for temperature and relative humidity data. The connected version (AER C) is available for data transmission by Internet of Things (IoT) Sigfox protocol (https://www.sigfox.com/en), where data are retrieved connecting with a client to an Algade server. Instruments are battery supplied with autonomy of one year. Since 2017, we started to test and deploy AER C in IRON stations.

2.3 Airthings Corentium Plus

Airthings Corentium Plus (https://airthings.com) is a small sized commercial solid-state radon detector, providing also local storage for temperature, relative humidity and atmospheric pressure data. The instrument is battery supplied with autonomy of two years. Presently, we are testing five Corentium Plus in IRON stations.

2.4 Durridge RAD7

Durridge RAD7 (https://durridge.com/) is a commercial electronic radon detector, generally employed for discrete measurements to assess the radon activity concentration in soil gas or dissolved in water. An electrostatic chamber, operated at a nominal voltage in the range 2,000 – 2,500 V, is intended for radon daughters' collection onto the surface of a solid-state silicon detector, which detects and separates alpha particles on the basis of their energies. Only alpha decays from the short-lived ^{218}Po (its half-life is about 3 minutes) can be selected (Sniff mode, according to

RAD7 protocols) to rapidly infer ^{222}Rn, since the radioactive equilibrium between them is reached in about 15 minutes. Temperature and relative humidity are recorded inside the instrument. A pump guarantees the circulation of the air in the set-up. INGV Radionuclide Laboratory operates two RAD7s used mainly for geochemical surveys.

2.5 Barasol MC2 probe

The Barasol MC2 is a commercial probe (http://www.algade.com/) used for measurements of radon in the ground (Papastefanou 2002). The unit is a cylindrical o-ring sealed device 62 mm in diameter, by approximately 520 mm long. It is constructed from fibreglass and corrosion-resistant stainless steel and weighs around 2 kg. Soil gas enters a detection volume through three cellulose filters that trap all the solid radon daughter products. The Barasol sensor is based on an implanted silicon detector with a depleted depth of 100 μm and 400 mm^2 of sensitive area; counting is made by alpha spectrometry from decays of ^{222}Rn and its daughter products created in the detection volume. MC2 sensitivity is typically 50 Bq m^{-3} per pulse h^{-1}. It is designed to be used in environments where electricity and solar power supply are not available, guaranteeing one year of operating time with two type D alkaline batteries, and integrates the acquisition electronics and a local memory. The probe also records temperature and atmospheric pressure. INGV Radionuclide Laboratory and Osservatorio Etneo operate seven MC2 probes mainly for volcanic surveillance and specific research projects.

2.6 AlphaNUCLEAR alphaMETER

The commercial model 611 alphaMETER (http://www.alphanuclear.com/index.html) is intended for the detection, counting, and recording of alpha particle radiation from radon gas present in the near surface soil gas. The unit is a cylindrical o-ring sealed device 51 mm in diameter, 350 mm long. It is constructed from stainless steel and weighs 1.2 kg. One end is open to provide the sensitive volume for counting. At the top of this open-ended chamber, at approximately 65 mm in from that end is located the alpha particle sensitive detector. The detector is a silicon-diffused junction (DJ) with a sensitive surface area of 400 mm^2. As this detector requires a dry, dark environment to operate, it is sealed behind a thin opaque film (6.35 μm aluminized mylar) of sufficiently low density to efficiently pass alpha particles. This fragile sealing is protected by a plastic grill located approximately 12 mm from the open end of the sensitive volume. The internal electronics include a pulse amplifier/conditioner, the power regulator circuits, a real-time clock, a non-volatile data memory and a micro-processor devoted to perform all necessary house-keeping functions, as well as the pulse counting and RS-232 communications (http://www.alphanuclear.com/manuals/611 Operating Manual V3.pdf). The sensitivity is around 60 Bq m^{-3} per pulse h^{-1} . INGV Osservatorio Etneo has three alphaMETER used mainly for volcanic surveillance.

2.7 Calibration facility

In order to verify, calibrate and characterize the above listed instruments and, most important, to evaluate the absolute humidity impact on the detection efficiency of the silicon detector based instruments, ad-hoc experiments were designed (Figure 1).

We used a 56 L stainless steel radon chamber equipped with a scintillation cell (ZnS), not sensitive to humidity, coupled to a photomultiplier whose pulses are shaped by a signal processing module (D) and recorded by a multichannel analyzer (MCA) set in multiscaler mode (M). Counts C accumulated during the selected acquisition time, T_{acq} (min), are stored in a channel (n), as a result a plot of C versus channels is available on the MCA screen. The radon activity concentration ($A_{Rn\ CR}$) in the radon chamber at a generic time t = n*T_{acq} elapsed from the chamber switch on is given by

$$A_{Rn\ CR}(t) = ((C(t) - B)/T_{acq}) / Cal_{CR} \qquad (1)$$

where B is the background signal in the T_{acq} time and Cal_{CR} is the chamber calibration factor expressed as counts per minute (CPM) per Bq m^{-3}.

Radon gas was extracted from an acidified (pH< 2) $RaCl_2$ source added with Ba (2,500 Bq), and injected in the chamber. Relative humidity and thus the amount of water molecules in the system, at given atmospheric pressure and temperature, were progressively varied by connecting the chamber to desiccant column (opening stopcocks O and Q and closing stopcocks P and R) or to a bubbling water bottle (opening stopcocks O and R and closing stopcocks P and Q) for drying or humidifying the closed circuit. When reached the desired conditions stopcock, P was opened and stopcocks O, Q and R were closed. The radon concentration within the chamber was always compared, for redundancy, with an online reference RAD7 (L) serviced and calibrated at least once per year at Durridge Company, Inc.

Depending on the instrument to be calibrated, a mini chamber, a slave chamber or the generic instrument were connected to the chamber or inserted in the basic loop according to the following configurations:

- Configuration A: an INGV instrument was connected to the B air tight connectors by means of a dedicated flange;
- Configuration B: the basic schematic, as is, with the generic RAD7 instrument instead of the reference one;
- Configuration C: a parallelepiped–shaped slave chamber made of steel containing small sized radon monitors was connected to the B air tight connectors. With a volume of around 28 L (430 mm x 180 mm x 360 mm) a maximum of 12 instruments can be power supplied and characterized at a time;
- Configuration D: a cylindrical mini chamber made of PVC equipped with proper flanges for AlphaNUCLEAR alphaMETER or Algade Barasol probes hosting was connected to the B air tight connectors. With a volume of 3.0 L (Φ 155 mm x 160 mm height) only one instrument can be characterized at a time.

Every instrument reading (counts or activity concentration) was compared with the activity concentration given at the same time by the radon chamber. A number of experiments were carried out according to a planned sequence of drying or humidification phases, if needed.

As a result, for A and D (AlphaNUCLEAR alphaMETER only) configurations, a calibration factor (Cal) was calculated as the ratio $CPM_{INSTRUMENT} / A_{Rn\ CR}$ being $CPM_{INSTRUMENT}$ the net counts per minute measured by the generic instrument and $A_{Rn\ CR}$ the corresponding radon activity concentration (Bq/m^3) in the radon chamber.

For B, C and D (Algade Barasol only) configurations, correction factors of activity concentration values obtained using RAD7, Algade AER, Airthings Corentium and Algade Barasol probes, defined as efficiency of the (electrostatic collection-based – only intended for RAD7) silicon detector, were calculated as the ratio $A_{Rn\ INSTRUMENT}(t) / A_{Rn\ CR}(t)$ and plotted versus the amount of water in the instrument detection volume at the time t, being $A_{Rn\ INSTRUMENT}$ the average radon activity concentration measured by the generic instrument and $A_{Rn\ CR}$ the corresponding radon activity concentration in the radon chamber. It is important to point out that, in order to compare the behaviour of different instruments, and/or when the detection volume is a patented feature, AH (absolute humidity) shall be considered instead of the amount of water in the instrument detection volume.

In order to reduce uncertainties on the calculation of the above mentioned calibration or correction factors $A_{Rn\ CR}(t)$ was calculated as in equation 1 by using the exponential interpolation $C_1(t)$ of $C(t) – B$ data available every T_{acq}, being $C_1(t) = A*e^{B*t}$, with the A and B parameters evaluated by OriginPro software (OriginLab™), where, in particular, -1/B is the interpolation time constant (min) and t is the time (min) elapsed from the first acquired data to be considered.

It is worth noting that only radon chamber data recorded after at least 5 hours from radon enrichment or upon reaching the desired gH_2O (or AH) values were considered, to account for the establishment of new equilibrium conditions (secular equilibrium and/or radon diffusion within the new system configuration) and to reduce the error.

Water amounts in the detection volume, expressed as grams of water ($gH_2O_{INSTRUMENT}$), are inferred from the psychrometric diagram as a function of the atmospheric pressure, temperature and relative humidity and calculated using equation 2, see details in De Simone et al., 2016 :

$$gH_2O_{INSTRUMENT} = AH * 1000 * \rho\ air_{T} * V_{INSTRUMENT} \quad (2)$$

where:

AH : absolute humidity (kg H_2O / kg dry air)

ρ air $_T$: air density at a given temperature (kg/m^3)

$V_{INSTRUMENT}$: detection volume of the monitor (m^3)

3. Results

3.1 Configuration A

Configuration A (Figure 1) is adopted to calibrate and verify the linearity of INGV radon monitors. INGV radon monitors are operated with measurement cycles ranging from 15 to 120 minutes. On Arduino-based devices, counts are accumulated for an acquisition time that coincides with the time of the cycle. Old instruments with a proprietary data acquisition and storage board need a time during which the acquisition is idle: this is intended to modify the parameters stored (i.e. current date and time, calibration parameters), therefore a programmable timer is employed to schedule typically 120 minute cycles (minimum time due to a limitation on the admitted number of commutations) and set the acquisition time usually at 115 minutes, during the remaining 5 minutes the acquisition is idle. Net counts per minute, calculated subtracting the background signal of the scintillation cell provided by the manufacturer, are compared to the simultaneous mean concentration value in the radon chamber obtaining the calibration factor. As example, typical calibration factors, expressed as CPM / Bq m^{-3}, for INGV radon monitors are reported in Table 1. Therefore, the activity concentration values $A_{Rn\ INGV}$ are calculated according to the following equation:

$$A_{Rn\ INGV}\ (Bq/m^3) = (C/T_{acq} - B) / Cal \tag{3}$$

where:

T_{acq} is the acquisition time (min)

C are the counts accumulated in T_{acq}

B is the background signal of the scintillation cell (CPM), provided by the manufacturer. Also the accumulation of ^{210}Po in the scintillation cell coating affects this value, and must be considered. Linearity has been verified since, after the secular equilibrium has been reached, counts decreases following an exponential trend $C_0e^{-\lambda t}$ where λ is the radon decay constant.

3.2 Configuration B

Configuration B (Figure 1) is adopted to verify the built-in calibration of Durridge RAD7 radon monitors, affected by absolute humidity. Water molecules are usually removed by a desiccant column placed upstream of the RAD7 instrument, however the assessment of RAD7 efficiency as a function of gH_2O is useful when the humidity cannot be reduced within a recommended range (0–0.002 gH_2O inside the RAD7), for instance when water nearly saturates the desiccant column or under extreme climatic conditions (high temperatures).

Upon monitor connection AH ranging from less than 0.0007 to around 0.007 kg H_2O per kg of dry air were obtained by properly operating stopcocks O, P, Q and R as stated above (see Figure 1). The average readings were compared with activity concentrations given by the radon chamber at each step. Correction factors of activity concentration values (defined as efficiency of the electrostatic collection-based silicon detector) to be applied when using RAD7 instruments were calculated as the ratio:

$$Efficiency(gH_2O) = A_{Rn\ RAD7\ RAW} / A_{Rn\ CR} \tag{4}$$

and plotted versus gH_2O, being $A_{Rn\ RAD7\ RAW}$ the average radon activity concentration measured by the RAD7 at water content gH_2O and $A_{Rn\ CR}$ the corresponding interpolated radon activity concentration in the radon chamber. The amount of water (gH_2O) inside the RAD7 detection volume was inferred from the psychrometric diagram as a function of the atmospheric pressure, temperature and relative humidity according to Eq. 2. Typical efficiency trends are shown in Figure

2 along with the linear interpolation of data and the equation for the corrected activity concentration; please note that RAD7 S.N. 2226, which behaves better, had been recently serviced at Durridge laboratories (our experience confirms that RAD7 should be serviced, or just calibrated, at least once per year as recommended by Durridge Company and according to U.S. EPA 402-R-92-004 protocols when continuous radon monitors are concerned). Consequently, the RAD7 output ($A_{Rn\ RAD7\ RAW}$) should be corrected according to the following equation we will refer to also for other instruments:

$$A_{Rn\ RAD7} = A_{Rn\ RAD7\ RAW} / \text{Efficiency}(gH_2O) \tag{5}$$

The relative efficiency of the silicon detector with respect to the scintillation cell decreases with the growth of the absolute humidity (AH), and thus with the water content expressed in gH_2O (g), inside RAD7. This dependence, with a fixed i) electrostatic chamber geometry and ii) nominal high voltage, is driven by the length of interaction of polonium atoms with water molecules, which impacts on the size of ^{218}Po clusters and thus on the neutralization process. Temperature does not affect the efficiency of electrostatic collection-based silicon detectors (De Simone et al., 2016). Uncertainties induced by the above mentioned corrections, for $0 < gH_2O < 0.006$, are within those related to 1σ of raw data concentrations values. For $0.006 < gH_2O < 0.007$ uncertainties may be higher because of the detector response to the increased water content and neutralization process. In Figure 3 the linear behaviour is indirectly demonstrated plotting RAD7 concentrations, obtained at fixed low humidity values versus radon chamber concentrations.

3.3 Configuration C

Configuration C (Figure 1) is adopted to verify the built-in calibration of small sized radon monitors (Algade AER or Airthings Corentium). Since these devices were originally designed for indoor use, they are calibrated at typical indoor humidity values or, cautiously, at the maximum expected humidity. Again, the monitor responses can be corrected versus the absolute humidity expressed as $kg_{H20}/kg_{dry\ air}$ and not as water in the detection volumes since they are very small in those instruments and, what's more, Airthings considers its value a patented feature. Algade AER and Airthings Corentium efficiency values versus AH are plotted in Figures 4 and 5, respectively, for two detectors. Equations obtained from linear interpolation in selected AH ranges are reported, representing the correction functions to be applied to the raw activity concentration data as in equation (5). At intermediate humidity values, the trend exhibits a similar change of slope as in De

Simone et al., 2016.

The raw and corrected radon activity concentrations, AH and the reference radon activity concentration values are plotted in Figures 6 and 7 for Algade AER and Airthings Corentium, respectively. All the instrument responses adhere to the reference trend given by the radon chamber. INGV operates an Algade customized version of the AER C instrument, not only aimed at radioprotection purposes, that comes from the factory with a pretty good built in calibration as a function of the AH. A cautious approach (raw concentration values always equal or greater than corrected concentration values) is not used and the raw concentration values are close to the ones from the radon chamber (and within a few per cent in dry conditions). A typical efficiency trend is shown in Figure 8; again, when corrections are applied to the raw data, AER C and radon chamber outputs are very similar (Figure 9).

3.4 Configuration D

Configuration D (Figure 1) is adopted to calibrate the AlphaNUCLEAR alphaMETER Mod. 611 or verify the built-in calibration of Algade Barasol probes produced for outdoor soil gas monitoring. Again, correction trends as a function of the absolute humidity can be determined. As stated by AlphaNUCLEAR, the alphaMETER Mod. 611 is not sensitive to water molecules, the detector being protected by an opaque mylar sealing. Consequently, its calibration can be performed at standard environmental conditions. Sample calibration processes involving one or more instruments are outlined in Figures 10 and 11. Each probe linearity has been investigated by changing the radon concentration in the chamber from 5 to 38 kBq/m^3. The calibration factors together with their uncertainties obtained i) at the highest activity concentration values available for each probe and ii) for the maximum number of observation for the best statistical conditions follow:

Cal_{AC-22} : 0.000277 ± 0.000023 CPM/Bq m^{-3}
Cal_{AC-23} : 0.000254 ± 0.000024 CPM/Bq m^{-3}
Cal_{AC-26} : 0.000256 ± 0.000025 CPM/Bq m^{-3}

For the linearity assessment all available data at different radon activity concentrations have been used:

AC-22 probe:
0.000268 ± 0.000063 CPM/Bq m^{-3} , concentration in the range 4.8 – 5.2 kBq m^{-3}
0.000277 ± 0.000023 CPM/Bq m^{-3} , concentration in the range 35 – 38 kBq m^{-3}

AC-23 probe:
0.000253 ± 0.000056 CPM/Bq m^{-3} , concentration in the range 5.3 - 6 kBq m^{-3}
0.000254 ± 0.000024 CPM/Bq m^{-3} , concentration in the range 32 - 34 kBq m^{-3}

AC-26 probe:
0.000258 ± 0.000052 CPM/Bq m^{-3} , concentration in the range 4.6 – 5.2 kBq m^{-3}
0.000256 ± 0.000025 CPM/Bq m^{-3} , concentration in the range 26 - 30 kBq m^{-3}

Therefore, the linear behaviour of the instruments has been verified, within the statistical error which is greater at low concentration values.

3.5 Electrical shielding

For those devices mostly used in outdoor permanent monitoring stations (i.e. INGV and Algade AER instruments), we have also investigated the possibility of external perturbations associated with atmospheric electromagnetic phenomena (i.e. lightnings). As it is known, the lightning is a current discharge of 2-200 kA on a voltage of 1-10 GV for duration of up to 1.5 s, which generates a broad-spectrum electromagnetic (EM) emission of several MHz of extension. Most of the EM radiation is limited to the low frequencies, which can penetrate the masonry and reach the basements.

To test this hypothesis, a piezoelectric generator was used to produce an electrical spark of at least 1000 V and about 2 mm in length. This can be considered a wide-spectrum EM source that, from the analysis of the EM signal in the ELF-VLF spectrum, seems to fairly simulate the lightning emission.

Actually only INGV instruments proved to be vulnerable to close exposure (less than 6 cm) of the small electric spark and as a matter of fact they produced spurious counts. Each compression cycle of the piezoelectric crystal caused about 10 spurious counts. We observed also that un-shielded INGV sensors were sensitive to electromagnetic field of mobile phone, placed very close to the instrument.

After this test, we investigated the electrical shielding of different versions of INGV proprietary instruments. The μ-metal tube intended for electromagnetic protection is not grounded. Besides, we observed that the sensitive element was the pulse shaping electronics together with its unshielded input cable, placed in front of the photomultiplier. The electrical shielding of these two elements definitively solved the problem of spurious counts generation.

Shielded INGV sensors will now be tested on site, together with original sensors, to experimentally test the hypothesis of thunderstorm interference, checking also available online lightning maps for real time presence and frequency of events near radon monitoring stations (i.e., www.lightningmaps.org).

4 Conclusions

A radon chamber available at the INGV Radionuclide laboratory has been used to verify, calibrate or even characterize instruments for the measure of soil gas or indoor radon activity concentration. The influence of water content in the detection volume has been accounted for, affecting solid-state detectors installed in various instruments. The instruments have also been tested and implemented for electrical shielding.

The response of every radon monitor installed in the IRON network has been verified and calibrated, also as a function of the absolute humidity depending on the kind of instrument, yielding comparable results as shown in Figure 12. Consequently, all the recorded trends are suitable, as is, for further analysis techniques.

Remarkably, low cost radon detectors originally designed for indoor use, after applying our procedures, exhibit performances (within their sensitivity figures) comparable with those granted by devices specifically designed for scientific applications and can be operated reliably in high performance monitoring networks like IRON.

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Figure captions

Fig. 1 Experimental set-up. A) radon chamber; B) air tight connectors (CPC) to be used when air circulation needs a pump; C) air tight connectors (CPC) when air circulation is guaranteed by an outer device; D) signal processing module; E) photomultiplier; F) scintillating flask; G) fan; H) desiccant column; I) humidifying device; L) Durridge RAD7 (required for Configuration B); M) multiscaler, N) low voltage supply; O), P), Q) and R) stopcocks.Configuration A: INGV radon sensor connected to the radon chamber. Configuration B (basic experimental set-up): Durridge RAD7 connected to the radon chamber. Configuration C: small sized instruments (i.e. Algade AER, Airthings Corentium) contained in a medium sized external box connected to the radon chamber. Configuration D: soil gas probes coupled to a small sized external box connected to the radon chamber.

Fig. 2 Efficiency trends versus the water content exhibited by two RAD7s. Equations for corrected activity concentration values are reported.

Fig. 3 Verification of the linear behaviour of a RAD7 instrument.

Fig. 4 Sample Algade AER efficiency versus AH. Equations for corrected activity concentration values are reported.

Fig. 5 Sample Airthings Corentium efficiency versus AH. Equations for corrected activity concentration values are reported.

Fig. 6 Correction of the built-in calibration factor for an Algade AER.

Fig. 7 Correction of the built-in calibration factor for an Airthings Corentium.

Fig. 8 Algade AER efficiency versus AH of a customized instrument. Equation for corrected activity concentration values is reported.

Fig. 9 Correction of the built-in calibration factor for a customized Algade AER.

Fig. 10 Background assessment, calibration and linearity check of one AlphaMETER probe.

Fig. 11 Operating sequence of a radon chamber to calibrate AlphaNUCLEAR alphaMETER probes. At least two radon concentrations have been used to check each probe linearity, except for the damaged AC-40.

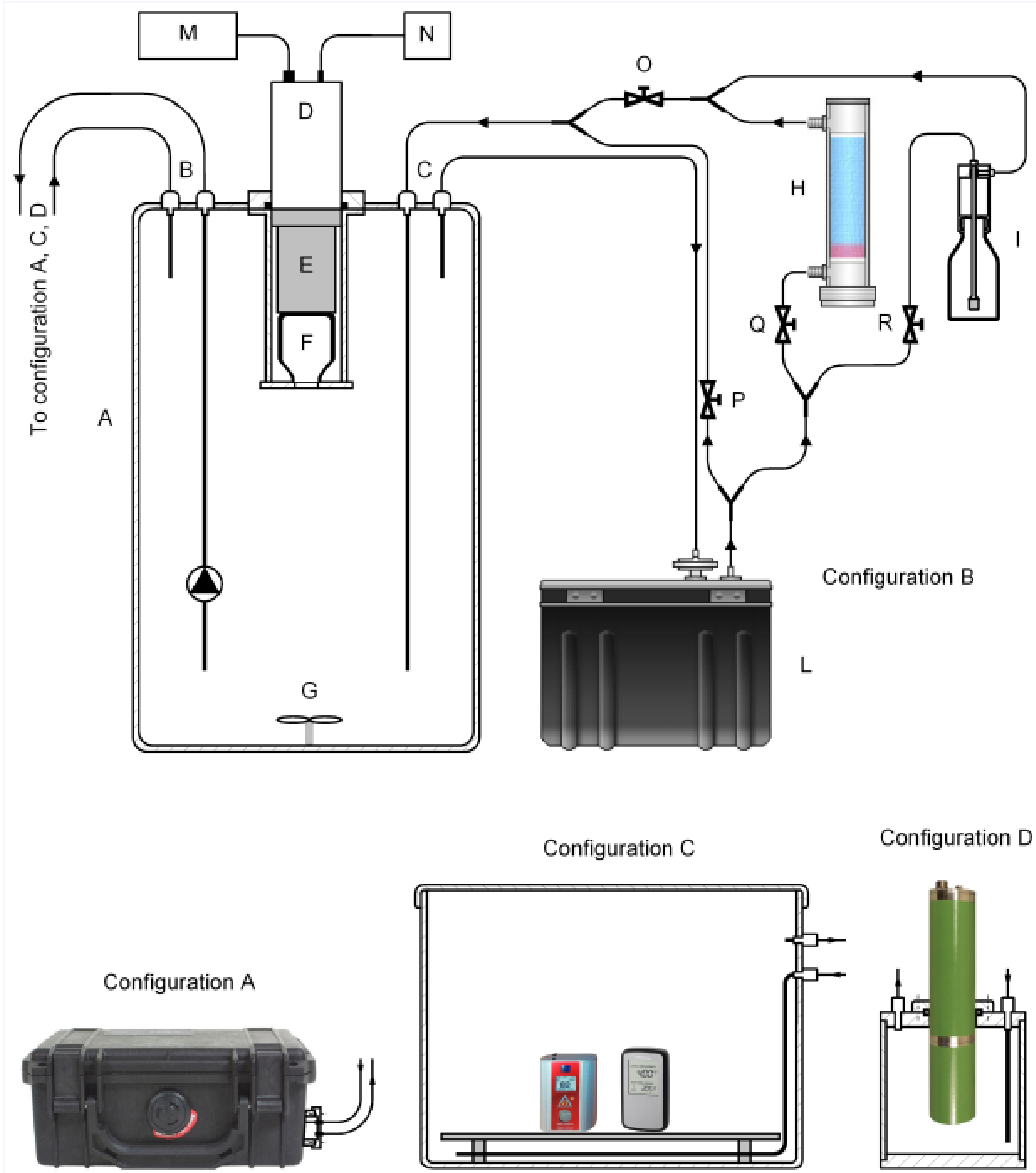
Fig. 12 Comparison of INGV, AER and Corentium radon monitors connected to a radon chamber.

Tables

Table 1 Typical calibration factors of INGV radon monitors

Sensor Id.	Cal (CPM / Bq m^{-3})
RNM_INGV_03_01	0.0513 ± 0.0005
RNM_INGV_03_02	0.0715 ± 0.0008
RNM_INGV_03_03	0.0689 ± 0.0007
RNM_INGV_03_04	0.0706 ± 0.0012
RNM_INGV_03_05	0.0650 ± 0.0009
RNM_INGV_03_06	0.0692 ± 0.0012
RNM_INGV_03_07	0.0653 ± 0.0009

Figure 1



M
N
D
O
B
C
E
F
H
I
To configuration A, C, D
A
Q
R
P
Configuration B
L
G
Configuration C
Configuration D
Configuration A

Figure 2

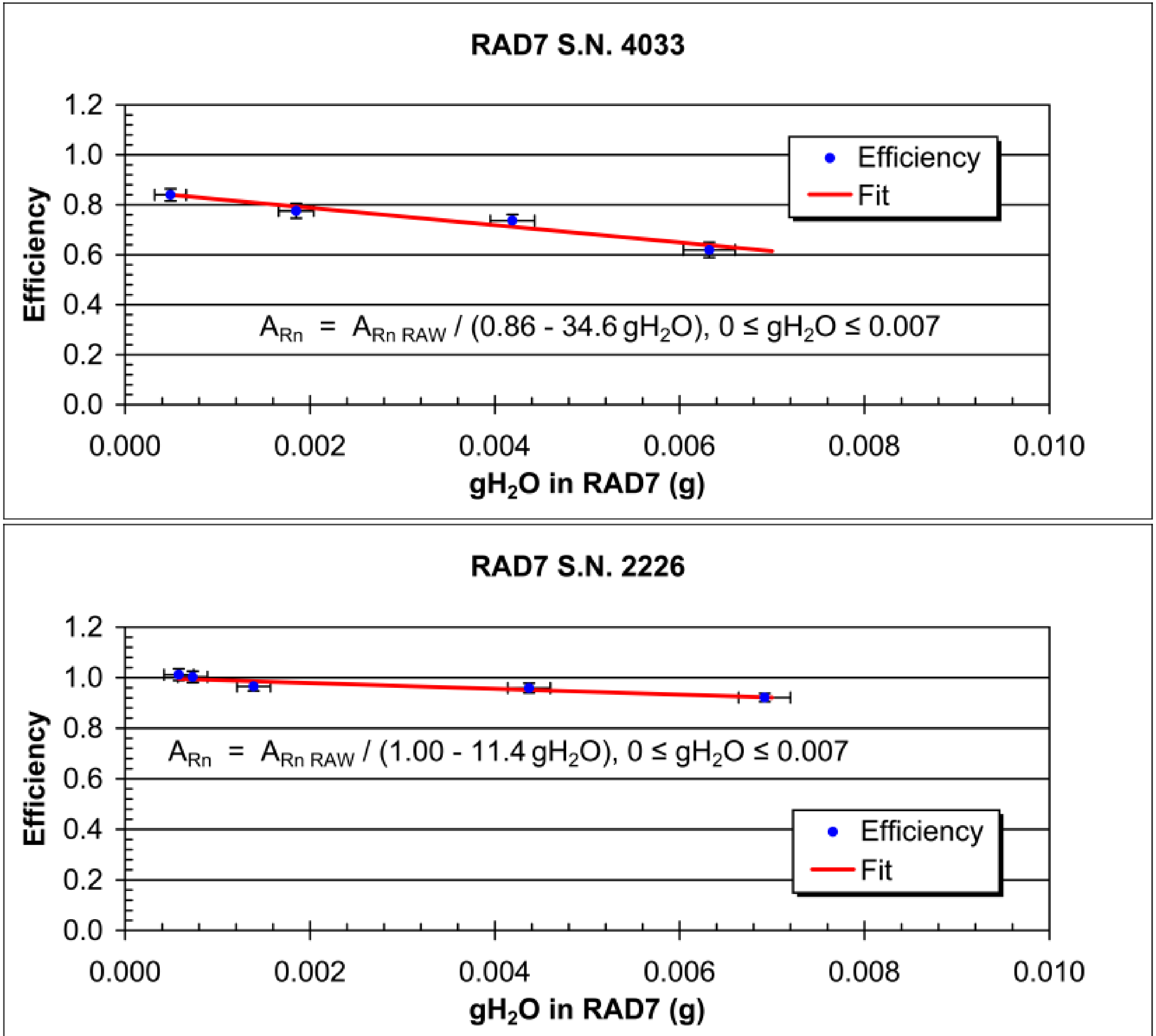
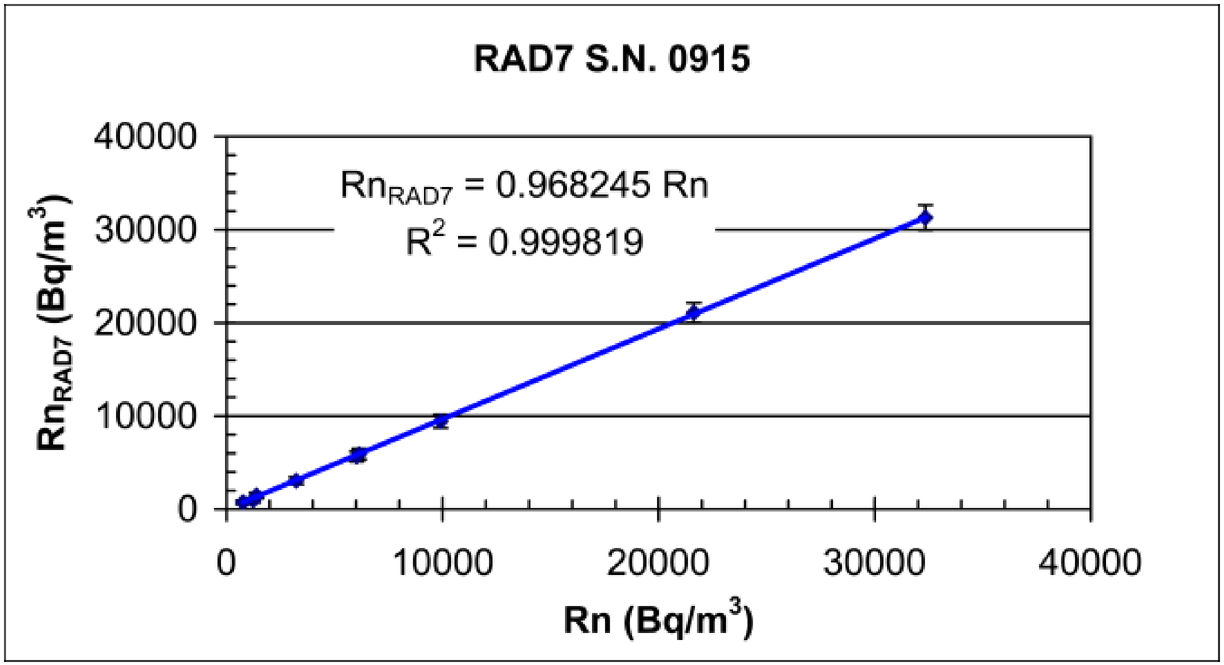
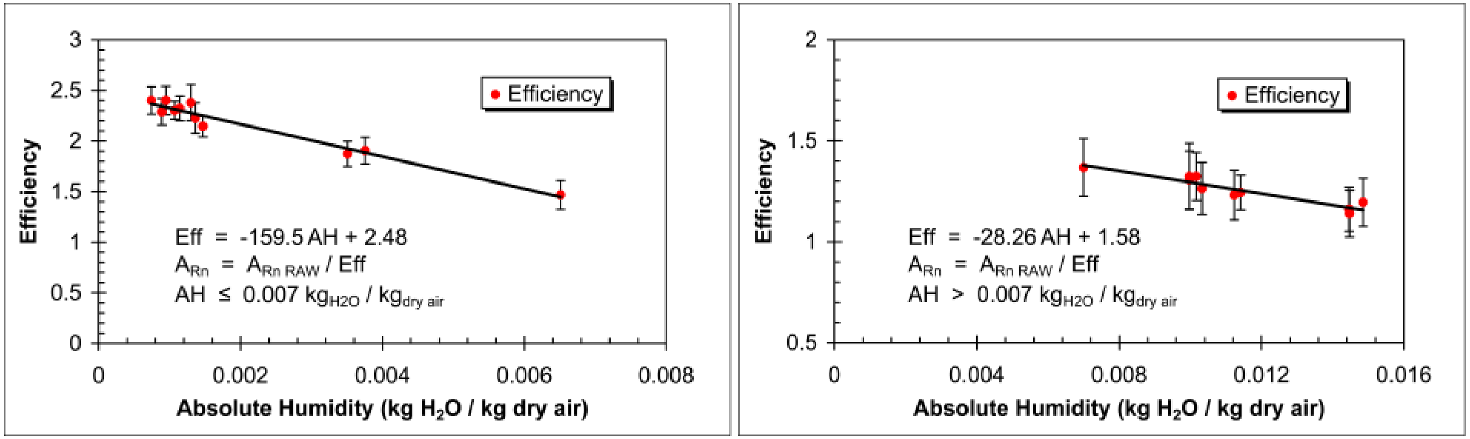

RAD7 S.N. 4033
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Efficiency
Efficiency
Fit
A_Rn = A_Rn RAW / (0.86 - 34.6 gH2O), 0 ≤ gH2O ≤ 0.007
0.000
0.002
0.004
0.006
0.008
0.010
gH2O in RAD7 (g)
RAD7 S.N. 2226
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Efficiency
A_Rn = A_Rn RAW / (1.00 - 11.4 gH2O), 0 ≤ gH2O ≤ 0.007
Efficiency
Fit
0.000
0.002
0.004
0.006
0.008
0.010
gH2O in RAD7 (g)

Figure 3



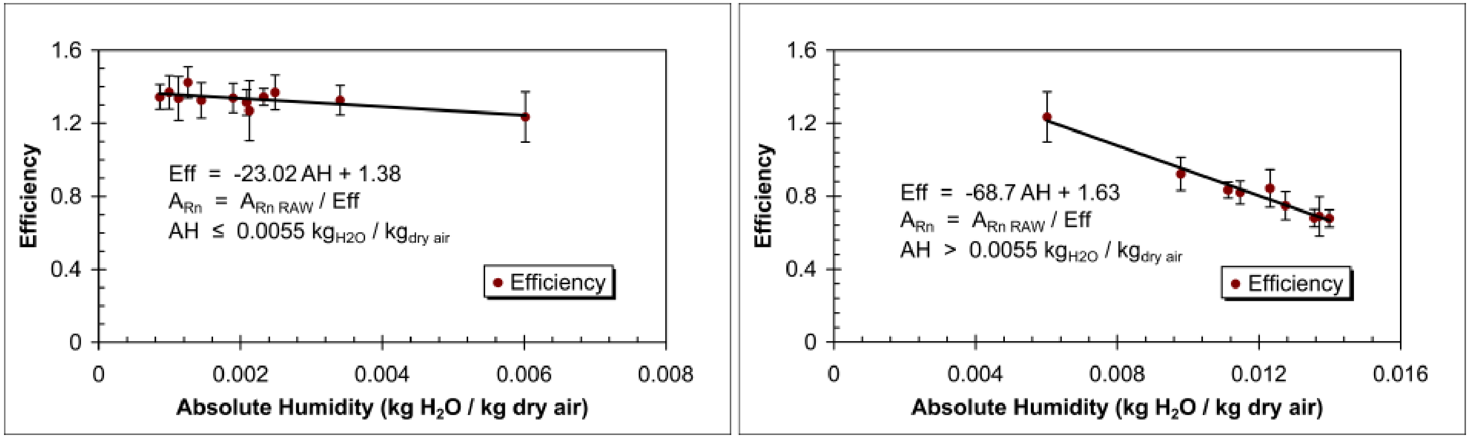
RAD7 S.N. 0915
Rn_{RAD7} = 0.968245 Rn
R^2 = 0.999819
40000
30000
20000
10000
0
Rn_{RAD7} (Bq/m^3)
0
10000
20000
30000
40000
Rn (Bq/m^3)

Figure 4



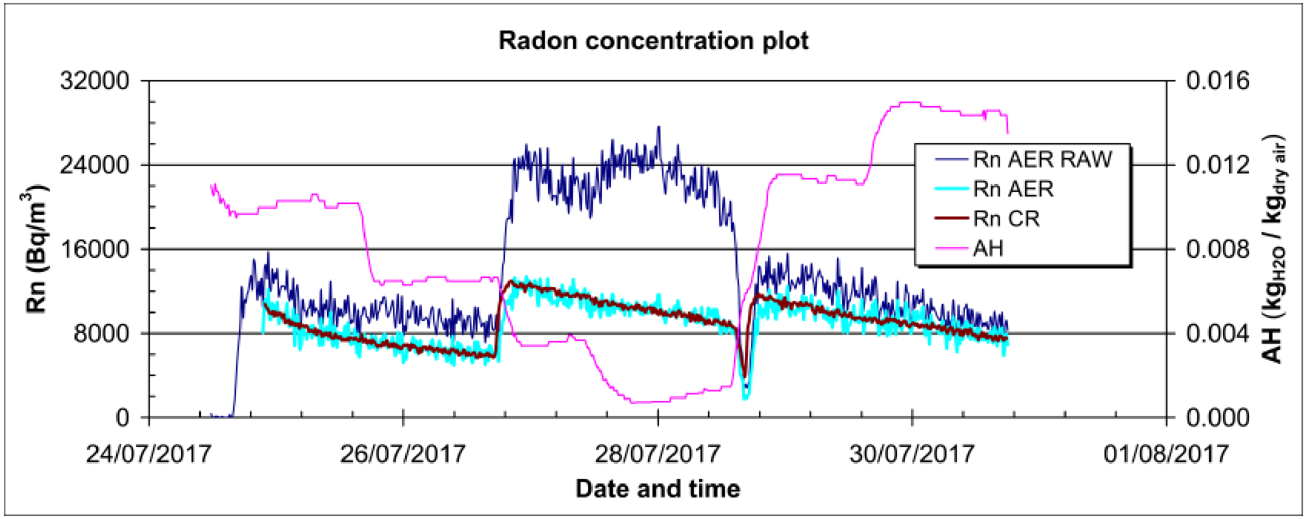
Efficiency
Eff = -159.5 AH + 2.48
A_{Rn} = $A_{Rn\ RAW}$ / Eff
AH ≤ 0.007 kg_{H2O} / $kg_{dry\ air}$
Efficiency
Absolute Humidity (kg H_2O / kg dry air)
0
0.002
0.004
0.006
0.008
0
0.5
1
1.5
2
2.5
3
Efficiency
Eff = -28.26 AH + 1.58
A_{Rn} = $A_{Rn\ RAW}$ / Eff
AH > 0.007 kg_{H2O} / $kg_{dry\ air}$
Efficiency
Absolute Humidity (kg H_2O / kg dry air)
0
0.004
0.008
0.012
0.016
0.5
1
1.5
2

Figure 5



1.6
1.2
0.8
0.4
0
Efficiency
Eff = -23.02 AH + 1.38
A_Rn = A_Rn RAW / Eff
AH ≤ 0.0055 kg_H2O / kg_dry air
Efficiency
0
0.002
0.004
0.006
0.008
Absolute Humidity (kg H2O / kg dry air)
1.6
1.2
0.8
0.4
0
Efficiency
Eff = -68.7 AH + 1.63
A_Rn = A_Rn RAW / Eff
AH > 0.0055 kg_H2O / kg_dry air
Efficiency
0
0.004
0.008
0.012
0.016
Absolute Humidity (kg H2O / kg dry air)

Figure 6



Radon concentration plot
32000
24000
16000
8000
0
0.016
0.012
0.008
0.004
0.000
Rn (Bq/m3)
AH (kgH2O / kgdry air)
24/07/2017
26/07/2017
28/07/2017
30/07/2017
01/08/2017
Date and time
Rn AER RAW
Rn AER
Rn CR
AH

Figure 7

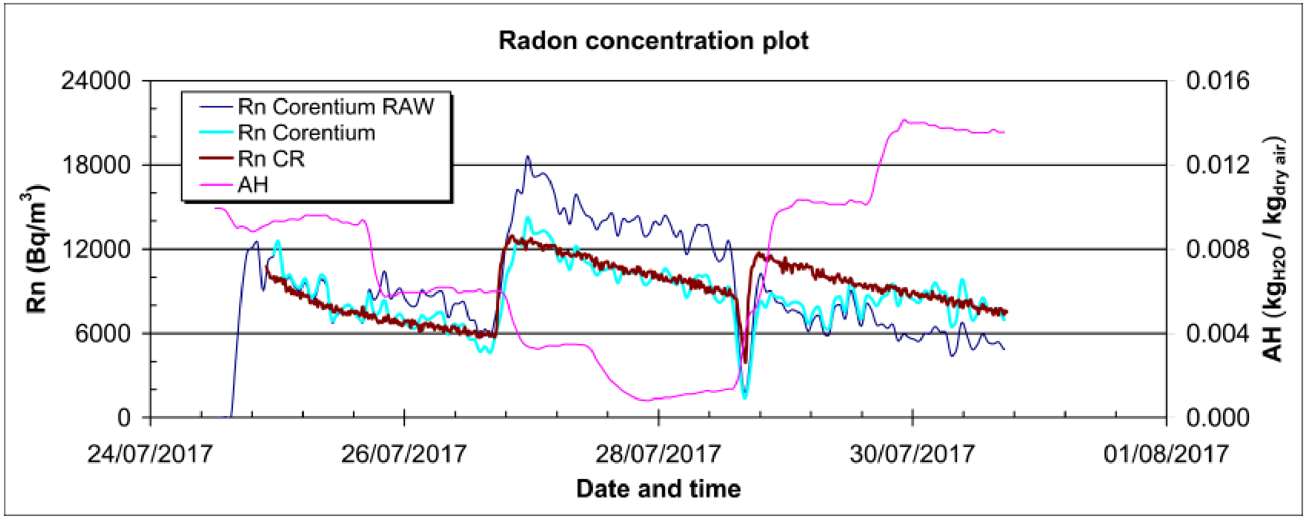
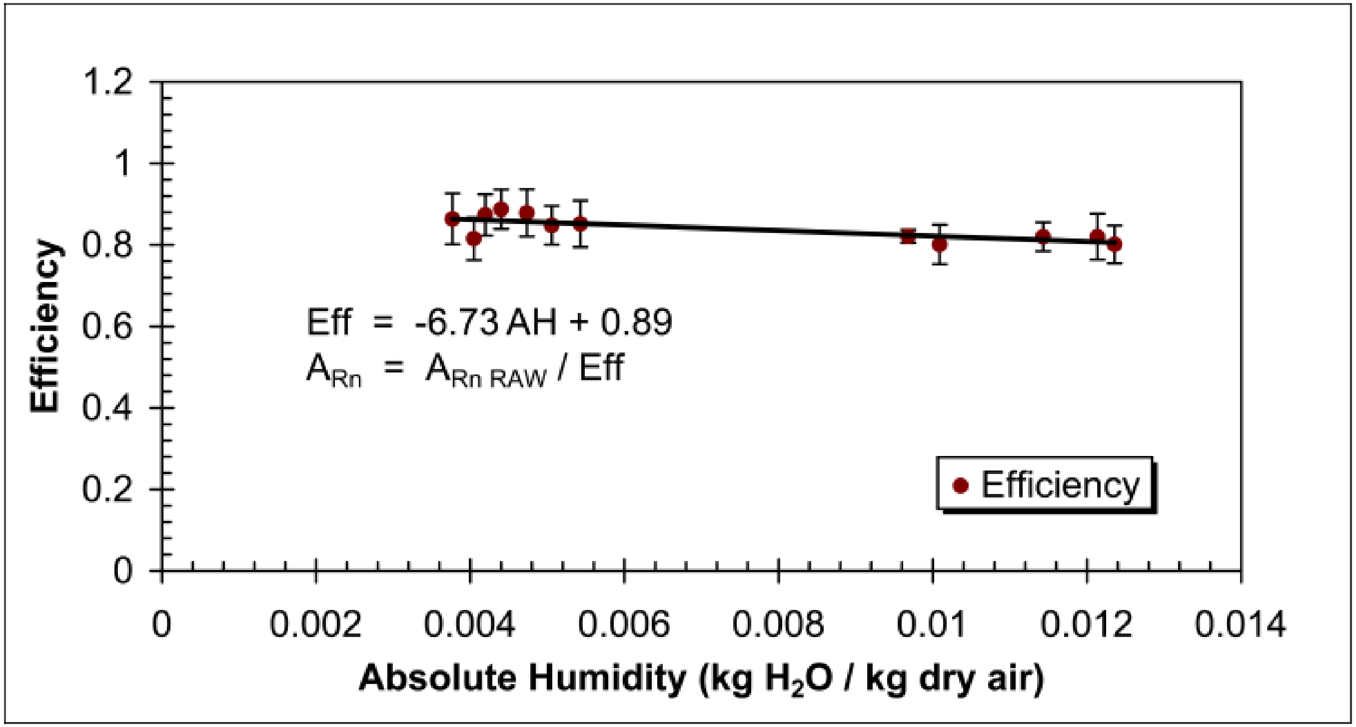
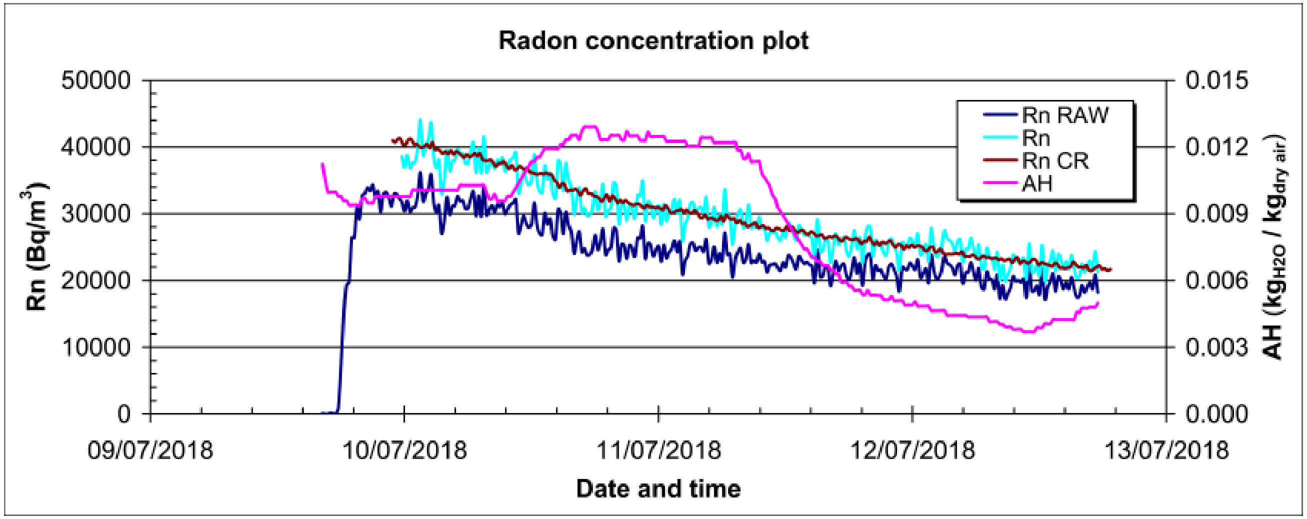

Radon concentration plot
Rn Corentium RAW
Rn Corentium
Rn CR
AH
24000
18000
12000
6000
0
0.016
0.012
0.008
0.004
0.000
Rn (Bq/m3)
AH (kgH2O / kgdry air)
24/07/2017
26/07/2017
28/07/2017
30/07/2017
01/08/2017
Date and time

Figure 8



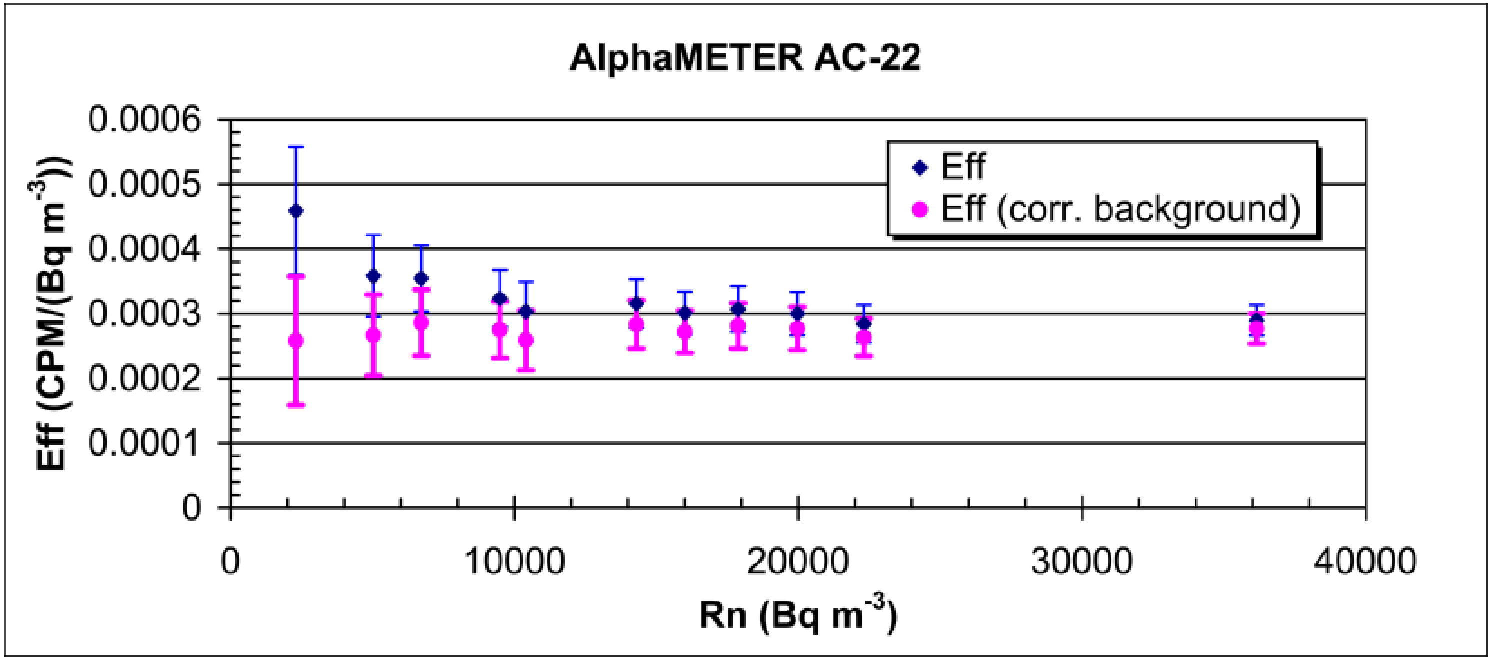
1.2
1
0.8
0.6
0.4
0.2
0
Efficiency
Eff = -6.73 AH + 0.89
A_Rn = A_Rn RAW / Eff
Efficiency
0
0.002
0.004
0.006
0.008
0.01
0.012
0.014
Absolute Humidity (kg H2O / kg dry air)

Figure 9



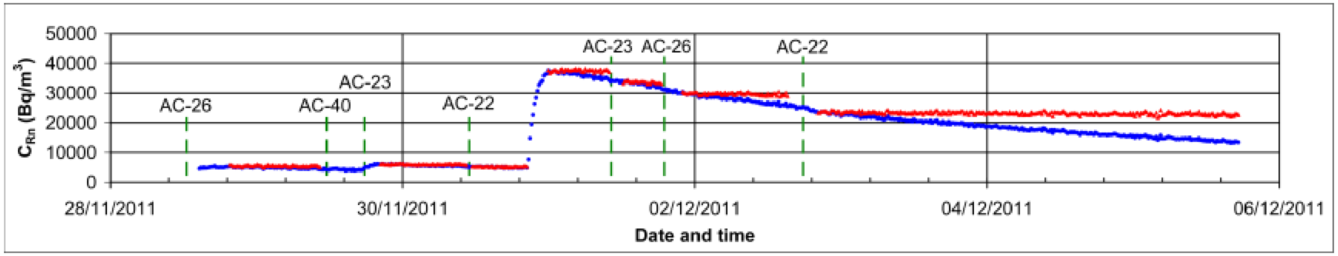
Radon concentration plot
50000
40000
30000
20000
10000
0
Rn (Bq/m³)
0.015
0.012
0.009
0.006
0.003
0.000
AH (kg_H2O / kg_dry air)
Rn RAW
Rn
Rn CR
AH
09/07/2018
10/07/2018
11/07/2018
12/07/2018
13/07/2018
Date and time

Figure 10



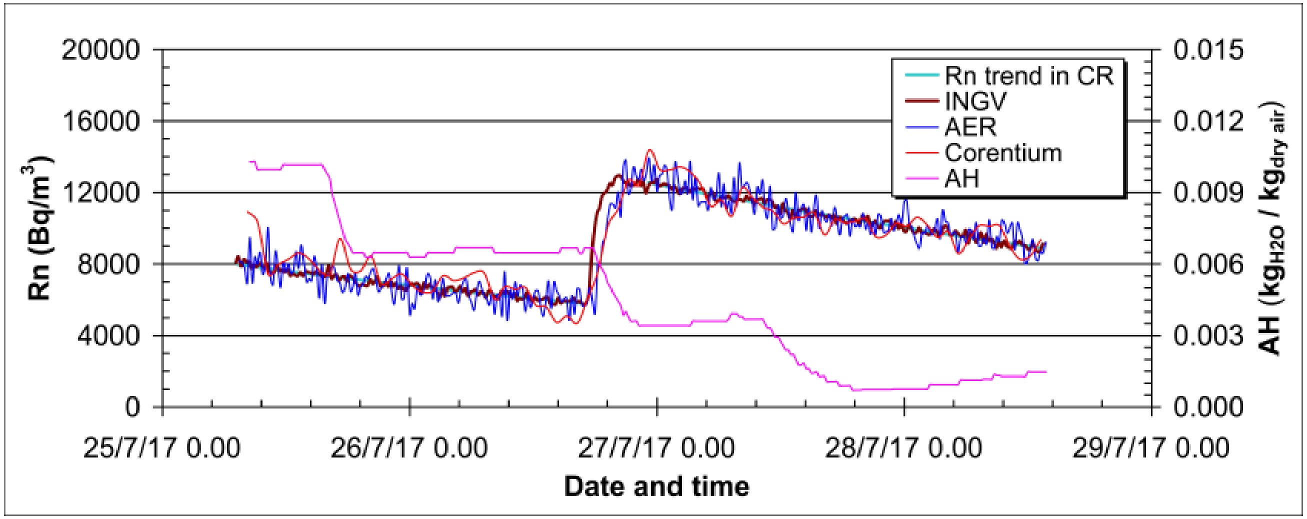
AlphaMETER AC-22
Eff (CPM/(Bq m-3))
0.0006
0.0005
0.0004
0.0003
0.0002
0.0001
0
0
10000
20000
30000
40000
Rn (Bq m-3)
Eff
Eff (corr. background)

Figure 11



50000
40000
30000
20000
10000
0
C_{Rn} (Bq/m^3)
AC-26
AC-40
AC-23
AC-22
AC-23
AC-26
AC-22
28/11/2011
30/11/2011
02/12/2011
04/12/2011
06/12/2011
Date and time

Figure 12



20000
16000
12000
8000
4000
0
Rn (Bq/m³)
0.015
0.012
0.009
0.006
0.003
0.000
AH (kgH2O / kgdry air)
Rn trend in CR
INGV
AER
Corentium
AH
25/7/17 0.00
26/7/17 0.00
27/7/17 0.00
28/7/17 0.00
29/7/17 0.00
Date and time