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Determination of the radon progeny activity size distribution at different types of workplaces

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ABSTRACT

Inhalation of radon and its short-lived progeny is one of the most significant contributors to the total effective dose from natural sources of ionising radiation. Exposure to radon progeny represents a substantial health risk, primarily due to its established link to lung cancer. Dose coefficients are derived from biokinetic models describing the behaviour of radon decay products in the respiratory tract, combined with dosimetric models that account for energy deposition from emitted radiation.

Given the variability of environmental and working conditions at different workplaces, obtaining site-specific aerosol data to support more accurate and tailored dose coefficient calculations is beneficial. The key parameters influencing effective dose include the equilibrium equivalent activity concentration (EEAC), total aerosol concentration, and the size distribution of radioactive aerosol particles. Additional factors such as work activity, relative humidity, and ventilation type significantly affect aerosol characteristics and, consequently, the equilibrium factor (F) and the unattached fraction (f_p), which can vary considerably between sites.

This study presents field measurements of the activity size distribution of short-lived radon progeny at several workplaces, using the Dekati ELPI + cascade impactor and the Graded Screen Array Diffusion Battery (GSA DB). The measurements were conducted primarily at underground workplaces with natural ventilation, including former mining excavations and tourist caves. For comparison, the study also includes one site with forced ventilation—a facility for disposing of low-level radioactive waste—and one outdoor location influenced by radon exhalation from a uranium mining waste rock dump.

1. Introduction

The general definition of an aerosol is a suspension of tiny solid or liquid particles in a gas [Hinds, 1998]. It means that aerosols are two-component systems with special properties that mainly depend on the size and concentration of the particles in the suspending medium. They are frequently convenient for delivering liquids and solids from storage containers to surfaces and airspaces. They can be a significant source of contamination in all branches, including the natural environment, industries, and dwellings. The origin of aerosols can be either natural (occurring without human intervention) or anthropogenic (related to human activities). The size distribution of common aerosols in the atmosphere can range from 0,001 μm–100 μm. The hazard caused by inhaled particles depends on their chemical composition and the site at which they deposit within the respiratory system. In general, smaller aerosol particles more effortlessly deposit in sensitive areas of the respiratory tract than larger aerosol particles [ICRP 66, 1994]. Today, regulations for safe levels of respirable aerosols in working environments often require careful monitoring of airborne particulates' size, concentration, and chemical content. Based on this, various mechanisms have been developed to counter aerosol hazards that restrict the access of particles to the sensitive regions of the lungs.

A radioactive aerosol is a suspension of solid or liquid particles in the air that contains radioactive materials (naturally occurring or human-made). Despite the great publicity of radioactive aerosols given to fallout from weapons testing and nuclear reactors, for the average citizen, by far, the most significant exposure to nuclear radiation (about 50 %) comes from naturally occurring radioactive aerosols in everyday housing formed from the decay products of radon gas. In fact, most radiation dose comes from the short-lived decay products of radon gas (^{222}Rn), such as ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po, which contribute the most to the potential alpha energy concentration. All these

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radionuclides are solid particles that attach to aerosol particles and then get deposited in the respiratory tract [Schery, 2001]. Potential alpha energy concentration (PAEC) is the concentration of any mixture of short-lived radon decay products in air in terms of the alpha energy released during complete decay through Pb-210 for Rn-222 progeny (ICRU 88, 2012). The unit equilibrium equivalent activity concentration (EEAC) is the activity concentration of radon in radioactive equilibrium with its short-lived decay products that has the same potential alpha energy concentration as the non-equilibrium mixture [ICRU 88, 2015]. The units of PAEC [$J \cdot m^{-3}$] and EEAC [$Bq \cdot m^{-3}$] can be recalculated into each other.

In addition to the absolute concentration of radon progeny in the air, for radioactive aerosols, an important issue is the size of the particles to which the radon decay products are attached. As mentioned before, different sizes of aerosol particles deposit in various parts of the human respiratory tract; therefore, it is essential to measure the size activity distribution of radioactive aerosol particles in air containing radon decay products, rather than measuring their total concentration [Porstendörfer, 1994].

Radon is a naturally occurring noble gas formed by the alpha decay of its mother radionuclide radium in rocks, soil, and water. It is a colourless, odourless, tasteless, and chemically inert radioactive gas, the only radionuclide from a natural decay series that occurs in gaseous form. A correlation exists between geological characteristics (uranium, thorium, and radium content in soil) and radon in soil, influenced by permeability and the presence or absence of geological faults. Based on the geological structure, the radon concentration in soil air could be dramatically different within a distance of the order of meters. Since radon is a gas, it can easily move through tiny spaces in soil and rock. The primary migration mechanisms are diffusion (radon atoms move from areas of higher concentration to lower concentration), convection (radon movement caused by temperature differences in the soil), and advection (radon movement caused by pressure differences between the soil and another structure) [Grossi et al., 2023].

Of all the radioisotopes that contribute to the natural background radiation, radon presents the most significant risk to human health. Although its concentration in open air is very low and contributes negligibly to health risks, radon might be a serious health risk problem in underground or closed spaces due to the migration mechanisms described above and its accumulation in indoor air. In most European countries, regulations require radon measurements in dwellings and workplaces to assess the risk of radon exposure. Although radon levels are usually limited to about 300 Bq/m^3, many workplaces, such as tourist underground routes, speleotherapy caves, repositories, or former mines with significantly higher radon concentrations during working hours, can also occur. Concerning the effective dose from radon daughters' inhalation, workplaces with high radon concentration, low ventilation levels, and low dustiness are potentially the most hazardous [Adam et al., 2025; Council Directive, 2013].

According to ICRP 137 [ICRP, 2017], aerosol characteristics must be defined to calculate doses from inhaled radon progeny. This document provides conversion values that can be used to calculate doses for typical situations. Moreover, in cases of doubt, when the distribution of aerosols could be significantly different from typical conditions, additional measurements of aerosol distributions can be made at the place where the risk is assessed. The activity size distribution of the radon progeny aerosol can vary based on the type of workplace, level of radon and radon progeny concentration, and ventilation conditions. These input parameters mainly affect an unattached fraction f_p (the fraction of the potential alpha energy concentration of short-lived radon progeny that is not attached to the ambient aerosol; f_p has diameters less than approximately 5 nm), an equilibrium factor F (the ratio of the actual concentration of radon decay products in the air to the concentration that would be present if the decay products were in complete equilibrium with radon gas) and AMAD (Activity Median Aerodynamic Diameter). As mentioned earlier, dose calculation parameters are provided for indoor workplaces, active mines, and tourist caves [ICRP, 2017]. These values were derived from numerous published measurement results of activity size distributions for the attached radon progeny, including [Postendörfer, 2001; Kranrod et al., 2009; Tu et al., 1991; Tokonami et al., 2005; Solomon et al., 1992, 1994]. In practice, if there is no information (measured results) about the aerosol conditions at the workplace, it is possible to use the ICRP-given values and dose coefficients to calculate the effective dose. The Czech legacy adopted the ICRP 137 conversion coefficients for determining the effective dose from the inhalation of radon progeny in 2022. Since then, the Czech Republic has used two conversion coefficients for workplaces with and without dust.

However, due to the complicated geological structure of the Bohemian Massif, there are many workplaces where aerosol conditions differ significantly from typical conditions. Volcanic activity occurred frequently, and rocks underwent regional and contact metamorphosis, creating the landscape's tectonic and structural settings. The presence of magmatic rocks indicates a correlation between the occurrence of radioactive materials and the acidity of the rocks. The concentration of uranium and radium in magmatic acidic rocks is up to seven times higher than in other rocks [Stacks, 2015].

In these cases, measuring the concentration of radon progeny, gaining reliable aerosol data, and calculating a site-specific dose coefficient help determine the exact effective dose. The activity size distribution of radon progeny can be determined over the whole size range of aerosol particles using a combination of a diffusion battery and a cascade impactor. The methodology has already been introduced and published by the SUJCHBO laboratories [Fialova, Otahal, 2024].

Between 2022 and 2025, employees of SUJCHBO conducted measurements of selected radiation quantities required to estimate the effective dose from the inhalation of radon decay products at various types of workplaces and in different environments. The measurement sites were selected based on prior knowledge of elevated radon concentrations. These sites differed in geological background, ventilation type, and airborne aerosol particulate levels (dustiness). Table 1 presents the measurement locations, grouped according to their characteristic properties. Fig. 1 presents a map of the Czech Republic indicating areas of radon risk and the locations of individual measurement sites.

1.1. Koneprus caves

The Koneprus Caves, situated in the Bohemian Karst Protected Landscape Area, approximately 7 km south of Beroun, are formed in Devonian limestone and are over 400 million years old. These caves form a complex, multi-level karst system with a vertical extent exceeding 70 m. Due to their geological composition and limited ventilation, elevated concentrations of radon and its progeny are typically present [Thinova et al., 2010]. Regular work in the cave system is carried out by staff responsible for maintenance and guided tours, who may experience prolonged exposure to radon decay products. As such,

Table 1
Summary and specification of measured sites.

Workplace name	Site specification	Origin	Type of ventilation
Koneprus caves	Tourist cave	Natural	Natural
Zbrasov caves	Tourist cave	Natural	Natural
Cisar caves	Speleotherapy	Natural	Natural
Jeronym Mine	Show mine	Anthropogenic	Natural
Barbora drainage gallery	Drainage gallery	Anthropogenic	Natural
Zlate Hory mine	Gold exploration gallery	Anthropogenic	Natural
Richard repository	Low-level radioactive waste repository	Anthropogenic	Forced ventilation
Uranium waste rock dump	Outdoor area	Anthropogenic	Natural

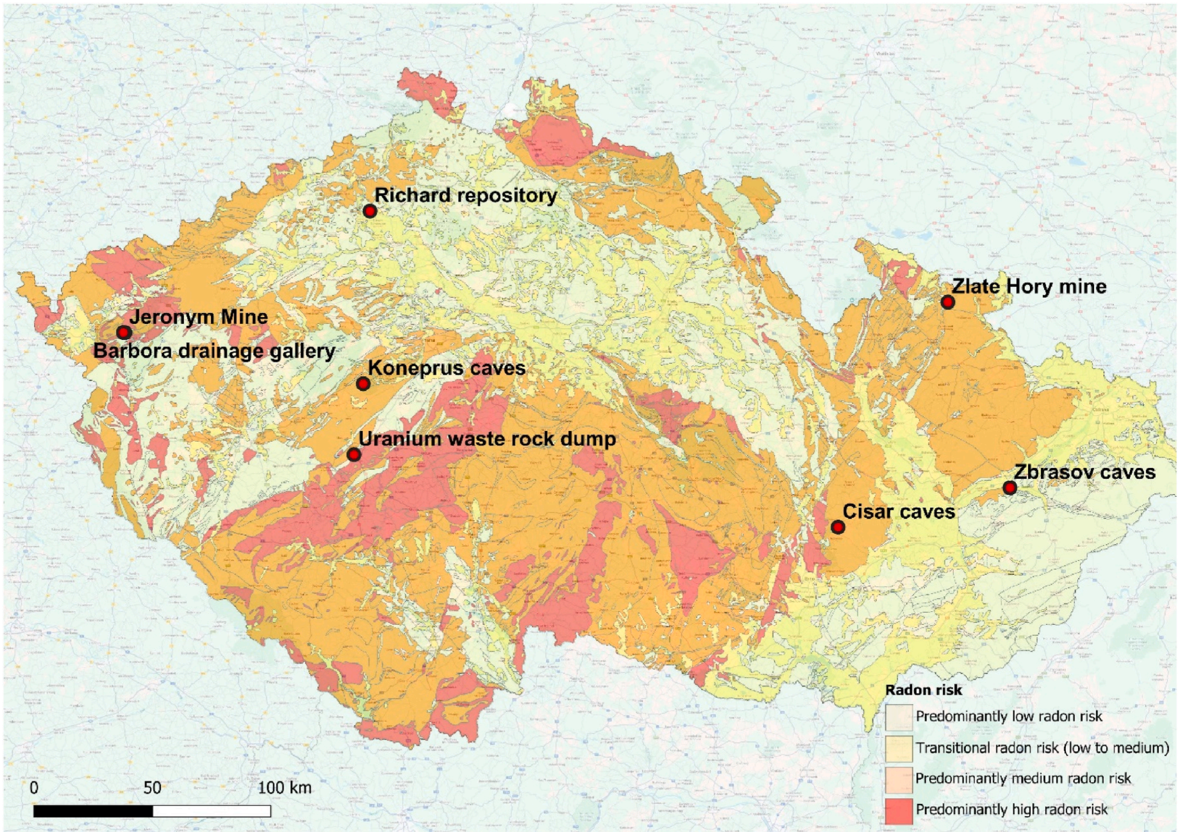

Fig. 1. Location of measured sites with indicated radon risk levels, source map [Czech Geological Survey, 2024].

the site represents a typical example of a workplace with an increased radon-related exposure relevant for effective dose assessment and radiological protection studies.

1.2. Zbrasov caves

The Zbrasov Aragonite Caves, situated in the spa town of Teplice nad Becvou in northeastern Moravia, are formed in Middle Devonian limestones and are unique for their combination of karst and hydrothermal origins. The cave system lies within a geologically active zone where carbon dioxide-rich (CO_2) gases rise from deep underground and contribute to the formation of aragonite structures. Due to natural CO_2 degassing and limited ventilation, the caves are known for elevated radon and carbon dioxide concentrations [Thinova et al., 2015]. The cave is accessible to the public and maintained by personnel responsible for operation, guidance, and visitor services. These conditions result in potentially increased exposure to radon decay products, making the location relevant for evaluating effective dose and radiological protection measures in underground tourist environments.

1.3. Cisar caves

The Cisar Cave, located near the village of Ostrov u Macochy in the Moravian Karst, is part of an extensive limestone cave system developed in Devonian and Carboniferous limestones. Measurements of CO_2 and radon concentrations in the Císařská Cave in relation to human presence in the cave environment and ventilation conditions have been carried out, for example, by Jiri Faimon [Faimon, Štelcl, Sas, 2006]. A cave section has been adapted for speleotherapy, a form of treatment that utilises the stable underground microclimate, particularly beneficial for patients with chronic respiratory conditions. The therapeutic chamber is characterised by high air humidity, stable temperature, and low levels of air pollutants. It is also characterised by elevated radon concentration and its decay products, typical for karst environments. Although the duration of the stay is medically supervised and limited, the facility is regularly operated by staff who enter the cave on a daily basis. This makes the location necessary for assessing occupational radon exposure under controlled conditions, as it is relevant for health protection and dose optimisation in specialised therapeutic settings.

1.4. Jeronym mine

The Jeronym Mine, located near the village of Cista in the Krusne hory (Ore Mountains) region, is a well-preserved historical tin mine developed in metamorphic rocks of the Krusnohorske krystalinikum. Mining activity began in the 16th century, and the underground system retains extensive hand-excavated chambers and shafts. Today, the site is managed by the Sokolov Museum as a national cultural monument and is open to the public as part of the Jeronym Mining Heritage Area. The study of the radioactivity of rocks in the Jeroným mine and the estimation of radiation risk for visitors and guides was published in [Malczewski et al., 2021]. It recommends measuring radon levels in the mine atmosphere for a more accurate assessment of the guide's effective dose from radon inhalation. Due to the geological setting and limited natural ventilation, the underground environment exhibits elevated concentrations of radon and its progeny, which are periodically monitored. Although the mine is not used for regular work, museum staff and researchers enter the site for maintenance, guided tours, and specialised measurements. This makes the location relevant for assessing intermittent radon exposure in a historically significant, controlled underground environment.

1.5. Barbora drainage gallery

The Barbora drainage gallery is an integral part of the historical Jeronym Mining Heritage Area, located near Cista in the Krusne Hory

(Ore Mountains) region. This horizontal underground passage, excavated in metamorphic rocks of the crystalline basement, historically served as a drainage gallery for the broader Jeronym mine complex. Its primary function was to manage mine water outflow, enabling deeper extraction levels to remain operational. In recent years, the Sokolov Museum, which administers the site, has expressed interest in re-establishing the adit's drainage function as part of the ongoing preservation and management of the mining field. To achieve this, the adit is planned to be reopened using traditional mining methods, ensuring safe access and structural stability. Although not currently accessible for regular work, the planned rehabilitation and future use of the Barbora drainage gallery represent a specific example of a low-access underground workplace, where monitoring of radon levels and worker exposure may become relevant as a part of operational planning and radiological protection.

1.6. Zlate Hory Mine

The Zlate Hory Mine, situated near the town of Zlate Hory in the Jeseniky Mountains of northeastern Czech Republic, has a rich history of gold and polymetallic ore mining dating back to the 13th century. The deposit is located within the Silesicum geological unit, which is predominantly hosted in mica schists and quartzites, and is intersected by hydrothermal quartz veins containing gold and sulfide minerals. In recent years, the state enterprise DIAMO has undertaken detailed geological exploration to assess the potential for renewed gold mining. As part of these activities, measurements conducted in underground workings have confirmed the presence of elevated concentrations of radon and its decay products, attributed to the geological conditions and limited ventilation. The site therefore represents a high-radon underground workplace, relevant for studies focusing on effective dose assessment, equilibrium factor determination, and activity size distribution of radon progeny under real working conditions in exploratory mining environments.

1.7. Richard repository

The Richard repository, located near Litomerice in northern Bohemia, is a former underground limestone mine used initially for extracting building stone. The site is developed in Cretaceous marine limestones of the Bohemian Cretaceous Basin. During World War II, parts of the mine were converted into an underground factory for the German armaments industry. Today, a section of the former mining field is operated by the Radioactive Waste Repository Authority (SURAO) as a repository for low-level radioactive waste, primarily from medical, research, and industrial sources. Regular activities at the site include waste emplacement, package handling, radiological monitoring, inspection of storage conditions, and construction and maintenance of repository chambers. A ventilation system is installed in the mine and operated whenever workers are on-site. It is activated in advance to allow sufficient time for radon to be ventilated from the workplace. The workplace is subject to regular oversight by the State Office for Nuclear Safety (SUJB) and International Atomic Energy Agency (IAEA) inspectors, making it a unique example of a ventilated underground repository with routine operational and regulatory oversight.

1.8. Uranium waste rock dump

The monitored site is located near the largest uranium mine waste rock dump in the Pribram region in Central Bohemia. The area was developed within the geological setting of Proterozoic and Cambrian formations, including shales, greywackes, and volcanic rocks intersected by uranium-bearing veins. The dump consists of unprocessed ore residues and mineral-rich waste materials from underground uranium mining. Field measurements were conducted during summer nighttime hours, characterised by thermal inversions and stagnant air layers that promote radon accumulation near ground level. These conditions and the dump's physical properties contribute to the elevated concentrations of radon and its decay products observed in the surrounding ambient air [Adam et al., 2025]. The measurement point was situated about 30 m from the base of the waste rock dump on its north-west part.

2. Materials and methods

The methodology applied in this study builds upon the experimental validation previously conducted under controlled laboratory conditions at the National Institute for Nuclear, Chemical and Biological Protection (SUJCHBO), as described by Fialova and Otahal (2024). The aim was to determine the activity size distribution of short-lived radon progenies in workplace atmospheres using a combination of two sampling systems: the Dekati ELPI + cascade impactor and a Graded Screen Diffusion Battery (GSA DB).

These methods were complemented by grab (single-time) sampling techniques using an aerosol filter and diffusion screen, which allowed for the determination of the equilibrium equivalent activity concentration (EEAC) and the unattached fraction (f_p) in each monitored environment. In parallel, continuous monitoring of radon activity concentration was carried out at all sampling sites using calibrated radon monitors to provide real-time information on indoor radon levels during the experimental sampling. Continual measurement of radon was carried out to determine the equilibrium factor F (the ratio of the equilibrium equivalent activity concentration and the radon activity concentration).

Before starting the measurements, the EEAC value was always first determined by the grab-sampling method. Then, the sampling time for measuring the activity size distribution of aerosols, ranging from 3 to 60 min, was adjusted based on the EEAC value. The reason is that the methodology working measurement range, corresponding to a maximum of 2.5 $kBq \cdot h \cdot m^{-3}$, was determined during laboratory measurements [Fialova, Otahal, 2024]. Experimental aerosol sampling was repeated at each measured location a minimum of three times within one day. The year-season during which the measurements were conducted at naturally ventilated workplaces was planned conservatively to ensure a higher radon concentration on the site. In naturally ventilated underground spaces, radon concentration is generally higher in the summer than in the winter season. However, at some locations, it was not possible, for organizational reasons, to carry out measurements with the complete equipment during the summer, as this would have disrupted the smooth operation of tourist routes.

Most of the measurement techniques applied in this study are regularly verified within the framework of the Authorised Metrological Centre operated by SUJCHBO [Burian et al., 2011]. The procedures used for sample collection and determining key radiological quantities are based on accredited methodologies following the international standard ISO/IEC 17025. This ensures the metrological reliability, traceability, and reproducibility obtained during laboratory and field measurements.

2.1. Cascade impactor system

The Dekati ELPI + cascade impactor (Dekati Ltd., Finland) [ELPI + User ELPI TM User Manual, 2011] was used to classify aerosol particles by aerodynamic diameter, ranging from 17 nm to 10 μm, across 14 deposition stages. Each stage was equipped with greased collection plates and prepared with a solid-state nuclear track detector (SSNTD, LR-115). Track detectors were combined with a 50 μm Mylar braking foil to discriminate alpha particles based on their energy. After sampling, the detectors were chemically etched, and track densities were determined using automated optical microscopy. The equilibrium equivalent activity concentration (EEAC) for each size fraction was derived from the observed track density, calibrated by laboratory reference data [Fialova, Otahal, 2024].

2.2. Diffusion battery for unattached fraction

To assess the unattached fraction (f_p) and measure sub-100 nm particles, a Graded Screen Array Diffusion Battery (GSA DB) was used. The design of the diffusion battery is based on the work of Prof. Robert Holub and Prof. E.O. Knutson, who developed and refined the graded screen technique for determining the diffusion properties and size distribution of radon progeny. Their foundational work laid the basis for differentiating unattached and attached fractions of short-lived radon decay products using sequential stainless-steel screens of increasing mesh density [Holub, Knutson, 1987].

The GSA DB consists of ten diffusion screens and a backup filter. After sampling, the alpha activity on each screen is measured using a two-channel alpha spectrometer (MAAF). This system enables the determination of the activity size distribution from approximately 0.3 to 100 nm, thereby covering the unattached fraction region that is inaccessible to standard cascade impactors.

2.3. Grab sampling for EEAC and unattached fraction verification

In addition to size-selective measurements, grab sampling methods were used to independently determine the equilibrium equivalent activity concentration (EEAC) and the unattached fraction (f_p) of radon progeny. These methods are regularly used in the accredited laboratory of the Authorised Metrological Centre of SUJCHBO, and the results are traceable to PTB Braunschweig.

For EEAC determination, a single open-face filter holder equipped with a microfiber aerosol filter is used. For f_p measurement, the setup includes a single stainless-steel diffusion screen in front of the backup filter. The sampled air is sucked through the filter assembly at a flow rate of 20 L/min for up to 20 min. Alpha activity is measured in four intervals using a two-channel alpha spectrometer (MAAF). EEAC is calculated via least-squares fitting of alpha decay curves using the Raabe–Patterson method. At the same time, f_p is derived from the ratio of alpha activity on the filter to that on the screen.

In field applications, these grab sampling methods are a reference for verifying the total activity measured using the cascade impactor and the diffusion battery. Since grab samples integrate the entire aerosol size spectrum in one filter, their results validate the sum of EEAC values determined from individual stages of the impactor and diffusion screens. This approach ensures consistency and allows control of potential activity losses or sampling artefacts in size-selective systems [Otahal et al., 2017].

3. Results and discussion

Measurements of short-lived radon progeny activity size distributions were performed at various workplaces representing both natural and anthropogenic environments. The results presented in Table 2 include the radon activity concentration (RAC), equilibrium equivalent activity concentration (EEAC), equilibrium factor F, unattached fraction f_p, and the activity median aerodynamic diameter (AMAD) of the attached aerosol fraction. These parameters are critical inputs for determining site-specific dose coefficients, as recommended by ICRU Report 88 [ICRU, 2015] and ICRP Publication 137 [ICRP, 2017].

Climatic conditions in caves and naturally ventilated underground sites (the first six sites in Table 2) are relatively stable during the whole year. The temperature ranges from 8 to 10 °C, and the relative humidity is generally very high, reaching nearly 100 %. Radon concentration is usually higher during the summer season, when the surrounding temperatures exceed 20 °C. The temperature at the underground radioactive waste repository Richard remains stable throughout the year, at 11.1 °C ± 0.5 °C. The relative humidity ranges from 70 % to 100 %, depending on whether ventilation is running or not. During the measurement campaign, ventilation was running, and the humidity level was 70 %. The measurement campaign at the uranium waste rock dump was conducted in the early morning during the summer season, following a night with temperatures remaining above 20 °C, which created ideal conditions for radon emanation from the base of the waste rock dump [Adam, Otahal, 2025].

Fig. 2 illustrates the equilibrium equivalent activity concentration (EEAC) of short-lived radon progeny measured at various workplaces, expressed in Bq·m^{-3}. These values represent the key radiation quantity used to estimate the inhalation dose from radon decay products, which are known to be the dominant contributors to the total effective dose in radon-exposed environments.

The highest EEAC value was recorded at the Barbora drainage gallery, significantly exceeding those measured at all other sites. This extreme level can be explained by the unique microclimatic conditions of the gallery, which is not in regular operation and is effectively isolated from the outside environment. Due to the absence of natural or forced ventilation, radon gas accumulates and its decay products remain suspended in stagnant air. With very few aerosol particles available for attachment, a large portion of the radon progeny remains in the unattached state, resulting in a high unattached fraction (f_p). Minimal air exchange causes rapid deposition of small particles on the walls, resulting in a relatively low equilibrium factor (F).

Despite its exceptional status, elevated EEAC levels were also observed at several other locations, including the outdoor uranium waste rock dump, the Koneprusy caves, and the Zlate Hory Mine, underscoring the significance of radon in such environments.

Fig. 3 presents the unattached fraction f_p measured at various sites. Workplace-specific aerosol characteristics showed significant variability, reflecting the diverse environmental and ventilation conditions across sites. An explanation of how ventilation affects the studied parameters can be found, for example, in ICRU Report 88. The correlation can be explained under conditions where the ventilation rate is not too high. When the aerosol particle concentration is high, the unattached

Table 2
Summary results of measured values at different sites.

Measured site - date of measurement	RAC [Bq·m^{-3}]	EEAC [Bq·m^{-3}]	F	f_p	AMAD [nm]
Koneprus caves - January 2025	2481 ± 292	1078 ± 29	0.44 ± 0.04	0.36 ± 0.03	205 ± 14
Zbrasov caves - February 2024	3242 ± 416	667 ± 171	0.21 ± 0.05	0.75 ± 0.07	391 ± 75
Cisar caves - February 2023	1483 ± 100	742 ± 27	0.5 ± 0.04	0.19 ± 0.02	178 ± 5
Jeronym Mine - October 2024	716 ± 419	532 ± 461	0.66 ± 0.35	0.13 ± 0.03	300 ± 36
Barbora drainage gallery - 09/2024	24282 ± 3670	7153 ± 1541	0.3 ± 0.07	0.32 ± 0.07	292 ± 29
Zlate Hory Mine - August 2022	2028 ± 120	780 ± 180	0.39 ± 0.10	0.23 ± 0.09	257 ± 67
Richard repository - March 2025	1231 ± 353	534 ± 165	0.43 ± 0.03	0.05 ± 0.01	336 ± 21
Uranium waste rock dump - 08/2024	10176 ± 1146	1902 ± 514	0.19 ± 0.05	0.31 ± 0.03	286 ± 15

RAC	*Radon Activity Concentration*	*F*	*Equilibrium Factor*
EEAC	*Equilibrium Equivalent Activity Concentration*	*f_p*	*Unattached Fraction*
AMAD	*Activity Median Aerodynamic Diameter*		

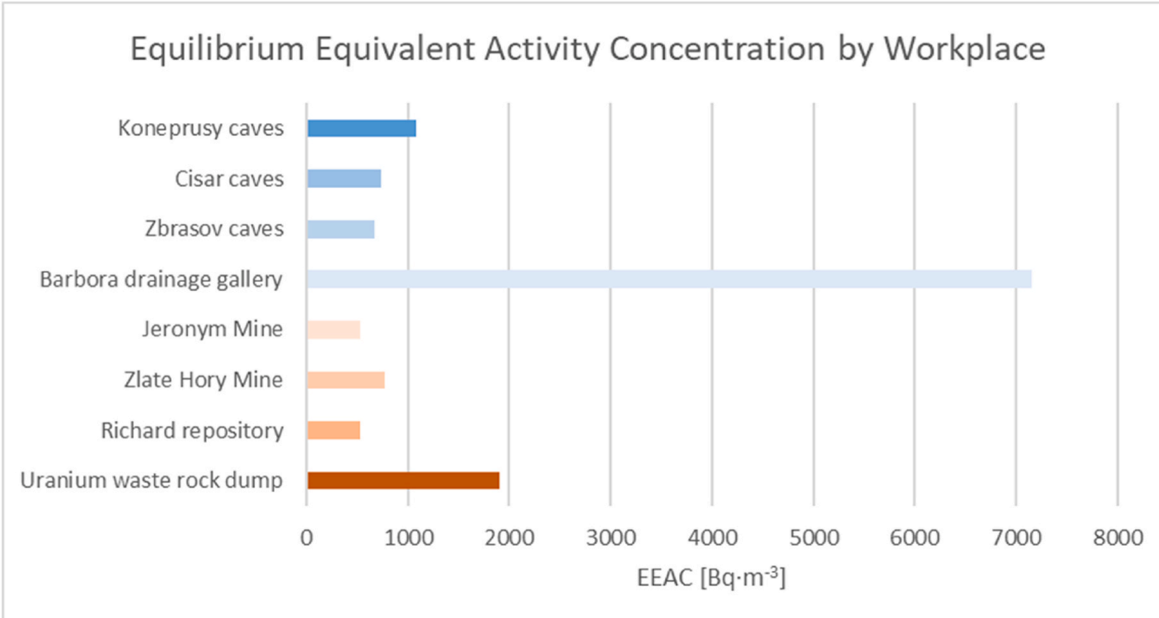

Fig. 2. Results of equilibrium equivalent activity concentration (EEAC) measured at various workplaces.

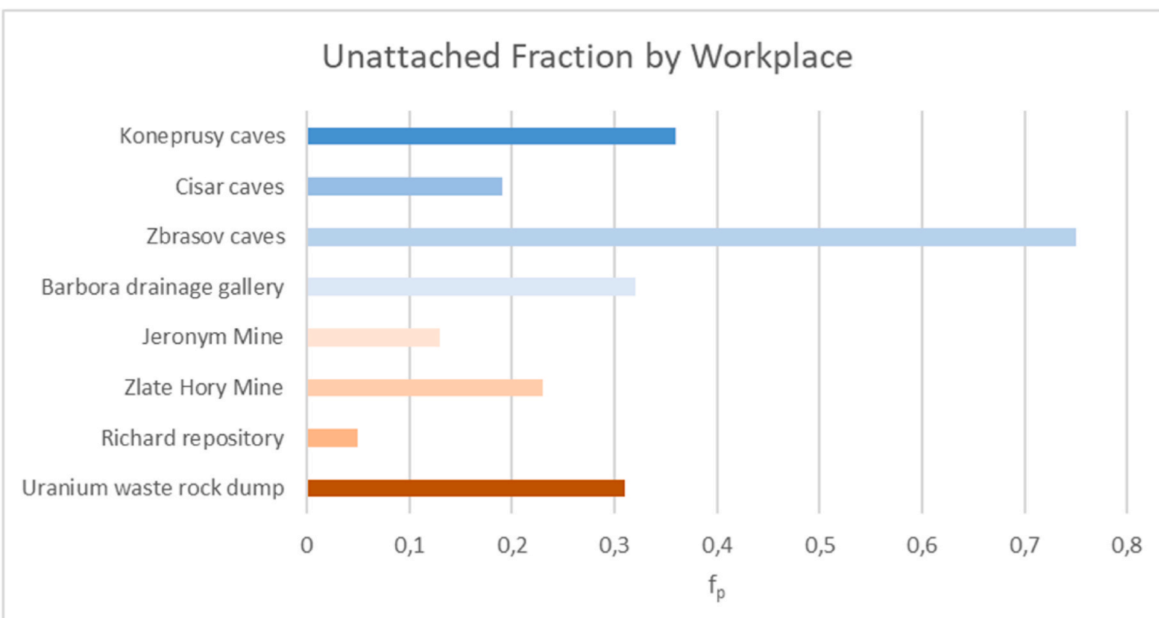

Fig. 3. Results of the unattached fraction measured at different workplaces.

fraction decreases, and the equilibrium factor increases, as more radon progeny attach to aerosols and remain airborne. This is because the plate-out (deposition) rates of aerosol-attached nuclides are significantly lower than those of unattached nuclides [ICRU, 2015]. In cases where the concentration of aerosols in the indoor atmosphere is low, the situation is reversed. The unattached fraction increases, and the equilibrium factor decreases, because of the significantly higher plate-out rate of the unattached fraction. In underground tourist caves such as the Koneprusy caves and Zbrasov caves, elevated f_p values (0.36 and 0.75, respectively) were observed, indicating a substantial portion of radon progeny in the unattached state. These values exceed typical reference values for tourist caves (ICRP 137: $f_p = 0.15$), demonstrating the need for tailored dosimetric assessments in such environments. The Zbrasov caves further exhibited the highest AMAD (391 nm), suggesting the presence of larger aerosol carriers, possibly due to CO_2-rich degassing and limited air movement.

Degassing plumes — gas emissions from subsurface reservoirs such as magmatic or hydrothermal systems — can generate aerosol particles through condensation and chemical reactions with surrounding air. In the case of the Zbrasov caves, carbon dioxide released from deep geological layers likely contributes to aerosol formation and growth, resulting in larger particle sizes compared to other sites. This process has been observed in volcanic and geothermal environments, where CO_2 emissions lead to the formation of coarse-mode particles with aerodynamic diameters up to several micrometres [Shcherbakov et al., 2016].

The outdoor site near the uranium waste rock dump demonstrated a relatively high f_p (0.31) and an elevated RAC exceeding 10,000 Bq·m^{-3}.

These findings highlight the potential radiological significance of such open-air sites under conditions that promote radon accumulation, such as nocturnal inversions [Adam et al., 2025].

Fig. 4 presents the calculated AMAD at various sites. Similar to the cases of f_p and EEAC, significant variability in results is observed across different types of workplaces, depending on site-specific aerosol and ventilation conditions.

The interrelationships between measured parameters were examined using a Pearson correlation coefficient in a matrix in Fig. 5. The Pearson correlation coefficient is a statistical measure of the strength of the linear relationship between paired data. It is donated by r, and its values range from −1 to 1. This matrix reveals the degree of linear association between key variables relevant to radon progeny dosimetry: radon activity concentration (RAC), equilibrium equivalent activity concentration (EEAC), equilibrium factor (F), unattached fraction (f_p), and activity median aerodynamic diameter (AMAD). In the matrix in Fig. 5, it is possible to compare the variables in the columns with those in the rows. For example, the relationship between EEAC and RAC is presented in the table cell located in the first column and second row (the same as in the second column and the first row). The Pearson correlation coefficient r = 0.98 indicates a strong dependence. In other words, the more radon there is, the more decay products are present.

Several notable correlations were observed.

- A strong positive correlation was found between RAC and EEAC (r = 0.98), unsurprisingly confirming that higher radon gas concentrations lead to proportionally higher equilibrium equivalent activity concentrations of its progeny. The unattached fraction of the radon decay products as a function of the particle concentration of the aerosol was described in [Postendörfer, 2001].
- The unattached fraction f_p showed only a weak positive correlation with AMAD when all sites were included (r = 0.41), which did not support the expected inverse relationship between particle size and unattached fraction. However, when the Zbrašov Aragonite Caves data — characterised by an exceptionally high f_p = 0.75 and AMAD = 391 nm — were excluded as an outlier, the correlation between f_p and AMAD shifted to a moderate negative value (r = −0.44), better aligning with theoretical expectations [ICRU 88, 2015] that higher unattached fractions are associated with smaller carrier particles. The change in the correlation after the extreme Zbrasov cave data elimination is shown in the graphs in Fig. 6. The graph on the left side shows the correlation between the unattached fraction and AMAD from all field measurements. The graph on the right side presents the rapid change in the correlation when the extreme data measured in Zbrasov cave are excluded.
- A moderate negative correlation was also observed between f_p and equilibrium factor F (r = −65), indicating that environments with higher unattached fractions tend to exhibit lower equilibrium conditions, likely due to limited attachment of radon progeny to available aerosols. The actual relationship between F and f_p depends primarily on the ratio of the deposition rates of the attached and unattached radon progeny. The deposition rate depends on the surface-to-volume ratio and the deposition velocity, which in turn depends on the particle size and the roughness of the surface [ICRU 88, 2015].

These findings confirm that relying solely on generic aerosol parameters (e.g., those recommended in ICRP 137) may not sufficiently reflect real exposure scenarios. Integrating site-specific measurements and statistical relationships enhances the robustness of inhalation dose assessments, supporting the development of refined models for radiation protection in radon-prone environments.

However, it is worth noting that the measurements were conducted during different seasons and at various times of day and night. The dataset does not cover the full annual variability, which may be significant, particularly in environments with natural ventilation. In such locations, seasonal or diurnal changes in air exchange rates can substantially affect aerosol dynamics and radon progeny distribution. Therefore, while the presented results represent the measured conditions, they do not account for the full range of potential variability throughout the year. Moreover, for a detailed understanding of the aerosol atmosphere in extreme cases such as Zbrasov cave, it would be helpful to carry out a physico-chemical analysis of the collected aerosol particles. These analyses were not performed as part of this study.

The measured activity size distributions of radon progeny across eight Czech workplaces, as shown in Fig. 7, exhibit pronounced site-specific characteristics that directly inform dosimetry assessments.

The Barbora drainage gallery recorded the highest equilibrium equivalent activity concentration (EEAC) of all locations, with attached-fraction peaks reaching over 1100 Bq·m^{-3} in the 170–260 nm range. Its

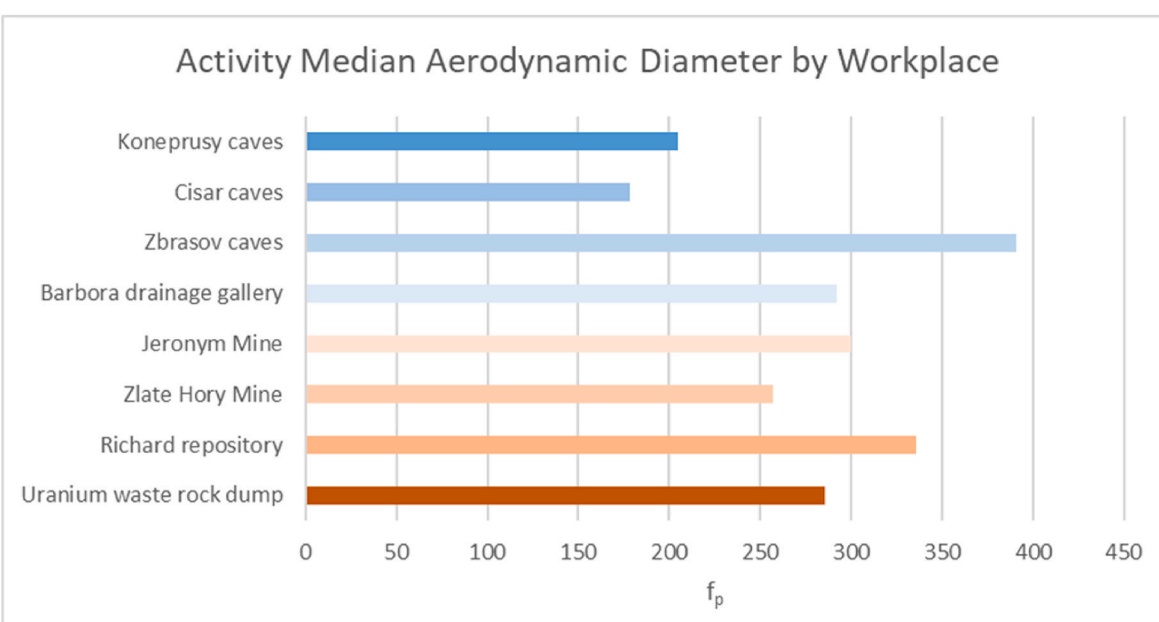

Fig. 4. Determined AMAD (Activity Median Aerodynamic Diameter) at different workplaces.

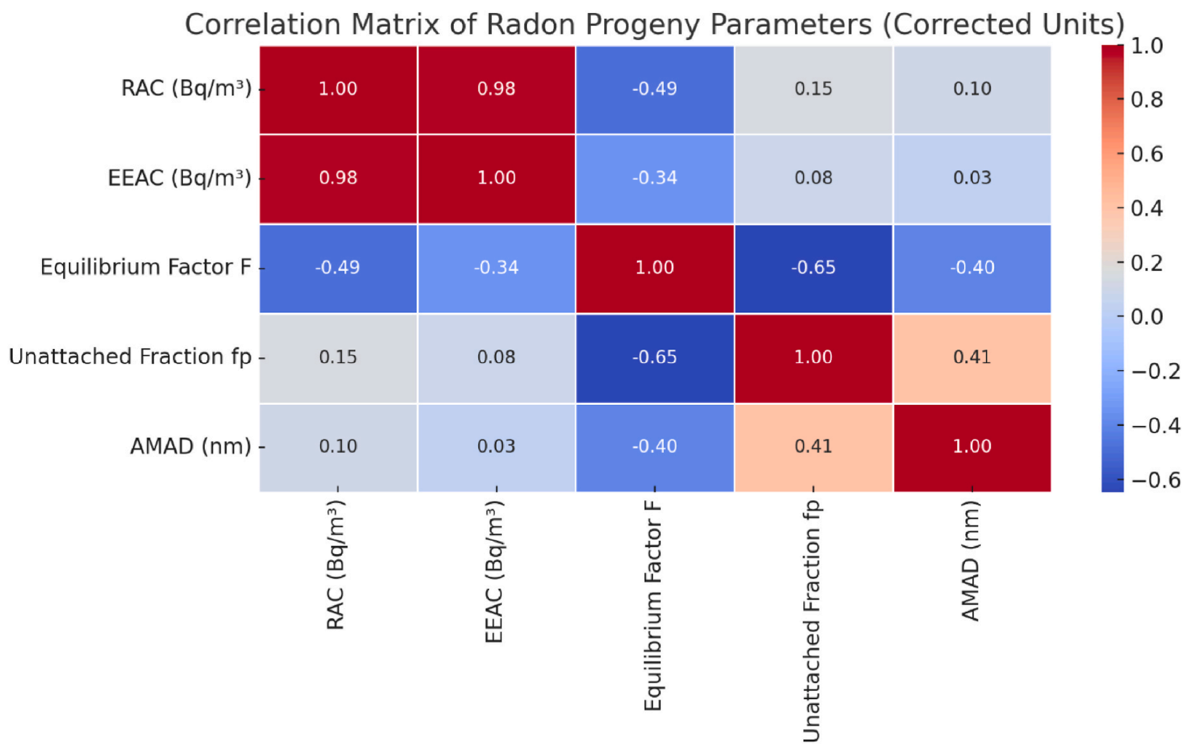

Fig. 5. Correlation matrix of radon progeny parameters.

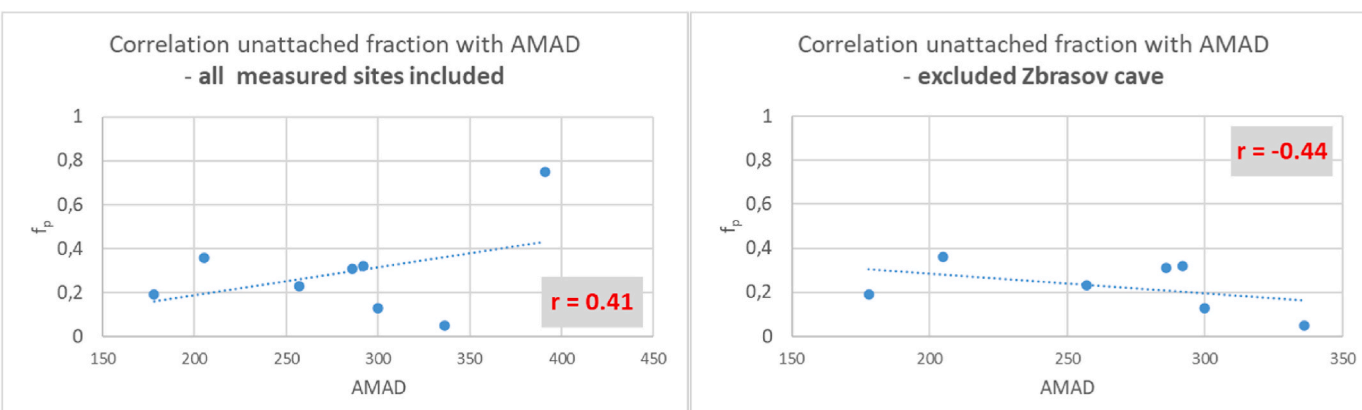

Fig. 6. Modification of the correlation after the Zbrasov cave data removal.

substantial unattached fraction ($f_p \approx 0.32$) further indicates a remarkably "clean" aerosol environment, where sub-5 nm particles dominate the potential alpha energy concentration.

By contrast, the Zbrasov Aragonite Caves displayed the most extreme unattached fraction behaviour: f_p peaked at 0.75, and the free fraction mode around 0.8 nm contributed more to the distribution than all attached particles combined.

In the case of the Richard low-level waste repository, where a forced-ventilation system actively draws exterior air into the underground chambers, a pronounced suppression of the unattached fraction was observed. Unlike the naturally ventilated show mines and caves, the mechanical airflow at Richard repository introduces a high concentration of ambient aerosol particles, driving f_p down to approximately 0.05. Consequently, nearly all radon progeny activity is carried on attached particles (AMAD ≈ 336 nm; EEAC peaks around 27 $Bq \cdot m^{-3}$).

No diffusion-battery (GSA DB) sampling was performed at the Zlate Hory exploration adit and the Cisar caves. In both cases, only the ELPI + cascade impactor captured the attached fraction distribution, which centres between 100 nm and 200 nm with EEACs of roughly 140–200 $Bq \cdot m^{-3}$.

4. Conclusion

This study demonstrated that the activity size distribution of short-lived radon progeny varies significantly across different types of workplaces, reflecting the complex interplay of environmental conditions, geological background, ventilation regimes, and aerosol characteristics. The field measurements confirmed that the equilibrium equivalent activity concentration (EEAC), unattached fraction (f_p), and activity median aerodynamic diameter (AMAD) exhibit substantial site-specific variability, which directly influences the resulting dose coefficients.

The correlation analysis further emphasised that generalised aerosol assumptions, such as those provided by ICRP Publication 137, may not sufficiently capture the diversity of real-world conditions. Therefore, site-specific measurements of key aerosol parameters such as f_p, F, EEAC, and AMAD are essential for accurate dose estimation and

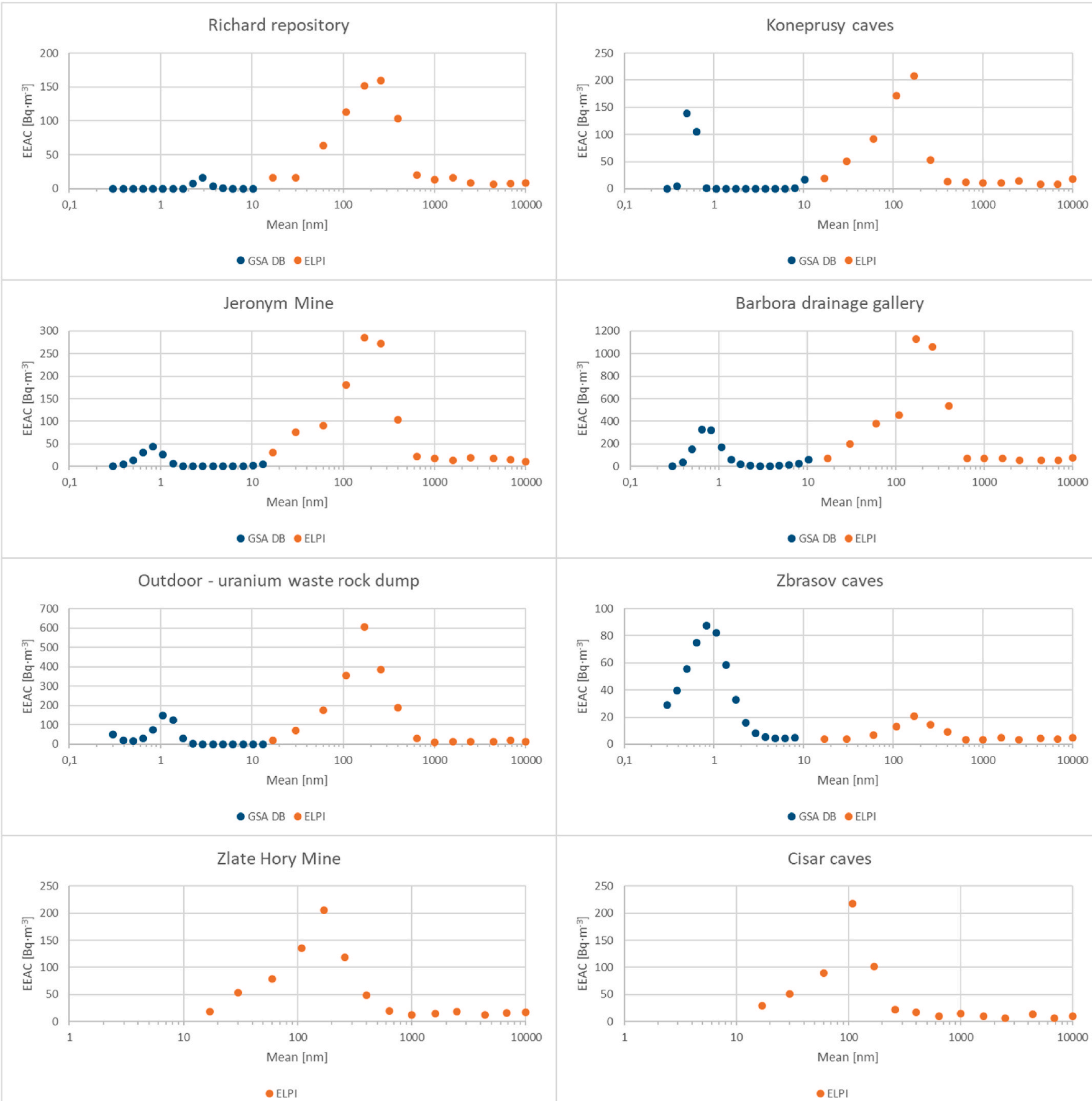

Fig. 7. Determined activity size distributions of radon progeny across different Czech workplaces.

effective radiation protection in radon-prone workplaces.

The measurements presented in this study were conducted predominantly at underground workplaces with natural ventilation, including former mining galleries and karst caves. One site with artificial ventilation (a low-level radioactive waste repository) and one outdoor location affected by radon exhalation from a uranium mine waste rock dump were also compared. These latter environments offered contrasting boundary conditions, highlighting the influence of external aerosol input and surface emissions on radon progeny behaviour.

The presented methodology for determining the activity size distribution of radon progeny using a cascade impactor and a diffusion battery is practically applicable, although it requires the use of expensive and complex measuring equipment as well as a well-equipped laboratory. A relatively simple method to improve the accuracy of effective dose estimation from inhalation of radon progeny is the determination of f_p using a wire screen and a microfiber filter. ICRP Report 137 provides the option to recalculate the dose conversion coefficient when the value of f_p is determined accurately.

CRediT authorship contribution statement

Petr PS. Otahal: Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Eliska Fialova:** Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of generative AI in scientific writing

While preparing this work, the authors used ChatGPT only for the writing process to improve the article's language and readability. The authors are not native English speakers. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

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Declaration of competing interest

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Glossary

EEAC	Equilibrium Equivalent Activity Concentration
PAEC	Potential Alpha Energy Concentration
F	Equilibrium factor
f_p	Unattached fraction
GSA DB	Graded Screen Array Diffusion Battery
AMAD	Activity Median Aerodynamic Diameter
SUJCHBO	National Institute for Nuclear, Chemical and Biological Protection
SURAO	Radioactive Waste Repository Authority of the Czech Republic
SUJB	State Office for Nuclear and Safety of the Czech Republic
IAEA	International Atomic Energy Agency
SSNTD	Solid-state nuclear track detector
RAC	Radon Activity Concentration
ICRU	International Commission on Radiation Units and Measurements
r	Pearson correlation coefficient

Data availability

No data was used for the research described in the article.

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