Publishable Summary for 19ENV01 traceRadon

Radon metrology for use in climate change observation and radiation protection at the environmental level

Overview

Radon gas is the largest source of public exposure to naturally occurring radioactivity, and concentration maps based on atmospheric measurements aid developers to comply with EU Basic Safety Standard Regulations (EU-BSS). Radon can also be used as a tracer to evaluate dispersal models important for identifying successful greenhouse gas (GHG) mitigation strategies. To increase the accuracy of both radiation protection measurements and those used for GHG modelling, traceability to SI units for radon release rates from soil, its concentration in the atmosphere and validated models for its dispersal are needed. This project has provided the necessary measurement infrastructure and used the data generated to apply the Radon Tracer Method (RTM) which is important for GHG emission estimates that support national reporting under the Paris Agreement on climate change.

Need

An overlapping need exists between the climate research and radiation protection communities for improved traceable low-level outdoor radon measurements, combining the challenges of collating and modelling large datasets, with setting up new radiation protection services. Compared to the large spatiotemporal heterogeneity of GHG fluxes, radon is emitted almost homogeneously over ice-free land and has a negligible flux from oceans. Radon flux relates to the transfer process of radon activity from soil to the atmosphere per square metre and second, whilst radon activity concentration is the amount of activity of radon in the atmosphere per cubic metre. Atmospheric measurements of radon activity concentrations can be used for the assessment and improvement of atmospheric transport models (ATM). However, traceability to the environmental level did not currently exist for measurements of radon fluxes and atmospheric radon activity concentrations. Therefore, significant improvements in such measurements were needed. Climatic Atmospheric Monitoring Networks (AMN) like the European Integrated Carbon Observation System (ICOS), are infrastructures that operate GHG monitoring stations and include atmospheric radon monitors in their stations. The radon data produced from such networks can be used to improve transport modelling and the estimation of GHG emissions based on the RTM, which uses the correlation between GHG and radon concentrations. However, this radon data needed significant improvement in terms of the accuracy of both radon flux measurements and environmental radon activity concentrations in the range 1 Bq m^{-3} to 100 Bq m^{-3} to be able to provide robust data for use in the RTM. Similarly, for radiation monitoring, all European countries have installed networks of automatic radiation dose and airborne contamination monitoring stations and report the information gathered to the European Radiological Data Exchange Platform (EURDEP), thus supporting EU member states and the EURATOM treaty. Currently, monitoring information on dose rates is collected from automatic surveillance systems in 39 countries, however, urgently needed data on outdoor radon activity concentrations is not yet collected due to a lack of ability to measure accurately at the low levels encountered in the environment. Furthermore, accurately detecting contamination from nuclear emergencies relies on rejecting false positive results based on radon washed from the atmosphere by rain. Therefore, improving contamination detection requires greater accuracy in determining environmental radon concentrations and their movement in the atmosphere. This project has provided new traceability chains from lab to field for the radon activity concentration and established a traceability chain for radon flux for the first time. This has triggered lots of interest worldwide from stakeholders wishing to include these approaches for quality assurance into their climate observation or radiation protection capabilities.

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

Objectives

The overall aim of this project is the development of metrological capacity (reference monitors, transfer standards and robust methodology) to measure low levels of radon in the environment, which can be used to determine emission reduction strategies of GHG and improve radiation protection of the general public.

The specific objectives are:

1. To develop traceable methods for the measurement of outdoor low-level radon activity concentration in the range of 1 Bq m^{-3} to 100 Bq m^{-3}, with uncertainties of 10 % for k=1, to be used in climate monitoring and radiation protection networks. These methods include two new traceable Rn^{-222} emanation sources below 100 Bq m^{-3}, a transfer instrument calibrated with these new sources to assure the traceability of the transfer instrument and a calibration procedure suitable to enable a traceable calibration of environmental atmospheric radon measurement systems in the field.
2. To develop the capability for traceable radon flux measurements in the field, based on the development of a radon exhalation reference system “exhalation bed” and a transfer standard (TS). To use this capability to harmonise existing radon flux instruments/methods by intercomparison campaigns. To develop a first standard protocol for the application of the radon tracer method (RTM) to enable retrieval of greenhouse gas fluxes at atmospheric climate gas monitoring stations and to use radon flux data for the identification of Radon Priority Areas (RPA).
3. To validate current radon flux models and inventories by the new traceable measurements of radon activity concentration and radon flux. To support the validation with dosimetric and spectrometric data from the radiological early warning networks in Europe. To improve process-based radon flux maps that will be available for use in the RTM, atmospheric dispersion modelling, and radiation protection.
4. To provide easy to use dynamic radon and radon flux maps for climate change research and radiation protection in line with Council Directive 2013/59/EURATOM, including their use to identify RPA and radon wash-out peaks.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs, calibration laboratories), standards developing organisations (e.g. IEC, ISO) and end users in greenhouse gas monitoring and European radiological early warning networks.

Progress beyond the state of the art

Traceable measurements of outdoor radon activity concentrations This project has developed the first traceable methods for measuring low-level outdoor radon activity concentrations in the range from 1 Bq m^{-3} to 100 Bq m^{-3} with uncertainties of 10 % for k=1. This is two orders of magnitude lower than the previous state of the art developed in the EMPIR project 16ENV10 MetroRADON. This project has also gone beyond the state of the art by targeting environmental radon activity concentrations in the outdoor air. In some Atmospheric Monitoring Network Stations (AMNS), monitors for radon activity concentrations are already in operation however their traceability has not yet been established. To be able to establish such a traceability chain this project has developed two new Rn- 222 emanation sources below 100 Bq m^{-3} for the traceable calibration of atmospheric radon monitors. In addition, this project developed two transfer standards for use in the field (ANSTO 200L and ARMON), which were validated in a field-based intercomparison.

Radon flux measurements

This project has developed a state-of-the-art radon flux calibration infrastructure, along with a transfer standard for radon flux monitors. The Autoflux system was chosen as a transfer standard and has been validated using a radon exhalation reference system “exhalation bed”, and this was subsequently used in intercomparison campaigns to harmonise different radon flux measurement methods. The outcome was a new validated radon flux dataset to assist with the identification of RPAs and the application of the RTM for GHG flux estimates.

Validation of radon flux models and inventories using radon flux and terrestrial data Environmental radon measurements in parallel with atmospheric GHG measurements can be used in the RTM to quantify GHG emission estimates. This project has worked to develop the first ever procedure for the RTM approach for use at AMNS. The procedure was systematically investigated, using traceability chains for the necessary radon activity concentration and radon flux input measurements and a validated radon flux map.

Radon flux inventories and models

Accurately representing the temporal variability and spatial distribution of the radon flux is essential for the application of radon flux maps and inventories in both atmospheric transport applications (for the climate community) and the identification of RPAs. This project has delivered work that is far beyond the state of the art by traceably measuring, under field conditions, outdoor radon activity concentrations and surface radon fluxes that were used for the validation of the radon flux maps and inventories. Further validation was achieved by inclusion of dosimetric and spectrometric data from radiological early warning networks in Europe.

Dynamic radon activity concentration and radon flux maps to identify RPA

The AMN, EURDEP and European Atlas of Natural Radiation (EANR) provided this project with dynamic radon maps from the new traceable outdoor radon activity concentrations and radon flux measurements. This new data was linked to established data from EURDEP and EANR and along with project data on natural radiological risks and outdoor radon activity concentrations, and this is now available to scientists, policy makers and end users https://remon.jrc.ec.europa.eu/About/Atlas-of-Natural-Radiation/Digital-Atlas/Radon-flux/Radon-flux .

The use of radon flux data and maps in the identification of RPA has never been attempted before, due to a lack of robust data. This project has started work that went beyond the state of the art by validating radon flux measurements and radon flux maps as parameters for the identification of RPA via the Radon Hazard Index (RHI). The RHI implemented in the preceding project 16ENV10 MetroRADON only contained static information. This project extended the RHI to include dynamic data (i.e. outdoor radon activity concentration and radon flux measurements).

Results

Objective 1: Traceable measurements of outdoor radon activity concentrations

A literature study of currently available radon sources for calibration of instruments capable of measuring radon activity concentrations below 100 $Bq\cdot m^{-3}$ was performed. Based on the results, environmental parameter ranges were evaluated and a list of suitable parameters for in-field calibration was defined. This work provided the project with the necessary information on the needed characteristics for new radon sources (i.e., needs not currently met by commercially available radon sources).

The development of new low activity emanation sources was started, and five different principles were used:

1. The first approach used is a radon emanation source created from an emulsion of salts of fatty acids in silicone rubber, formed from the weighed standard solution. Traceability of the Ra^{-226} activity is established by weighing and gamma spectrometry. Using a stainless-steel cylindrical case with valves and aerosol filters, applying ultra-dried air and a mass flow controller with a humidifier (to control the dilution of the activity concentration), a time-stable radon activity concentration is achieved. This approach established a radon source with time-stable radon activity concentration in a low-level radon chamber.

2. The second approach is the development of a low-level, low activity emanation sources based on the electrodeposition from a carrier- free Ra-226 solution on a stainless-steel plate. The emanation rate of Rn-222 of these sources is followed online via gamma-spectrometry using portable scintillation detectors such as Lanthanum Bromide ($LaBr_3$) crystals. The emanation of the Rn-222 follows differential equations, by nature, that include the build-up and decay of the Rn-222. In order to overcome this constraint, the project has developed an algorithm using a new statistical method based on Bayes filtering (Kalman filter, assumed density filtering). With this algorithm the emanated Rn-222 in the unit atoms per second as well as the associated uncertainty is determined online from spectrometric data including the knowledge of the already measured spectra.

3. The third approach uses accelerator mass spectrometry separated Ra-226 ion implanted emanation sources in aluminium or tungsten backings. These sources are high grade metrological sources, that show ideal activity distribution (sharp Gaussian distribution) and little to no dependence from environmental conditions (humidity, temperature) due to the fact, that the emanation is manly driven by recoil. The drawback of these sources are the very rare production possibilities and thus their price, which restricts their application.

4. The fourth approach is the thermal vapor deposition of $RaCl_2$ directly to a backing. These sources show good performance, less dependency of environmental conditions and are relatively easy to produce and to characterise.

5. The fifth approach is an integrated radium source-detection system operated in real time monitoring mode. To produce this, an ion-implanted silicon semiconductor detector is coated in a defined manner with radium chloride ($(Ra\text{-}226)Cl_2$),using thermal vapor deposition, directly onto the dead layer of the detector.

Thus, the detector is simultaneously both the source of radon and the spectrometric detector for the resulting alpha radiation. Both the absolute activity of Ra-226 and the loss of Rn-222 can be determined directly by analysis of the alpha-spectra. This yields the absolute activity of Rn-222 emanating from the “Integrated Radium Source/Detector” (IRSD).

To establish the chain of traceability the new sources were used to generate a non-constant but undisturbed radon reference atmosphere in a climate chamber. This preliminary primary measurement procedure resulted in a calibration factor of (26.0 ± 1.3) $\mathrm{s \cdot Bq \cdot m^{-3}}$ for k=1, for the new Australia's Nuclear Science and Technology Organisation (ANSTO) 200 L radon monitor.

Nowadays a variety of radon monitors are available, based on different measurement techniques. Often the trade-off between commercial and research-grade radon monitors is a reduction in their portability for an increase in accuracy for low-level activity concentration measurements. The matrix of properties was used to identify the suggested parameters for a transfer standard for the traceable calibration of atmospheric radon monitors according to IEC 61577. Using the results from the matrix of properties two direct monitors, a novel portable 200 L version of the ANSTO monitor and an optimised version of ARMON (v2) from partner UPC have been designed and built by the project:

- The ANSTO 200 L can fit within a 19” instrument rack, has low power requirements (~100 W at 240 VAC), is suitable for low-maintenance long-term indoor or outdoor operation and records internal environmental parameters.
- an optimised ARMON v2 for measuring atmospheric radon below 100 Bq $\mathrm{m^{-3}}$ based on electrostatic deposition of ^{218}Po, using alpha spectrometric analysis to determine radon activity concentration was designed and built. The monitor was previously characterised at the Spanish radon chamber of the Universitat Politècnica de Catalunya.

Both the ANSTO 200 L and the ARMON v2 were candidates for a transfer standard for radon monitors. Both detectors have been used in intercomparison campaigns. Also at the atmospheric tower of USVQ a long term intercomparison campaign was performed installing an air sampling at 100 m a.g.l. for two month including a variety of other Radon detectors like the HRM or two ANSTO 1500 L detectors.

Objective 2: Radon flux measurements

A literature review of continuous radon flux systems was carried out including an analysis of the different available types. Based on the results, the best radon flux system option currently available, was identified for use in this project and was the Autoflux system designed and built by ANSTO (which includes a commercial radon monitor, an automatic drum and several environmental sensors). The Autoflux system was adopted and improved by partner UPC and tested for its suitability to be used as a transfer standard (TS) in the project. Preliminary results show that this system can measure radon fluxes every 3 h and its response is optimal for radon fluxes between 20 Bq $\mathrm{m^{-2}\ h^{-1}}$ and 300 Bq $\mathrm{m^{-2}\ h^{-1}}$.

In addition to this, partner ENEA designed and developed a new radon accumulation chamber which has an open vent port to be able to monitor radon concentration variability inside with a commercial radon monitor (AlphaGuard 2000 pro). Laboratory tests carried out at ENEA have shown that the leakage rate from the vent port is in the order of 0.01 $\mathrm{h^{-1}}$. Measurements in the field with this system were also performed at ENEA during October 2021 and the results showed that radon release may occur not only by diffusion, but also by convection. Great care must also be taken not to change with the sampling the quantity of interest (here the radon flux). Therefore, closed and sealed accumulation chambers should be equipped with a vent port. Currently reliable results can only be achieved if the flux is stable over a suitable time interval of some hours.

Based on the needs identified in the literature review of radon flux systems, a radon “exhalation bed” that can be used as a calibration facility has been designed and constructed by the project. The main structure of the exhalation bed is stainless steel and has a total surface area of 1 $\mathrm{m^2}$, with an effective height of 0.2 m. Two different soils were used with low and high radium content were used with the radon “exhalation bed”. The soils were dried and winnowed by a sieve to obtain a grain size of 2 mm and then homogenised to achieve a radon flux as spatially consistent and stable as possible under laboratory conditions. Several experiments were carried out to test the reliability of an exhalation bed, using a characterised radon flux, to calibrate radon flux systems under different environmental conditions.

Different radon flux systems, designed and built by project partners and collaborators, were simultaneously tested on the exhalation bed surface under dynamic or static conditions. Then during September and October 2021, Cantabria University organised and performed two intercomparison campaigns of the same radon flux systems. The campaigns were conducted in high and low radon source areas with typical radon flux values of about 2000 Bq m^{-2} h^{-1} and 50 Bq m^{-2} h^{-1}, respectively. The high radon level intercomparison campaign was carried out at a Spanish uranium mine located in Saelices el Chico (Salamanca, Spain) from 6th to 8th of October 2021 and the low level at Esles de Cayón (Cantabria, Spain) between 13th and 28th of October 2021.

The project has finished the measurement campaigns at selected AMNS and RMS. This has included deciding: (i) the design of the radon flux campaigns, (ii) the variables and parameters to be measured and (iii) the main requirements of the sites. Additionally, RTM application at the AMNS has been performed. This included the selection of the station where the RTM was tested.

The station of Saclay, France was chosen due to its characteristics, i.e. it can make vertical radon gradient measurements, it has the capability for making GHG mixing ratio measurements at multiple heights and thus it can estimate GHG fluxes by two independent methods. Saclay is located 30 km south-west of Paris, 482.7217 °N, 2.142 °E, 160 m above mean sea level. The values for radon activity found at Scalay varied between 18 Bq m^{-2} h^{-1} and 54 Bq m^{-2} h^{-1} for observations and models. The footprints of the Saclay station are available on the ICOS Carbon Portal, see https://stilt.icos-cp.eu/viewer/ for 2014 to 2019.

A new code to calculate the GHG flux has been developed by the project using Jupyter python notebooks and is hosted on the ICOS Carbon Portal. This code allows GHG flux to be calculated using the footprints and the radon map hosted on the ICOS Carbon Portal and has been upgraded by the project.

Sensitivity tests have been running with three different radon exhalation maps (two from the traceRadon project), two different Lagrangian models to estimate footprints and up to 4 different ways of estimating the radon exhalation to be used in the RTM. One more model should be tested as well as the impact of the radioactive decay term on the radon flux. The analysis of the results is on-going.

Objective 3: Validation of radon flux models and inventories using radon flux and terrestrial data

A literature review was conducted to provide an overview of processes determining the production, transport and exhalation of radon from soils and strategies to estimate radon fluxes based on soil parameters and/or dosimetric and spectrometric data from the radiological early warning networks in Europe. Based on this literature review, suitable radon flux models and inventories were identified. This has included a process-based radon flux model that describes the spatial and temporal variability of the radon flux based on soil properties, uranium content and soil moisture reanalysis, which was further developed and refined in the project. The resulting process-based radon flux maps for Europe with monthly and daily resolution are available online at the ICOS Carbon Portal.

The dosimetric and spectrometric data from radiological early warning networks in Europe were extracted to improve the radon flux models and to validate process-based radon flux maps. Suitable dose rate monitors and spectrometers were calibrated and characterised in calibration laboratories of the partners. The schedule for the characterisation of the dose rate monitors and spectrometers with respect to their inherent background as well as their sensitivity to small variations of ambient dose equivalent rates was agreed by the partners and the corresponding measurements were performed at PTB in June 2021 accordingly.

A new spectrometric system, named DoRayMon, was also developed at UPC for continuously monitoring environmental gamma radiation. The DoRayMon system can connect to 3G/4G and automatically send the measured spectra to a database. The DoRayMon, the spectrodosemeter developed by PTB, and an ionising chamber were first tested at PTB tand later deployed in the four measurement campaigns. The data from these campaigns were analysed to support improvement of radon flux estimations.

The process-based modelling of radon flux requires as input high-resolution data of uranium content, distribution of soil types and porosity, as well as soil moisture and temperature. These input data are obtained for Europe from diverse models and databases with varying accuracy and diverse spatial and temporal resolutions, and thus the validation of radon flux maps encompasses not only the comparison of the modelled radon flux with direct radon flux measurements, but also the validation of these input data used in the process-based model. The direct measurements used for validation were performed during the four traceRadon intensive campaigns at PTB, ENEA, Saclay (SAC) and Weybourne (WAO) sites. Since soil moisture is a major factor influencing the diffusion of radon in the soil, a further detailed assessment of the two soil moisture reanalyses used in the radon flux maps was performed using stations measurements from ICOS Ecosystem stations and from the International Soil Moisture Network (ISMN). The validation results indicate a reasonable agreement between monthly measured and modelled radon flux values when using local input data but show a discrepancy in terms of the temporal pattern observed at the daily scale. The radon flux measurements performed in the four traceRadon intensive campaigns show substantial short-term variability, contrasting with much smoother model estimates. For the radon flux maps based on reanalyses, the spatial and temporal representativeness of the local measurements limits the validation. In general, radon fluxes based on one of the soil moisture reanalyses are in better agreement with radon flux measurements, when compared at monthly scale, which is consistent with the results obtained from the evaluation of soil moisture.

Objective 4: Radon flux inventories and models and the provision of access to radon flux maps

Concerning the radiation protection research area, two new applications were developed and applied that involve the use of outdoor radon and radon flux data.

In the first application we investigated the possibility of using outdoor radon and radon flux to predict the radon risk of areas. According to the European Council directive 2013/59/Euratom Member States need to identify areas - often called “radon priority areas -RPA”, where specific radon protection measures should be applied, e.g. mandatory radon measurements in work places in basement and ground floor. To identify those areas, the Geogenic Radon Potential can be used, and the concept of the Geogenic Radon Hazard Index was developed and discussed in the last years, especially in the MetroRadon project (http://www.metroradon.eu/). Firstly, an extensive literature research of outdoor radon and radon flux was carried out (REF). Then, we evaluated the possibility of using outdoor radon activity concentration, radon flux measurements and radon flux maps in the estimation of the GRHI and which data are best suitable for a possible improvement of RPA. These parameters were compared with other parameters used for radon risk prediction as geological information, physical and chemical soil properties and weather data. Random forest models were used using European and regional data (Belgium and Germany). The key message of that work is, that it strongly depends on the setting and the area, which input features can be used as predictors for the radon potential. A predictor proven to work in one area might not necessarily do so in another, and there is still a potential for input features not selected by our models to work in other areas. It was showed that Radon flux can be used for the prediction of the radon potential and increases model performance, but it depends on the area if it is needed as parameter. In addition, outdoor radon could become a valuable predictor in other settings and areas even if not selected by our best models but was frequently used within the 100 best models. Outdoor radon and shows a high correlation factor with indoor radon concentration. Taking into account, that the source for the predicted outdoor radon were only 228 measurements, the impact of outdoor radon for prediction might increase with an increasing number of measurements.

The second application relates to improve warning alarms of gamma dose rate monitoring. These real-time measurements are widely used in nuclear/radiological emergency preparedness and response systems. In order to be able to detect dose rate peaks due to artificial sources, it is important to develop automatic methods to filter false positives, i.e. peaks due to natural events. EURDEP (European Radiological Data Exchange Platform) is an example of network susceptible to such problems and could benefit of these previous commented filtering methods. Indeed, peaks observed in ambient dose rate time series due to natural events are frequent and they can create false positive responses of the monitoring networks. Examples of the possible natural causes are: i) the so-called radon wash-out peaks due to the deposition on the ground of radon progenies after rain; ii) atmospheric radon accumulation peaks due to the variation of the height of the planetary boundary layer during the night. In the framework of the traceRadon project a first inter-comparison exercise of different automatic methods to identify and to classify ambient dose rate peaks has been organized in collaboration with researchers from EURADOS (European Radiation Dosimetry Group). The exercise was carried out in two rounds. In the 1st round, a 3-month time series of ambient dose equivalent rate H*(10) data with hourly resolution were provided to the six participants. In the 2nd round rain time series data were also provided to the participants. Each participant may provide peak occurrence dates (start-end) and their classification (natural, artificial, etc.). The main conclusions from the exercise are: sensitivities for peak identification increased for each method between 1st and 2nd round; the percentage of peaks identified during the 2nd round ranged from 80% to 100%; radon wash-out peaks were identified by all the participants during the 2nd round; nocturnal radon accumulation peaks identification and classification highly improved during the 2nd round; suspect-anomaly peaks were identified by most of participants at the 1st round and the classification highly improved during the 2nd round; spectrometric data are necessary to know the origin of the peaks (natural or artificial); rain information is fundamental for a good classification of the peaks. Moreover, traceRadon project has been proven to be a good platform to foster collaborations among groups. By building on the current experience and promoting community work it is expected that additional analysis can be efficiently conducted to improve the currently available methods. Since the identification of the peaks is particularly challenging, these results could constitute a benchmark for future developments.

Impact

The project has created a website at http://traceradon-empir.eu/ and a traceRadon newsletter in order to promote itself to end users. A project Twitter account was created https://twitter.com/traceradon as well as a notice board on ResearchGate until ResearchGate removed the possibility to have project webpages. Further to this, the project has been presented 71 times at conferences and events such as the Atmospheric Composition & Chemistry Observations & Modelling Conference, the Romanian Society for Radiological Protection, the ICOS MSA (Monitoring Station Assembly) Atmosphere Meeting, the Sensor and Measurement Science International, the EGU General Assembly 2021, 2022, 2023 in the session of geoscience applications of environmental radioactivity, the 20th international metrology congress CIM 2021, the 15th International Workshop on the Geological Aspects of Radon Risk Mapping, the Final Conference LIFE-Respire, 6th European IRPA Congress, ICRM-LLRMT 2022, ICRM 2023, EURADOS WG3-S3 2021, 2022, 2023, ICOS Science Conference 2022, the IAEA: Second International Conference on Applications of Radiation Science and Technology (ICARST 2022), the Conference on Climate Change Impact on Radon and Human Health Dose Assessment, Yukon University, the IMEKO Conference of TC8, TC11, TC24 and many more. The project presented results on all continents, in different communities and receives even after its end still applications to join.

Moreover, several invited talks have been given by the project partners to stakeholders such as the Radiation protection platform (Austria), the Sciences du Climat et de l'Environnement (LSCE, France), the European Radon Week with the 9th ERA Workshop on International Collaborations on Radon, the 2nd HERCA Workshop on National Radon Action Plans, and the European Atlas of Natural Radiation (EANR). These talks have been the result of dissemination of the project, including four newsletters and six articles in the popular press. So far interest in the project has comes from a broad range of different sectors: legislation, health and climate protection, physics and geology as well as voluntary organisations.

A highlight on the political level was the Delegation trip of the coordinator with Prime Minister of Lower Saxony Stephan Weil to Oslo/Norway from May 21 to 24, 2023 together with Olaf Lies, Minister for Economic Affairs, Transport, Building and Digitalization and to Tallinn/Estonia, May 24-26, 2023, which gave the opportunity to address the metrology needs for the future to combat climate change.

Impact on industrial and other user communities

European climate observation groups and radiological protection groups both benefited from this project i.e. (i) climate related Atmospheric Monitoring Network stations (AMNS) (e.g. ICOS), and (ii) the European Radiological Data Exchange Platform (EURDEP) and the EANR. By improving the traceability of low-level radon and radon flux measurements this project supported collaboration between these currently independent groups. Such interdisciplinary collaboration provided new insight and understanding on the links between geology, the atmosphere, and anthropogenic activity and their combined impact.

Accurate knowledge of environmental outdoor radon activity concentrations and radon flux is key for improving Greenhouse Gas (GHG) flux estimates for climate observation and radiological protection. Current climate related AMNS were established for measurements of GHGs in order to support interpretation of the ATM (Atmospheric Transport Model) and to better understand GHG levels using long-term observations. Atmospheric radon measurements are carried out at such AMNS and therefore, this project supported European AMNS in performing atmospheric radon and radon flux measurements for a variety of radon tracer applications. The project did this through its development of new low activity Rn-222 emanation sources, a reference instrument for atmospheric radon measurements and a traceability chain for low radon activity concentration measurements (from 1 Bq m^{-3} to 100 Bq m^{-3}). All of which supported the comparability of real time atmospheric radon activity concentration data between different measurement sites and over time provide these radon measurements with the required traceability to the SI.

To support its engagement with industry and other user communities the project has set-up a Stakeholder Committee which currently has 20 members and includes high impact, multi- national stakeholders such as: the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), the World Meteorological Organisation (WMO), the International Commission on Radiological Protection (ICRP), the International Committee for Radionuclide Metrology (ICRM), the European Radon Association (ERA), the European Radiation Dosimetry Group (EURADOS) and EURAMET’s Technical Committee for Ionising Radiation (TC-IR). Further to this, the stakeholder committee also includes standardisation bodies such as the Commission Electrotechnique Internationale (IEC) and the International Organisation for Standardisation (ISO) as well as representative organisations from individual nations e.g., ANTSO, Australia’s Climate Science

Centre, Oceans & Atmosphere (CSIRO), Germany's Federal Office For Radiation Protection (Bundesamt für Strahlenschutz), Germany's Meteorological Service (Deutscher Wetterdienst), Spain's Centre for Energy, Environmental and Technological Research (CIEMAT), Environment and Climate Change Canada, Ireland's Environmental Protection Agency Office of Radiation Protection and Environmental Monitoring, the UK's Society for Radiological Protection (SRP), the UK's Met Office, the National Metrology Institute of South Africa (NMISA), Japan's National Institutes for Quantum and Radiological Science and Technology (QST), Italy's Politecnico di Milano - Department of Energy, Italy's National Research Council/ Biometeorology lab (IBIMET-CNR), Romania's National Commission for Nuclear Activities Control (CNCAN) and the University of Novi Sad (Serbia).

Further to this the project has received interest from stakeholders in the uptake of its results. These include the Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, Germany), who is interested in the results of the source development for its calibration services. The company Radonova Laboratories AB (a leader in radon measurement based in Sweden) is interested in the project's research activities and capacity building. A prototype detector developed in the scope of the project is on its way to be commercialized by Radonova, too.

Finally, the European Radon Association (ERA) is interested in the project's development of new method to identify RPAs.

Impact on the metrology and scientific communities

The project's data on outdoor radon activity concentration and radon flux measurements can be used to provide key information on atmospheric radon activity concentrations; one of the greatest natural radiological risks. The project's data was made available online for scientists, policy and decision makers and end users. The project's developments in techniques for measuring low-level environmental radon activity concentration and radon fluxes is and will be useful for the metrological community working in this field, for regulatory authorities, civil protection or official measuring bodies, and for manufacturers of radon monitors or dosimeters. In addition, the project has significantly advanced radon flux metrology. It did this by providing a calibration infrastructure, including a radon exhalation reference system "exhalation bed" and a transfer standard. The project used this capability to harmonise existing radon flux instruments/methods using field-based comparisons. Radon flux measurements carried out over Europe during the project validated existing European radon flux models and inventories in order to obtain online real-time European radon maps. These radon and radon flux maps are now available for atmospheric studies and for radiological protection such as the identification of RPAs.The project has provided training to the metrology and scientific communities at sixteen events such as:

Workshops (8): Two general scientific workshops on traceRadon, New Procedures for Radon Monitoring, New Procedures, guidelines an methodologies for radon instruments calibration and measurements, Gap workshop oon radiation protection metrology, traceRadon as a tool for the national GHG strategy for Hungary, Precise and traceable Radon activity concentration measurements, Precise and traceable measurement of Rn flux and the application of the Radon Tracer Method, Strategy on making available the radon flux campaign data

Training courses (4): New procedures, guidelines and methodologies for radon instrument calibration and measurements, Radioactivity and radiation: New methods for climate observation and climate modelling. Details in opperation of radon and radon flux monitors, Radon measurements in the Arctic: the challenges, technology and research benefits

Internal training for members and collaborators (3): Operation and calibration of the ANSTO monitors and the new prototype the ANSTO 200L, Installation of Radon Flux Campaign Equipment: Technical Training, Data Review of the Field Campaign

Further to this the project was collaborating with organisations in the scientific community including the EMN Climate and Ocean Observation, ERA, EURADOS, the UK's Metrological Office, the Universität Heidelberg, Germany, the University of Novi Sad, Serbia, the Politecnico di Milano, Italy, the University of Codoba, Spain, the Universität Siegen, Germany, Institut de radioprotection et de sûreté nucléaire (IRSN, responsible for performing radiological monitoring of the environment throughout France), The Regional Environmental Protection Agency (Agenzia regionale per la protezione ambientale, ARPA Valle d'Aosta and ARPA Piemonte) Italy, Radonova, Sweden, the LIFE-Respire, retired expert Peter Bossew and Ulrich Stöhlker, the University of Groningen and ANSTO, Australia.

Impact on relevant standards

The project has provided input to HERCA (Heads of the European Radiological Protection Competent Authorities), the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), DKE GK 851 Activity measuring devices for radiation protection, ISO/TC 85 Nuclear energy, nuclear technologies, and radiological protection, BIPM and CIPM CCRI (I) (x- and gamma rays, charged particles),CIPM CCRI (Measurement of radionuclides), CIPM CCRI (Consultative Committee for Ionising Radiation) in particular the CCRI Strategy 2018-2028, EURAMET TC-IR (Ionising Radiation), EURADOS WG3 Environmental dosimetry, EURATOM, the Professional Association for Radiation Protection Environmental Monitoring Working Group and the European Radioecology Alliance Topical Working Group Atmospheric radionuclides in transfer processes.

In addition, the project provided input to: IEC/TC 45 Nuclear Instrumentation SC45B Radiation protection instruments, WG9 Detectors and systems, ISO/TC 142 Cleaning equipment for air and other gases ISO/TC146 Air quality and related activities and ICRM (Gamma-Ray Spectrometry WG, Alpha-Particle Spectrometry WG and Low Level Measurement Techniques WG).

Longer-term economic, social and environmental impacts

Climate change and radiological protection both affect humankind and the environment, worldwide. For the planet to combat both climate change and radiation exposure, measurements must be supported by reliable metrology. By addressing a topic (i.e. the measurement of low levels of radon in the environment) that supports both climate observation and global radiological protection, this project simultaneously supports the long-term economic, social and environmental work of ICOS, the Integrated Pollution Prevention and Control (IPPC) Directive 2008/1/EC, the IAEA, Analytical Laboratories for the Measurement of Environmental Radioactivity (ALMERA) and WHO.

The project’s data on low level measurement of radon in the environment improved ATMs and their ability to estimate GHGs fluxes which in turn supports the EU Emissions Trading System (EU ETS). The EU ETS is a cornerstone of the EU's long-term policy to tackle climate change through a cost-effective reduction of emissions of carbon dioxide (CO_2) and other GHG in the power, aviation and industrial sectors. The projects results will thus support Europe in its movement towards a competitive low carbon economy. At the same time, the project has provided the EC (through project partner the JRC) with access to reliable data of outdoor radon activity concentrations, which can be used in combination with soil exhalation flux measurements, for dynamic mapping of radon in the environment. By supporting the provision of accurate knowledge of RPA this project supported European radiation protection measures and thus in longer-term help to lower radiation protection costs. The EC JRC has taken the already taken the approach to their information page in the Digital Atlas of Natural Radiation, subsection radon flux, Monthly maps display the radon flux from the earth for atmospheric tracer transport and radon protection analysis on a 0.05° x 0.05° grid.

List of publications

1. Mertes, F et. al.: D3.3 Approximate sequential Bayesian filtering to estimate Rn-222 emanation from Ra-226 sources from spectra, https://doi.org/10.5162/SMSI2021/D3.3
2. Röttger, A. et al: New metrology for radon at the environmental level *2021* Meas. Sci. Technol. *32,* 124008, https://doi.org/10.1088/1361-6501/ac298d
3. Radulescu, I et al.: Inter-comparison of commercial continuous radon monitors responses, Nuclear Instruments and Methods in Physics Research Section A, Volume 1021, 2022, 165927, https://doi.org/10.1016/j.nima.2021.165927
4. Mertes, F. et. al.: Ion implantation of ^{226}Ra for a primary ^{222}Rn emanation standard, Applied Radiation and Isotopes, Volume 181, March 2022, 110093, https://doi.org/10.1016/j.apradiso.2021.110093
5. Čeliković, I. et. al.: Outdoor Radon as a Tool to Estimate Radon Priority Areas - A Literature Overview, Int. J. Environ. Res. Public Health 2022, 19, 662, https://doi.org/10.3390/ijerph19020662
6. Mertes, F et. al.: Development of ^{222}Rn emanation sources with integrated quasi 2π active monitoring, Int. J. Environ. Res. Public Health 2022, 19, 840, https://doi.org/10.3390/ijerph19020840
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8. Röttger, S. et al: Radon metrology for use in climate change observation and radiation protection at the environmental level, Adv. Geosci., 57, 37–47, 2022, https://doi.org/10.5194/adgeo-57-37-2022

9. Chambers, S. et al: Portable two-filter dual-flow-loop 222Rn detector: stand-alone monitor and calibration transfer device, Adv. Geosci., 57, 63–80, 2022, https://doi.org/10.5194/adgeo-57-63-2022
10. Calin, M. R., et. al.: Analysis of the radon concentrations in natural mineral and tap water using Lucas cells technique. Journal of Environmental Engineering and Landscape Management, 30(3), 370–379, 2022, https://doi.org/10.3846/jeelm.2022.17411
11. Čeliković, I. et. al.: Overview of Radon Flux Characteristics, Measurements, Models and Its Potential Use for the Estimation of Radon Priority Areas. Atmosphere, 13, 2005, 2022, https://doi.org/10.3390/atmos13122005
12. Röttger, S., et al.: Evolution of traceable radon emanation sources from MBq to few Bq, Applied Radiation and Isotopes, Volume 196, 110726, 2023, https://doi.org/10.1016/j.apradiso.2023.110726.
13. Mertes, F., Röttger, S., and Röttger, A.: Approximate sequential Bayesian filtering to estimate 222Rn emanation from 226Ra sources using spectral time series, J. Sens. Sens. Syst., 12, 147–161, 2023, https://doi.org/10.5194/jsss-12-147-2023
14. Röttger, A. et al: Beyond the state of art: New metrology infrastructure for radon measurements at the environmental level, Proceedings of IMEKO TC11 & TC24 Joint Hybrid Conference, 2022, https://www.imeko.org/publications/tc11-2022/IMEKO-TC11-2022-05.pdf
15. Grossi, C., et al.: Characterizing the automatic radon flux transfer standard system Autoflux: laboratory calibration and field experiments, Atmos. Meas. Tech., 16, 2655–2672, 2023, https://doi.org/10.5194/amt-16-2655-2023
16. Röttger, A., et al.: Metrology infrastructure for radon metrology at the environmental level, Acta IMEKO, Vol. 12, No.2 (2023), https://acta.imeko.org/index.php/acta-imeko/article/view/1440

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	01 June 2020, 36 months	
Coordinator: Annette Röttger, PTB	Tel: +49 531 592 3000	E-mail: annette.roettger@ptb.de
Project website address: http://traceradon-empir.eu/		
Internal Funded Partners:	External Funded Partners:	Unfunded Partners:
1. PTB, Germany	8. AGES, Austria	18. IDEAS, Hungary
2. BFKH, Hungary	9. CLOR, Poland	
3. CMI, Czechia	10. INESC TEC, Portugal	
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7. VINS, Serbia	14. UC, Spain	
	15. UoB, United Kingdom	
	16. UPC, Spain	
	17. UVSQ, France	
RMG: -		