NUKLEONIKA 2020;65(2):139–144
doi: 10.2478/nuka-2020-0022

ORIGINAL PAPER

Radon soil-gas measurement campaign in Hessen: an approach to identifying areas with enhanced geogenic radon

Till Kuske, Steffen Kerker, Joachim Breckow, Rouwen Lehné, Tatjana Laupenmühlen, Lena Jedmowski

Abstract. The new radiation protection law in Germany, which came into effect 2018, puts greater emphasis on the protection against naturally occurring radiation, especially radon as a known health hazard. The law requires the delineation of radon priority areas, where prevention and remediation of high indoor radon concentrations should be taken with priority. In Germany, radiation protection is the administrative responsibility of the federal states. The state of Hesse has early on decided to fully survey the state for radon priority areas. To identify radon priority areas, the geogenic radon potential has to be determined. To achieve that radon, soil-gas measurements combined with soil permeability are a necessity. The University of Applied Sciences (THM) in Giessen is responsible for the radon soil-gas measurement campaign in Hessen. To achieve a statistically sound survey of the state of Hessen with an achievable amount of different measurement locations, and in the given time-frame, a geology-based concept has been designed. Taking into account the known geological information about geological structures in combination with the administrative counties, a survey strategy has been established. Prior known information regarding soil thickness, moisture, digability, and other technical limitations are used to determine the exact measuring locations. At every location, the radon activity in soil gas is measured. The soil permeability is determined for every measurement as well. Three measurements are performed at each location. Having completed the first set of measurements, the design criteria of the campaign and the practical experiences will be presented.

Keywords: Radiation protection law • Radon-priority-areas • Radon • Soil gas

T. Kuske✉, S. Kerker, J. Breckow
Technische Hochschule Mittelhessen
Institute of Medical Physics and Radiation Protection (IMPS)
Wiesenstraße 14, 35390 Giessen, Germany
E-mail: till.kuske@mni.thm.de

R. Lehné, T. Laupenmühlen, L. Jedmowski
Hessisches Landesamt für Naturschutz, Umwelt und Geologie
Rheingaustraße 186, 65203 Wiesbaden, Germany

Received: 4 December 2019
Accepted: 27 January 2020

Introduction

Radon, being one of the noble gases, occurs as a multitude of isotopes, all of which are radioactive. Of the naturally existing isotopes ^{222}Rn and ^{220}Rn, the latter of which is commonly referred to as thoron, are the most common. The major part of natural occurring radon is provided by ^{222}Rn. ^{222}Rn is the most stable radon isotope and has a half-life of 3.8 days. Originating from the decay chains of uranium and thorium, it is produced in minerals and soils where trace amounts of these slowly decaying elements are found. Radon created in the top layers of the soil is emanated before decaying and is able to enter buildings. There it can accumulate in badly ventilated basements or other earth-touching rooms. Aerosols enriched with daughter nuclides from radon decay can enter the lungs through breathing. Radioactive daughter nuclides like lead and polonium will accumulate there and provide the major part of radiation exposure for the public as shown in Fig. 1 [1]. With an effective yearly dose of 1.1 mSv per person,

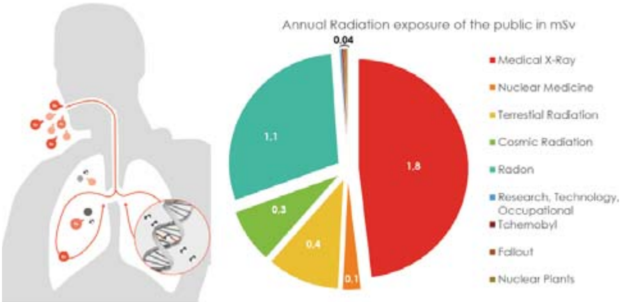

Fig. 1. Radon ingestion, distribution and damage mechanism (left – BfS); radiation exposure of the public (right – Umweltradioaktivität und Strahlenbelastung im Jahr 2011, Parliament report, Germany).

radon is the main contributor to naturally occurring radiation accounting for more than one-third of the total average radiation exposure [2].

To protect the population from health hazards in Germany, the new radiation protection act (Strahlenschutzgesetz, StrlSchG) requires a delineation of areas radon prone areas by the end of 2020. These areas are referred to as radon-priority areas and require a radon screening of all workplaces and enforce stricter codes for new buildings or modernizations.

The threshold for delineation is that a given area is expected to have more than 10% of houses exceeding the reference value (300 Bq/m^3) for average yearly indoor radon concentration.

To delineate radon-prone areas, the Federal Office for Radiation Protection (Bundesamt für Strahlenschutz, BfS) provides a continuously updated forecast map of the so-called radon potential for Germany. The necessary input data for this map are measurements of indoor radon and radon concentration in soil gas with the corresponding soil permeability [3].

The radon strategy of the Hessian environmental ministry aims to improve the predictions and reliability of the radon potential map by increasing the density of the measurement locations. The University of Applied Sciences in Giessen (Technische Hochschule Mittelhessen, THM) has been tasked to conduct this radon potential measurement campaign with support from the geology department of the Hessian Agency for Nature Conservation, Environment and Geology (Hessisches Landesamt für Naturschutz, Umwelt und Geologie, HLNUG).

Conceptual design of the measurement campaign

The measurement campaign aims to increase and improve the data set used to update the radon potential map for the state of Hesse. One of the goals is to guarantee a lawful delineation of radon-prone areas. To achieve extensive coverage, measurements of activity concentration of radon in soil gas all over Hesse are required with a meaningful representation of all counties. To ensure a fast roll-out of the campaign, the distribution of measurement locations has been optimized in regard to effort and costs.

Input parameters for the optimization are the geographical distribution of counties, information about geological units and structures as digability, groundwater levels, exclusion of faults or shear zones as well as the accessibility of the location.

Choosing measurement locations based on geology and administrative organization

The federal state of Hesse is administratively organized in 21 counties and five district-free cities and nine different geological structures can be found. Taking into account the areal fraction of all counties and cities and pairing it with the geological structures determines the distribution of locations. Using this approach, the number of measurement locations could be reduced to 750 with very little compromise to overall significance. Without prior information and pure statistical distribution, 2000 different locations would be needed. Table 1 and Fig. 2 show the area coverage of all geological structures and the resulting number of measurement locations.

Within the counties, the distribution is keyed again to the areal coverage, as shown in Table 2, resulting, for example, in just two measurement locations of the district-free city of Offenbach and 66 for the largest of the counties, Waldeck-Frankenberg.

The ability to dig and a top soil layer of minimum 1 m and the water level are key to classify a measurement location. The geologists of the HLNUG created this process and follow these criteria to deliver new measurement locations at regular intervals.

Figure 3 shows an example of the achieved coverage for the county of Lahn-Dill. With respect to the underlying geological structure, the 38 measurement

Table 1. Geological structures and the resulting amount of measurements in Hesse

Geological structure	Area [km^2]	Fraction [%]	Number of measurements
Alluvial deposits	1938.85	9.19	69
Quaternary sediments	4827.43	22.87	172
Tertiary sediments	1104.06	5.23	39
Tertiary volcanics	1783.55	8.45	63
Bunter sandstone	5804.06	27.50	207
Mesozoic/upper Permian	1108.74	5.25	39
Lower Permian	239.57	1.13	8
Rhenohercynian	3790.17	17.96	135
Crystalline basement	512.17	2.43	18
Total	21 108.60	100.00	750

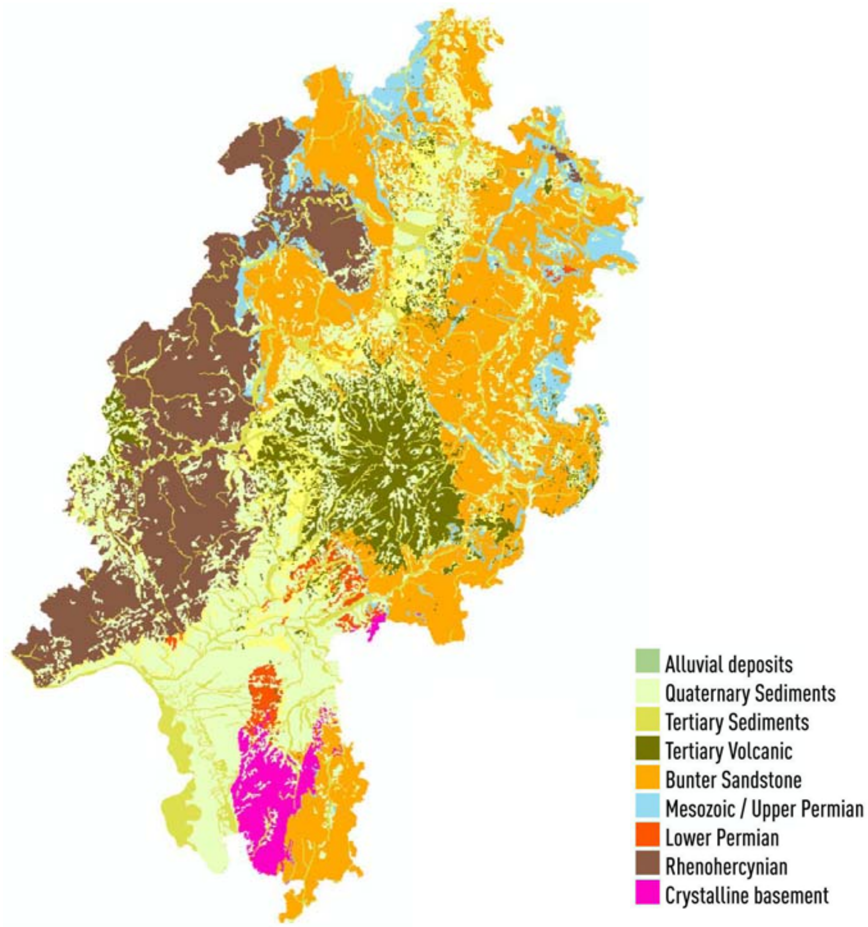

Fig. 2. Geological structures in the state of Hesse, HLNUG.

Table 2. County area coverage and the resulting amount of measurements in Hesse

Counties	Area [km²]	Fraction [%]	Number of measurements
District-free city Offenbach am Main	44.86	0.21	2
District-free city Kassel	106.67	0.51	4
District-free city Darmstadt	122.13	0.58	4
Landeshauptstadt Wiesbaden	203.73	0.97	7
Main-Taunus-Kreis	222.32	1.05	8
District-free city Frankfurt am Main	248.16	1.18	9
Offenbach	355.96	1.69	13
Groß-Gerau	452.70	2.15	16
Hochtaunuskreis	481.51	2.28	17
Odenwaldkreis	623.56	2.96	22
Darmstadt-Dieburg	657.93	3.12	23
Bergstraße	718.90	3.41	26
Limburg-Weilburg	737.94	3.50	26
Rheingau-Taunus-Kreis	810.82	3.84	29
Gießen	853.90	4.05	30
Werra-Meißner-Kreis	1023.94	4.85	36
Lahn-Dill-Kreis	1065.35	5.05	38
Hersfeld-Rotenburg	1096.88	5.20	39
Wetteraukreis	1099.84	5.21	39
Marburg-Biedenkopf	1261.48	5.98	45
Kassel	1292.36	6.13	46
Fulda	1379.64	6.54	49
Main-Kinzig-Kreis	1396.04	6.62	50
Vogelsbergkreis	1457.63	6.91	52
Schwalm-Eder-Kreis	1537.83	7.29	55
Waldeck-Frankenberg	1847.23	8.75	66
Total	21 099.31	100	750

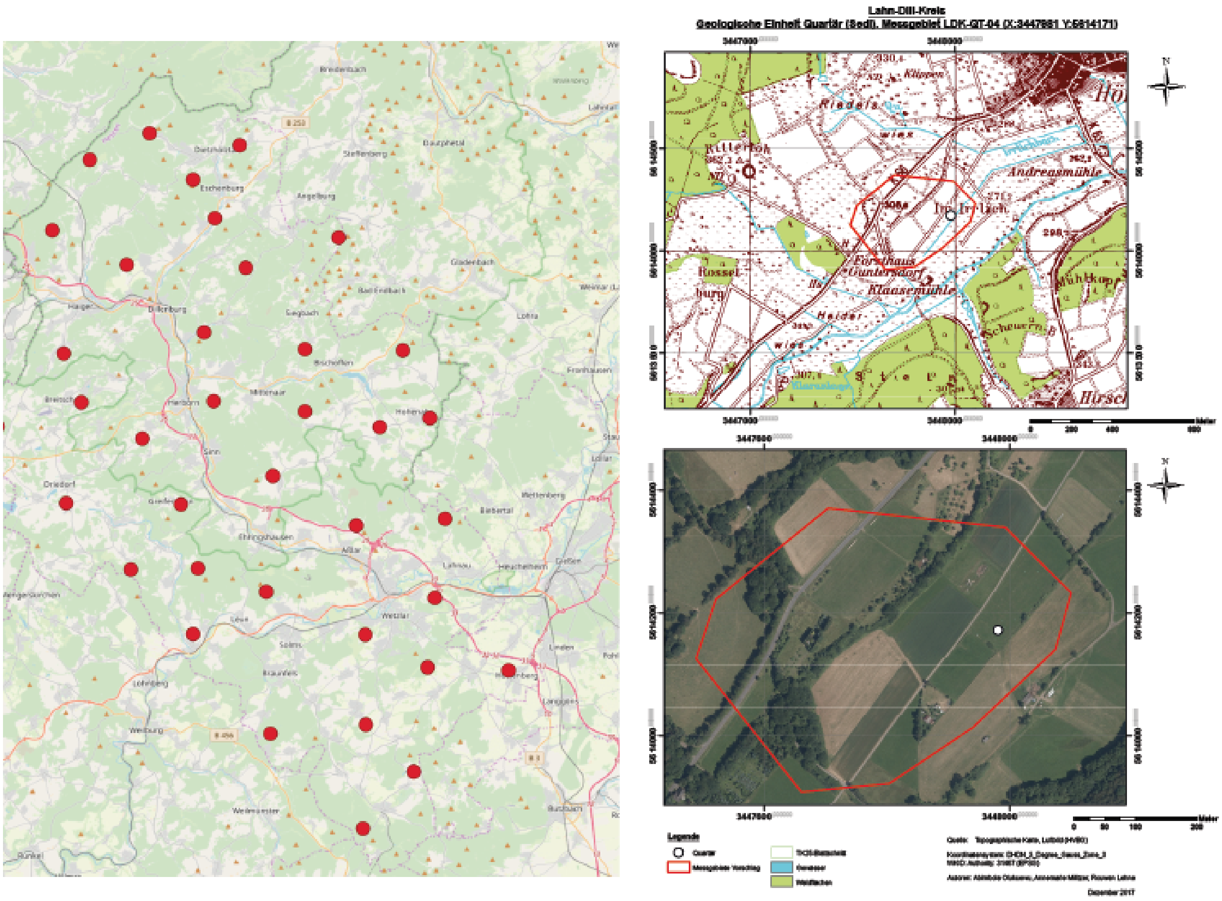

Fig. 3. Left: coverage of the county of Lahn-Dill with respect to the underlying geological structures; right: map-work provided by the geology department of HLNUG to ensure measurements in the right geological area.

locations are distributed equally in a way to ensure sufficient area coverage of the whole county. On the right-hand side in Fig. 3 the maps provided by the geology department of HLNUG can be seen. This way the measurement locations can be reached easily by our different teams and measuring the right geological structure is ensured. The red-bordered zone marks an area with the same underlying geology.

Different smaller measurement campaigns have been done in the past. But, most of these had a specific task or goal and are not statistically equally distributed over the state of Hesse.

The current work is prioritized by the significance of the *a-priori* knowledge of the radon potential. Areas with higher uncertainties regarding the radon potential are measured first.

Measuring the geogenic radon potential

Radon in soil gas

In accordance with DIN ISO11665-11, the radon activity concentration in soil gas is actively measured by using packer probes (Bonner probes) to withdraw a sample. The probe is placed into a 45 mm borehole with a depth of 1 m. On the lower part of the probe, a balloon ensures to seal off the upper atmosphere and create a defined cavity at the lower end as shown in Fig. 4.

The soil-gas samples are extracted from this geometrically defined cavity. For activity concentration measurements an active set-up with an ionization chamber (AlphaGuard, Bertin GmbH) is used. A CO_2-detector (Wöhler CDL210, Wöhler GmbH) following the ionization chamber is used to check for the leaking of atmospheric air into the measurement cavity or if the soil-gas sample is exhausted. Normally this type of CO_2-detector is used for indoor measurements. To work with the high percentages of

Fig. 4. Active probe in the borehole, on the right the pressure balloon for sealing is seen.

Table 3. Results of measurement in the county of Lahn-Dill, activity concentration and permeability

Measurement	Rn^{222} [$Bq \cdot m^{-3}$]	ΔRn^{222} [$Bq \cdot m^{-3}$]	Permeability [m^2]	Temperature [°C]	Relative humidity [%]
1	**75.025**	**7702**	**8.7E-13**	28.8	41.8
2	70.165	7612	3.2E-13	28.9	43.0
3	65.587	3324	9.1E-13	28.9	43.0

CO_2 in soil gas, we expand the measurement range by controlled addition of atmospheric air to the sensor. After flushing the whole measurement system with soil gas, the volume flow is stopped, and after pressure equalization, the ionization chamber flow is shorted. From the time evolution of the following activity measurement, the radon activity concentration is then deduced. At each location, three different measurements in distinct boreholes are performed. The holes are located in the corners of an equilateral triangle with a side length of ca. 5 m [4].

Gas permeability

In addition to the radon concentration, permeability is the second decisive factor to determine the geogenic radon potential. It can be measured *in-situ* as described in this article or determined later on by the evaluation of soil samples [6].

To quantify the gas permeability, an air pump is used to pressurize the measurement cavity in the ground. Setting an over pressure of 40 mbar the needed air-flow rate to achieve this is obtained. To accurately determine the volumetric flow, rotameters with different ranges are used. This way the permeability can be measured from 10 ml/min up to 65 l/m with an accuracy of 1%. Using Darcy's law, the permeability can be calculated from these two values and the geometrical dimensions of the cavity in the ground [5].

Obtaining soil core samples

At each location, three different core samples are retrieved. The samples have a diameter of 45 mm and are obtained when drilling the hole for the radon measurement. These cores are transferred to the Department of Soil Science and Plant Nutrition of the HLNUG for further analysis. Focusing on quality control and an additional source for permeability information this provides further insight into the radon distribution.

Experience

Radon soil-gas activity concentration

When measuring the soil-gas activity, the activity concentration of radon and the CO_2 percentage are determined. From the evolution of both values, one can deduce the real value. The CO_2 logging is crucial to exclude a break in the seal or the introduction of top air small capillaries. In Fig. 5, a typical measurement is displayed. This dataset is from the Lahn-Dill county, geologically from the Rhenohercynian structure. From the time evolution of the observed variable, the quality of the measurement can be deduced.

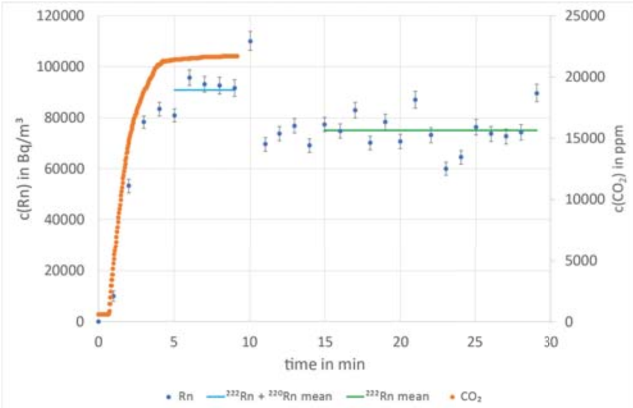

Fig. 5. Time evolution of the activity concentration of radon and the CO_2-concentration during the measurement of soil gas. Location is in Lahn-Dill county; the underlying geology is Rhenohercynian.

The steep increase of the measurement signal in the beginning is due to flushing of the ionization chamber and the measurement pipes. When the equilibrium state is reached, the activity concentration is stable and further measurement can be conducted. In this state, the soil gas has a mixture of different radon isotopes, mainly ^{222}Rn and ^{220}Rn. ^{220}Rn known as thoron is not relevant for the geogenic radon potential due to its very short half-life of 55.6 s. As we only want the pure radon value, we will close the ionization chamber after reaching equilibrium and wait for at least five halftimes of thoron to ensure a virtual total decay. The activity concentration of the relevant isotope ^{222}Rn is received from the average value of the following 15 minutes. In this case 75 ± 8 $kBq \cdot m^{-3}$, and thus the maximum value for radon activity concentration of the three measurements. The permeability of the soil is measured subsequently. The results are shown in Table 3. In this case, the three measurements are in the same order of magnitude. The main impact factors of permeability are the granularity of the soil as well as the humidity and by that seasonal fluctuations are to be expected.

Status

The campaign is designed for a duration of five years. During this time, all of the 750 different locations will be measured. A total number of 225 locations have already been measured until the end of 2019.

For quality assurance, we have opted for a perpetual improvement scheme with a rolling update of the measuring handbook and ongoing improvements in the workflow. To ensure high precision, the regular participation in international intercomparison measurements is mandatory.

Acknowledgments. We would like to thank the Hessian Ministry of the Environment, Climate Protection, Agriculture and Consumer Protection for tasking us with the design and roll-out of the measurement campaign.

References

1. Bundesamt für Strahlenschutz. (2019). *Wie wirkt Radon auf die Gesundheit?* Salzgitter: BfS. Retrieved May 2, 2019, from www.bfs.de/DE/themen/ion/umwelt/radon/wirkungen/wirkungen_node.html.
2. Deutscher Bundestag. (2008). *Umweltradioaktivität und Strahlenbelastung im Jahr 2007.* (Wahlperiode 16). Drucksache 16/10750.
3. Hofmann, B., & Bossew, P. (2018). *Die Prognose des geogenen Radonpotentials in Deutschland und die Ableitung eines Schwellenwertes zur Ausweisung von Radonvorsorgegebieten.* Salzgitter: Bundesamt für Strahlenschutz.
4. DIN e.V. (2017). DIN ISO 11665-11:2016: *Ermittlung der Radioaktivität in der Umwelt – Luft: Radon-222 - Teil 11: Verfahren zur Probenahme und Prüfung von Bodenluft*. Berlin: VDE VERLAG GmbH.
5. Kemski, J., Siehl, A., Stegemann, R., & Valdivia-Manchego, M. (2001). Mapping the geogenic radon potential in Germany. *Sci. Total Environ*., *272*(1/3), 217–230. DOI: 10.1016/S0048-9697(01)00696-9.
6. Neznal, Matěj, Neznal, Martin, Matolin, M., Barnet, I., & Miksova, J. (2004). *The new method for assessing the radon risk of building sites*. Praha: Czech Geological Survey.