About Radon

The structure of human radiation exposure

It is known that radiation exposure of the public is formed by two main types of ionizing radiation sources – artificial (man-made) and natural. The natural sources are ubiquitous and permanent physical environmental factors. They make a dominant contribution to the exposure of the population and account over 80% of the radiation dose from all known sources of radiation (United Nations Scientific Committee on the effects of Atomic Radiation (UNSCEAR, 2008). **The most powerful source of natural radiation is radon**, which accounts for 42% (1.3 mSv/y) of the total dose (3.0 mSv/y), while the average dose from diagnostic procedures in medicine does not exceed 20%, and the contribution from the pollution caused by technogenic sources, for example, the Chernobyl accident or nuclear power generation (including uranium mining) does not exceed 0.1% and 0.01%, respectively (UNSCEAR, 2008)

Radon hazard and US household risks

The consequences of exposure to radon are expressed by the risk of lung cancer. For example, the increased concentration of indoor radon is considered the most dangerous domestic factor in USA, since the risk of premature death from radon exposure is estimated by **Environmental Protection Agency (US EPA)** at level **21,000 people per year**, which exceeds the annual death rate from other household risks such as drunk driving (17,400), falls in the home (8,000), drowning (3,900) and home fires (2,800). Almost the same level of mortality was obtained for European Union (EU) by results of case-control studies in **13 European countries**. According to the World Health Organization (WHO), between 3 and 14% of lung cancer is caused by the influence of radon.

Reference levels of indoor radon

The radon exposure can be regulated and mitigated, in contrast to other sources, such as cosmic radiation.

The International Commission on Radiological Protection (ICRP) recommends setting a national reference level for the **annual average indoor radon (AAIR) concentration** as low as reasonably achievable in the range of 100-300 Bq/m^3. The WHO guidance is basically the same: a national reference level of 100 Bq/m^3 is recommended, and wherever this is not possible, the chosen level should not exceed 300 Bq/m^3. Recently, the EC issued the 2013/59/Euratom Directive, in which the general reference value was set to 300 Bq/m^3, and the obligation was introduced for member countries to periodically prepare and update a Radon National Plan, which consists of a multi-annual plan to implement the set of actions necessary to reduce the risk of lung cancer associated with radon exposure. The national radon protection strategy should be straightforward and realistic and be considered in conjunction with other public health policies, such as energy saving, non-smoking, and indoor air quality. It should address exposures in new and existing buildings, aiming to reduce the overall exposure of the general population and the highest individual exposures. To help guide action, authorities should set a national reference level for indoor radon levels.

The current indoor reference level in Israel is 200 Bq/m^3 for residential buildings, and 500 Bq/m^3 for work places.

Usually, the concentration of the substance is expressed as a ratio of mass to volume. However, radon is a very rare chemical element; for example, its global mass in the Earth's atmosphere is only about 2 kg when a global atmosphere weight of more than 10^{18} kg. Nevertheless, this very tiny global mass of radon releases much more energy than whole Israel consumes electricity. Such a minor mass concentration of outdoor or indoor radon cannot be measured by weighing. Therefore, instead of mass, the rate of decay of radon atoms (activity) is measured, expressed in "Bq" (one disintegration per second), which is proportional to mass.

Sources of indoor radon

The main source of radon in buildings is an underlying soil, in which a greater or lesser concentration of radon is continuously generated, depending on the soil properties: concentrations of parent uranium or radium, soil density and porosity, presence of cracks, etc. Therefore, the indoor radon in the ground floors and in the cellars is usually higher than in the upper floors. An additional source of indoor radon is building materials that made from minerals extracted from the Earth's crust. If the building is reliably protected from migration of soil radon and emanation from building materials, the indoor radon is usually in the range of 10 (global average outdoor radon) to 50 Bq/m^3, that is not dangerous. If the protection of the building from radon is missing (it happens often in old buildings), the indoor radon may exceed 300 Bq/m^3, representing a serious danger to residents, because people spend indoors about 80% of their lifetime.

Principles for reducing indoor radon (mitigation)

The radon factor was taken into account when designing and construction of buildings relatively recently. To ensure the radiation safety of the building, information is used both about the potential radon hazard of the soil at the construction site, and about the radiation quality of building materials. In the construction of buildings in radon prone areas, passive protection measures (without electricity consumption), such as:

i) special joint of the basement structures and slabs of the ground floor, which prevents the soil radon entering inside building, as shown in the **presentation** .

ii) the use of waterproofing coatings and films with a low diffusion coefficient of radon in the construction of the basement and flooring of the ground floor,

iii) sealing of engineering communications in the underground part of the building,

iv) during the construction of the foundation, laying of material with high air permeability or drainage channels into the ground to enable ventilation, if passive protection measures were insufficient.

For existing buildings with high levels of radon, active measures of protection against soil radon, called mitigation, are generally applied. The greatest effect is achieved by creating a reduced pressure under the foundation of the building or below the floor of the ground floor, as shown in the **presentation** . In addition, an effective solution can be the organization of supply and exhaust ventilation with simultaneous installation of hermetic doors, the location of which depends on the power and spatial distribution of the sources of soil radon.

The problem of measuring and regulating indoor radon

Radon is colorless and odorless, so indoor radon can only be monitored by measuring activity concentration in the air. Extensive, country-wide (mass) measurements of indoor radon concentrations began in the USA, the United Kingdom and Sweden about 25 years ago. However, despite the extensive international experience, there is still neither accepted method to estimate the uncertainty of an average due to temporal variability, nor a unified standard or measurement protocol to determine the AAIR with a given confidence interval.

The problem with the reliable determination of the AAIR is that indoor radon concentrations have significant temporal variation - diurnal, weekly and seasonal. Obviously, the most accurate estimate of the AAIR may be achieved, if the measurements were carried out during the whole year. Obviously, the increase of measurement duration tends to decrease the uncertainty of AAIR. However, in the overwhelming majority of cases (for example, in USA), the indoor radon test is based on short-term measurements (George, 2015). This is due to the fact that the AAIR in the majority of buildings is much lower than the reference level, because most probable value of the AAIR worldwide is ~30 Bq/m^3 (UNSCEAR, 2006). In these cases, the high uncertainty of the AAIR (even at 100% or more) is entirely acceptable for indoor radon test, so there is no necessity for long-term measurements. However, the accuracy of the AAIR assessment based on short-term tests is different due to the inconsistency in the duration of the tests, which may last minutes, days or even months (International Atomic Energy Agency, IAEA-TECDOC-1810, 2017). The uncertainty of the AAIR based on long-term tests (from several months to one year) is lower than that of short-term tests, but also remains unknown.

A review of the evolution of the radon measurement protocols in homes in the USA, from 1993 (EPA, 1993, 1997) to the present time (ANSI/AARST MAH, 2014), shows that the quality assurance regulates only the uncertainty associated solely with the procedure for measuring the radon activity concentration. At the same time, another, much more significant problem related to the estimation of the uncertainty due to indoor radon temporal variation, has not been discussed in depth, and is not resolved yet. The national documents of the USA (ANSI/AARST MAH, 2014; EPA, 1993, 1997), the international ISO standard (ISO 11665-8, 2012), the IAEA publications (IAEA, 2013, 2015, 2017) – none of these documents discuss the AAIR uncertainty and how it depends on the measurement duration. The running EURAMET project “MetroRADON” deals with the uncertainty of radon devices (**10-30%**), but also does not take into account the uncertainty of temporal indoor radon variation.

Tabulated values of coefficient of temporal radon variation considering the mode and duration of the measurements are reported in the paper **(Tsapalov & Kovler, 2018)** . This coefficient expresses the temporal radon uncertainty and varies from 0 (if the test duration is 1 year, but without year-to-year variations) to **100%** or even **more than 200%** (if the test is shorter than 60 or 2 days, respectively). However, increasing the duration and number of the measurements in order to obtain values of this coefficient lower then (20-25)%. i.e. achieve more accurate estimation of the AAIR level, would be inappropriate - due to the existence of year-to-year variations of the AAIR level itself. On average, the amplitude of such variations is approximately estimated in the range of 14% (Bochicchio et al, 2009) to 26% (Steck, 2009) with a maximum year-to-year variation of about 40% (Hunter et al, 2005, Lubin et al, 2005).

Indoor radon regulation principle and measurement strategy

The general principle of indoor radon regulation can be formulated as simple as possible: it is to determine the confidence interval of AAIR in the range from $\overline{C} - U(\overline{C})$ to $\overline{C} + U(\overline{C})$ (or range from 0 to $\overline{C} + U(\overline{C})$ if $U(\overline{C}) > \overline{C}$), and compare the boundaries of this interval with the reference level, according to the following three criteria.

Criterion 1. The AAIR does not exceed the reference level, if the condition (1) is met; then the measurements are stopped, and radon-protective measures are not needed.

$$\overline{C} + U(\overline{C}) \leq C_{RL} \text{ or } k \cdot C(t) \cdot \left[1 + \sqrt{K_V(t)^2 + U_D{}^2}\right] \leq C_{RL}\,, \tag{1}$$

where

$\overline{C}$ is the measured or calculated AAIR value, Bq·m^{-3};

C_{RL} is the reference level, Bq·m^{-3};

$U(\overline{C})$ is the uncertainty of the AAIR, Bq·m^{-3};

$C(t)$ is the measured average indoor radon concentration over the time period of t, Bq m^{-3};

k is a correction factor (rel), taking into account the influence of environmental factors on the “predictable” behavior of indoor radon under certain testing conditions, in which radon behaves with a given probability according to a known (experimentally determined) law; if the signs of the predictable behavior of radon are not established, then k=1;

$K_V(t)$ is the coefficient of temporal radon variation, or the temporal radon uncertainty (rel); it depends on the mode and duration of the measurements and varies from 0 (if t = 1 year, but without year-to-year variations) to **more than 200%** (if t < 2 days); this coefficient expresses the value of the maximum deviation of $C(t)$ from the AAIR and its values are given in the **(Tsapalov & Kovler, 2018)** U_D is the uncertainty of the radon device (rel) or the relative uncertainty of the value of $C(t)$, which is usually in the range **(10-30)%**.

Criterion 2. The AAIR exceeds the reference level, if the condition (2) is met; then the measurements are stopped, and radon-protective measures are carried out.

$$\overline{C} - U(\overline{C}) > C_{RL} \text{ or } k \cdot C(t) \cdot \left[1 - \sqrt{K_V(t)^2 + U_D{}^2}\right] > C_{RL}\,, \tag{2}$$

Criterion 3. If both conditions (1) and (2) are not met, then the continuation of the measurements leads to the situation when one of these conditions will be met, because the parameters $C(t)$ and $K_V(t)$ depend on the measurements duration, while the values of $K_V(t)$ will always decrease. If, from the results of the additional measurements, the conditions (1) and (2) are still not fulfilled, then it is recommended to assume that the AAIR exceeds the reference level.

Thus, the parameter $K_V(t)$ represents the important part of AAIR uncertainty - especially during the short-term measurements, when condition $K_V(t)^2 >> U_D{}^2$ is usually satisfied. It must also be taken into account that under certain testing conditions the values $K_V(t)$ can be reduced by applying coefficient k.

The proposed principle is based on the recommendations of (ISO/IEC Guide 98-3, 2008) and guarantees reliable quality control for indoor radon tests from the metrological point of view, regardless the devices and methods of measuring the radon activity concentration. This simple and clear principle is widely used for quality control in scientific and industrial measurements, but it is still not used in testing indoor radon yet.

This principle is the first step to develop a universal standard and strategy for indoor radon regulation and the most effective measurement protocol, based on a scientific approach. This means that both the most suitable (optimal) and reliable measurement protocol can be created by quantifying such important factors as: (a) the level of potential radon hazard of the territory, (b) the planned number of surveyed buildings in this area, (c) time and financial resources, (d) available radon devices, regardless of the measurement principle, etc. This is especially true in the case of large-scale surveys conducted to identify buildings with a high radon concentration, exceeding the reference level.

The strategy of radon control will be optimized based on the obvious concept that low radon concentration (greatly below the RL) is not worth to measure with high accuracy, because it is costly and consumes long time. This concept is especially relevant in mass measurements, since in most cases the AAIR levels are significantly lower than the RL. Thus, at the first stage of a mass indoor radon monitoring, it is expediently to use inexpensive (simple) devices and short-term methods, involving school children and students. Only in cases when the RL is exceeded by screening results (characterized by high uncertainty), more accurate long-term methods and measuring devices (more expensive) should be used with the participation of radon professionals.

Measurement methods of indoor radon

The main characteristic of indoor radon measurement methods is the test duration, which can be several days or weeks (short-term measurements) or several months (long-term measurements). The most popular are the following methods:

i) The method of passive adsorption of radon using the samplers with activated charcoal. The duration of test is from 3 to 6 days (short-term measurements). The measurement procedure consists of three steps: (a) regeneration of activated charcoal and preparation of samplers, (b) passive exposure of samplers, (c) measurement of the activity of radon adsorbed in the charcoal, and calculation of the radon concentration considering the conditions of sampling. A gamma spectrometer, or a liquid scintillator, or a gamma-beta radiometer is used to measure the radon activity in charcoal.

Note that in the USA, more than 24 million indoor radon tests were carried out using the method of radon adsorption, while the share of long-term tests is about 2% (George, 2015).

We have developed and use for passive exposure the miniature (about 20 ml) charcoal flacon type CF-13 which contains 13 ml granular activated charcoal. The volume equivalent of the CF-13 varies from about 10 to 20 liters, depending on the duration of exposure and air humidity. The effect of air humidity is taken into account by determining the increase in the mass of the flacon over the test period.

ii) The electret method, based on measuring the difference in surface charge of a teflon film before and after the test, the duration of which usually ranges from several days to several months depending on the level of radon concentration. The reduction of the charge of the teflon film is due to the ionization of air in the sampling chamber created by the alpha radiation of radon and its progeny.

iii) The method using solid-state nuclear track detectors (SSNTD) based on recording the density of tracks (defects) on a thin film resulting from alpha radiation generated by radon and its progeny over the test period from one month to one year (long-term measurements). The film is located in the sampling chamber, into which radon penetrates by diffusion. After exposure the film is chemically etched to improve the visibility of the tracks.

iv) The method of continuous measurements using a radon-monitors with a period of recording the result from one to several hours with unlimited test duration. Usually, the ionization chamber or semiconductor detector located inside the chamber is used.