Reacting upon the increasing concern of possible harmful effects due to radon, more and more countries established, or intend to establish in the near future, legislation for the radon level both for homes and workplaces. The dose due to radon seems to be more complicated to assess for workplaces than for homes, although the basic principles of dose estimation are the same. The doses at workplaces need to be estimated by individual approaches, but such requirement is usually not reflected in the legislations. The present study deals with characteristic situations and refers to findings and considerations in the cases of offices, schools, underground workplaces, and open air working situations with relatively high radon level. It discusses the possible inaccuracies caused by the improper selection of time periods and methods in the measurements of the average radon concentration. The purpose of this paper is to provide some examples (mainly based on the authors’ experiences) to show difficulties that might emerge in the determination of average radon concentrations in various workplaces. This will help choose the proper measurement methods for each case and contribute to the regulator’s work in the precise and unambiguous legislation phrasing.

KEY WORDS: radon, workplaces, legislation, dose assessment.

I INTRODUCTION

In the past decades, the concern for public exposures due to natural radiation sources has increased. Among the many sources for radiation exposure to the general population, the natural sources are generally main contributors and radon is the most important. Historically, the detrimental health effect attributed to radon came to light in connection with frequent lung disease (lung cancer) incidence among underground miners. Studies of underground miners firmly demonstrate the connection between lung cancer and elevated radon level in air. Recently, several epidemiological surveys seem to support the assumption that even the relatively low level of ambient radon could increase the risk of lung cancer. These findings can justify the reason why increasing attention is paid to radon both at workplaces and homes nowadays.

Although people usually spend less time at workplaces than at home, the workplaces present a wide range of difference concerning the exposure due to radon and its progeny. For most of the countries which have legislations about radon, regulations for workplaces are different from those for homes. These regulative rules attempt to reflect the special features of the work environments.

The International Commission on Radiological Protection (ICRP) provides guidance to regulatory authorities on the radon action levels in its publication of ICRP-65. It suggests that workers who are not regarded as being occupationally exposed to radiation should be treated in the same way as the general public. By applying this guideline, the suggested action level is estimated to be between 500 – 1,500 Bq m⁻³ assuming (1) the ratio of time one spent at work versus at home, (2) a widely accepted average equilibrium factor of 0.4 and (3) dose conversion conventions. The action level recommended by the European Union (EU) is in accordance with the recommendations of ICRP-65, which suggest the level between 500 – 1,500 Bq m⁻³. A number of EU member countries established uniform reference level for all types of workplaces. However, some recommendations suggest that, for workplaces with high occupancy such as hospitals, residential institutions, schools, kindergartens etc., it would be appropriate to adjust the action level to reflect the increased occupancy or they should be treated as homes for the purpose of setting an action level for remedial measures.

In the UK, the Health and Safety Executive (HSE) have adopted a radon action level of 400 Bq m⁻³ for workplaces based on advice from the National Radiological Protection Board (NRPB). Assuming a daily average concentration of 400 Bq m⁻³ and an equilibrium factor of 0.5, the dose results in an annual dose of 5 mSv, which is the UK limit for non-radiation workers.

In the Scandinavian countries detailed regulations were established. Their recommended action level for radon in aboveground workplaces, defined as an annual average radon concentration during working hours, is 400 Bq m⁻³. An action level for radon in underground workplaces, expressed as the average activity concentration over working hours, is recommended to be within the interval 400 – 1,500 Bq m⁻³. If the working time is less than 2,000 hours per year, this level
could be corrected. Additionally, special attention is paid to children; the action level for schools and kindergartens was set to 400 Bq m\(^{-3}\) for existing buildings and 200 Bq m\(^{-3}\) for new ones.\(^{15}\) This is the same level as for homes.

It seems that some other countries also emphasized attention for schools. For example, in Ireland, the advisory reference level for schools is 150 Bq m\(^{-3}\) and for other workplaces it is 200 Bq m\(^{-3}\).\(^{16}\) Israel has one enforced reference level, 200 Bq m\(^{-3}\), for schools and day care homes and one advisory reference level, 400 Bq m\(^{-3}\), for all other workplaces. For new schools and day care homes, Israel applies an advisory reference level of 40 Bq m\(^{-3}\), whereas the level for other new workplaces is 200 Bq m\(^{-3}\).\(^{15}\)

The USA has a single reference level (150 Bq m\(^{-3}\)) which is applied to schools as well.\(^{16}\)

It can be seen from the above cited examples that various legislation systems are adopted in the world, and only a small part of the cases supplemented detailed recommendations or guidelines for the measurement of radon in air in workplaces. Using different methods in the measurements can lead considerable differences in the results and make more difficult in the comparability of the cases. Because radon concentration is affected by a lot of factors (season, period of the day, temperature, air pressure, air exchange rates, etc.), the average radon concentration should be determined with caution. Several studies have been devoted to the seasonal, monthly and daily variations of radon concentration in dwellings\(^{17}\) and offices\(^{18,19}\) providing useful information for measurement-planning.

The year-long integrated measurements are considered as the most reliable ones. However, these might not be acceptable in many cases because of the expense and the urgent need for knowing the results. In the Scandinavian countries the regulation requires that the average has to be determined from statistically sufficient measurements.\(^{9}\) Other authors suggest 1 - 3-month-long measurements for workplaces.\(^{20}\)

The determination of the average radon concentration over the working hours (i.e. excluding the non-working periods), which is a demand in some regulations, might also presents a problem. This can be done by using expensive apparatus which continuously measure the hourly radon concentration or by conducting measurements only during the working hours with integrating detectors. In the second case, the storage of these detectors in a radon-free place during the ineffective periods can present difficulties. In some cases, it seems to be reasonable to introduce a correction factor for converting the 24 h monitoring data to work-day values for radon concentrations.\(^{16}\)

For example, in Hungary, the action level for workplaces is 1,000 Bq m\(^{-3}\) for average radon concentration over the working hours.\(^{21}\) This legislation actually became effective in January 2003. For the setting of this action level, an occupational exposure of 2,000 hours per year and an equilibrium factor of 0.4 were assumed. This level is in accordance with the ICRP-65 and the EU suggestion, i.e., the level is the mid-value of their advised interval (500 - 1,500 Bq m\(^{-3}\)).

This paper discusses the possible inaccuracies caused by the improper selection of time periods and methods in the measurements of the average radon concentration at workplaces.\(^{22,23}\) Examples are presented such as radon concentrations measured in different workplaces: a hospital cave, a manganese mine, a uranium tailings pond, schools and offices.\(^{18,22 - 24}\) Based on this data, this paper discusses the possible differences of the outcome of calculation the average radon concentration in case of absence of a clear and detailed description of measurement procedure.

II MEASURING TERM

The measurements carried out in two underground workplaces were analyzed to show the importance of choosing the
ideal measuring term (time period). The first place is a hospital cave situated in a karstic rock under the town hospital of Tapolca, Hungary.\(^{24}\) It is used for treating respiratory disease because of the clear air. The inside air of the cave contains usual pollutants such as dust and aerosols in relatively low concentration. The cave has no any artificial ventilation; that is, high level of radon can be expected. The radon concentration was measured continuously (hourly averages) in the cave over a period of three years using a Dataqua (Dataqua Elektronikai Kft. Hungary) device.

The monthly average radon activity concentrations during the three-year-period in the hospital cave can be seen in Fig. 1. The seasonal variation of radon concentration here is considerable.

Table 1 shows the minimum and maximum values of average radon activity concentration in the cases of different measuring duration (1, 3, 6 or 12 months) taken during the three years of the total investigation period.

In the one-month-long measurements the averages were 0.51 kBq m\(^{-3}\) in December and 12.4 kBq m\(^{-3}\) in August, showing 24-fold difference. Even if one chooses six-months-long measuring periods the result can show 7-fold difference. If the six-months-long measurements are executed in the first and second part of the year (January – June, and July – December), the averages are 3.64 ± 0.37 kBq m\(^{-3}\) and 5.7 ± 0.40 kBq m\(^{-3}\) respectively. Although these are different from the yearly average (4.67 ± 0.12 kBq m\(^{-3}\)) by approximately 20%, the difference is acceptable. These findings are in good accordance with other results referring to the typical summer maxima and winter minima of cold karstic caves.\(^{25,26}\)

The second example place is a manganese mine in Ürküt, Hungary. Here 9 sampling sites were chosen, taking the different mining technology used at the given sites into account. The monthly average radon concentrations were measured with alpha track detectors (CR-39) changed monthly for a year. The min-max and the monthly average radon concentrations measured at 9 points of the mine are presented in Fig. 2. The average radon concentration for the whole mine was 807 Bq m\(^{-3}\). Comparing this value to the averages for the different places (570 – 997 Bq m\(^{-3}\)), the variation is not higher than ± 30%. In the main tunnel the yearly average was 756 Bq m\(^{-3}\), which is very close to the whole average measured at the different location of the mine. The averages come from the one-month and three-month measurements showed 3 – 10-fold differences indicating that they should apply with great caution.

### Table 1

<table>
<thead>
<tr>
<th>Measuring duration (month)</th>
<th>Average radon concentration (kBq m(^{-3}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (December)</td>
<td>0.51 ± 0.03 (August)</td>
</tr>
<tr>
<td>3 (December – February)</td>
<td>0.67 ± 0.23 (June – August)</td>
</tr>
<tr>
<td>6 (October – March)</td>
<td>1.11 ± 0.38 (April – September)</td>
</tr>
<tr>
<td>12 (January – December)</td>
<td>4.67 ± 0.12</td>
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Fig. 2 Monthly average radon concentrations at different points of the manganese mine.
Consequently, in workplaces where the expected changes of radon concentrations with the seasons are considerable, 12-months-long measurements are strongly recommended. If it is not possible, a minimum six-month period should be chosen that contains both summer and winter months (for example, February – July or August – January).

III THE ACTUAL WORKING TIME

Because some regulations, including the Hungarian one, require that the average radon level should refer to only the actual work periods, it is important to investigate the effect of this consideration. Thus, the ratio of the average radon activity concentrations measured during the actual working time to the average over the whole-time period was analyzed in the cases of the hospital cave, the manganese mine, a uranium tailing ponds under recultivation, schools, kindergartens and offices.

The measurements were executed continuously, with 10 minutes or one-hour integration time, for several days or months using different devices (Pylon AB-5, Dataqua, Radim 2P, Radim 3P (Radon Analytics) and AlphaGUARD PQ-2000 (Genitron Instruments GmbH)). Additionally, track etch detectors (CR-39) were also applied.

Analyzing the results of measurements executed in the hospital cave, it was found that the yearly average radon concentration was lower than the average measured in the working hours. Therefore, it is 16% higher than the average level for those who spend 8 hours in the treatment rooms of the cave. This means, however, that the average is slightly higher during the working hours than the non-working periods, but the difference is not considerable. It is reasonable to expect that it cannot be assigned to the work-activity in the rooms, but presumably to the given circumstances (daily variation of radon concentrations due to changes of temperature, air pressure, etc.).

In the manganese mine the work was in eight-hour shift. Figure 3 shows the change of radon activity concentration in the mine tunnel. The ventilation system works only during the working hours, therefore the radon level increases at nights and in the weekends, while during the working hours it is considerably lower. In this experiment track detectors were placed at the different locations of the mine and some miners wore the same type of detectors on their clothing during work. These detectors were kept in a place with low radon concentration (< 12 Bq m⁻³) after the working hours. The detectors were evaluated each month. The average radon concentration shown by detectors placed in the mine was 807 (570 - 997) Bq m⁻³, which represent the value over 24 hours a day. On the other hand, the average level coming from the detectors worn by the workers (representing the working hours) was only 399 (325 – 517) Bq m⁻³, which means 2 times difference. The artificial ventilation strongly effects the radon concentration during working hours; accordingly, it would be advisable to know the levels during the effective working time for a decision about mitigation.

Another example is an open-air work place, namely a uranium tailing pond under recultivation. Recultivation works started immediately after the uranium mine was closed in Hungary. The tailing pond was covered with soil after dewatering. In the surface of the dry tailing pond, however, an intensive radon exhalation was expected. Continuous measurements were carried out to investigate the variation of the radon concentration at the tailing pond and the workers had worn alpha track detectors on their clothes. The detectors were kept in a building close to the tailing pond after work.

Figure 4 shows the monthly average radon concentrations during the working hours and over the whole time, in the case of the uranium tailings pond site. The yearly average over the whole time was 625 Bq m⁻³, which is high considering that this is an open-air place. Monthly differences are well-marked. The ratio of the averages during the working time to the averages over the whole days (Fig. 5) is changing significantly. Probably the work-activities resulted in intensive
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Furthermore, it was found that the personal dosimeters worn by the workers on their clothing showed two times higher radon concentration than the radon detectors placed directly at the workplace. The reason, which turned out later, was that, during the non-working periods, the personal detectors were stored in the dressing-room, where the radon concentration was higher than the workplace. This finding also suggests, if one wants to take the exact working hours into account, radon concentration should be measured at the storage place as well. Keeping the detectors at places with considerably lower radon concentration during non-working periods was applied in other investigations as well.28)

Other differences were found from the results of measurements in two Hungarian schools. The radon concentrations increased during the nights and weekends, so the average was 497 Bq m$^{-3}$ (a) and 287 Bq m$^{-3}$ (b). During the time when the children were inside, the averages were 125 Bq m$^{-3}$ (a) and 84 Bq m$^{-3}$ (b). Consequently, the average radon concentration during the effective time was considerably lower than the most rigorous regulation level (150 – 200 Bq m$^{-3}$). Similar results were found in other schools and kindergartens in Hungary and other European countries as well.30) Therefore, it is reasonable to state that it would be unnecessary to mitigate in these cases because the levels during the effective time are significantly lower than the levels over the whole time.

Fig. 4 Monthly average radon concentrations, during the working hours and over whole days, at a uranium tailings site.

Temporal variations in radon concentrations in typical office buildings in Tokyo were investigated.9) In this survey long-term measurements were executed for 5 years using CR-39
nuclear track detectors which were exchanged for new detectors every two months. For the short-term measurements AlphaGUARD and Pylon AB-5 instruments were used. The average radon concentration throughout the entire observation period was 63 Bq m\(^{-3}\). (This is higher than the average in Japan (16 Bq m\(^{-3}\))\(^{31}\) probably due to the airtight structure of these buildings.) The continuous measurements showed a very similar pattern to the ones experienced in the cases of schools represented by Fig. 6. This means that average over working hours considerably lower than the average over the whole day. The difference between the two averages is more than 2-fold. This pattern can easily be explained by the use of air-conditioning during work and keeping them switched off in non-working periods. Other authors presented similar results concerning offices.\(^{19}\)

**IV CONCLUSIONS**

The findings cited above indicate that much more disturbing effects emerge at the determination of the average radon concentration in workplaces than in homes. The one-month-long measurements might show very high variation (as it is demonstrated in the examples of the cave and the mine).

The average radon concentration during working hours can considerably differ from the average of the whole-day period in cases of frequent air change or using artificial ventilation.

These mistakes can result in considerable over- or underestimations in the dose calculation and can influence the decision about the intervention of the places in question. So, it would be advisable to execute short-term (a week) continuous measurements parallel with the long-term (some months) ones to follow the daily variations of the radon concentration as well.

Also, it would be reasonable to introduce a correction factor for converting from 24-hours monitoring data to effective working hours values for workplaces, such as offices, schools, kindergartens, etc., where the frequent air change or air conditioning during working hours are usual practice. Suggesting some kind of correction factor reflect to the monthly and seasonal variations in special workplaces such as mines, caves, open air uranium tailing ponds, etc. seems to be more complicated. They need different approaches to determine the radon concentration during work and to estimate the resulting dose. In these cases the individual approach seems to be not evaluable.

Investigations discussed in this paper can provide useful scientific background for regulators who are responsible to work out a reasonable, practical and clear legislation for radon in workplaces.

**Acknowledgement**

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