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# ASSESSMENT OF EFFECTIVE DOSES BASED ON VARIOUS RADON MEASURING TECHNIQUES

MASTER'S THESIS

Nataša Smrekar

Supervisor: Prof. Dr. Janja Vaupotič

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# OCENA EFEKTIVNIH DOZ RADONA, KI TEMELJIJO NA RAZLIČNIH MERILNIH TEHNIKAH

MAGISTRSKA NALOGA

Nataša Smrekar

Mentor: prof. dr. Janja Vaupotič

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**TITLE**

**Assessment of effective doses based on various radon measuring techniques**


**ABSTRACT**

In my master's thesis, I have focused on radon gas in 43 buildings used for different purposes (23 schools, 3 kindergartens, 16 offices and a residential house) in which preliminary measurements had shown higher concentrations of radon gas. I carried out measurements of radon and short-lived radon products whilst simultaneously employing different measurement techniques. In all 43 buildings, I measured the instantaneous concentration of radon by using scintillation cells; in 18 buildings, I additionally measured the average concentration of radon by using solid state nuclear track detectors and in 10 buildings, I measured concentration retrospectively with solid state nuclear track detectors. In four selected buildings (a school, a kindergarten, an office and a residential house), I carried out the measurements by using all of the available equipment. I monitored the daily fluctuations of concentration of radon and short-lived radon products by using continuous monitors in 14 buildings. This is how I obtained the factor of radioactive equilibrium between radon and its short-lived products. Based on the results obtained, I calculated the effective doses. As the basis for calculating the doses, I used the instantaneous and average concentrations of radon and the equilibrium factor taken from literature (0.40) or own measurements. I compared the doses and critically evaluated them.

In contrast to the previous research, I researched radon exclusively in areas with increased risk for radon. I studied the influence of the working regime on the concentration of radon in different working environments (i.e. a school, a kindergarten and an office).



**KEY WORDS:** Radon, short-lived radon products, measurement technique, scintillation cell, solid-state nuclear track detector, retrospective detector, equilibrium factor, effective dose, comparison.

**NASLOV**

**Ocena efektivnih doz radona, ki temeljijo na različnih merilnih tehnikah**

**IZVLEČEK**

V svoji magistrski nalogi sem se osredotočila na radon v 43 zgradbah različne namembnosti (23 šol, 3 vrtci, 16 pisarn in stanovanjska hiša), kjer so predhodne meritve pokazale povišane koncentracije.

Izvedla sem meritve radona in radonovih kratkoživih produktov in pri tem sočasno uporabila različne merilne tehnike. V vseh 43 zgradbah sem izmerila trenutno koncentracijo radona s scintilacijskimi celicami, v 18 zgradbah dodatno tudi povprečno koncentracijo z detektorji jedrskih sledi in v 10 zgradbah retrospektivno koncentracijo z detektorji jedrskih sledi. V štirih izbranih zgradbah (šola, vrtec, pisarna, stanovanjska hiša) sem izvedla meritve z vso razpoložljivo opremo. Dnevno spreminjanje koncentracije radona in radonovih kratkoživih produktov sem spremljala s kontinuirnimi merilniki v 14 zgradbah in tako dobila faktor radioaktivnega ravnotežja (ravnotežni faktor) med radonovimi kratkoživimi produkti in radonom. Na osnovi dobljenih rezultatov sem ocenila efektivne doze. Kot osnovo za izračun doz sem uporabila izmerjene trenutne in povprečne koncentracije radona ter ravnotežni faktor iz literature (0.40) ali meritev. Doze sem primerjala med seboj in jih kritično ocenila.

Za razliko od dosedanjih raziskav, sem radon preiskovala izključno na področjih s povečanim tveganjem. Študirala sem vpliv delovnega režima na koncentracijo radona v različnih delovnih okoljih (šola, vrtec, pisarna).

**KLJUČNE BESEDE**

Radon, radonovi kratkoživi razpadni produkti, merilne tehnike, scintilacijske celice, detektorji jedrskih sledi, retro detektorji, ravnotežni faktor, dozni pretvorbeni faktor, efektivna doza, primerjava.

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# 1. INTRODUCTION

Cosmic and terrestrial radiation are the two main sources of natural radioactivity, which contributes to the major part of the dose received by a human being from different sources of ionizing radiation. Terrestrial radiation is an outcome of the following radionuclides in the Earth crust: $^{40}$K, $^{87}$Rb, $^{238}$U, $^{235}$U and $^{232}$Th. The decay chain of $^{238}$U contains fourteen and of $^{232}$Th eleven significant radionuclides, respectively, which contribute to terrestrial radiation. The most important are radon isotopes and their progeny: radon ($^{222}$Rn) with short lived products ($^{218}$Po, $^{214}$Pb, $^{214}$Bi and $^{214}$Po) formed in the uranium ($^{238}$U) decay chain and thoron ($^{220}$Rn) with its progeny ($^{216}$Po, $^{212}$Pb, $^{212}$Bi in $^{212}$Po), formed in the thorium (Th) decay chain. On world average, these radionuclides contribute about half to the annual effective dose (about 1.2 mSv of the total 2.4 mSv) a member of the general public receives from all sources of ionizing radiation (UNSCEAR, 2000). The contribution of toron and its products is usually less than 10 %.

Due to alpha, beta and gamma radioactive transformations of radon and its progeny (RnDP) in the respiratory tract, where they release high amount of energy, breathing in air causes damage to sensitive lung tissue. Especially harmful are alpha rays, which have the highest energies (around 6 MeV) and are absorbed in the tissue at a distance of 40–70 μm. Long-term exposure to increased concentrations of radon and its progeny are a major cause of lung cancer (Doll, 1992), second only to cigarette smoking. A comprehensive European epidemiological study indicates that radon in homes cause 9 % of deaths from lung cancer and 2 % of all deaths from other cancers (Darby et al., 2006).

Although natural radionuclide radon may be present everywhere in the environment, its highest concentrations are usually found in soil gas. Radon is formed in bedrocks and soils by the radioactive transformation of radium ($^{226}$Ra) in the decay chain of uranium ($^{238}$U). As a gas, radon may escape from mineral grains and migrate through the media (soil gas or water) towards the Earth's surface, dissolved either in water or in carrier gases (e.g. $CO_2$, $CH_4$ and $N_2$) (Etiope and Martinelli 2002). When it reaches the surface, radon dilutes very rapidly with

Earth's atmospheric air. By contrast, in closed underground cavities (karst caves, mines, tunnels) and buildings (rooms in cellars and ground floors of living and working environments), which are usually poorly ventilated, radon may accumulate. In such places radon may reach high concentrations. Due to a large number of various parameters that influence radon and it progeny concentrations in a room, radon is a very complex problem and currently existing physico-mathematical models are not reliable enough to predict radon concentration and replace measurements. Parameters that determine radon concentration and its fluctuations in living or working environments may be divided into two groups. The first group includes natural factors, such as the geological composition and structure of the ground, as well as climate and microclimate conditions. In the second group are factors influenced by human activities, such as the quality of building construction and living or working patterns (e.g. room ventilation, air conditioning).

Consequently, measurements are still the basis for dose estimates of population and risk assessments, caused by exposure to radon and its progeny. Measurements need to be carried out systematically (EC, 2005), with an emphasis on geology (lithology and pedology) of the area examined and on an appropriate choice of measurement techniques and instruments.

Slovenia started systematic radon survey in living and working environments in 1990 within the Slovenian national radon programme. In the period from 1990 to 1994, radon concentrations were measured in the air of all 730 kindergartens (Vaupotič et al., 1994), 890 elementary schools and 1000 randomly selected dwellings (Vaupotič et al., 2000). These data provided basic information about the radon problem in the country and have served as a basis for further activities. Over the following years radon was examined in 123 kindergartens and schools (Kobal et al., 1997; Vaupotič, 2003; Vaupotič, 2010; Vaupotič, 2011) where radon concentration exceeded 400 Bq $m^{-3}$, the Slovenian radon limit value (Ur. L. RS, 2002; Ur. L. RS, 2004a). The most recent study was carried out in the period 2011/2012 in 400 dwellings distributed within a regular grid of 7 km × 7 km (Vaupotič et al., 2013a). Taking into account all results of the measurements so far,

increased radon concentrations (> 400 Bq $m^{-3}$) may be expected in about 8 % of buildings in Slovenia (Popit and Vaupotič, 2002). Increased radon could be ascribed mostly on the geological foundation with porous bedrocks with high permeability (e.g. carbonates).

Since 1990 radon has been examined in about 4000 homes and workplaces in Slovenia (Humar et al., 1992; Vaupotič et al. 2013a). The results have been used to identify radon-prone areas. It was found that increased radon may be expected in the southern part of the country (e.g. Kočevje, Novo mesto, Idrija, Sežana regions).

However, knowing radon concentrations in the environment is only the first step in the identification of the radon problem and is usually followed by risk assessment of the target population. This research is known as radon dosimetry and is very complex and specific. Namely, the radon dose received by a lung tissue cannot be measured; it may be estimated by applying dosimetric models. Using a dosimetric model enables the estimation of the effects of radiation on cells, taking into consideration structure of the respiratory system, mechanisms of radioactive aerosols depositions, its clearance from lung and physiological factors. The outcome of the model calculations is the dose conversion factor, a crucial parameter for dose calculations besides radon progeny concentration in inhaled air. It is evident that radon dosimetry is very complex and thus still under development.

Radon progeny (RnDP) are present in the air as nanoparticles in a range up to 10 nm (called nano RnDP or unattached RnDP) and as radioactive particles ranging from 200 to 600 nm (called attached RnDP). The ratio of unattached-attached RnDP depends on microclimatic factors: air temperature and relative humidity, number concentration and size distribution of aerosols, air movement and human activities in the room. During inhalation, unattached and attached RnDP deposit along the airways in the respiratory tract. With applying complementary measurements, the international radon society tries to bring in some new knowledge about dependence of radon and its progeny on different factors, mentioned above, in various environments. This research is very important and may improve radon dosimetry.

My research was focused on radon in schools and some workplaces (health care centres, community buildings, police stations, post offices, and railway and bus stations). First I carried out measurements of radon and its progeny through applying various active and passive complementary measurement techniques. Instantaneous radon concentrations were measured by scintillation cells, while average radon concentrations were measured by solid state nuclear track detectors and retro detectors. In my research, retro detectors were used for the first time in Slovenia. Daily variations of radon and its progeny were measured by continuous devices, which enabled me to calculate equilibrium factor, the ratio between radon progeny and radon. Results of above listened measurements have served me as input data for dose calculations. The basic data were instantaneous and average radon concentrations, as well as the calculated or literature-based equilibrium factor. The doses obtained on the basis of concentrations, measured with different methods, have been compared and critically evaluated. Contrary to previous studies, I took into account target population on selected areas where increased risk for radon was expected. I have studied the influence of working regime to radon and radon progeny concentrations in different working environments.

# 2. THEORETICAL BACKGROUND

## 2.1. Physico-chemical properties of radon and its progeny

Radon gas is formed in the Earth's crust by the radioactive decay of radium ($^{226}$Ra) in the decay chain of uranium ($^{238}$U), thorium ($^{232}$Th) and actinium ($^{235}$U) (Figure 1). It has three isotopes with masses of 222, 220 in 219 ($^{222}$Rn, $^{220}$Rn, $^{219}$Rn), which are called radon, thoron and actinon. Their properties are defined in Table 1.

The half-life ($t_{1/2}$) of $^{222}$Rn is 3.83 days, which allows radon to migrate by diffusion and convection from deeper layers into the atmosphere despite radioactive decay. Since thoron and actinon have shorter half-lives than radon, they mostly decay in the Earth's crust and do not rise to the surface. Therefore, unless provided otherwise, I always mean $^{222}$Rn when I talk about radon. Radon is radioactive and decays further into polonium ($^{218}$Po and $^{214}$Po), lead ($^{214}$Pb) and bismuth ($^{214}$Bi), which are also radioactive. They are called short-lived radon decay products or radon progeny (RnDP). $^{220}$Rn (thoron) also has two short-lived decay products – the alpha-emitters $^{216}$Po and $^{212}$Po, both of which are very short-lived, and two beta-gamma emitters, $^{212}$Pb and $^{212}$Bi. $^{219}$Rn (actinon) is found in the air only in exceptional circumstances, because it has an extremely short half-life and already decays in the Earth's crust into its decay products.

Upon formation, radon decay products are free atoms, but they quickly recombine on dust particles and aerosol particles, and deposit to the ground surface, the walls or objects in closed spaces (Figure 2). Therefore, in the air, or outside or in closed spaces, the short-lived radon decay products are not in radioactive equilibrium with radon. With regard to the microclimatic conditions in closed spaces, this equilibrium is from 0.3 to 0.8, whilst in living spaces it is around 0.4 (UNSCEAR, 2000).

Radon and its short-lived products are measured in Bq $m^{-3}$. The unit is usually presented as concentration, although it would be more accurate to talk about activity concentration.

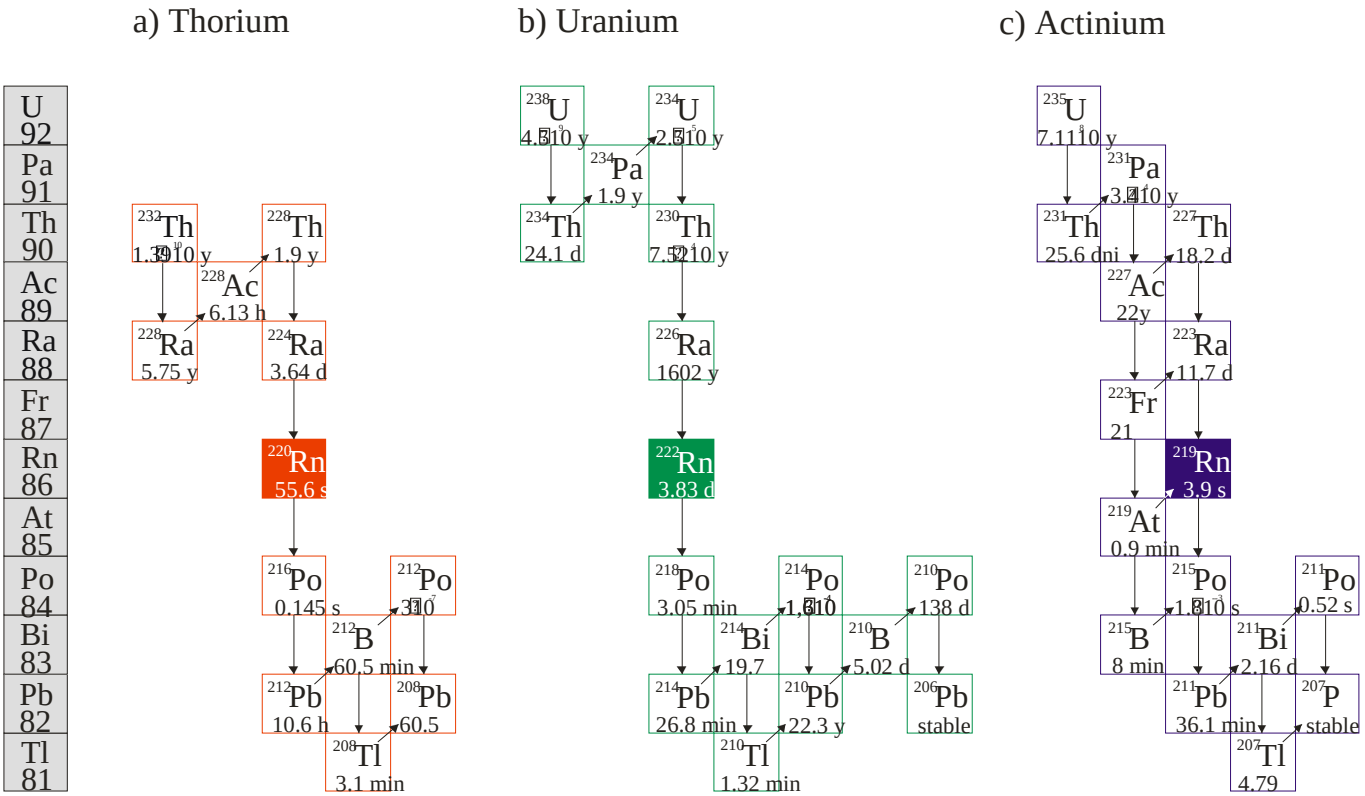


***Figure 1:*** *Decay chains of a) thorium ($^{232}$Th), b) uranium ($^{238}$U) and c) actinium ($^{235}$U)*

The formation of radon products is graphically presented in Figure 3. As can be seen in Figure 1, after approximately three hours a radioactive equilibrium is established between radon and its short-lived decay products. This means that during this time we get from 1 Bq of the initially present radon 1 Bq of each of its short-lived decay products. Therefore, from the initial 1 Bq of alpha-emitters ($^{222}$Rn), we get a total of 3 Bq alpha-emitters ($^{222}$Rn and $^{218}$Po).

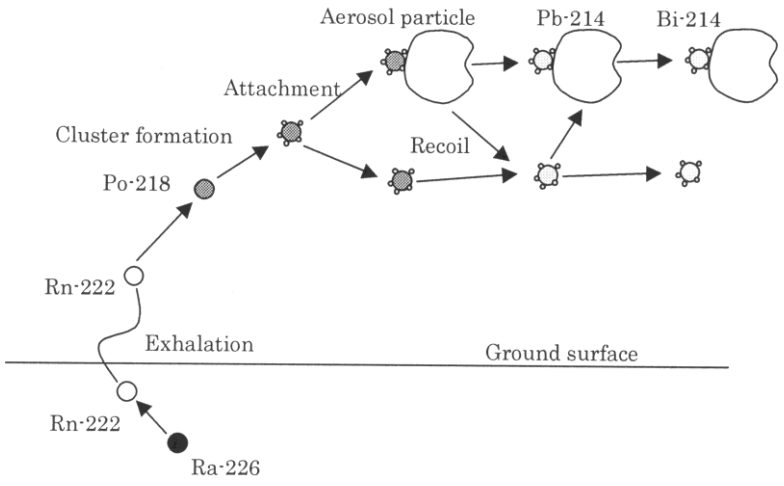


***Figure 2:*** *Schematic view of radon progeny in attached and unattached form (Porstendörfer, 1993)*

***Table 1:*** *Properties of radon, thoron, actinon and their progeny*

| ***Radionuclide*** | ***Half-life*** | ***Type of radiation and energy (MeV)*** | | |
|---|---|---|---|---|
| | | ***alpha*** | ***beta*** | ***gamma*** |
| ***Radon*** | | | | |
| ***$^{222}$Rn*** | *3.825 d* | *5.4897* | | |
| *$^{218}$Po* | *3.05 min* | *6.0026* | | |
| *$^{214}$Pb* | *26.8 min* | | *0.67*<br>*0.73* | *0.2952*<br>*0.3520* |
| *$^{214}$Bi* | *19.7 min* | | *1.51*<br>*1.54*<br>*3.17*<br>*3.27* | *0.6094*<br>*1.1204* |
| *$^{214}$Po* | *163.7 µs* | *7.6869* | | *1.7645* |
| *$^{210}$Pb* | *22.3 y* | | *0.017*<br>*0.061* | |
| *$^{210}$Bi* | *5.013 d* | | *1.161* | |
| *$^{210}$Po* | *138.376 d* | *5.3044* | | |
| ***Thoron*** | | | | |
| ***$^{220}$Rn*** | *55.6 s* | *6.2883* | | |
| *$^{216}$Po* | *150 ms* | *6.7785* | | |
| *$^{212}$Pb* | *10.64 h* | | *0.331*<br>*0.569* | *0.2386*<br>*0.3001* |
| *$^{212}$Bi* | *60.6 min* | *6.051*<br>*6.091* | *2.251* | *0.7271* |
| *$^{212}$Po* | *0.298 µs* | *8.7844* | | |
| *$^{208}$Tl* | *3.053 min* | | *1.796*<br>*1.28*<br>*1.52* | *0.5106*<br>*0.5831*<br>*2.6146* |
| ***Actinon*** | | | | |
| ***$^{219}$Rn*** | *3.96 s* | *6.425*<br>*6.5531*<br>*6.8193* | | *0.2711*<br>*0.4017* |
| *$^{215}$Po* | *1.78 ms* | *7.3136* | | |
| *$^{211}$Pb* | *36.1 min* | | *1.38* | *0.4049*<br>*0.427*<br>*0.8319* |
| *$^{211}$Bi* | *2.14 min* | *2.279*<br>*6.623* | | |
| *$^{207}$Tl* | *4.77 min* | | *1.43* | *0.8972* |

The concentration of short-lived radon decay products is often provided as the total alpha energy concentration contributed by short-lived radon decay products during their radioactive decay. For this purpose, the unit *WL* (Working Level) was introduced. It was deduced from the concentration of radon then allowed in mines: 3700 Bq $m^{-3}$ (100 pCi $l^{-1}$). Assuming that there would be a radioactive equilibrium

between radon and its short-lived decay products in the air of the mine, the concentrations of an individual product would be even 3700 Bq $m^{-3}$, which represents $1.284\times10^5$ MeV of alpha energy per litre of air. The data for the definition of the unit are collected in Table 2. In the table, the energies for $^{214}$Pb and $^{214}$Bi are in brackets, because these are two short-lived radon decay products, beta-gamma emitters. They decay through $^{214}$Po and emit alpha energy during this decay (Robkin, 1987).

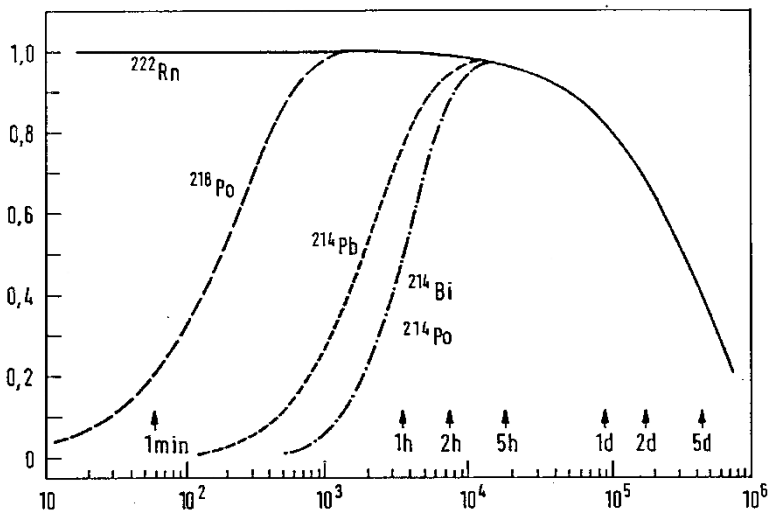


***Figure 3:*** *The speed of growth and decay of short-lived radon decay products in the initial pure sample of radon*

***Table 2:*** *Data for the definition of the unit WL: concentrations for each of the products are 3700 Bq $m^{-3}$; $N_i$ is the number of atoms of the decay product* i *with activity of 3700 Bq $m^{-3}$. $E_\alpha$ is alpha energy with the decay of 1 atom of the decay product* i

| ***Radionuclide*** | $t_{1/2}$ ***s*** | $N_i$ | $E_\alpha$ ***MeV*** | $N_i$–$E_\alpha$ $10^5$ ***MeV*** |
|---|---|---|---|---|
| $^{218}$*Po* | *187* | *996* | *13.69* | *0.136* |
| $^{214}$*Pb* | *1608* | *8583* | *(7.69)* | *0.660* |
| $^{214}$*Bi* | *1188* | *6342* | *(7.69)* | *0.488* |
| $^{214}$*Po* | *0.0002* | *0.001* | *7.69* | *< 0.001* |
| ***total*** | | | | *1.284* |

Although the radioactive equilibrium has never been achieved, if we measure the concentrations of decay products and calculate their alpha energies per litre of air, we calculate the *WL* by using the following equation:

$$WL = \frac{13.69 * n^{218}\mathrm{Po} + 7.69 * (n^{214}\mathrm{Po} + n^{214}\mathrm{Bi})}{1.284 * 10^{5}} \quad (1)$$

For comparison and conversion of concentration of radon and concentration of short-lived radon products, two quantities have been implemented. The first one is *F* (equilibrium factor) and the second is EEC (equilibrium equivalent concentration). *F* is defined with the following equation:

$$F = \frac{0.136 * C^{218}\mathrm{Po} + 0.660 * C^{214}\mathrm{Pb} + 0.488 * C^{214}\mathrm{Bi}}{1.284 * C_{\mathrm{Rn}}} \quad (2)$$

and is in the following connection with the concentration provided in *WL*:

$$WL = \frac{F * C_{\mathrm{Rn}}}{100} \quad (3)$$

The equilibrium equivalent concentration of radon (*EEC*) is defined through the concentration of radon in the air ($C_{\mathrm{Rn}}$) with the following relation:

$$EEC = F * C_{\mathrm{Rn}} \quad (4)$$

or from the equation (2):

$$EEC = 0.106 * C^{218}\mathrm{Po} + 0.514 * C^{214}\mathrm{Pb} + 0.380 * C^{214}\mathrm{Bi} \quad (5)$$

Thus the equations (2) and (5) allow us to compare the concentrations of radon and short-lived radon decay products in various units.

## 2.2. Radon in environment

When we talk about radioactivity in the living environment, we think of the concentration of radon and its short-lived decay products in the air, as well as the gamma radiation emitted from the walls.

The majority of radon gas is formed from radium ($^{226}$Ra) in mineral grains of soils and rocks in the Earth crust. When radium atom decays, an alpha particle is ejected and the newly formed radon atom recoils in the opposite direction. Alpha recoil is the most important factor affecting the release of radon from mineral grains. To a lesser extent, radon migrates from the place of origin into the space between particles by diffusion and is released into the atmosphere. Emanation of radon from the soil into the interstice depends on radium concentration (from 20 to 50 Bq $kg^{-1}$), emanation coefficient, soil porosity and the differences in air pressure. The emanation coefficient is the quantity which tells us what share of the formed radon atoms may ecsape from mineral grains into the space between the particles. It can be in the range from 0.01 to 0.80 (UNSCEAR, 2000; NCRP, 1984). The average speed of emanation from soil is 0.016 Bq $m^{-2}$ $s^{-1}$ (UNSCEAR, 2000).

The Earth's crust is the richest source of radon. Since its geological composition is very varied (the presence of uranium, thorium and actinium decay chain), the concentration of radon may be very different in different parts of soil, but usually it is from 7 to 220 kBq $m^{-3}$ (Sextro et al., 1987). Radon thus contaminates ground air which is in equilibrium with outdoor air. Outside, radon is diluted very quickly with the Earth's atmospheric air – its average concentration in outdoor air varies between 5 and 15 Bq $m^{-3}$, in the littoral area even lower (UNSCEAR, 2000).

In the Earth's crust, radon comes into contact with groundwater in which it dissolves (solubility in water is 230 $cm^3$ $kg^{-1}$ at temperature of 293 K and pressure of 101.3 kPa). In groundwater, radon is usually present in high concentration. In Finland, they measured a concentration of around 25 kBq $m^{-3}$ (Salonen, 1988) in tap water, whilst in well water it was even 460 kBq $m^{-3}$ (Vesterbacka et al., 2005). In Slovenia, these values are lower, usually around 1 kBq $m^{-3}$. In surface waters and rainwater, the

concentrations of radon are usually much lower and their contribution of radon to the living environment is usually negligible.

Of course radon is present in natural gas and when gas is burning in gas cookers and stoves, radon is released into air. In the United States of America, the concentrations are from 40 to 4000 Bq $m^{-3}$ (U. S. EPA, 1973). In Slovenia, the concentration of radon in natural gas was measured in the Ljubljana region – the concentration was just around 60 Bq $m^{-3}$ and this contribution to the overall concentration of radon is negligible.

We also know sources of radon which are connected with technological activity. These are mostly uranium mines, phosphate-processing plants and thermal power plants. With all of the aforementioned activities, huge amounts of waste are produced which are deposited to dumping grounds, or companies attempt to find further uses for them. Both tailings and processed ore from uranium mines are deposited to well-fortified dumping grounds from which radon emanates. Fly ash from thermal power plants can also be deposited or used as a foundation for motorways and for filling abandoned mineshafts. Moreover, in the 1970's, fly ash and slag were used as additives to construction materials. Because this material contains more radium, even up to 300 Bq $kg^{-1}$, we can find higher concentrations of radon in the air of apartments built from this kind of so colled fly ash brick.

Phosphorus plaster, which is created as solid waste during phosphate processing, has in most cases (depending on the phosphate and technological processes involved) an average content of radon of around 27 Bq $kg^{-1}$. Consequently, the production of construction elements (plates) from this material has been mostly abandoned to avoid unduly increasing the concentration of radon in living environments.

All of the aforementioned sources of radon may affect its concentration in buildings. The contribution of radon emanating from the walls is small and the contribution due to water and gas can in most cases be ignored. The air, enriched with radon, is constantly diffused from the soil into the atmosphere. This process depends on the pressure time gradient: with a negative gradient, the emanation of radon is higher.

Radon enters into the living spaces through cracks and openings in the concrete floor slab, through the contact edges between the foundation and the walls, through sewage openings and poorly sealed plumbing/water installations.

According to assessments of the Commission of the European Community, radon emanating from construction materials is in 10 – 20 % of cases the main reason for increased concentrations of radon in residential spaces. They also assess that construction materials cannot be the main reason for higher concentrations of radon in places where the average annual concentrations exceed 400 Bq $m^{-3}$ (CEC, 1987). Although construction materials do not significantly affect the concentration of radon in living spaces, they can nevertheless increase it in some cases. Therefore, it is very sensible to be cautious when choosing construction materials.

During the colder months of the year, the concentrations of radon are usually two to three times higher than during the summer months. Since radon from the soil contributes the most to the overall concentration, it is understandable that the highest concentrations of radon can be found in the basements. Not only because of high concentrations of radon in the soil and its emanation into the basement, but especially because these spaces are usually poorly ventilated. From here, radon emanates into the higher floors, usually along the poorly sealed installations and the staircase. Figure 4 shows how radon enters a building.

***Figure 4:*** *Common radon entry points (U. S. EPA, 2001)*

Four main factors drive radon entry into homes. All of these factors exist in most homes (U.S. EPA, 2001):

- Uranium and radium contain present in soil;
- Soil permeability (high enough to allow soil air to migrate into the home through the slab into cellar);
- Presence of pathways for the radon to enter the cellar (such as small holes, cracks, plumbing penetrations or sumps);
- An air pressure difference between the basement and the surrounding soil draws radon into the home.

The living habits of people significantly affect the concentration of radon in the living environment. Ventilation of rooms is very important with higher concentrations of radon in the living space, because we can maintain a low enough concentration of radon with regular and frequent enough ventilation. A word of caution, though, because during the winter months, with temperature inversions and when the air pressure is falling it may happen that the concentrations in outdoor air are even higher than indoor concentrations. In such cases, ventilation can be harmful rather than beneficial.

In addition to the increased concentration of radon, we may also have increased gamma radiation which emits from the walls. Natural materials such as stone and clay brick can contain higher concentrations of certain radionuclides. Moreover, in recent times new materials have been used, such as aerated concrete, clay pellets and phosphorus plaster panels, in which higher concentrations of certain natural radionuclides can be found due to technological processes. Gamma radiation also increases if the walls are painted with radon-proof paint (to reduce the concentration of radon in the room), because this keeps radon and its products, i.e. gamma emitters, in the wall.

### 2.2.1 Delineating and reporting radon levels

In their national radon regulations, most countries use the European recommendation of the annual mean indoor concentration 400 Bq $m^{-3}$ in existing buildings and 200 Bq $m^{-3}$ for new constructions. That levels should not be exceeded and serve as reference for defining radon risk maps. As recommended by the UK, the criterion for identifying radon areas is frequently considered to be those where the number of dwellings with concentrations higher than 200 Bq $m^{-3}$ exceeds 1 % (EC, 2005).

To find out indoor radon concentrations and to identify radon-prone areas, the majority of the European countries have carried out national radon programmes. Unfortunately there is still no common protocol available for radon survey and therefore each country is trying to find out the best way to establish a high quality and cost-effective radon programme (e.g. building type, location selection, measurement technique, duration of measurements). The greater part of measurements is usually carried out in dwelling and workplaces (e.g. kindergartens, schools, offices, hospitals, health care centres).

National sampling efforts for monitoring radon and statistics for the European radon surveys in dwellings are collected in Table 3 (EC, 2005). As seen in Table 3, the highest average annual radon concentrations, those exceeding 100 Bq $m^{-3}$, have been found in the Czech Republic, Finland, Luxembourg, Serbia–Montenegro, Slovakia and Sweden. For Slovenia, an annual radon average of 87 Bq $m^{-3}$ is reported. So far, the highest number of measurements has been carried out in Sweden, the United Kingdom and the Czech Republic. The percentage of buildings with radon concentration exceeding 400 Bq $m^{-3}$ is reported to be from 0 to 11, with the highest value in Slovakia (Table 3).

***Table 3:*** *Results of radon surveys and statistics in the European countries (EC, 2005)*

| ***Country*** | ***Population ($\times 10^6$)*** | ***Number of dwellings monitored*** | ***Estimated annual mean levels in Bq $m^{-3}$*** | ***% of dwellings >200 Bq $m^{-3}$ and <400 Bq $m^{-3}$*** | ***% of dwellings >400 Bq $m^{-3}$*** |
|---|---|---|---|---|---|
| *Austria* | *8.2* | *16 000* | *97* | *8* | *4* |
| *Belgium* | *10.4* | *9 000* | *48* | *1.7* | *0.3* |
| *Croatia* | *4.5* | *782* | *68* | *5.4* | *1.8* |
| *Cyprus* | *0.8* | *84* | *19* | *0* | *0* |
| *Czech Republic* | *10.2* | *150 000* | *140* | *10-15* | *2-3* |
| *Denmark* | *5.4* | *3 120* | *53* | *2.7* | *0.2* |
| *Estonia* | *1.3* | *515* | *60* | *2-2.5* | *0.2* |
| *Finland* | *5.2* | *73 074* | *120* | *8.7* | *3.6* |
| *France* | *60.7* | *12 261* | *63* | *6.5* | *2* |
| *Germany* | *82.4* | *>50 000* | *50* | *2.5* | *<1* |
| *Greece* | *10.7* | *1 277* | *55* | *2* | *1.1* |
| *Ireland* | *4.0* | *11 319* | *89* | *6* | *1.5* |
| *Italy* | *58.1* | *5 361* | *70* | *3.2* | *0.9* |
| *Lithuania* | *3.6* | *400* | *55* | *2.5* | *0.3* |
| *Luxembourg* | *0.5* | *2 619* | *115* | *NA* | *3* |
| *Malta* | *0.4* | *90* | *40* | *0* | *0* |
| *Netherlands* | *16.4* | *1 846* | *23* | *0.3* | *0* |
| *Norway* | *4.6* | *51 925* | *89* | *6* | *3* |
| *Slovakia* | *5.4* | *4 019* | *108* | *14* | *11* |
| *Slovenia* | *2.0* | *2 512* | *87* | *5.5* | *2* |
| *Spain* | *40.3* | *5 600* | *90* | *4* | *2* |
| *Sweden* | *9.0* | *500 000* | *108* | *6–7* | *3–4* |
| *Switzerland* | *7.5* | *55 000* | *77* | *10* | *7* |
| *United Kingdom* | *60.4* | *450 000* | *20* | *0.4* | *0.1* |

**province of Vojvodina only*
*NA…not available*

### 2.2.2. Overview of radon limits in different countries

Radon concentration limits in living spaces are not uniformly defined in individual countries. Above all, each country takes into consideration its own geological and microclimate characteristics when preparing such recommendations. All of these recommendations are prepared for existing and future buildings. Sweden prepared concentration limits very early; for houses the concentration limit is set at 200 Bq $m^{-3}$ and for future buildings at 200 Bq $m^{-3}$. The United Kingdom, Ireland and Denmark have the same concentration limits. In Germany, concentration limits are stricter at 100 Bq $m^{-3}$ for existing and future buildings, whilst in Switzerland the concentration limits are much higher at 1000 Bq $m^{-3}$ for existing and 200 Bq $m^{-3}$ for future buildings (WHO, 2009). The Environmental Protection Agency of the USA has determined a uniform concentration limit for the existing and future buildings at 150 Bq $m^{-3}$. The International Commission on Radiation Protection (ICRP) recommends that the average annual concentration of radon in the air at home should not exceed 200 to 600 Bq $m^{-3}$ and at workplaces it should not exceed 500 to 1500 Bq $m^{-3}$ (ICRP, 1994).

In Slovenia, the radon concentration limit is 400 Bq $m^{-3}$ for existing and 200 Bq $m^{-3}$ for future buildings. The same action level values are in use in Austria, the Czech Republic and Lithuania (WHO, 2009). In Slovenia, the systematic inspection of working and living environments is set out in Article 45 of the Ionising Radiation Protection and Nuclear Safety Act (Ur. L. RS, 2004a). The rules on the ventilation and air-conditioning of buildings also set out the concentration of radon, stipulating that the average annual concentration of radon allowed in residential buildings is 400 Bq $m^{-3}$, with an additional recommendation of only 200 Bq $m^{-3}$ (Ur. L. RS, 2002). Rules on the conditions and methodology for estimating doses in the ionising radiation protection of workers and the population in Article 9 categorises the effective doses for natural radiation and radiation from artificial sources (Ur. L. RS, 2004b).

International organizations (IAEA - International Atomic Energy Agency; WHO - World Health Organization) recently proposed a lower limit value for radon, i. e.,

300 Bq $m^{-3}$ (IAEA, 2013), and this recommendation will be soon followed also by Slovenia.

## 2.3. Radon dosimetry

Humans receive approximately 2.4 mSv of a total effective dose from natural sources of ionising radiation per year. The most – no less than 1.34 mSv – is contributed by radionuclides of uranium decay chain, wherein concentration of radon and short-lived radon decay products contribute around 1.2 mSv. Radionuclides of thorium decay chain contribute 0.34 mSv, of which thoron with decay products contributes approximately 0.16 mSv. Outdoor radiation (especially gamma radiation) contributes significantly, with $^{40}K$ to the total annual dose of around 0.33 mSv. All of the aforementioned data refers to the areas with normal radioactivity. Gamma radiation and cosmic radiation are distributed rather evenly along the entire Earth's surface, whilst the presence of radionuclides of uranium and thorium decay chain varies greatly. Thus we have many parts of the world, for example the Scandinavian countries and certain regions of China, Iran, India and the United States, where the population receives much higher doses.

Radon enters into our bodies through inhalation. Since radon is a gas, we also exhale it together with the air and because of its relatively long half-life only a smaller number of radon nuclei decay inside the lungs. Therefore, the contribution of radon to the entire dose due to breathing is small. Its decay products are metals and are present in the air either as free atoms (to a lesser extent) or bound to aerosols (Wilkening and McNamee, 1988). When breathing, the lungs retain these products and in places where they deposit and decay, they damage the nearby tissue with alpha, beta and gamma rays (UNSCEAR, 2000; BEIR, 1988; Jacobi, 1988). The alpha rays are especially dangerous for the tissue, because the greatest amount of energy is released during the alpha decay (Table 1) at a distance of only a few millimetres. The most dangerous decay products for lungs are therefore $^{218}Po$ and $^{214}Po$, both of which are alpha emitters. How deep into the respiratory tract radon

products enter depends on whether they are free atoms or attached to aerosols, as well as on their size (Bodansky et al., 1987; Harley, 1988) (Figure 5).

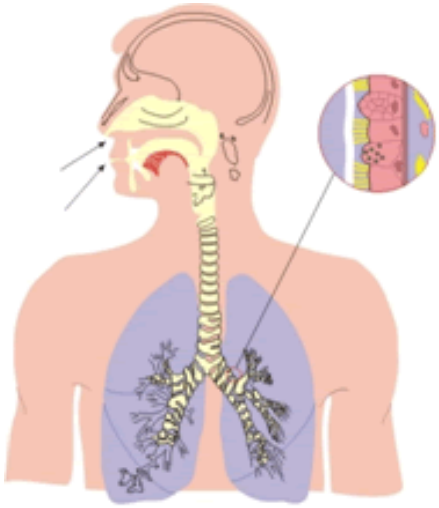

***Figure 5:*** *Schematic view of radon and its progeny inhalation and deposition in lungs*

We cannot measure the dose received by the lung tissue. We can only assess it with the aid of model research. In the dosimetric model, we can assess the effects of radiation on cells by taking into account the structure of the respiratory tract, the mechanisms of deposition of aerosols, their removal and physiological parameters of breathing. We present them as dose conversion factors (*DCF*). Several dosimetric models have been developed, but their assessments of doses often differ. Current research focuses mostly on finding a general model which would satisfactorily record what happens in the lungs and assess the effects of radiation on the cells.

### 2.3.1. Methodology of dose calculations

The contribution to the dose of radon itself is negligible in comparison with the contribution of radon products. Therefore, when calculating doses, we use the concentration of short-lived radon decay products. If we measure the concentration of radon, but not of short-lived radon decay products, we calculate the concentration of products by multiplying the concentration of radon with the equilibrium factor. The radiation exposure to radon and its short-lived decay products is expressed as a product of concentration and time of exposure.

The concentration of short-lived radon decay products is often expressed in WL units (see equation 1 and Table 2) due to simplicity and wide use. If a person is exposed to 1 WL concentration of radon for a month (170 hours), we talk about exposure of 1 WLM (working level month). Although these units are not used in Slovenia, they are generally known and I used them in my calculations for practical reasons.

Exposure *E*p is thus defined with the following expressions:

$$\frac{E\mathrm{p}}{\mathrm{Bq\,m^{-3}}} = C * F * t \tag{6}$$

$$\frac{E\mathrm{p}}{\mathrm{WLM}} = \frac{C * F * t}{\frac{3700}{170}} \tag{7}$$

in which:

*C* ..... concentration of radon in the air (Bq $m^{-3}$)

*t* ..... time of exposure – time of breathing radon (h)

*F* ..... equilibrium factor between short-lived radon decay products and radon.

If we multiply exposure with the dose conversion factor (*DCF*), we get a dose. The dose conversion factor primarily depends on the methodology used. In accordance with the methodology from the International Basic Safety Standards 115 (IAEA, 1996) the dose conversion factors for workers are 5 mSv $WLM^{-1}$ (workplaces) and for residents (dwellings) 4 mSv $WLM^{-1}$. I have also used them for calculating doses which are presented in this thesis.

For an accurate calculation of the dose, we ought to know the concentration of radon and the equilibrium factor for each volume of inhaled air. Since this is practically impossible, we mostly help ourselves with the average concentrations of radon and the average values of the equilibrium factor. The averages are different: daily, weekly, monthly and quarterly and depend on the used measurement technique.

I used the instantaneous concentrations of radon for my calculations of doses, measured by using scintillation cells, and the average concentration of radon, measured with solid state nuclear track detectors and retrospective detectors. For the equilibrium factor I used the value of 0.40, which is provided by the International Basic Safety Standards 115 in Table II-II (IAEA, 1996) or equilibrium factors which I calculated from the data of continuous measurements of concentration of radon and its short-lived decay products.

Radiation dose is most often reported as an effective dose. The effective dose is a sum of equivalent doses in all the tissues or organs irradiated, weighted with the tissue weighting factor.

Effective doses have been calculated using the general equation in the form written below:

$$E = C * F * t * cf \qquad (8)$$

where *t*, *C* and *F* have the same meaning as in equations 6 and 7, other quantities stand for:

*cf* ..... conversion factor defined as *DCF*/3700/170
*DCF* ... dose conversion factor in mSv $WLM^{-1}$ (5 in workplace and 4 in dwelling) (IAEA, 1996).

# 3. EXPERIMENTAL WORK

## 3.1. Measurement techniques

The measurement techniques for determining concentration of radon are, in general, based on the following principle. Radon enters together with the air by diffusion (passively) or by drawing (actively) into the space of the detector (precisely determined volume) through a filter which retains the short-lived radon decay products. In the detector we measure radon directly by detecting its alpha rays or indirectly by detecting alpha, beta and gamma rays of its decay products. If we measure radiation of one of the products for which we know the radioactive equilibrium between radon and the short-lived decay product, we can calculate the activity of radon from the activity of this product. Most of the methods are based on measuring alpha radiation, but the measurement techniques greatly differ from one another, especially in terms of duration and sampling.

With most measurement techniques for measuring the short-lived radon decay products, we draw air through the filter to retain the products. We measure the activity on the filter and calculate the concentration of each short-lived radon decay product separately, or of all short-lived radon decay products together.

The most widely and frequently used measurement devices for radon measurements are listed in the Table 4.

***Table 4:*** *Radon measurement devices and their characteristics (WHO, 2009)*

| ***Detector type (abbreviation)*** | ***Passive active*** | ***Typical uncertainty* (%)*** | ***Typical sampling period*** | ***Cost*** |
|---|---|---|---|---|
| *Etched track detector (ETD)* | *passive* | *10 – 25* | *1 – 2 months* | *low* |
| *Activated charcoal detector (ACD)* | *passive* | *10 – 30* | *2 – 7 days* | *low* |
| *Electret ion chamber (EIC)* | *passive* | *8 – 15* | *5 days – 1 year* | *medium* |
| *Electronic integrating device (EID)* | *active* | *~ 25* | *2 days – year(s)* | *medium* |
| *Continuous radon monitor (CM)* | *active* | *~ 10* | *1 hour – year(s)* | *high* |

**uncertainty expressed for optimal exposure duration and for exposure ~200 Bq $m^{-3}$*

Etched track detector (solid state nuclear track detector) technique is usually the first choice for radon detection worldwide. It is assumed that this technique is used in about one third of all measurements (WHO, 2009).

Within my research the following measurement techniques and devices were used:

- Alpha scintillation cells (SC) for instantaneous radon concentration measurements,
- Continuous monitors (CM) for 8 to 14-day long radon and its progeny concentration measurements in a room with the highest radon concentration in each building,
- Etched track detectors (ETD-KfK) for average radon concentration measurements, produced and provided by the KfK Karlsruhe (Germany),
- Etched track detectors (ETD-UFO) for average radon and thoron measurements, provided by the Vinča Institute of Nuclear Sciences, University of Belgrade (Serbia) and produced at the National Institute of Radiological Sciences (Japan),
- Retrospective detectors (RETRO) for average radon concentration measurements produced and provided by the University College Dublin (Ireland).

They are described in the next sub chapters.

### 3.1.1. Alpha scintillation cells (SC)

Alpha scintillation cells, known as Lucas cells (Van Dilla and Taysum, 1955; Lucas, 1957) have been in use for radon measurement for more than half a century. Alpha scintillation method for instantaneous radon concentration measurement is designed on total alpha activity measurement of radon and its short-lived products of polonium ($^{218}$Po in $^{214}$Po) (Figure 3).

In a room where radon is to be measured, an air sample is filled into an alpha scintillation cell and after some time (minimum 3 hours, when radioactive equilibrium between radon and its short-lived products is reached), its activity is measured in an alpha scintillation counter in the laboratory. When alpha particles created by radioactive transformations of radon and its products hit zinc sulphide scintillator layer in the scintillation cell, 600 nm light is emitted. Light flashes are transformed into electrical signals and multiplied by a photo multiplayer tube, to be counted by the electronics of the scintillation counter. Based on calibration, radon concentration is calculated.

In my research, scintillation cells (Vaupotič et al., 1992) and scintillation counter PRM-145 (AMES, Slovenia) were used (Figure 6).

a) b)

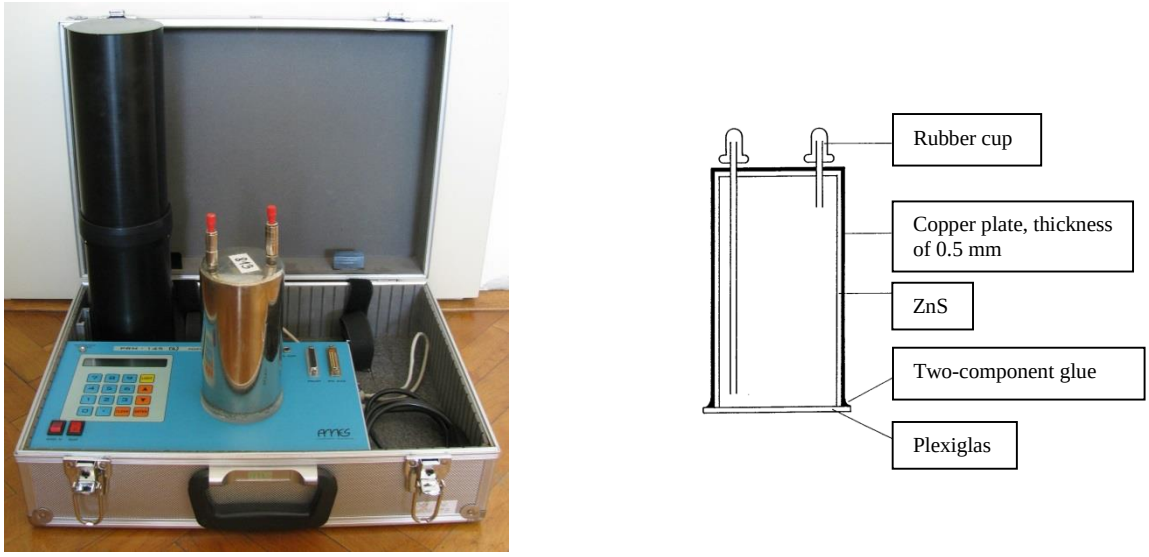


***Figure 6:*** *Alpha scintillation cell: a) alpha scintillation cell with PRM-145 alpha scintillation counter, b) schematic view of alpha scintillation cell*

Scintillation cells have been calibrated indirectly, using glass scintillation cells calibrated by the standard solution of radium chloride (NIST-SRM no. 4966) (Rushing et al., 1964; Kristan and Kobal, 1973). Cell constants (efficiency) are around $2\times10^{-3}$ $s^{-1}$ $Bq^{-1}$ $m^3$ and their backgrounds about 3 $min^{-1}$; with 30 minute counting, the lower limit of detection of 15–30 Bq $m^{-3}$ (Vaupotič et al., 1992) is obtained.

### 3.1.2. Instruments for continuous monitoring (CM)

#### 3.1.2.1. Radon Thoron Monitor RTM 1688-2

RTM 1688-2 (Sarad, Germany) is an active portable continuous monitor for radon and thoron, which can draw 0.5 or 2 l of air per minute. Radon enters along with the air the measuring chamber through a filter which filters out the short-lived radon decay products. The chamber contains a semi-conductor detector under high negative voltage, so that positive ions $^{218}$Po (from $^{222}$Rn) and $^{216}$Po (from $^{220}$Rn), are deposited on it, which are created in the chamber from $^{222}$Rn or $^{220}$Rn. The frequency of sampling and analysis can be set at once per minute to once per hour. The measurement range is from 2 Bq $m^{-3}$ to 10 MBq $m^{-3}$ (Figure 7).

***Figure 7:*** *Radon Thoron Monitor RTM 1688-2*

3.1.2.2. Radon and radon decay product monitor EQF-3020 and EQF-3020-2

EQF 3020 and EQF 3020-2 (Sarad, Germany) are active instruments which, in addition to the concentration of radon in the air, also measure the concentration of short-lived radon decay products in unattached and attached form, the equilibrium factor, the temperature and relative humidity of the air (Figure 8).

***Figure 8:*** *Radon and radon progeny monitor EQF-3020-2*

The air enters into the measuring chamber of the instrument at the speed of 2.4 l $min^{-1}$ through the glass fibre filter (diameter of 12 mm and 1 μm of effective porosity), which retains the attached fraction of short-lived radon decay products. The unattached fraction of short-lived radon decay products is caught by the wire mesh (diameter of 12 mm), which spins around the filter. The instrument draws air for 6 minutes every two hours. The air fills the chamber with the volume of 0.25 l, which is where the concentration of radon is measured. After measurement is completed, one measuring head or detector spins across the filter, and the other underneath the mesh. The instrument separately records the concentrations of radon and the short-lived radon decay products and calculates the equilibrium factor *F*.

The measurement range for radon is from 0 Bq $m^{-3}$ to 10 MBq $m^{-3}$ and for unattached and attached short-lived radon decay products it is from 0 to 500 kBq $m^{-3}$.

### 3.1.3. Etched track detectors (ETD)

We measure the alpha activity with a film which is sensitive to alpha particles. Once these particles hit the film, invisible damage to the surface occurs; the film is then etched in an alkaline solution and visible traces occur on the damaged spots which are counted under the microscope. The density of the traces is relative to the average concentration of radon in space in the period of exposure of the detector.

This method for measuring the average concentrations of radon is the most widely used method in the world today and many research groups have developed their own detectors and systems for etching, counting and evaluation of results. The films are produced by companies such as Kodak. Most frequently the cellulose nitrates are used (LR-115), polycarbonates (Makrofol, Lexan) and allyl diglycol carbonates (CR-39) (Urban and Schmitz, 1993). The containers with detectors (the housing of the detector) into which the film is placed are made of different materials, shapes and sizes. Some have a filter through which radon enters into the interior of the detector, while with detectors without filters (made from more porous materials) radon enters the interior of the detector through its entire surface. The role of the detector is to retain the short-lived radon decay products while radon diffuses into the interior of the container with the detector. Processing the film differs in terms of the manner and level of automatisation of systems and depends on the scope of measurements or the number of samples. Etching is chemical and electrochemical, while the side conditions (chemicals, electric field and duration) for the optimal size of traces on the film, which is several μm, is determined by each research group for its system and based on their experience.

In the space where we want to measure the concentration of radon, we expose the detector so that the air can pass through to the detector with the least hindrance.

3.1.3.1. KfK etched track detectors (ETD-KfK)

The etched track detector ETD-KfK (Figure 9) was developed at the "Forschungszentrum Karlsruhe Technik und Umwelt", Karlsruhe, Germany, and they have a fully automated system for film processing. The films are polycarbonate foils with a protected name Makrofol E (Urban and Schmitz, 1993). In a space, they are usually exposed for the period of one to three months.

***Figure 9:*** *Etched track detector ETD-KfK*

3.1.3.2. UFO etched track detectors (ETD-UFO)

Etched track detector ETD-UFO (Figure 10) for the measurement of average radon and thoron concentrations (with the system for etching and evaluation of films) was developed on the National Institute of Radiological Sciences in Chiba, Japan. The system was donated to Institute Vinča from Belgrade, Serbia, approximately 10 years ago and they evaluated our films.

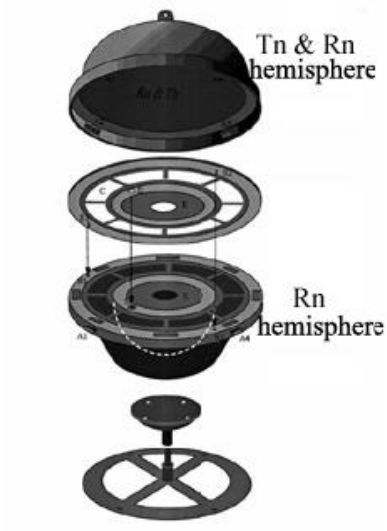


***Figure 10:*** *Etched track detector ETD-UFO (Žunić et al., 2003)*

ETD-UFO detector consists of two ground airs. One polycarbonate film is placed in each hemisphere. In the upper, larger thoron and radon hemisphere, the film detects both radon and thoron with their progenies. The smaller, radon hemisphere is connected to the larger hemisphere through a single pinhole with diameter of 1 mm. Diffusion to the radon hemisphere is small enough to practically prevent thoron from entering the hemisphere because of its short half-life of 55 seconds. Radon with longer half-life of 3.83 days easily enters the radon hemisphere. Therefore, the film in the radon hemisphere detects only radon and its progeny (Žunić et al., 2003). Detectors are usually exposed for the period of one to three months (Žunić et al., 2003).

### 3.1.4. Retrospective radon method (RETRO)

With retrospective methods (retrospective assessment of radon exposure), long-lived radon product polonium ($^{210}$Po) is detected on glass surfaces (surface traps) or in porous materials (volume traps). In my study, the surface retrospective method was used (Figure 11).

It has been long known that radon could give rise to an "active deposit" of its long-lived progeny on surfaces such as glass. Some of this activity absorbed on the surface is removable by cleaning, but some of it is permanently implanted to a maximum depth of approximately 100 nm into the surface of the glass as a result of alpha recoils following the decay of $^{218}$Po and $^{214}$Po. This activity can be monitored through long-lived $^{210}$Pb ($t_{1/2}$ = 22 y) to give information about the previous radon history (McLaughlin, 2001). This gives an alternative or complementary method to the traditional measurements of the current average radon concentration. One limiting factor at low exposure levels is the alpha background activity in the sub-surface material.

The method uses two different etched track detector materials. By exposing one Kodak LR-115 cellulose-nitrate film and one CR-39 detector side-by-side on glass panes, the background of the glass is measured with the LR-115 and both the background and the signal by the CR-39 detector. An exposure of more than 1000 Bq y $m^{-3}$ to a glass surface can be measured with this technique (Falk at al., 1996). Retrospective detectors are usually exposed for three months.

***Figure 11:*** *RETRO detector on the glass of the picture*

## 3.2. Study design

### 3.2.1. Measurements

I chose the buildings included in the research based on the radon map for kindergartens and schools (Vaupotič and Gregorič, 2013) (Figure 12). I carried out measurements in 43 buildings (BU) and researched a total of 49 rooms. In the majority of the buildings selected, higher concentrations of radon were discovered in previous cases of research. These were mostly older buildings with poor quality of construction. As a rule, I chose only one room for measurement per individual building.

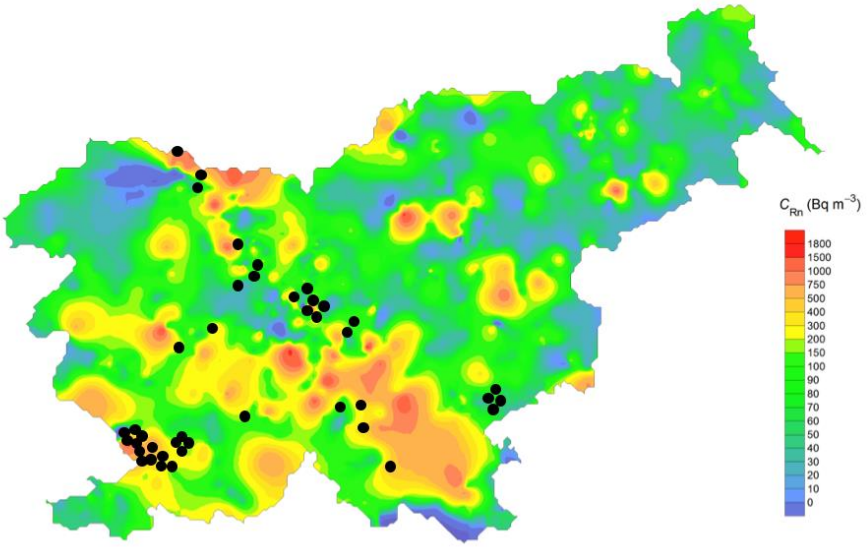


***Figure 12:*** *Radon map of Slovenian kindergartens and schools (Vaupotič and Gregorič, 2013) (locations chosen for measurements in my study marked by dots)*

I coded the names of the buildings. Each code comprises three parts. The first part of the code denotes the purpose of the building: (school (S), kindergarten (K), office (O) and home (H). The second part of the code is the place where the building is located and the third part of the code is the sequence number of the building. In the case of the residential house, where I carried out measurements in several rooms, the last part of the code is the shortened name of the purpose of the

space. With regard to their purpose, I divided the buildings into four sets which are, together with their codes, provided in Table 5.

***Table 5:*** *Codes of schools (S), kindergartens (K), offices (O) and of home (H)*

| ***Codes of buildings*** |
|---|
| ***a) Schools (14 localities, 23 buildings)***<br>*S-LJ-1, S-LJ-2, S-LJ-3, S-LJ-4*<br>*S-KR-1, S-KR-2*<br>*S-NM-1, S-NM-2, S-NM-3, S-NM-4*<br>*S-GR-1, S-GR-2*<br>*S-KO-1*<br>*S-RA-1*<br>*S-RI-1*<br>*S-ST-1*<br>*S-ŠG-1*<br>*S-VL-1*<br>*S-JE-1*<br>*S-KŽ-1*<br>*S-RD-1, S-RD-2*<br>*S-ŠL-1* |
| ***b) Kindergartens (3 localities, 3 buildings)***<br>*K-VL-1*<br>*K-VO-1*<br>*K-ID-1* |
| ***c) Offices (4 localities, 16 buildings)***<br>*O-DI-1, O-DI-2, O-DI-3, O-DI-4*<br>*O-KO-1, O-KO-2, O-KO-3*<br>*O-KZ-1, O-KZ-2, O-KZ-3*<br>*O-SE-1, O-SE-2, O-SE-3, O-SE-4, O-SE-5, O-SE-6* |
| ***d) Home (1 locality, 1 building)***<br>*H-DI-1 (H-DI-1-kit, H-DI-1-liv, H-DI-1-deb, H-DI-1-wor, H-DI-1-gar, H-DI-1-cav1, H-DI-1-cav2)* |

I carried out the following measurements of concentration of radon in the air:

- Measurements of instantaneous radon concentrations using scintillation cells (SC),
- Continuous monitoring (8 to 14 days) of radon and radon progeny concentrations in a room with the highest instantaneous radon concentration using portable continuous monitors (CM),
- Measurements of one-month average radon concentrations using etched track detectors KfK Karlsruhe (ETD-KfK),

- Measurements of one-month average radon and thoron concentrations using etched track detectors Vinča/NIRS institutes (ETD-UFO),
- Measurements of three-month radon average concentration using retrospective detectors of the University College Dublin (RETRO).

However, I did not carry out all of the aforementioned measurements in all of the 43 buildings selected. Table 6 presents a numerical overview of the measurements carried out. The main criteria for selecting buildings for the extended programme of measurements was the highest possible daily occupancy of these spaces.

In all 43 buildings I took air samples to determine the instantaneous concentration of radon by using scintillation cells (SC) in non-ventilated spaces and exposed the ETD-KfK etched track detectors for about a month to determine the average concentrations of radon. In the 14 spaces where I discovered higher instantaneous concentrations of radon, I carried out additional continuous measurements of concentrations of radon and its short-lived decay products for 8 to 14 days in 12 different offices. In the office O-DI-4 I carried out a continuous measurement twice in different seasons. In the 14 buildings with the exposed ETD-KfK detectors I additionally placed the ETD-UFO detectors and in 10 buildings I placed the RETRO detectors. I received the ETD-UFO detectors too late to expose them at the same time as the ETD-KfK detectors and intercompare both methods, so I exposed them approximately 10 days later than the ETD-KfK detectors. I exposed additional detectors in spaces where I expected higher concentrations of radon. Most of the measurements were carried out in October and November 2004; a small percentage of the measurements was carried out in 2005 and 2006.

***Table 6:*** *Summary of analysis in four categories of buildings*

| ***Analysis (abbreviation)*** | ***Sum*** | ***a) School (S)*** | ***b) Kindergarten (K)*** | ***c) Office (O)*** | ***d) Home (H)*** |
|---|---|---|---|---|---|
| *Building (BU)* | *43* | *23* | *3* | *16* | *1* |
| *Room (RO)* | *49* | *23* | *3* | *16* | *7* |
| *Scintillation cell (SC)* | *49* | *23* | *3* | *16* | *7* |
| *Continuous monitor (CM)* | *14* | *8* | *1* | *3* | *2* |
| *Etched track detectors KfK (ETD-KfK)* | *18* | *7* | *1* | *6* | *4* |
| *Etched track detectors UFO (ETD-UFO)* | *14* | *7* | *1* | *6* | *0* |
| *Retrospective detectors (RETRO)* | *10* | *5* | *1* | *4* | *0* |

I placed the detectors on shelves and cabinets, away from the floor and walls. This procedure is required due to thoron, which can be found mostly close to the ground and walls, since it has a shorter half-life than radon. I was interested in the concentration of both gases in the central part of the space, where people are usually located. I placed the ETD-UFO detectors as close as possible to the ETD-KfK detectors. The RETRO detectors were glued to the cleaned glass surfaces (mirrors, paintings).

In my research, I focused on measurements on the ground floor; if the workplace was in the basement, I gave priority to those spaces. As a rule, the concentration of radon is the highest in the basements. I present the measurements with regard to the spaces in Table 7.

***Table 7:*** *Number and percentage of measurements within floors in each category of buildings*

| ***Building*** | ***Cellar*** | ***Ground floor*** | ***First floor*** |
|---|---|---|---|
| *Schools* | *9 (39 %)* | *14 ( 61 %)* | *0 (0 %)* |
| *Kindergartens* | *1 (33 %)* | *2 (67 %)* | *0 (0 %)* |
| *Offices* | *0 (0 %)* | *14 (87.5 %)* | *2 (12.5 %)* |
| *Home* | *3 (43 %)* | *3 (43 %)* | *1 (14 %)* |

I also provide a short description of the buildings in which I carried out the measurements with all of the available equipment.

**School S-RI-1**

The masonry building has a basement and three floors. It was built in 1907. I carried out the measurements in the classroom in the basement. During the school class times, up to 10 children and 1 adult are present in the classroom on a daily basis. During the school class times, the classroom is not ventilated due to dust and noise from outside. Ventilation only takes place during the breaks.

**Kindergarten K-ID-1**

The masonry building does not have a basement, it has one floor and is of an elongated shape. It was built in 1965. The space where I carried out the measurements is regularly ventilated. During the time of daily child care, up to 15 children and 2 adults are present in the space.

**Office O-DI-4**

This is a two-floor masonry building without a basement. It was built in 1850. There are 40 employees in the building and increased concentrations of radon were discovered in 5 rooms where 21 people work. Work in the office takes place in three shifts, also during the weekends.

**Home H-DI-1**

The masonry house has a basement and two floors. Underneath the house there is a karst cave (depth 10 m, length 10 m, width 5 m). A family of four lives in the house and they regularly ventilate the living spaces.

### 3.2.2. Dose calculations

I have calculated the annual effective doses which the employees receive at their workplaces due to the presence of short-lived radon decay products in the air (schools, kindergartens, offices) and the residents in their home.

For calculations of equilibrium doses the following input data have been used:

- Indoor radon concentrations ($C_{Rn}$), measured with various devices (SC, CM, ETD-KfK, ETD-UFO, RETRO),
- Equilibrium factor $F$ between radon progeny and radon, adopted from the literature ($F_L$=0.40) (IAEA, 1996) or measured ($F_M$) by continuous devices,
- Dose conversion factors $DCF$ (5 mSv $WLM^{-1}$ for workplace and 4 mSv $WLM^{-1}$ for dwelling),
- Time, spent in the room provided by users/owners of buildings.

Summary of effective doses calculations is summarized in Table 8. In total, 97 calculations were made using various measurement techniques and two different equilibrium factor approaches: 71 calculations based on an equilibrium factor adopted from the literature ($F_L$) and remaining 26 on an equilibrium factor taken from my own measurements ($F_M$) in four categories of buildings.

***Table 8:*** *Number of effective dose calculations on the basis of radon concentration obtained with SC, CM, ETD-KfK, ETD-UFO and RETRO and equilibrium factor $F_L$ (literature) or $F_M$ (measurements)*

| ***Analysis (Abbreviation)*** | ***Sum*** | ***a) School (S)*** | ***b) Kindergarten (K)*** | ***c) Office (O)*** | ***d) Home (H)*** |
|---|---|---|---|---|---|
| *Effective dose by $F_L$ (E-FL)* | *71* | *36* | *5* | *26* | *4* |
| *Effective dose by $F_M$ (E-FM)* | *26* | *16* | *2* | *4* | *4* |

# 4. RESULTS AND DISCUSSION

I have classified the results into three parts. In the first part, I present the results of the measurements of the instantaneous and average concentrations of radon. In the second part, I present the results of continuous measurements of concentrations of short-lived radon decay products. In the third part, I present the effective doses calculated.

In the four selected buildings (a school, a kindergarten, an office and a residential house) I carried out measurements by using all of the available complementary equipment and calculated the doses based on concentrations measured by using different measuring techniques. These results are discussed for each building separately.

## 4.1. Radon concentrations

The basis of my research was the measurement of radon which I carried out in 43 buildings. The instantaneous concentrations of radon were my orientation for choosing buildings for all subsequent measurements. The average monthly concentrations, which provide more complete information on the concentration of radon in a particular space, presented the basis for the assessment of effective doses. In some cases I supplemented the average concentrations with retrospective concentrations which provide information on radon over a period of several years.

### 4.1.1. Instantaneous radon concentrations

The instantaneous concentrations of radon in schools are presented in Table 9 and for kindergartens and offices in Table 10. Both tables also present the data on the floor and purpose of the building. The instantaneous concentrations of radon in schools were between 30 and 6870 Bq $m^{-3}$ (Table 9), in kindergartens between 41

and 995 Bq $m^{-3}$ and in work environments between 32 and 1325 Bq $m^{-3}$ (Table 10).

The instantaneous concentrations of radon in 890 schools in Slovenia were between 10 and 4690 Bq $m^{-3}$ (Vaupotič et al., 2000) and in 730 kindergartens they were between 7 and 5750 Bq $m^{-3}$ (Vaupotič et al., 1994). In schools in the area of Prizren (Kosovo) the instantaneous concentrations of radon measured were between 11 and 492 Bq $m^{-3}$ (Bahtijari et al., 2006), in kindergartens in Osijek (Croatia) they were between 20 and 180 Bq $m^{-3}$ (Vaupotič et al., 1992), in Belgrade (Serbia) they were between 12 and 227 Bq $m^{-3}$ (Vaupotič et al., 1992), in Sarajevo (Bosnia and Herzegovina) they were between 11 and 148 Bq $m^{-3}$ (Vaupotič et al., 1992) and in Lublin (Poland) they were between 12 and 128 Bq $m^{-3}$ (Vaupotič et al., 1993). In our studies, the concentrations of radon are significantly higher than in studies of the aforementioned countries, because more than half of Slovenia is covered by porous bedrock with high permeability, such as carbonates, which makes it easier for radon to come to the surface (Vaupotič et al., 1992; Vaupotič et al., 2000).

I carried out 30 measurements on the ground floor, 10 measurements in the basements and 2 measurements on the first floor. The arithmetic mean values of concentration of radon were as follows: ground floor 831 ± 1245 Bq $m^{-3}$, basement 355 ± 390 Bq $m^{-3}$ and first floor 267 ± 274 Bq $m^{-3}$. As a rule, the concentrations of radon are higher in the basements, but in our case, these spaces included a library, a laboratory, a gym and boiler room with good ventilation, so the results are not surprising. In contrast, the spaces on the ground floor were mostly without basements and their construction was of lower quality; consequently, ground air can enter into the space through the cracks in the foundation without any hindrance.

The instantaneous concentrations of radon in a private house are provided, along with other results, in sub-chapter 4.2.4. Buildings (school, kindergarten and office), which I chose for additional measurements with all of the available equipment, are shaded in Tables 9 and 10.

***Table 9:*** *Instantaneous radon concentrations ($C_{Rn}$) measured with scintillation cells (SC), place, floor and date of measurement in schools (b=basement, g=ground floor)*

| ***Code*** | ***Place*** | ***Floor*** | ***Date*** | ***$C_{Rn}$ SC Bq m$^{-3}$*** |
|---|---|---|---|---|
| ***a) schools*** | | | | |
| *S-LJ-1* | *library* | *b* | *22.10.04* | ***180 ± 15*** |
| *S-LJ-2* | *laboratory* | *b* | *20.10.04* | ***31 ± 7*** |
| *S-LJ-3* | *classroom* | *g* | *20.10.04* | ***1185 ± 40*** |
| *S-LJ-4* | *gym* | *b* | *22.10.04* | ***355 ± 25*** |
| *S-KR-1* | *office* | *b* | *21.10.04* | ***260 ± 15*** |
| *S-KR-2* | *meeting room* | *g* | *21.10.04* | ***1120 ± 30*** |
| *S-NM-1* | *classroom* | *g* | *18.10.04* | ***46 ± 17*** |
| *S-NM-2* | *office* | *b* | *18.10.04* | ***252 ± 43*** |
| *S-NM-3* | *workshop* | *b* | *18.10.04* | ***288 ± 52*** |
| *S-NM-4* | *office* | *g* | *18.10.04* | ***6870 ± 120*** |
| *S-GR-1* | *hall* | *g* | *18.10.04* | ***610 ± 25*** |
| *S-GR-2* | *classroom* | *g* | *18.10.04* | ***30 ± 12*** |
| *S-KO-1* | *classroom* | *g* | *18.10.04* | ***88 ± 12*** |
| *S-RA-1* | *gym* | *g* | *19.10.04* | ***1360 ± 40*** |
| *S-RI-1* | *classroom** | *b* | *18.10.04* | ***1340 ± 50*** |
| *S-ST-1* | *gym* | *g* | *19.10.04* | ***1660 ± 50*** |
| *S-ŠG-1* | *classroom* | *b* | *22.10.04* | ***72 ± 11*** |
| *S-VL-1* | *classroom* | *g* | *18.10.04* | ***460 ± 30*** |
| *S-JE-1* | *classroom* | *g* | *20.10.04* | ***170 ± 45*** |
| *S-KŽ-1* | *classroom* | *b* | *20.10.04* | ***665 ± 65*** |
| *S-RD-1* | *office* | *g* | *20.10.04* | ***425 ± 45*** |
| *S-RD-2* | *classroom* | *g* | *20.10.04* | ***1620 ± 50*** |
| *S-ŠL-1* | *meeting room* | *g* | *20.10.04* | ***270 ± 15*** |

**additional measurements using complementary techniques (with graphs of continuous measurements shown)*

***Table 10:*** *Instantaneous radon concentrations ($C_{Rn}$) measured with scintillation cells (SC), place, floor and date of measurement in kindergartens and offices (b=basement, g=ground floor, I=first floor)*

| ***Code*** | ***Place*** | ***Floor*** | ***Date*** | ***$C_{Rn}$ SC Bq m$^{-3}$*** |
|---|---|---|---|---|
| ***b) kindergartens*** | | | | |
| *K-VL-1* | *playroom* | *g* | *18.10.04* | ***41 ± 10*** |
| *K-VO-1* | *boiler room* | *b* | *22.10.04* | ***106 ± 12*** |
| *K-ID-1* | *playroom** | *g* | *19.10.04* | ***995 ± 70*** |
| ***c) office*** | | | | |
| *O-DI-1* | *office* | *I* | *18.10.04* | ***73 ± 12*** |
| *O-DI-2* | *office* | *g* | *21.10.04* | ***590 ± 25*** |
| *O-DI-3* | *ambulance* | *g* | *19.10.04* | ***850 ± 30*** |
| *O-DI-4* | *traffic office** | *g* | *19.10.04* | ***855 ± 35*** |
| *O-KO-1* | *office* | *I* | *21.10.04* | ***460 ± 25*** |
| *O-KO-2* | *office* | *g* | *21.10.04* | ***865 ± 30*** |
| *O-KO-3* | *laboratory* | *g* | *21.10.04* | ***1325 ± 40*** |
| *O-KZ-1* | *meeting room* | *g* | *21.10.04* | ***420 ± 25*** |
| *O-KZ-2* | *office* | *g* | *21.10.04* | ***300 ± 50*** |
| *O-KZ-3* | *traffic office* | *g* | *19.10.04* | ***930 ± 45*** |
| *O-SE-1* | *office* | *g* | *19.10.04* | ***37 ± 10*** |
| *O-SE-2* | *office* | *g* | *03.11.04* | ***1010 ± 40*** |
| *O-SE-3* | *office* | *g* | *21.10.04* | ***345 ± 20*** |
| *O-SE-4* | *office* | *g* | *02.11.04* | ***90 ± 15*** |
| *O-SE-5* | *ambulance* | *g* | *19.10.04* | ***32 ± 9*** |
| *O-SE-6* | *office* | *g* | *19.10.04* | ***337 ± 17*** |

**additional measurements using complementary techniques (with graphs of continuous measurements shown)*

### 4.1.2. Average radon (and thoron) concentrations

The average concentrations of radon were measured in 14 buildings (7 schools, 1 kindergarten, 6 offices) with the ETD-KfK and ETD-UFO detectors, and in 10 buildings (5 schools, 1 kindergarten, 4 offices) additionally with the RETRO detectors. The results were then compared (Table 11).

The average concentrations of radon measured with the ETD-KfK detectors were higher in all of the buildings, i.e. between 460 and 5300 Bq $m^{-3}$. The concentrations of radon, measured with the ETD-KfK detectors, were on average higher by factor 2.07 than the concentrations measured with the ETD-UFO detectors. Although the difference is expected, because the period of exposure of detectors only partially overlaps, the difference is too high. The correlation of concentrations based on both types of detectors is very good (r=0.96), which merely shows inappropriate calibration of the ETD-UFO detectors (Figure 13). Because the ETD-KfK detectors come from an accredited laboratory which has achieved excellent results in international intercomparison measurements, the concentrations measured with these detectors are of primary importance in our study and I used them as reference values.

I used the ETD-UFO detectors on a trial basis. In my study I used them to carry out the first measurements of thoron in Slovenia (Vaupotič et al., 2008). Since concentrations of thoron in the environment reach on average up to 15 % of the values of radon – in our case 21 % (when compared with the concentrations of radon based on the ETD-KfK detectors) – I can assume that the calibration of the ETD-UFO detectors for thoron was suitable. Of course there are areas where thoron is very high, for example in Serbia (Vaupotič et al., 2013b) or in China (Yamada et al., 2006).

***Table 11:*** *Average radon concentrations ($C_{Rn}$) measured with etched track (ETD-KfK, ETD-UFO) and (RETRO) detectors, and thoron ($C_{Tn}$) concentrations measured with (ETD-UFO) detectors, and dates of measurements*

| ***Code*** | ***$C_{Rn}$ ETD-KfK Bq m$^{-3}$*** *2004* | ***$C_{Rn}$ ETD-UFO Bq m$^{-3}$*** *2004* | ***$C_{Tn}$ ETD-UFO Bq m$^{-3}$*** *2004* | ***$C_{Rn}$ RETRO Bq m$^{-3}$*** *2004 – 2005* |
|---|---|---|---|---|
| *S-LJ-3* | *20.10.-22.11.* ***1800 ± 23*** | *27.10.-22.11.* ***860 ± 66*** | *27.10.-22.11.* ***308 ± 245*** | – |
| *S-KR-2* | *21.10.-18.11.* ***2400 ± 120*** | *29.10.-18.11.* ***1210 ± 90*** | *29.10.-18.11.* ***530 ± 345*** | *29.11.-02.03.* ***610*** |
| *S-NM-4* | *18.10.-17.11.* ***5300 ± 270*** | *28.10.-17.11.* ***2680 ± 190*** | *28.10.-17.11.* ***1330 ± 730*** | *28.10.-15.02.* ***510*** |
| *S-RA-1* | *19.10.-25.11.* ***1200 ± 60*** | *26.10.-25.11.* ***655 ± 50*** | *26.10.-25.11.* ***400 ± 190*** | – |
| *S-RI-1* | *18.10.-17.11.* ***4700 ± 235*** | *28.10.-25.11.* ***1710 ± 120*** | *28.10.-25.11.* ***990 ± 470*** | *28.10.-15.02.* ***8990*** |
| *S-ST-1* | *19.10.-25.11.* ***840 ± 40*** | *26.10.-25.11.* ***390 ± 30*** | *26.10.-25.11.* ***210 ± 120*** | *26.10.-25.02.* ***1020*** |
| *S-RD-2* | *20.10.-18.11.* ***1400 ± 70*** | *29.10.-18.11.* ***710 ± 60*** | *29.10.-18.11.* ***265 ± 210*** | *29.11.-02.03.* ***530*** |
| *K-ID-1* | *19.10.-18.11.* ***700 ± 40*** | *26.10.-26.11.* ***235 ± 20*** | *26.10.-26.11.* ***100 ± 80*** | *26.10.-02.03.* ***120*** |
| *O-DI-3* | *19.10.-24.11.* ***1500 ± 75*** | *02.11.-24.11.* ***975 ± 75*** | *02.11.-24.11.* ***110 ± 85*** | *02.11.-17.02.* ***210*** |
| *O-DI-4* | *19.10.-24.11.* ***1800 ± 90*** | *02.11.-24.11.* ***930 ± 70*** | *02.11.-24.11.* ***340 ± 270*** | *02.11.-17.02.* ***1010*** |
| *O-KO-2* | *21.10.-24.11.* ***460 ± 30*** | *02.11.-24.11.* ***335 ± 30*** | *02.11.-24.11.* ***< 10*** | – |
| *O-KO-3* | *21.10.-24.11.* ***780 ± 40*** | *02.11.-24.11.* ***450 ± 40*** | *02.11.-24.11.* ***< 10*** | – |
| *O-KZ-3* | *02.11.-24.11.* ***490 ± 35*** | *02.11.-24.11.* ***255 ± 25*** | *02.11.-24.11.* ***185 ± 90*** | *02.11.-17.02.* ***760*** |
| *O-SE-2* | *19.10.-24.11.* ***1500 ± 75*** | *02.11.-24.11.* ***630 ± 50*** | *02.11.-24.11.* ***335 ± 190*** | *02.11.-17.02.* ***480*** |

Radon survey in public buildings has been carried out by etched track detectors in many countries in Europe, also in our neighbouring countries (Vaupotič, 2011). In schools in Austria, the average radon concentration ranged from 5 to 4000 Bq m$^{-3}$ (Maringer et al., 2008), in schools in Italy from 49 to 222 Bq m$^{-3}$ (Gaidolfi et al., 1998) and in schools in Hungary from 50 to 916 Bq m$^{-3}$ (Somlai et al., 1997).

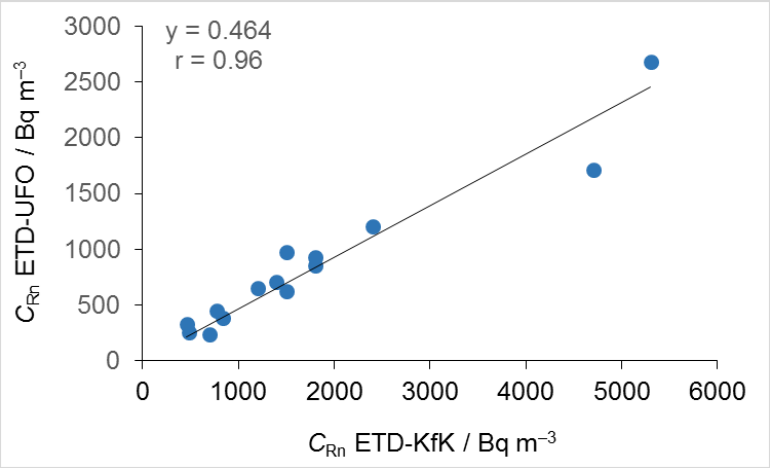


***Figure 13:*** *Correlation of radon concentration ($C_{Rn}$) obtained with ETD-UFO and ETD-KfK detectors*

Retrospective radon concentrations, measured with RETRO detectors, are a factor 2 to 10 lower than average radon concentration obtained with ETD-KfK detectors. Retrospective concentrations correlate with the contemporary radon concentrations, obtained with ETD-KfK detectors, with a correlation coefficient of 0.54. In the first Norwegian study of retrospective radon concentrations in 17 dwellings, the correlation coefficient of 0.88 was obtained (Birovljev et al., 2001). The difference may be explained with inexact information concerning the age of exposed glass in our case (public buildings) in comparison to the Norwegian study (dwellings). However, annual radon concentrations are usually a factor 2 to 3 lower than winter ones, thus, retro measurement technique may be classified as promising, when the accurate data concerning the duration of glass exposure can be obtained.

## 4.2. Radon and radon product concentrations

With continuous measurements I obtained data on radon, short-lived radon decay products and equilibrium factor in one-hour intervals. From this data I calculated the average concentrations of radon, the average concentrations of short-lived radon decay products and the average equilibrium factor for the entire periods of continuous measurements (Table 12).

For the four selected buildings, I also include graphs of continuous measurements (Figures 14 to 19). On these graphs, the blue curves show the concentration of radon, the orange curves the concentration of short-lived radon decay products (we obtain the value of the equilibrium factor from the ratio between the concentration of radon and concentration of short-lived radon decay products).

At the H-DI-cav location (a karst cave underneath the house) I continually measured only the concentration of radon (Figure 19).

For the selected three buildings (school S-RI-1, kindergarten K-ID-1, office O-DI-4) I calculated from the continuous measurements process the concentration of radon, short-lived radon decay products and the equilibrium factor only for the working hours and for the residential house (home H-DI-1) only for the time of resident occupancy of the kitchen (H-DI-1-kit).

***Table 12:*** *Average radon ($C_{Rn}$), radon product ($C_{RnDP}$) concentrations and equilibrium factor (F) calculated on the basis of continuous monitoring (CM)*

| ***Code Profile*** | ***$C_{Rn}$ CM Bq m$^{-3}$*** | ***$C_{RnDP}$ CM Bq m$^{-3}$*** | ***F*** |
|---|---|---|---|
| *S-LJ-3* | *2560* | *1392* | *0.54* |
| *S-KR-2* | *1902* | *732* | *0.38* |
| *S-NM-4* | *4580* | *3237* | *0.71* |
| *S-RA-1* | *464* | *256* | *0.55* |
| *S-RI-1* | *3450* | *2568* | *0.74* |
| *S-ST-1* | *260* | *150* | *0.58* |
| *S-ŠG-1* | *305* | *119* | *0.39* |
| *S-RD-2* | *626* | *424* | *0.68* |
| *K-ID-1* | *397* | *251* | *0.63* |
| *O-DI-3* | *986* | *617* | *0.63* |
| *O-DI-4* | *2367*<br>*1194* | *750*<br>*436* | *0.32*<br>*0.34* |
| *H-DI-1-kit* | *245* | *92* | *0.38* |
| *H-DI-1-cav1* | *778* | – | *0.40* |

As can be seen in Table 12, the concentrations of radon were increased in most buildings, whilst the equilibrium factor was higher than 0.40 (the value listed for residential spaces in literature) (ICRP, 1994) in 8 buildings. Especially high

concentrations of radon and its short-lived decay products were measured in buildings S-NM-4 and S-RI-1. In the first building, I carried out the measurement in the workshop and in the second in the classroom; both spaces were located in the basement. A very high equilibrium factors (0.71 and 0.74) show very poor ventilation of spaces. A very high equilibrium factor was also measured by other authors, for example Harley et al. (2012), who carried out the measurements in six residential homes and three laboratory rooms in different office buildings in the city of Ottawa from 77 to 162 days. The equilibrium factor ranged from 0.60 to almost 1.0 with an average of 0.75.

I the next part of the thesis, I present the results of all measurements (instantaneous, continuous, average, and retrospective) which I carried out in four buildings by using complementary measuring equipment.

### 4.2.1. School S-RI-1

The results of all measurements carried out in the classroom of the school S-RI-1 are presented in Table 13. We can see elevated radon concentrations. As expected, the values significantly differ, because the measurements cover different periods. The instantaneous concentration of radon ($C_{Rn}$ SC = 1340 Bq m$^{-3}$) is the lowest. The measurement was carried out in the morning hours, after the space had likely been partially ventilated. The average of the continuous measurement ($C_{Rn}$ CM = 3450 Bq m$^{-3}$) is lower than the average of the etched track detector ($C_{Rn}$ ETD-KfK = 4700 Bq m$^{-3}$). The opposite situation would be expected, because the concentrations of radon are, as a rule, higher during the winter months and the continuous measurement covered a later period (November) than the detector (October – November). The differences can be illustrated with the curve of the continuous measurement (Figure 14), where we can see that from 22 to 24 November there was a significant decrease of the concentration of radon and this had at least partly affected the lower average concentration of the 9-day measurement. With regard to the ETD-UFO detectors, I have explained in chapter 4.1.2. that they are poorly calibrated for radon and the concentration was too low ($C_{Rn}$ ETD-UFO = 1710 Bq m$^{-3}$), whilst the concentration of thoron ($C_{Tn}$ ETD-UFO

= 990 Bq $m^{-3}$) was likely measured correctly, because the part of thoron of 0.21 (with regard to the ETD-KfK detectors) was within the expected values. The retrospective concentration of radon is very high ($C_{Rn}$ RETRO = 8990 Bq $m^{-3}$) and it is likely that we did not get sufficiently accurate data on how many years the glass, on which we had glued the detector, had been in the space.

***Table 13:*** *Radon ($C_{Rn}$) and radon product ($C_{RnDP}$) concentrations measured with different techniques (SC, CM, ETD-KfK, ETD-UFO, RETRO) in a classroom of the school S-RI-1*

| ***$C_{Rn}$ SC Bq $m^{-3}$*** *2004* | ***$C_{Rn}$ CM Bq $m^{-3}$*** *2004* | ***$C_{Rn}$ ETD-KfK Bq $m^{-3}$*** *2004* | ***$C_{Rn}$ ETD-UFO Bq $m^{-3}$*** *2004* | ***$C_{Tn}$ ETD-UFO Bq $m^{-3}$*** *2004* | ***$C_{Rn}$ RETRO Bq $m^{-3}$*** *2004 – 2005* |
|---|---|---|---|---|---|
| *18.10.* ***1340 ± 50*** | *16.11.– 25.11.* ***3450 ± 170*** | *18.10.– 25.11.* ***4700 ± 235*** | *28.10.– 25.11.* ***1710 ± 120*** | *28.10.– 25.11.* ***990 ± 470*** | *28.10.– 15.02.* ***8990*** |

The run of the curve of continuous measurement is typical of a work space (classroom) (Figure 14), where ventilation is the most intensive during the morning hours (school classes) and in the afternoon (cleaning), whilst the concentration gradually increases overnight (the windows and doors are closed) and remains high over the weekend (Vaupotič, 2010). Other studies report on similar curves for radon measurements carried out in schools (Rydock et al., 2001; Kávási et al., 2006; Chang et al., 2011). The concentration of short-lived radon decay products follows the concentration of radon and the ratio of their concentrations presents the equilibrium factor. The concentration of radon at the beginning of school classes is usually higher than 4000 Bq $m^{-3}$, whilst at the end of school classes it mostly remains higher than 1000 Bq $m^{-3}$.

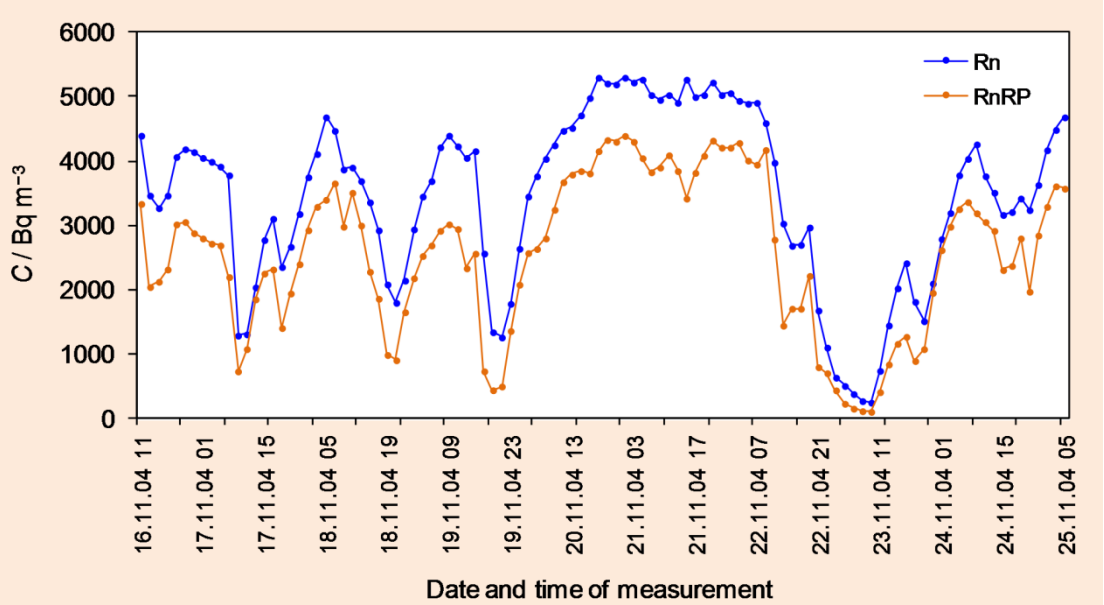


***Figure 14:*** *Continuous measurement of radon (Rn) and radon products (RnDP) in a classroom of the school S-RI-1 in the period November 16−25, 2004*

From the run of continuous measurement I calculated the average 24-hour concentration of radon and its short-lived decay products, as well as the concentration of radon and its short-lived decay products during working hours (Table 14). The overall 24-hour concentration was higher by a factor 1.25 than the concentration during the working hours. This was expected, because the concentration over the weekend was high all the time. The equilibrium factor during working hours (0.63) was lower than the equilibrium factor for the 24-hour period (0.74), but still surprisingly high. Due to the noise and dust from the surroundings, the classroom is only briefly ventilated during breaks.

***Table 14:*** *Average 24-hours and working hours radon ($C_{Rn}$) and radon products ($C_{RnDP}$) concentrations in a classroom of the school S-RI-1 calculated from the continuous measurements (CM) in the period November 16−25, 2004*

| ***Period*** | $C_{Rn}$ ***Bq m*$^{-3}$** | $C_{RnDP}$ ***Bq m*$^{-3}$** | ***F*** |
|---|---|---|---|
| *Working hours* | *2750* | *1745* | *0.63* |
| *24-hours* | *3450* | *2570* | *0.74* |

### 4.2.2. Kindergarten K-ID-1

The concentrations of radon which were measured with different techniques in the playroom of the kindergarten K-ID-1 are presented in Table 15. We can see that they are a size class lower than in the school and the difference between the different techniques of measurements is smaller. The highest is the instantaneous concentration of radon ($C_{Rn}$ SC = 995 Bq m$^{-3}$), which is the morning concentration of the space that was closed overnight. This is confirmed by the curve of the continuous measurement (Figure 15), since the morning maximums of radon are even slightly lower. It remains unexplained why the morning maximum in October was higher than the maximums in November (perhaps the weather conditions were less favourable in October and the inflow of radon into the space was more pronounced). The average concentration of radon calculated from the continuous measurement ($C_{Rn}$ CM = 397 Bq m$^{-3}$) is nearly half of the average concentration detected with the etched track detectors KfK ($C_{Rn}$ ETD-KfK = 700 Bq m$^{-3}$), which could confirm the assumption that the weather conditions were less favourable in October. As with all previous measurements, the concentration of radon with the UFO detector is too low ($C_{Rn}$ UFO-KfK = 235 Bq m$^{-3}$), which is explained by poor calibration of the detector, while the concentration of thoron ($C_{Tn}$ ETD-UFO = 100 Bq m$^{-3}$) is real, since its part with regard to the radon KfK detector was 0.14. The retrospective concentration of radon ($C_{Rn}$ RETRO = 120 Bq m$^{-3}$) is low; with regard to the climate conditions in Slovenia, the overall concentration is on average lower than the winter concentration by factor 0.70 (Križman and Mljač, 1994), therefore we would expect a retrospective concentration between 200 and 400 Bq m$^{-3}$.

***Table 15:*** *Radon ($C_{Rn}$) and radon product ($C_{RnDP}$) concentrations measured with different techniques (SC, CM, ETD-KfK, ETD-UFO, RETRO) in a playroom of the kindergarten K-ID-1*

| $C_{Rn}$ **SC** **Bq m$^{-3}$** *2004* | $C_{Rn}$ **CM** **Bq m$^{-3}$** *2004* | $C_{Rn}$ **ETD-KfK** **Bq m$^{-3}$** *2004* | $C_{Rn}$ **ETD-UFO** **Bq m$^{-3}$** *2004* | $C_{Tn}$ **ETD-UFO** **Bq m$^{-3}$** *2004* | $C_{Rn}$ **RETRO** **Bq m$^{-3}$** *2004 – 2005* |
|---|---|---|---|---|---|
| *19.10.* ***995 ± 70*** | *18.11.–26.11.* ***397± 20*** | *19.10.–26.11.* ***700 ± 40*** | *26.10.–26.11.* ***235 ± 20*** | *26.10.–26.11.* ***100 ± 80*** | *26.10.–02.03.* ***120*** |

In the playroom, the run of continuous radon and its decay product concentrations (Figure 15) is similar to in the school (Figure 14), with a typical decrease during the day and an increase overnight and during the weekend. The concentration of radon at the beginning of the daily child care was usually between 400 and 700 Bq $m^{-3}$, whilst in the afternoon it fell to around 100 Bq $m^{-3}$.

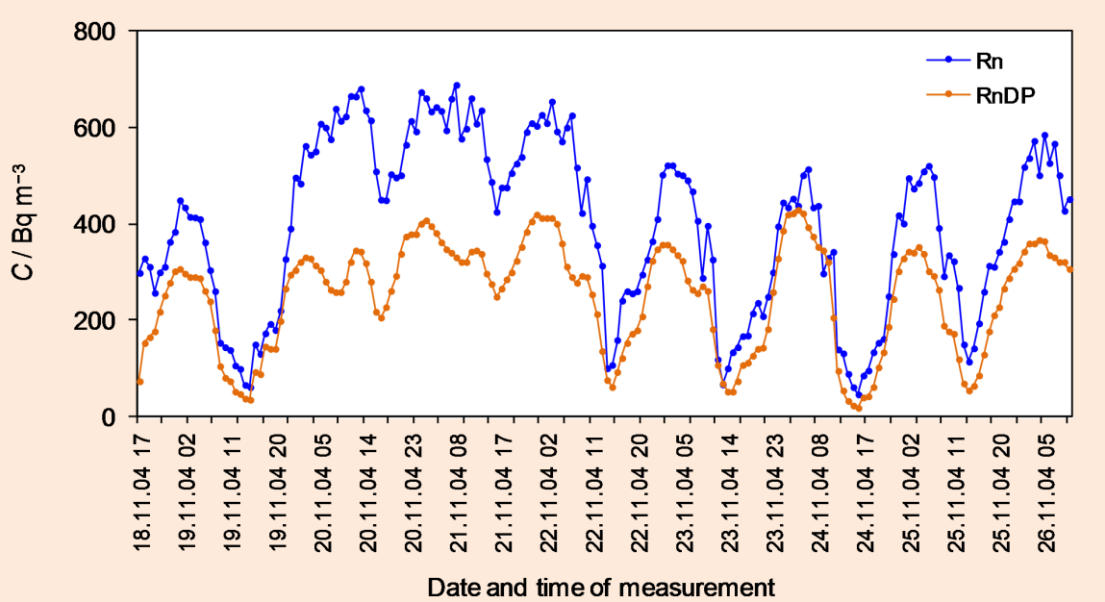


***Figure 15:*** *Continuous measurement of radon (Rn) and radon products (RnDP) in a playroom of the kindergarten K-ID-1 in the period November 18−26, 2004*

In Table 16 are presented concentrations of radon and its short-lived decay products which were calculated during the working hours. The overall 24-hour concentration was higher by the factor 1.5 than the concentration during the working hours, whilst the equilibrium factor was 0.63 in both cases.

***Table 16:*** *Average 24-hours and working hours radon ($C_{Rn}$) and radon products ($C_{RnDP}$) concentrations in a playroom of the kindergarten K-ID-1 calculated from the continuous measurements (CM) in the period November 18−26, 2004*

| ***Period*** | ***$C_{Rn}$*** ***Bq $m^{-3}$*** | ***$C_{RnDP}$*** ***Bq $m^{-3}$*** | ***F*** |
|---|---|---|---|
| *Working hours* | *259* | *163* | *0.63* |
| *24-hours* | *397* | *251* | *0.63* |

### 4.2.3. Office O-DI-4

The results of the measurements of radon are presented in Table 17. In all periods when the measurements were carried out, elevated radon concentrations were obtained. The instantaneous concentration reflects the ventilation of the space at the time the air sample was taken. The first concentration in 2004 ($C_{Rn}$ SC = 855 Bq $m^{-3}$) was significantly lower than the second one in 2006 ($C_{Rn}$ SC = 3310 Bq $m^{-3}$). High fluctuations in the concentration of radon, from several Bq $m^{-3}$ to around 9000 Bq $m^{-3}$, can be seen on the continuous curve for the period between January 18 − February 04, 2005 (Figure 16). In the next period of continuous measurement, February 03 − March 02, 2006, the concentration was lower, from several Bq $m^{-3}$ to around 3500 Bq $m^{-3}$ (Figure 17). Since work takes place in the office during the weekends as well, the curves (Figures 16 and 17) do not show the increases of radon during the weekends which are typical of schools and kindergartens. The average concentration of radon, measured with the KfK detector ($C_{Rn}$ ETD-KfK = 1800 Bq $m^{-3}$), is higher by factor 2 than the concentration with the UFO detector, which is inappropriately calibrated. The concentration of thoron ($C_{Tn}$ ETD-KfK = 340 Bq $m^{-3}$) is real and its part with regard to radon with the KfK detector is 0.19. The retrospective concentration of radon is also real and lower by factor 0.56 than the average concentration with the KfK detector.

***Table 17:*** *Radon ($C_{Rn}$) and radon product ($C_{RnDP}$) concentrations measured with different techniques (SC, CM, ETD-KfK, ETD-UFO, RETRO) in the office O-DI-4-1*

| ***$C_{Rn}$*** ***SC*** ***Bq m$^{-3}$*** *2004* | ***$C_{Rn}$*** ***CM*** ***Bq m$^{-3}$*** *2004* | ***$C_{Rn}$*** ***ETD-KfK*** ***Bq m$^{-3}$*** *2004* | ***$C_{Rn}$*** ***ETD-UFO*** ***Bq m$^{-3}$*** *2004* | ***$C_{Tn}$*** ***ETD-UFO*** ***Bq m$^{-3}$*** *2004* | ***$C_{Rn}$*** ***RETRO*** ***Bq m$^{-3}$*** *2004 – 2005* |
|---|---|---|---|---|---|
| *18.01.* ***855 ± 35*** | *18.01.– 04.02.* ***2370 ± 120*** | *19.10.– 24.11.* ***1800 ± 90*** | *02.11.– 24.11.* ***930 ± 70*** | *02.11.– 24.11.* ***340 ± 270*** | *02.11.– 17.02.* ***1010*** |
| *2006* *20.01.* ***3310 ± 80*** | *2006* *03.02.– 02.03.* ***1190 ± 60*** | | | | |

I calculated 24-hour and working concentrations of radon from both periods of continuous measurements (Table 18). Since work in the office takes place in three

8-hour shifts, the differences between the 24-hour and the working hours radon concentrations are practically non-existent and the equilibrium factor is low (from 0.32 to 0.36), which reflects better ventilation of the space than in the case of the classroom (Table 14) and the playroom (Table 16). Despite good ventilation the concentration of radon remains high, which suggests a rich source for inflow of fresh radon into the space.

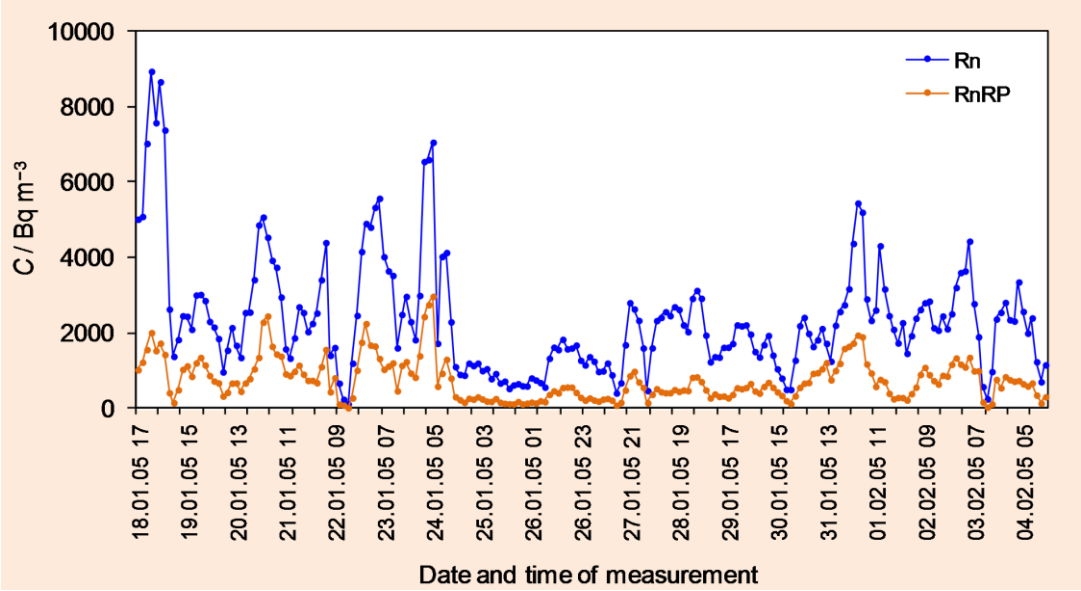


***Figure 16:*** *Continuous measurement of radon (Rn) and radon products (RnDP) in the office O-DI-4 in the period January 18 − February 04, 2005*

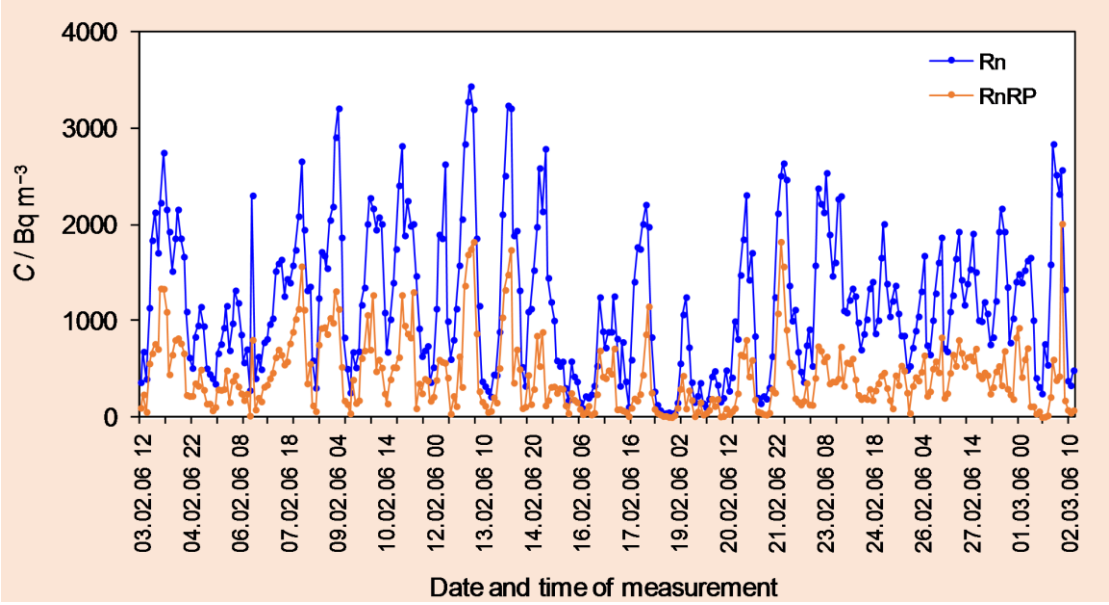


***Figure 17:*** *Continuous measurement of radon (Rn) and radon products (RnDP) in the office O-DI-4 in the period February 03 − March 02, 2006*

***Table 18:*** *Average 24-hours and working hours radon ($C_{Rn}$), radon product concentrations ($C_{RnDP}$) and equilibrium factor (F) in the office O-DI-4 calculated from continuous measurements (CM) in the periods January 18 − February 04, 2005 and February 03 − March 02, 2006*

| ***Period*** | ***$C_{Rn}$*** ***Bq m$^{-3}$*** | ***$C_{RnDP}$*** ***Bq m$^{-3}$*** | ***F*** |
|---|---|---|---|
| ***January 18 − February 04, 2005*** | | | |
| *Working hours* | *2210* | *725* | *0.33* |
| *24-hours* | *2150* | *680* | *0.32* |
| ***February 03 − March 03, 2006*** | | | |
| *Working hours* | *1150* | *385* | *0.33* |
| *24-hours* | *1190* | *430* | *0.36* |

### 4.2.4. Home H-DI-1

In the private house I carried out measurements in seven rooms and the results are presented in Table 19. As expected, the concentrations of radon were the highest in the karst cave underneath the house. It is well known that radon accumulates in underground spaces such as karst caves. In certain parts of the tourist trail of the Postojna Cave, the concentrations of radon during the summer months are up to 6000 Bq m$^{-3}$ and during the winter months around 2000 Bq m$^{-3}$ (Vaupotič, 2008). In our case, the concentrations in the cave were 50 % lower. The air from the karst cave, which is rich in radon, spreads into the basement (i.e. garage, workroom) and from there into the rooms of the house. As we can see, the concentrations of radon in the residential part of the house were below the limit value of 400 Bq m$^{-3}$ (Ur. L. RS, 2004b), and mostly lower than 200 Bq m$^{-3}$ (Ur. L. RS, 2002). The average concentration of radon, measured with the KfK detector in the kitchen, was satisfyingly low ($C_{Rn}$ ETD-KfK = 293 Bq m$^{-3}$).

***Table 19:*** *Radon concentrations ($C_{Rn}$) measured by different techniques (SC, CM, ETD-KfK) in the private house H-DI-1*

| ***Place*** | ***$C_{Rn}$ SC*** ***Bq m$^{-3}$*** *18.01.2005* | ***$C_{Rn}$ SC*** ***Bq m$^{-3}$*** *04.02.2005* | ***$C_{Rn}$ CM*** ***Bq m$^{-3}$*** *18.01.–4.02.2005* | ***$C_{Rn}$ ETD-KfK*** ***Bq m$^{-3}$*** *18.01.–17.02.2005* |
|---|---|---|---|---|
| *H-DI-1-kit* | *207 ± 18* | *61 ± 16* | *245 ± 12* | *293 ± 26* |
| *H-DI-1-liv* | *200 ± 17* | *76 ± 16* | – | – |
| *H-DI-1-bed* | *173 ± 17* | *< 30* | – | – |
| *H-DI-1-wor* | *381 ± 24* | *163 ± 24* | – | *509 ± 36* |
| *H-DI-1-gar* | *477 ± 27* | *67 ± 27* | – | *548 ± 38* |
| *H-DI-1-cav1* | *1000 ± 40* | *282 ± 40* | *778 ± 39* | *932 ± 47* |
| *H-DI-1-cav2* | *965 ± 35* | *908 ± 35* | – | – |

I carried out the continuous measurement in the kitchen (Figure 18). In the early morning hours, the concentrations of radon achieved maximum values around 600 Bq m$^{-3}$, whilst in the afternoon they fell to around 100 Bq m$^{-3}$.

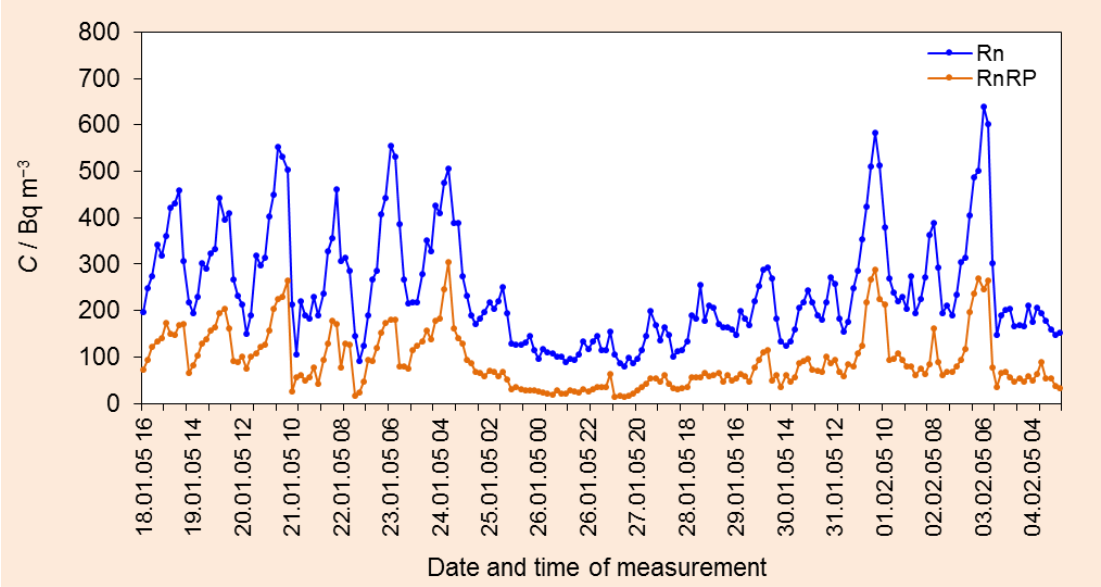


***Figure 18:*** *Continuous measurement of radon (Rn) and radon products (RnDP) in the kitchen H-DI-1-kit in the period January 18 − February 04, 2005*

Based on the continuous measurement, I calculated the average 24-hour concentrations of radon and concentrations during the time the residents of the house were occupying the kitchen (Table 20). We can see that the 24-hour concentration is higher by factor 1.3 than the concentration at the time the residents were present; the

equilibrium factor is satisfyingly low, even lower than 0.40, which is the value listed for residential environment in the literature (UNSCEAR, 2000; ICRP, 1994).

***Table 20:*** *Average 24-hours and average occupancy hours radon ($C_{Rn}$) and radon decay product ($C_{RnDP}$) concentrations in kitchen H-DI-kit of a private house calculated from continuous measurements (CM) in the period January 18 – February 04, 2005*

| ***Period*** | ***$C_{Rn}$*** ***Bq m$^{-3}$*** | ***$C_{RnDP}$*** ***Bq m$^{-3}$*** | ***F*** |
|---|---|---|---|
| *Occupancy hours* | *189* | *70* | *0.37* |
| *24-hours* | *245* | *92* | *0.38* |

I also carried out the continuous measurement of radon in the cave (with monitor RTM 1688-2) which is directly connected with the house; it is from here that the air rich with radon spreads into the house (Figure 19). We can see high fluctuations in the concentration of radon, from several Bq m$^{-3}$ to around 2200 Bq m$^{-3}$.

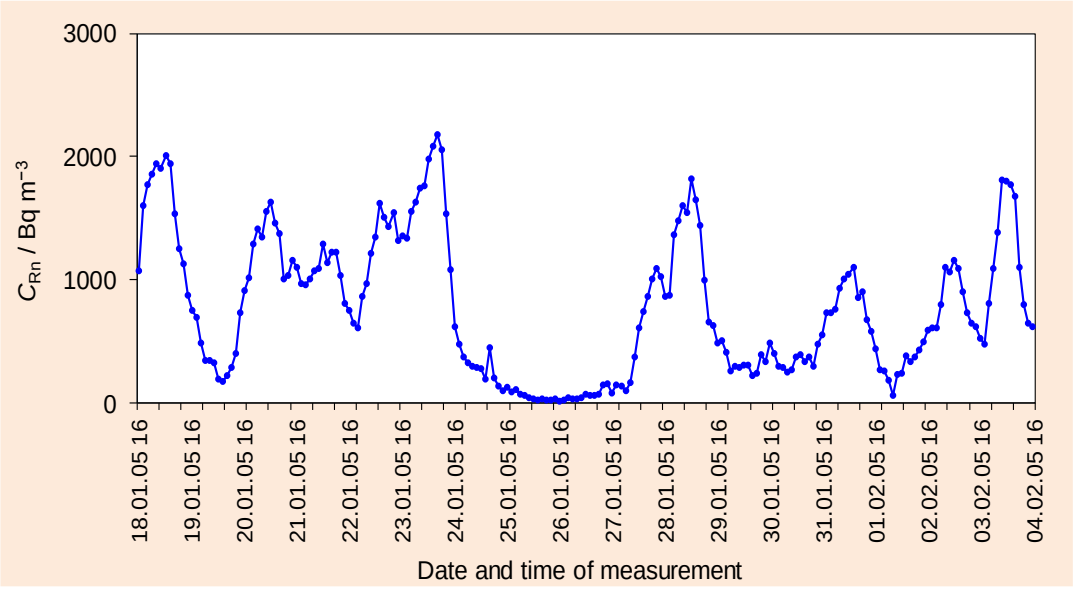


***Figure 19:*** *Continuous measurement of radon (Rn) in the cave H-DI-1-cav1 (situated below the house) in the period January 18 – February 04, 2005*

## 4.3. Annual effective doses

I calculated the effective doses based on the instantaneous (SC), continuous (CM), average (ETD-KfK) and retrospective (RETRO) concentrations of radon. The equilibrium factor F=0.40 ($F_L$) was taken from literature (ICRP, 1994). For spaces where I obtained the equilibrium factor with continuous measurements, I calculated the dose based on the measurement equilibrium factor ($F_M$). The results are presented in Table 21 for schools and in Table 22 for kindergartens, offices and the private house. In schools, the effective doses refer to teachers, in kindergartens to educators, in offices to employees and in the private house to residents in a kitchen. In addition to concentrations of radon, the annual periods of exposure are also provided in the tables. I calculated the dose based on the assumption that the person is exposed throughout to a concentration of radon which I measured.

The effective dose, calculated on the basis of the instantaneous concentration of radon (SC) is just a preliminary information and is usually not used in the dosimetry of radon. For the most part, the effective doses are calculated based on the average concentration of radon (in our case the KfK detector), but the longer the detector is exposed, the more accurate the dose is.

The closest approximation to the effective dose received is the calculation based on the continuous measurement, which is what I used. This kind of approach is used only for research purposes, because in mass dosimetry it would be too expensive and would require too much time. However, with this approach we can obtain valuable data on short-lived radon decay products and the equilibrium factor; in addition to the dose on the basis of the 24-hour concentration, we can also calculate the dose for the actual exposure (working hours in public buildings, occupancy hours at homes).

I did not calculate the effective dose based on the UFO detectors, because these detectors showed too low concentrations of radon due to poor calibration. I did not calculate the dose of thoron, because its part with regard to radon is low and does not present a significant additional dose burden.

The effective dose on the basis of the RETRO detectors was unreliable, because the deviations in the concentration of radon between the reference KfK detectors – if the concentration was calculated for the annual level – and the RETRO detectors was too high for the concentration to be deemed real.

***Table 21:*** *Annual effective doses calculated on the basis of radon concentration obtained with SC, CM, ETD-KfK, ETD-UFO and RETRO measurements and $F_L$ (literature) or $F_M$ (measured) in schools*

| ***Code*** | ***Time exposed h*** | ***E–$F_L$ SC mSv $a^{-1}$*** | ***E–$F_L$ ETD-KfK mSv $a^{-1}$*** | ***E–$F_M$ ETD-KfK mSv $a^{-1}$*** | ***E–$F_M$ CM mSv $a^{-1}$*** | ***E–$F_M$ RETRO mSv $a^{-1}$*** |
|---|---|---|---|---|---|---|
| ***a) schools*** | | | | | | |
| *S-LJ-1* | *1920* | *1.1* | | | | |
| *S-LJ-2* | *960* | *0.1* | | | | |
| *S-LJ-3* | *700* | *2.6* | *4.0* | *5.4* | *7.7* | |
| *S-LJ-4* | *980* | *1.1* | | | | |
| *S-KR-1* | *2080* | *1.7* | | | | |
| *S-KR-2* | *20* | *0.1* | *0.2* | *<0.2* | *0.1* | *< 0.05* |
| *S-NM-1* | *200* | *0.03* | | | | |
| *S-NM-2* | *280* | *0.2* | | | | |
| *S-NM-3* | *630* | *0.6* | | | | |
| *S-NM-4* | *143* | *3.0* | *2.4* | *4.3* | *3.7* | *0.2* |
| *S-GR-1* | *152* | *0.3* | | | | |
| *S-GR-2* | *245* | *0.02* | | | | |
| *S-KO-1* | *1000* | *0.3* | | | | |
| *S-RA-1* | *105* | *0.4* | *0.4* | *0.6* | *0.2* | |
| *S-RI-1** | *768* | *3.2* | *11.5* | *21.0* | *15.6* | *22.0* |
| *S-ST-1* | *114* | *0.6* | *0.3* | *0.4* | *0.1* | *0.4* |
| *S-ŠG-1* | *640* | *0.1* | *0.2* | *0.2* | *0.6* | |
| *S-VL-1* | *1050* | *1.5* | | | | |
| *S-JE-1* | *52* | *0.03* | | | | |
| *S-KŽ-1* | *875* | *1.8* | | | | |
| *S-RD-1* | *1640* | *2.2* | | | | |
| *S-RD-2* | *1845* | *9.3* | *8.2* | *14.0* | *6.2* | *3.1* |
| *S-ŠL-1* | *730* | *0.6* | | | | |

**additional measurements using complementary techniques (with graphs of continuous measurements shown)*

***Table 22:*** *Annual effective doses calculated on the basis of radon concentration obtained with SC, CM, ETD-KfK, ETD-UFO and RETRO measurements and $F_L$ (literature) or $F_M$ (measured) in kindergartens, offices and home*

| ***Code*** | ***Hours*** | ***E–F$_L$ SC mSv a$^{-1}$*** | ***E–F$_L$ ETD-KfK mSv a$^{-1}$*** | ***E–F$_M$ ETD-KfK mSv a$^{-1}$*** | ***E–F$_M$ CM mSv a$^{-1}$*** | ***E–F$_M$ RETRO mSv a$^{-1}$*** |
|---|---|---|---|---|---|---|
| ***b) kindergartens*** | | | | | | |
| *K-VL-1* | *1120* | *0.1* | | | | |
| *K-VO-1* | *1* | *< 0.001* | | | | |
| *K-ID-1* | *1362* | *4.2* | *3.0* | *4.8* | *2.7* | *0.5* |
| ***c) offices*** | | | | | | |
| *O-DI-1* | *1900* | *0.4* | | | | |
| *O-DI-2* | *2048* | *3.7* | | | | |
| *O-DI-3* | *1840* | *4.8* | *8.8* | *13.8* | *9.1* | *1.2* |
| *O-DI-4** | *2184* | *5.8* | *12.5* | *10.0* | *13.1* | *7.0* |
| *O-KO-1* | *2100* | *3.0* | | | | |
| *O-KO-2* | *4096* | *11.0* | *6.0* | | | |
| *O-KO-3* | *368* | *1.5* | *0.9* | | | |
| *O-KZ-1* | *92* | *0.1* | | | | |
| *O-KZ-2* | *1840* | *1.7* | | | | |
| *O-KZ-3* | *1808* | *5.2* | *2.8* | | | *4.4* |
| *O-SE-1* | *1840* | *0.2* | | | | |
| *O-SE-2* | *2048* | *6.4* | *9.8* | | | *3.2* |
| *O-SE-3* | *1840* | *2.0* | | | | |
| *O-SE-4* | *1700* | *0.5* | | | | |
| *O-SE-5* | *2500* | *0.2* | | | | |
| *O-SE-6* | *2096* | *2.2* | | | | |
| ***d) home*** | | | | | | |
| *H-DI-1-kit** | *1460* | *0.8* | *1.1* | *1.0* | *0.9* | |
| *H-DI-1-bed** | *2920* | *3.5* | *4.1* | | | |
| *H-DI-1-wor** | *365* | *0.9* | *0.9* | *0.9* | *0.7* | |

**additional measurements using complementary techniques (with graphs of continuous measurements shown)*

If I focus on the effective doses (Table 21 and 22), calculated on the basis of average concentrations of radon with the KfK detectors, they are between <0.02 and 21 mSv a$^{-1}$. Taking into consideration that the measurements were carried out during the winter months, when the concentrations of radon are the highest, the real annual doses could be lower by factor 1.5 to 3 and the results comparable to the results obtained in schools and kindergartens in certain other countries, i.e. 0.11–0.24 mSv a$^{-1}$ in Austria (Kindl et al., 2003), 0.15–0.68 mSv a$^{-1}$ in Italy (Gaidolfi et al., 1998) and 0.3–1.60 mSv a$^{-1}$ in Greece (Geranios et al., 2001). However, in my research I came across five extreme examples of high doses (S-RI-1, S-RD-2, O-DI-3 O-DI-4

and O-SE-2) due to the high concentration of radon or a large number of hours in the space. Nevertheless, the purpose of my work was not so much calculation as presentation of the different approaches to calculation and the differences which occur while doing it.

It turned out that the correlation (Figure 20) between the effective dose calculated from the instantaneous concentration of radon (Tables 21 and 22, column $E\ F_L$–SC) and the dose calculated from the average concentration of radon (Tables 21 and 22, column $E\ F_L$–ETD-KfK) is strong (r=0.59). The effective doses from the instantaneous concentrations are lower than the doses of the average concentrations of radon, but the average concentration in public buildings (schools, kindergartens, offices) is revalued with regard to the actual concentration during working hours and the high concentrations during weekends, when the spaces are not ventilated. Therefore, to obtain a quick overview of the situation, we can effectively calculate the dose also on the basis of the instantaneous concentration of radon; nevertheless, it is advisable to carry out long-term measurements as well.

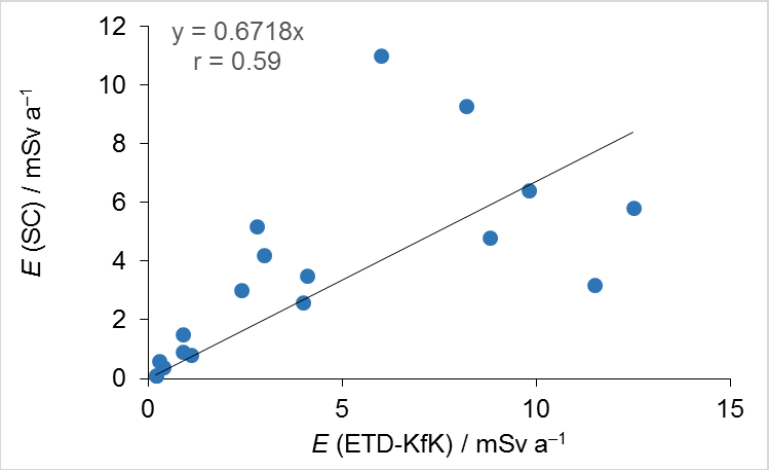


***Figure 20:*** *Correlation between effective dose, calculated with instantaneous (SC) and average (ETD-KfK) radon concentrations*

Similarly, I calculated the correlation coefficient between the effective dose from the continuous measurement of concentration of radon (Tables 21 and 22, column $E\ F_M$–CM) and the effective dose calculated from the average concentration of radon Tables 21 and 22, column $E\ F_L$–ETD-KfK) and got a strong relationship (r=0.95) (Figure 21). The results have confirmed that the etched track detector, which

measures the average concentration of radon, is an excellent choice for measuring and further assessment of doses. This was also the most favourable method in terms of costs for massive-scale measurements of radon.

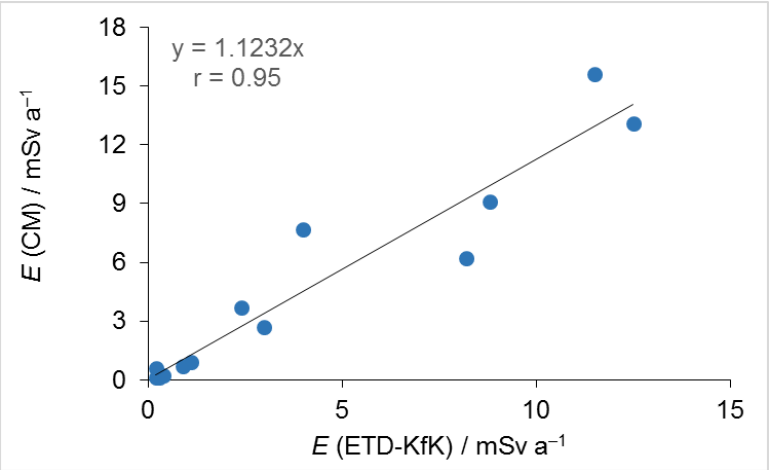


***Figure 21:*** *Correlation between effective dose, calculated with instantaneous (CM) and average (ETD-KfK) radon concentrations*

In Table 23 are presented effective doses for four selected buildings, calculated on the basis of 24-hour concentrations and concentrations only during working hours (a school, a kindergarten, an office and a residential house). The concentration of radon was measured with the continuous monitor (CM) or the KfK detector (ETD-KfK) and retrospective detector (RETRO). The equilibrium factor was calculated from continuous measurements for a 24-hour period ($F_T$) and the working level period ($F_W$), whilst factor $F_L$ (0.40) was taken from literature. For the house, I only provide the dose on the basis of $F_T$. The most real and accurate effective dose is based on continuous measurement (CM) and the equilibrium factor at the time of being present in the room ($F_M$), but since the KfK detector was exposed for longer than the continuous monitor, it is an even better approximation of the ETD-KfK dose by using $F_W$. Therefore, the most accurate calculation of the annual effective dose is 19.5 mSv for the school S-RI-1, 4.8 mSv for the kindergarten K-ID-1 and 10.0 for the office O-DI-4. In the case of the office O-DI-4, the dose was calculated only for the first period of continuous measurement, since in the second period the KfK detector was not exposed. In the case of the house H-DI-1-kit, I calculated the dose only on the basis of $F_T$.

***Table 23:*** *Annual effective doses due to radon decay products calculated on the basis of radon and radon decay product concentrations obtained by different measuring techniques (SC, CM, ETD-KfK, ETD-UFO, RETRO) and measured equilibrium factor $F_M$ ($F_T$ – total, $F_W$ – working) or equilibrium factor from the literature $F_L$ (F=0.40)*

| ***Code*** | ***Annual effective dose / mSv*** | | | | | |
|---|---|---|---|---|---|---|
| | ***CM $F_T$*** | ***CM $F_W$*** | ***ETD-KfK $F_L$*** | ***ETD-KfK $F_T$*** | ***ETD-KfK $F_W$*** | ***RETRO $F_L$*** |
| *S-RI-1* | *15.6* | *14.3* | *11.5* | *21.0* | *19.5* | *22.0* |
| *K-ID-1* | *2.7* | *2.6* | *3.0* | *4.8* | *4.6* | *0.5* |
| *O-DI-4* | *13.1* | *13.1* | *12.5* | *10.0* | *10.0* | *7.0* |
| *O-DI-4* | *7.0* | *6.6* | – | – | – | – |
| *H-DI-1-kit* | *0.9* | – | *1.1* | *1.0* | – | – |

The effective doses are presented in graphic form as well, in which the column with the best approximation to the real dose was coloured in green for each building (Figures 22 – 25).

### 4.3.1. School S-RI-1

In the classroom of the school S-RI-1, the effective doses were between 11.5 and 22.0 mSv $a^{-1}$ (Table 23). Since the measurement with the KfK detector took place for longer than with the continuous monitor (CM), the best approximation to the real dose is the calculation on the basis of the average concentration of radon (ETD-KfK) and the equilibrium factor $F_W$ between working hours (the green column in Figure 22).

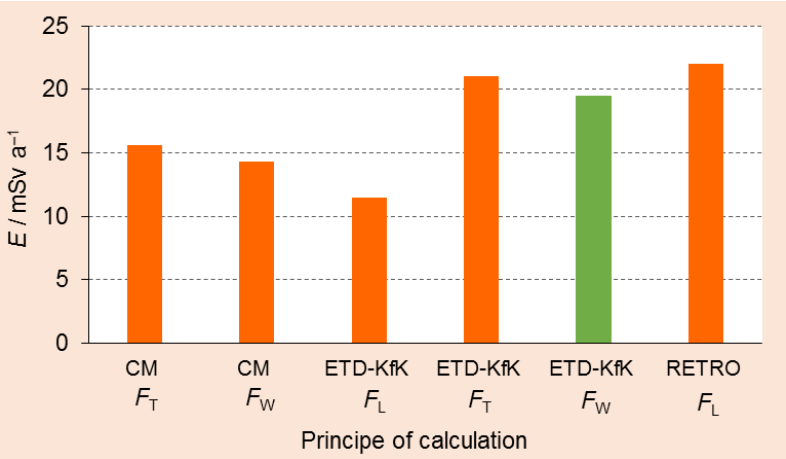


***Figure 22:*** *Annual effective dose; based on radon concentration obtained with different measurement techniques (CM, ETD-KfK, RETRO) and equilibrium factor measured ($F_M$: $F_T$ – total, $F_W$ - working) or from the literature ($F_L$=0.4) in a classroom of the school S-RI-1*

### 4.3.2. Kindergarten K-ID-1

In the playroom of the kindergarten K-ID-1, the effective doses were between 0.5 and 4.8 mSv $a^{-1}$ (Table 23). Similarly as with the school, the best approximation to the real dose in the kindergarten is the calculation on the basis of the average concentration of radon (ETD-KfK) and the equilibrium factor $F_W$ between working hours (the green column in Figure 23).

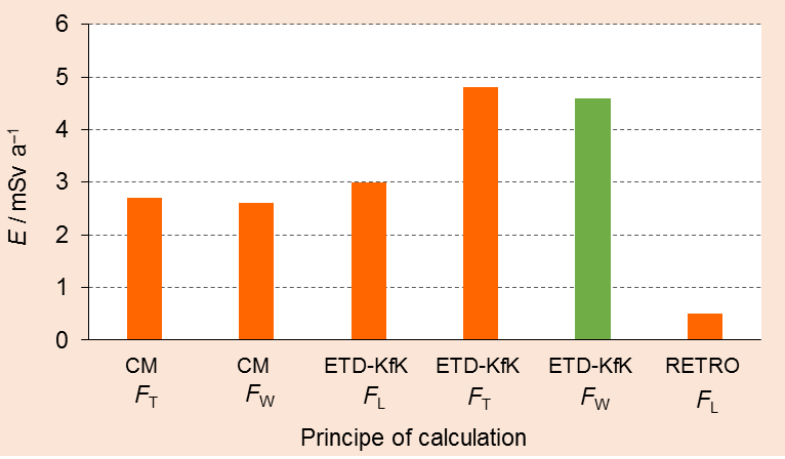


***Figure 23:*** *Annual effective dose; based on radon concentration obtained with different measurement techniques (CM, ETD-KfK, RETRO) and equilibrium factor measured ($F_M$: $F_T$ – total, $F_W$ - working) or from the literature ($F_L$=0.4) in a playroom of the kindergarten K-ID-1*

### 4.3.3. Office O-DI-4

In the office O-DI-1, the effective doses were between 7 and 13.1 mSv $a^{-1}$ (Table 23). Since the period of continuous measurement is different from the period of exposure of the detector, and the continuous measurement was carried out in January, the concentrations of radon are, as a rule, higher. I chose the dose based on the concentration of radon measured with a continuous monitor (the green column in Figure 24) as an optimal effective dose. Since work in the office takes place in three shifts, there is no difference between the effective dose based equilibrium factor $F_T$ (total) in $F_W$ (working).

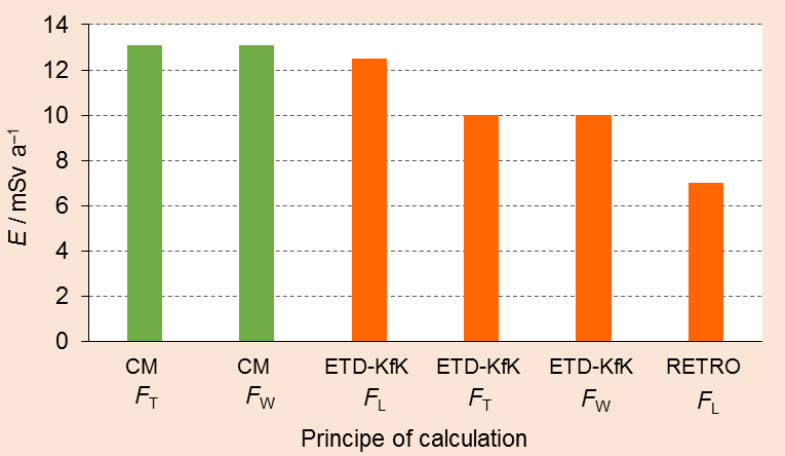


***Figure 24:*** *Annual effective dose; based on radon concentration obtained with different measurement techniques (CM, ETD-KfK, RETRO) and equilibrium factor measured ($F_M$: $F_T$ – total, $F_W$ - working) or from the literature ($F_L$=0.4) in the office O-ID-4 (period of continuous measurement January 18 – February 04, 2005)*

### 4.3.4. Home H-DI-1

At home H-DI-1, the effective doses were between 0.9 and 1.1 mSv $a^{-1}$ (Table 23), which is only slightly more than the average effective dose 0.88 mSv $a^{-1}$, which can be obtained in the homes around Slovenia (Koželj et al., 2006). I calculated the effective doses only on the basis of the equilibrium factor for the entire period of measurement $F_T$ (total). The differences between the individual calculations are small

and I chose as the best approximation the dose based on a one-month concentration which was obtained with the KfK detector (the green column in Figure 25).

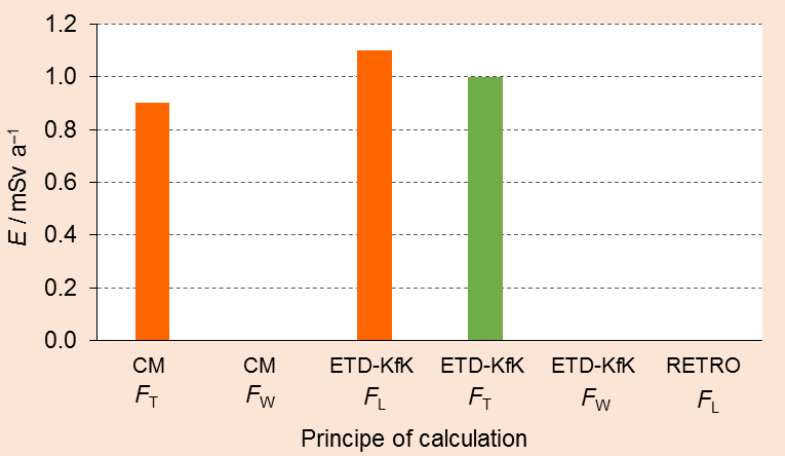


***Figure 25:*** *Annual effective dose; based on radon concentration obtained with different measurement techniques (CM, ETD-KfK, RETRO) and equilibrium factor measured ($F_M$: $F_T$ – total, $F_W$ - working) or from the literature ($F_L$=0.4) in the kitchen H-DI-1-kit of the home*

In schools, kindergartens and offices in which I measured concentrations of radon higher than 1000 Bq $m^{-3}$, the concentrations were successfully lowered with corresponding recovery measures.

## 5. CONCLUSIONS

In my master's thesis I focused on radon in working environments (schools, kindergartens and offices) and radon in a living environment (residential house). I researched 43 buildings. First, I carried out measurements of radon and short-lived radon products whilst employing a variety of active and passive complementary measurement techniques. I measured the instantaneous concentrations of radon by using scintillation cells and the average and retrospective concentrations of radon by using solid state nuclear track detectors (etched track detectors). I monitored the daily fluctuations of concentration of radon and short-lived radon products with continuous measurements. This is how I obtained the factor of radioactive equilibrium between radon and its short-lived products. Based on the results obtained, I calculated the effective doses.

From the 43 buildings I chose 4 buildings (a school, a kindergarten, an office, a residential house) in which concentration of radon was the highest. In one room (classroom, playroom, office, kitchen) I measured radon and its short-lived products with all of the measuring equipment available. Based on the measured concentrations of radon and by using six different approaches, I calculated the effective doses for each space, compared them and explained which dose is the best approximation to the real dose (in the kitchen I used three approaches).

My findings can be summed up as follows:

Instantaneous concentrations of radon in the 49 spaces measured: in schools they were between 30 and 6870 Bq $m^{-3}$, in kindergartens they were between 41 and 995 Bq $m^{-3}$, in work environments they were between 32 and 1325 Bq $m^{-3}$ and in the residential house they were between 173 and 477 Bq $m^{-3}$.

I measured the average concentrations of radon with different solid state nuclear track detectors (ETD-KfK, ETD-UFO and RETRO). With the ETD-KfK detectors I got on average higher concentrations by factor 2.07 than with the ETD-UFO detectors, which shows inappropriate calibration of the ETD-UFO detectors for

radon. With the ETD-UFO detectors I measured the concentrations of thoron as well, which were <10 do 1330 Bq $m^{-3}$. The part of thoron with regard to radon was mostly lower than 0.20, which are expected values. The concentrations of radon based on the ETD-KfK detectors were reference values in my study.

The retrospective concentrations of radon, measured with the RETRO detectors were lower by factor 2 to 10 than the average concentrations measured with the ETD-KfK detectors. The reason for this is probably an inaccurate assessment of the age of the glass (on which the RETRO detector was glued), which we obtained from the users of the building.

With continuous measurements I obtained the data on radon, short-lived radon decay products and equilibrium factor in one-hour intervals. From this data I calculated the average concentrations of radon, the average concentrations of short-lived radon decay products and the average equilibrium factor for the entire periods of continuous measurements. The continuous measurements also showed elevated radon concentrations in most buildings. The equilibrium factor in 8 buildings was higher than 0.40 (the value listed for residential spaces in literature), in two cases even very high (0.71 and 0.74), which points to very poor ventilation of spaces.

In four selected buildings (a school, a kindergarten, an office and a residential house), the concentrations of radon were increased and I got significant deviations between the results from using different measuring techniques. By using the continuous measurements, I calculated the 24-hour equilibrium factor and the equilibrium factor during working hours (a school, a kindergarten, an office) or the time a resident spent in the kitchen. In the classroom, the equilibrium factor during working hours was 0.63, whilst the 24-hour was 0.74. In the playroom, the equilibrium factors were the same at 0.63. Since work in the office takes place in three 8-hour shifts and the space is well-ventilated, the equilibrium factors were lower (the 24-hour was 0.36 and the working hour was 0.33 with the first measurement and 0.32 and 0.33, respectively, with the second measurement). In the kitchen, the 24-hour equilibrium factor was 0.38 and during the time of occupancy it was 0.37.

The effective doses which I calculated on the basis of average concentrations of radon with the KfK detectors, were between <0.02 and 21 mSv $a^{-1}$ and are for the most part comparable to the doses from the neighbouring countries. However, some doses were extremely high and those buildings have already been renovated.

The correlation between the effective dose calculated from the instantaneous concentration of radon and the dose calculated from the average concentration of radon based on the KfK detector is good (r=0.59). Therefore, to obtain a quick overview of the situation, we can calculate the effective dose on the basis of the instantaneous concentration of radon, but it is advisable to carry additional measurements of the average concentration of radon over a longer period of time and later calculate the dose on this basis.

The best approximation to the real dose is the calculation on the basis of the average concentration of radon measured with the solid state nuclear track detector, which is a competitively-priced measurement technique and therefore suitable for mass-scale measurements. If we have measured the equilibrium factor, the dose can be more accurate than the one obtained on the basis of the equilibrium factor from the literature. However, our results have shown that the correlation coefficient – between the dose, calculated on the basis of the solid state nuclear track detector and the equilibrium factor from the literature, as well as the effective dose on the basis of continuous measurement and the measured equilibrium factor – is 0.95, which shows that continuous measurements with mass-scale research of radon and calculations of doses are not necessary.

In special cases, when we find extremely high concentrations of radon, it is still advisable to carry out continuous measurement of radon and its short-lived decay products to make sure about the equilibrium factor, especially since the buildings are poorly ventilated and the equilibrium factor may be higher.
In dosimetry there is a rule saying, that it is better to assess the doses in a more conservative manner and re-evaluate them, than assess them too low.

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