RADON CONCENTRATION MEASUREMENTS IN CAVES OF BUDAPEST*

By

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(Received May 3, 1970)

Presented by Gy. CSOM

1. Introduction

The most significant component of the natural radioactivity of atmosphere is radon (^{222}Rn) and its decay products. The radon concentration in air is of the order of 10^{-13} Ci/litre in general, but in closed spaces it may be higher, depending on the radium in the environment. In this case, radiation exposure on persons on the spot increases, primarily due to the radon decay products.

Near the Gellért-bath, in the interior of the Gellért-hill, Budapest, a two-level cave system is now being detected. On the upper level, the Research Institute for Water Research Station, while on the lower level thermal caves for asthmatics are being examined. Experiments made in common by the Radiation Protection Group of the Atomic Reactor of the Budapest Polytechnical University and the Health Physics Dept. of Budapest Hygiene and Epidemiology Institute involved determination of radon concentrations in the air of each cave space. ICRP recommended a maximum radon concentration of $1 \cdot 10^{-11}$ Ci/litre air, but since it is usual to take its thirtieth part as permissible for the population, it is advisable to make estimations in every case where specific radon activity in air is above the average.

In what follows, radon determination data in the air of this cave system will be discussed, beginning with the determination method; radon concentration determination was based on the so-called "Tsivoglou-method". Several types of aerosol samplers have been applied, with different filtration efficiencies which were determined by a simple method to be presented.

Thereafter determination results will be described, concerning both the radon concentrations of different cave spaces, and the efficiency of ventilation. Evaluation will be followed by assessments of radiation exposure based on known concentration values.

* Presented at the Second Congress of the International Radiation Protection Association, Brighton, May 3—8, 1970.

2. Determination of radon concentration

The applied determination method of radon concentration will be described, beginning with the primordial characteristics of the radioactive radon, then the Tsivoglou-method will be presented, followed by the determination of the filtering efficiency of samplers.

2.1. Characteristics of radon and its decay products

Radon (^{222}Rn) is the first decay product of radium, the heaviest gas known. As to its chemical properties, it is an inert gas, liquid between —61 °C and —71 °C, and solid below this limit. It has a half life of 3.825 days, according to the scheme in Fig. 1. Table 1 contains some data on radon and short-lived radon daughters, demonstrating that half lives of isotopes RaA . . . RaC' are much shorter than that of radon, therefore these will be relatively soon (in 4—5 hours) in equilibrium with the initial radon quantity in closed space.

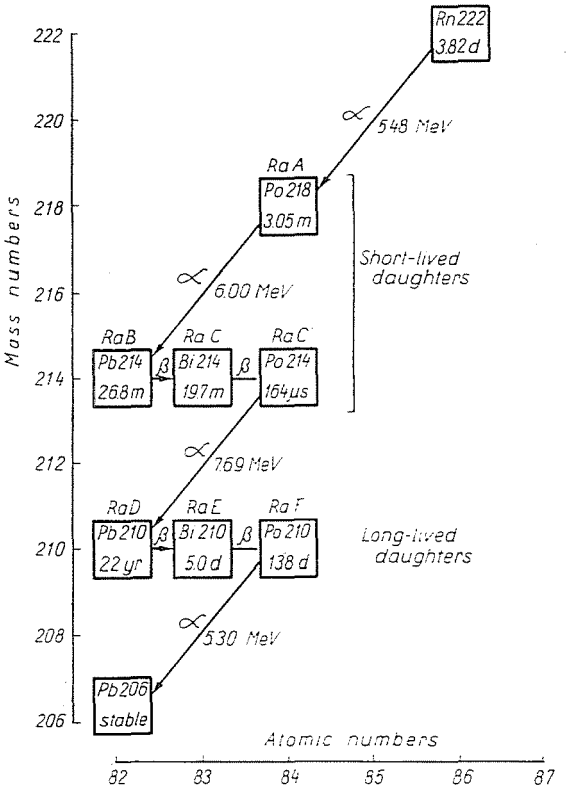

Fig. 1. ^{222}Rn decay scheme

Table 1

Predominant radiations from ^{222}Rn and its short-lived daughters

i	Nuclide	Type of radiation	Energy [MeV]	Half-life [min.]	Decay constant [min.$^{-1}$]
1	Rn	α	5.48	$5.508 \cdot 10^{3}$	$1.258 \cdot 10^{-4}$
2	RaA	α	6.00	3.05	0.2272
3	RaB	β	0.65	26.8	0.02586
4	RaC	β	3.15	19.7	0.03518
5	RaC'	α	7.69	$2.5 \cdot 10^{-5}$	$2.77 \cdot 10^{5}$

The radon MPC in air recommended by ICRP is $1 \cdot 10^{-11}$ Ci/litre. In this country, the actual protection by the law [1] distinguishes between occupants of isotopic working (group A) places, those not working with isotopes but working near isotopic working places (group B) and inhabitants of the environment of working places with radiation hazard (group C). These values are compiled for radon in Table 2.

Table 2

Maximum permissible concentrations of ^{222}Rn in air (Hungarian standards)

Group	MPC [Ci/litre]
A	$3 \cdot 10^{-11}$
B	$1 \cdot 10^{-11}$
C	$3 \cdot 10^{-12}$

2.2. The Tsivoglou-method

In general, atmospheric radon determination is done by ionization chambers or special scintillation detectors. The method to be presented is based on the alpha-activity of short-lived radon daughters bound to aerosol particles of air to estimate the atmospheric radon concentration during sampling.

The determination comprises the following steps:

1. aerosol sampling,
2. determination of the alpha-activity of the air sample, (decay curve recording),
3. use of the decay curve to calculate concentration values.

Three types of samplers were available: aerosol sampler type Fleming, aerosol sampler NA-2 (System KFKI-Hungary), and an aerosol sampler type FH-422 (Frieseke-Hoepfner) operating by the principle of electrostatic condensation. For the two former samplers, a membrane filter AUFS manufactured in ČSSR has been applied.

Alpha-activity of short-lived radon daughters has been determined by means of a scintillation alpha-crystal NP-227 (System Gamma-Hungary) connected to a line printing scaler: after sampling, the filter was placed on the alpha-crystal to measure the decrease with time of the alpha-activity of short-lived daughters on the filter (recording decay curve).

The decay curve had been analysed by the Tsivoglou-method: from the knowledge of alpha-activities at 5, 15 and 30 minutes, the specific RaA, RaB and RaC activities could be calculated, with respect to the sampling time. This evaluation method has the advantage of being not conditioned by radioactive equilibrium between radon and its short-lived daughters.

Before considering mathematical relationships, let us examine the process during and after the sampling time.

At the beginning of assay no active atoms are found on the filter. During air sampling, aerosols to which solid decay products of radon are bound, are deposited on the filter. At the end of sampling a definite number of RaA, RaB, RaC ... etc. atoms are found on the filter. Number of RaA atoms depends on the mean sampling flow rate, filtering efficiency, RaA concentration in air and decay during sampling, while for the other daughter elements, the number of active atoms arising from the previous member of the decay set is to be taken into consideration. After the sampling ended, collected active atoms decay with half lives seen in Table 1. From the time-dependence of the reduction of alpha-activity on the filter, the number of RaA, RaB and RaC atoms on the filter at the end of the sampling can be determined, then from these numbers average concentrations in air of each isotope during sampling can be calculated.

Notations applied in mathematical deductions are:

N_i — number of i-th atoms on the filter
Q_i — concentration in air of the i-th isotope (atoms/litre)
A_i^s — specific activity of the i-th isotope (Ci/litre)
t — sampling time (min)
T — decay time after the end of sampling (min)
$A(T)$ — alpha-activity at time T after sampling ended (imp/min)
v — mean sampling flow rate (litre/min)
η — filtering efficiency.

The described process is expressed by the differential equation:

$$\frac{dN_i(t)}{dt} = \eta \cdot Q_i \cdot v + \lambda_{i-1} N_{i-1} - \lambda_i N_i \tag{1}$$

Our determinations being made with 5 min sampling times, substituting $t = 5$ and solving the differential equation yields for the number of RaA, RaB and RaC atoms gathered on the filter at the end of sampling:

$$N_2^0 = 2.988 \cdot Q_2 \cdot \eta \cdot v \tag{2}$$

$$N_3^0 = (1.91 \cdot Q_2 + 4.69 \cdot Q_3) \cdot \eta \cdot v \tag{3}$$

$$N_4^0 = (0.11 \cdot Q_2 + 0.31 \cdot Q_3 + 4.58 \cdot Q_4) \cdot \eta \cdot v \tag{4}$$

Notice that because of its state, the radon gas is not bound on the filter (therefore no test is made for $i = 1$), on the other hand, half life of RaC' is so short that it can be omitted from the aspect of results (thus, N_5^0 is negligible).

T min after the end of sampling, the magnitude of alpha-activity is given by the sum of RaA and RaC' alpha-activities:

$$A(T) = \lambda_2 N_2 + \lambda_5 N_5 \tag{5}$$

N_2 and N_5 can be expressed in terms on N_i^0, and N_5^0 being negligible, T min after sampling, the alpha-activity is:

$$A(T) = 0.2326 \cdot N_2^0 \cdot e^{-\lambda_2 T} + (9.761 \cdot N_3^0 + 11.016 \cdot N_2^0) \cdot 10^{-2} \cdot e^{-\lambda_4 T} +$$
$$+ (3.518 \cdot N_1^0 - 9.761 \cdot N_3^0 - 11.511 \cdot N_2^0) \cdot 10^{-2} \cdot e^{-\lambda_4 T} = f(Q_i, \eta, v) \tag{6}$$

Substituting $T = 5$, 15 and 30 min, respectively, into (6):

$$A(5) \cdot 10^2 = 7.459 \cdot N_2^0 + 0.388 \cdot N_3^0 + 2.951 \cdot N_4^0 \tag{7}$$

$$A(15) \cdot 10^2 = 1.428 \cdot N_2^0 + 0.863 \cdot N_3^0 + 2.076 \cdot N_4^0 \tag{8}$$

$$A(30) \cdot 10^2 = 1.077 \cdot N_2^0 + 1.096 \cdot N_3^0 + 1.225 \cdot N_4^0 \tag{9}$$

The decay curve is being used to practical analysis, from which $A(5)$, $A(15)$ and $A(30)$ can be determined (the counted impulse number has to be corrected by the detection efficiency of the alpha-crystal), hence, the numbers of RaA, RaB and RaC atoms on the filter by the end of sampling are:

$$N_{\mathrm{RaA}}^0 = 17.3 \cdot A(5) - 39.3 \cdot A(15) + 24.8 \cdot A(30) \tag{10}$$

$$N_{\mathrm{RaB}}^0 = -6.9 \cdot A(5) - 84.9 \cdot A(15) + 160.6 \cdot A(30) \tag{11e}$$

$$N_{\mathrm{RaC}}^0 = -9.1 \cdot A(5) + 110.5 \cdot A(15) - 83.8 \cdot A(30) \tag{12}$$

In knowledge of the N_i^0, Q_i concentrations in air are obtained making use of (2), (3) and (4):

$$Q_{\mathrm{RaA}} = \frac{0.335 \cdot N^0_{\mathrm{RaA}}}{\eta \cdot v} \tag{13}$$

$$Q_{\mathrm{RaB}} = \frac{0.213 \cdot N^0_{\mathrm{RaB}} - 0.407 \cdot Q_{\mathrm{RaA}} \cdot \eta \cdot v}{\eta \cdot v} \tag{14}$$

$$Q_{\mathrm{RaC}} = \frac{0.218 \cdot N^0_{\mathrm{RaC}} - (0.024 \cdot Q_{\mathrm{RaA}} + 0.0677 \cdot Q_{\mathrm{RaB}}) \cdot \eta \cdot v}{\eta \cdot v} \tag{15}$$

Concentration values can be converted into the practically used Ci/litre units according to the relationship:

$$A^s_i = \frac{\lambda_i \cdot Q_i}{2.22 \cdot 10^{12}} \tag{16}$$

With numerical values of the decay constant:

$$A^s_{\mathrm{RaA}} = 1.02 \cdot 10^{-13} \cdot Q_{\mathrm{RaA}} \tag{17}$$

$$A^s_{\mathrm{RaB}} = 1.16 \cdot 10^{-14} \cdot Q_{\mathrm{RaB}} \tag{18}$$

$$A^s_{\mathrm{RaC}} = 1.44 \cdot 10^{-14} \cdot Q_{\mathrm{RaC}} \tag{19}$$

If RaB and RaC concentrations are known, radon concentration values can be determined by means of Fig. 2, according to the theoretical considerations by LOCKHART and PATTERSON [3]. Dashed line is taken into consideration

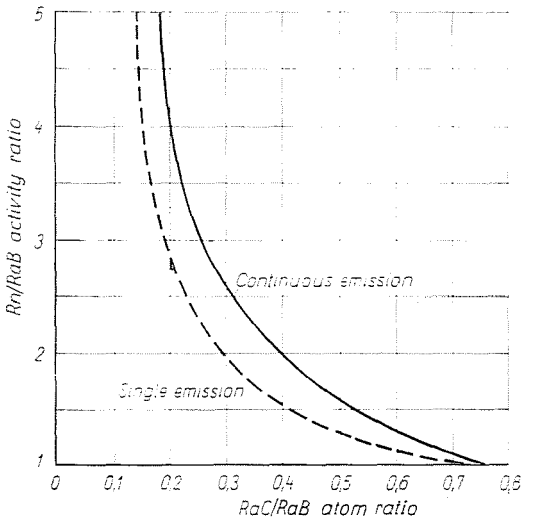

Fig. 2. Rn to RaB specific activity ratio as a function RaC to RaB atom number ratio [3]

if no constant radon emission is to be reckoned with at the sampling spot; otherwise the continuous line is to be used.

2.3. *Determination of the filtering efficiency of aerosol sampler FH-422*

As it has been mentioned, an aerosol sampler type FH-422, operating by the principle of electrostatic condensation was available. To correctly determine radon concentration values, exact filtration efficiency of the sampler must be known. Air in tested caves being generally of high vapour content, filtering efficiency of sampler FH-422 was assumed to be below 40 and 22 per cent, rated by the producer, and determined by TRITREMMEL [5], respectively.

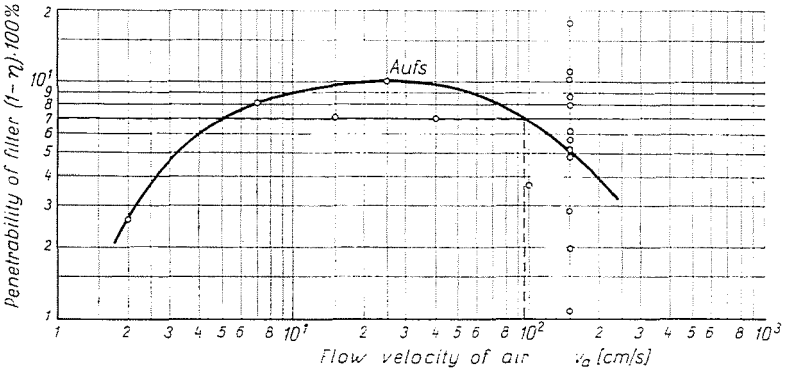

Fig. 3. Penetrability of membrane filters AUFS as a function of air flow rate [5]

Filtering efficiency can be determined by calibrating with an aerosol sampler of known filtering efficiency. Essentials of the procedure consist in confronting the alpha-decay curve of the aerosol sample by the principle of electrostatic condensation to that of a sample on a filter with known filtering efficiency. Simultaneous samplings will deliver decay curves of identical shape. Magnitude difference between both curves is due to differential filtering efficiencies and to generally different sampling flow rates, as it appears from Eqs (2). (3) (4) and (6). Thus, standardizing the curves for identical sampling flow rates, the quotient of alpha-activities determined from decay curves at an arbitrary time after the end of sampling will be constant. Filtering efficiency of the filtering material being known, that of the sampler operating by the principle of electrostatic condensation can be determined.

In conformity with this principle, the sampler FH-422 was compared to an aerosol Fleming sampler, using membrane filter AUFS as filtering material. Filtering efficiency of membrane filters AUFS is known to be at 90 to 100 per cent, depending on the flow speed of the air through the filter. For data see HERRMANN [6] (Fig. 3).

In our tests, air was sampled for 5 min in a vapour-rich cave. Decay curve data are compiled in Table 3. In knowledge of the counting efficiency of the alpha-counter, alpha-activity of samples have been calculated (Table 3. columns 2 and 3). The sampling flow rate of sampler FH-422 and of the Fleming sampler being $v^{FH} = 500$ litre/min and $v^{FL} = 114$ litre/min. respectively, measured alpha-activities were standardized to a sampling flow rate of 100 litre/min (Table 3, columns 4 and 5). Values were plotted as a function

Table 3

Determination of the filtering efficiency of the aerosol sampler FH-422

T [min.]	n_0^{FH} [dpm]	n_0^{FL} [dpm]	$n_0^{FH}/v^{FH} = A$ $\left[\frac{\text{dpm}}{100 \text{ litre/m}}\right]$	$n_0^{FL}/v^{FL} = B$ $\left[\frac{\text{dpm}}{100 \text{ litre/m}}\right]$	$k = \frac{A}{B}$
2	3125	3778	625	3325	0.19
5	2751	3281	550	2875	0.19
10	2376	3019	475	2650	0.19
15	2249	2782	450	2437	0.18
20	2059	2637	414	2312	0.18
25	2002	2548	400	2212	0.18
30	1875	2396	375	2100	0.18

tion of time after the end of sampling (Fig. 4). It is obvious from the figure, too, that curve shapes are identical, in conformity with theoretical considerations.

Thereafter, quotient

$$k = \frac{A}{B} = \frac{\eta_{FH}}{\eta_{AUFs}} \tag{20}$$

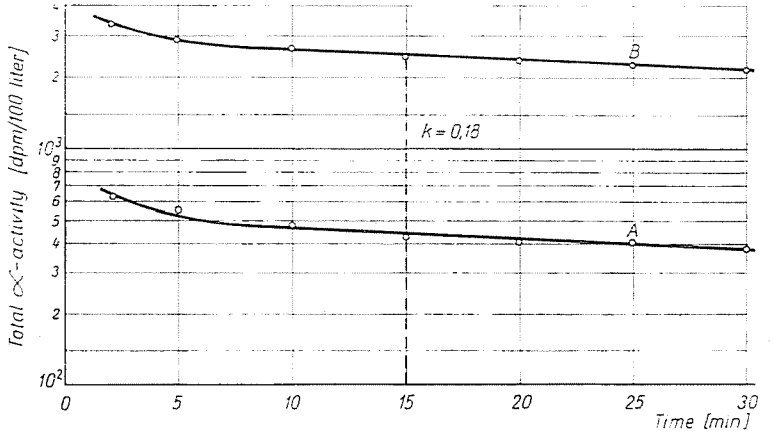

Fig. 4. Alpha decay curve normalized to 100 litre/min sampling flow rate

has been determined for an arbitrary abscissa of the curve (in our example $T = 15$ min), where η_{FH} and η_{AUFS} are filtering efficiencies of samplers FH-422 and AUFS membrane filter, respectively. Taking into consideration the 20 sq. cm of effective surface of filtering material AUFS and sampling flow rate $v^{FL} = 114$ litre/min of the sampler, the air flow rate through the filter is $v_a = 95$ cm/s. At this flow rate the filtering efficiency of filter AUFS is 93 per cent (Fig. 3), i.e. $\eta_{AUFS} = 0.93$.

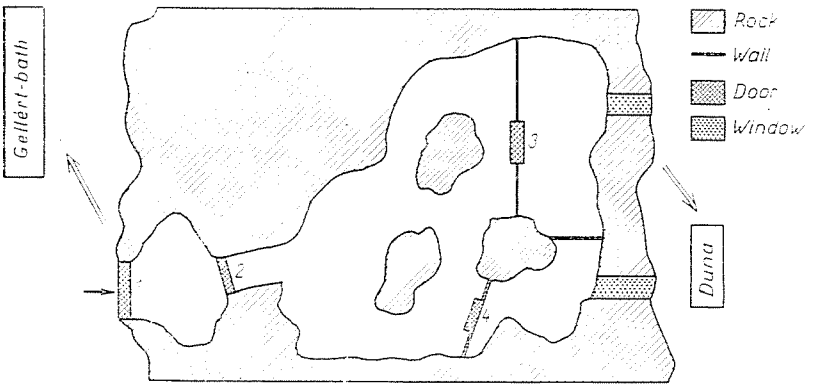

Fig. 5. Layout of the Karstic Water Research Station (upper cave system inside Gellért-hill)

According to relationship (20) with $k = 0.18$ (in conformity with Fig. 3 and last column in Table 3):

$$\eta_{FH} = k \cdot \eta_{AUFS} = 0.18 \cdot 0.93 = 0.17$$

Thus, the filtering efficiency of the FH-422 aerosol sampler for a nearly 100 per cent relative humidity is as low as 17 per cent.

Test results confirmed the preassumption that for a high relative humidity the filtering efficiency of the electrostatic sampler decreases, probably since short-lived radon daughters are adsorbed also on suspended water droplets in addition to solid aerosols in air. Because of their great volume and in accordance with electrostatic condensation laws, water droplets are condensed on the sampler pan at an inferior efficiency, resulting in the decrease of sample activity and of filtering efficiency.

3. Test results and evaluation

Let us see first the schematic layout of the test ambience (Fig. 5). The Research Institute of Water Resources have developed a Karstic Water

Research Station on the top level of the tested two-level cave system. This fact helped us to make tests in real cave environment but in the same time under excellent technical conditions (power supply etc.).

Our tests aimed at determining ventilation efficiency. To this purpose, doors 1, 2, 3 and 4 (in Fig. 5.) were closed down for a day, during this time radioactive equilibrium came about between radon and its short-lived daughters. Thereafter doors 1 and 2 were opened for 100 min. In view of this short time, exact determination of concentration values of radon and its decay products had to be omitted, as it would have required 45 minutes as it was indicated at the description of the test method. Instead of this, air sampling was taken for 1 min and for another min. after sampling the total-activity of the filter was measured. Though no direct relationship can be established between total alpha-activity and radon concentration, efficiency of ventilation could be approximated.

Table 4

Total alpha-activity as a function of ventilation time

Time of ventilation [min.]	Volume of air flow [litre]	n_0 [dpm]	A [pCi]	A^s $\left[\frac{pCi}{litre}\right]$	%
0	470	9159	2015	4.28	100
5	470	7550	1661	3.53	82
10	470	6745	1484	3.16	74
15	470	5968	1313	2.79	65
20	470	5323	1171	2.49	58
25	470	4327	952	2.02	47
30	470	4395	967	2.06	48
35	470	4200	924	1.97	45
40	470	4127	908	1.93	45
45	470	4095	901	1.92	45
65	470	3973	874	1.86	43
90	470	3527	776	1.65	38
100	470	3600	792	1.68	39

Test results are compiled in Table 4. The first column shows durations after ventilation started. The second column contains air volumes flown through the filter during 1 min, the third one the counting rates in the first minute after sampling corrected for efficiencies of alpha-counting and of filtering. The fourth column shows total alpha-activitives in pCi, while the fifth one the calculated specific activities, taking into account the transmitted air volumes. The last column of Table 4 presents the percentage lost of total alpha-activity taken initially as 100 per cent. Percentages as a function of ventilation time are shown in Fig. 6.

From the tabulated results and Fig. 6 it seems that the total activity decreases rapidly at the beginning, then this decrease slows down and after about 35 to 40 min it is so slow that no practically important changes occur.

Previously it has been indicated that technical difficulties prevented us from determining anything else than the total alpha-activity in its dependence on ventilation time. Tough specific concentration values cannot be determined, roughly correct values can be found for the rate of decrease. It will be seen later that after 100 minutes of ventilation, specific activities decreased to about 25 to 30 per cent of saturation values, so no significant deviation occurred as compared to the loss of total alpha-activity. In spite of the rather poor ventilation conditions, evacuation rate of radon gas may be over that of decay products, from the radiation exposure aspect, however, decay product concentration is more important, hence reality is better approached by the examination of the evacuation of decay products.

After 100 minutes of ventilation, doors were closed again, and from this time, Rn, RaA, RaB and RaC concentrations have been determined by the presented method.

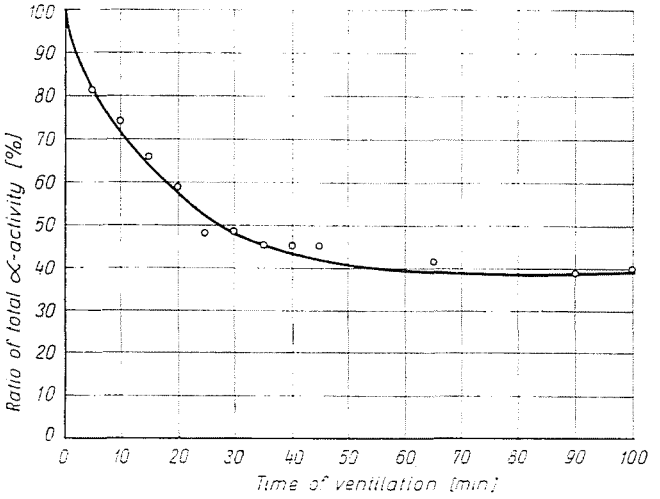

Fig. 6. Decrease of total alpha-activity as a function of ventilation time

The number of RaA, RaB and RaC atoms found in 1 litre of air as a function of time after the end of ventilation are compiled in Table 5. The last column contains Q_{RaC}/Q_{RaB} ratios confronted to results of LOCKHART and PATTERSON [3] who made tests in a room of 35 cu. m capacity, with 0.5 pCi/litre radon background, by introducing 0.2 μCi radon gas and recording Q_{RaC}/Q_{RaB} ratios in function of the time after introduction. Comparing the ratios theoretically calculated, those determined by LOCKHART and PATTERSON and those gained by our measurements (Fig. 7) we found that, according to our curve, the Q_{RaC}/Q_{RaB} ratio was growing more slowly. This fact is likely to be attributed to the single radon emission in the tests by the authors referred to, while in our case a constant radon emission should be reckoned with. Hence, RaB

Table 5

Increase of the number of RaA, RaB, RaC atoms and of the ratio of RaC to RaB atom numbers as a function of time after finishing of the ventilation

Sample number	Time [hour]	Q_{RaA}	Q_{RaB}	Q_{RaC}	$\frac{Q_{RaC}}{Q_{RaB}}$
1	0	23	165	63	0.38
2	0.75	39	262	125	0.48
3	1.5	57	447	234	0.52
4	2.25	69	566	308	0.55
5	3.0	84	680	368	0.55
6	4.0	100	850	501	0.59
7	5.0	99	807	562	0.69
8	5.5	97	908	554	0.61
9	15.0	102	1089	705	0.65

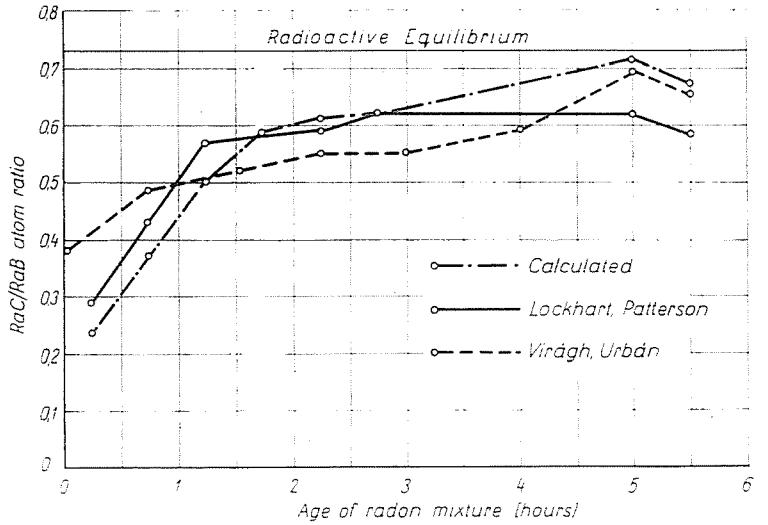

Fig. 7. See Table 5

develops at a higher rate, resulting in a lower Q_{RaC}/Q_{RaB} ratio, in view of the longer half life of RaC. Further, the high value of the surface to volume ratio of the cave has to be taken into consideration, since rough cave walls increase significantly the effective surface of the room, the apparent increase of the Q_{RaC}/Q_{RaB} ratio is below the theoretical value.

Table 6 compiles data on specific activity increase of Rn, RaA, RaB and RaC vs. time after the end of ventilation, plotted in Fig. 8. For an equilibrium between radioactivities of radon and its short-lived daughters, specific activities of $1.1 \cdot 10^{-11}$ Ci/litre can be observed in the cave. On this basis,

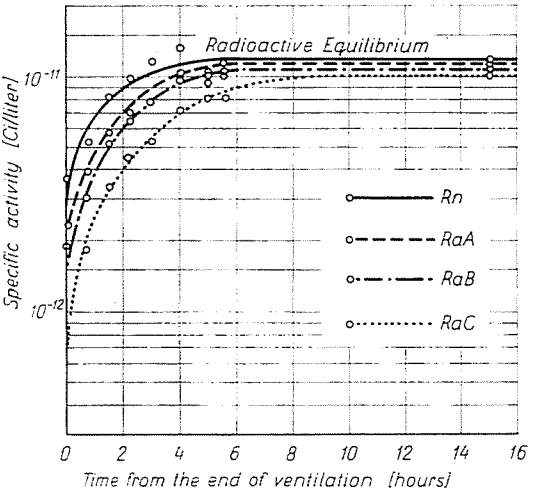

Fig. 8. See Table 6

Table 6

Specific activity increase of Rn, RaA, RaB and RaC as a function of time after the end of ventilation

Sample number	Time [hour]	A^{5}_{Rn}	A^{6}_{RaB}	A^{6}_{RaA}	A^{3}_{RaC}
		$\times 10^{-12}$ Ci/litre			
1	0	3.65	2.36	1.90	0.91
2	0.75	5.30	3.94	3.03	1.80
3	1.5	8.28	5.81	5.18	3.37
4	2.25	9.84	7.03	6.56	4.44
5	3.0	11.8	8.53	7.89	5.30
6	4.0	13.2	10.2	9.86	7.21
7	5.0	9.9	10.1	9.36	8.09
8	5.5	11.5	9.9	10.53	7.98
9	15.0	11.8	10.4	11.9	10.15

after 100 min of ventilation, specific activities of Rn, RaA, RaB and RaC decreased to 31, 23, 16 and 9 per cent respectively.

After the ventilation ended, concentration values increase exponentially, Rn and RaA concentrations by about the same rate and after 4 to 5 hours they approach saturation. This is more or less valid for RaB, while the specific activity of RaC increases at a lower rate: 5.5 hours after ventilation 78 per cent of the specific activity of equilibrium was reached.

It can be concluded that ventilation conditions in the tested caves are rather poor, since, naturally no artificial ventilation system has been constructed, and besides, the door used for ventilation is rather small. What is

more, in winter months, research workers work in confined spaces, and because of the slight rate of natural ventilation, practically saturation activity has to be taken into consideration throughout.

On the bottom of the cave system, the termal caves mentioned before will be developed. Since excavation operations are now in process, only a few test could be made, with results compiled in Table 7.

Table 7

Rn, RaA, RaB and RaC concentrations found in the "Aragonite" cave system inside Gellért-hill

Sample number	A^{s}_{Rn}	A^{s}_{RaA}	A^{s}_{RaB}	A^{s}_{RaC}
	$\times 10^{-12}$ Ci/litre			
1	5.4	3.9	2.7	1.4
2	7.5	7.1	5.6	4.9
3	6.6	6.4	6.0	5.4
4	11.8	10.4	10.9	10.1

Tabulated values show concentrations of radon and its short-lived daughters to be multiples of 10^{-12} Ci/litre at the tested spots, and sometimes to be as high as of the order of 10^{-11} Ci/litre. In addition, radioactivities of radon and its short-lived daughters appear to approach equilibrium state, which can be attributed to the poor ventilation conditions in the lower cave system, since here the natural circulation of air is inferior even to that in the top cave system.

4. Estimation of radiation exposure

Examination of problems of radiation exposure due to radon and its decay products is justified by cases of pulmonary cancer frequent among miners — especially uran miners. Shortly after the discovery of natural radioactivity, several authors related cases of pulmonary cancer frequent among miners ("mountain thickness") to the high natural radioactivity in mines. NOSTOKI and co-workers, on the basis of their tests in 1921—26 miners of Schneeberg, concluded that about 50 per cent of miners died of pulmonary cancer. The high radiation exposure was attributed to the radon gas, and BALE was the first to demonstrate in 1951 that radiation exposure was primarily dependent on decay product concentrations. During the recent two decades, several physical and biological tests have been made to determine radiation exposures due to radon and its decay products, but the authors' views are rather different in this aspect. For the sake of illustration, Table 8. shows dose values due to radon and its decay products. Calculation by

Table 8

Theoretical calculations of the radiation dose from inhaled radon and daughters [7]

Investigators	Critical tissue	Calc. dose [rem/yr]	Reference atmosphere
Absorbed Radon			
Holaday et al. (1957)	Lung	0.062	10 pCi/l radon only
Morgan (1954)	Bronchi	0.010	10 pCi/l radon only
Holleman, Martz, Schiager (1968)	Whole body	0.080	10 pCi/l radon only
Radon decay in airways			
Holaday et al. (1957)	Largest bronchi	0.59	10 pCi/l radon only
Inhaled radon + daughters			
Holaday et al. (1957)	Bronchi	13.9	1p pCi/l radon + equil. RaA + .5 equil. RaB—RaC
Morgan (1954)	Bronchi	3.6	8.8 pCi/l radon + equil. RaA + .5 equil. RaB+RaC
Schapiro (1954)	Tert. bronchioles	11.6	10 pCi/l radon + equil. daughters
Chamberlain and Dyson (1955)	Trachea	4.6	10 pCi/l radon + unattached RaA only
Jacobi (1964)	Sec.-quat. bronchioles	20.1	10 pCi/l radon + daughters as in ordinary air
Altschuler, Nelson, Kuschner (1964)	Segment bronchi	240.0	200 pCi/l daughter only
Haque and Collinson (1967)	Segment bronchi	138.0	10 pCi/l radon + equil. daughters

Based on a quality factor of ten and adjusted to 40 hr/wk. Biologically significant dose, in rems-physical dose, in rads multiplied by the appropriate quality factor for the type of radiation producing the dose. 1 rad = 100 erg absorbed energy per gram of the material.

HAQUE and COLLISON [10] gave especially high dose values. Deviation between calculated results can be attributed to the following causes:

— starting from different lung models;
— assumption of different aerosol spectra;
— deviation in the assumed distribution within the lung;
— different QF factor values;
— assumption of different conditions of inhalation;
— different assumptions as to the ratio of the respired and exhalated active aerosols.

A further difficulty is due to the fact that theoretical calculations can hardly be confirmed by animal tests, since smaller animals (mice, rats) generally applied for biological tests have air circulations rather different from that of man.

Occupants of the tested cave system pertain to two great groups: 1. patients to be treated in thermal caves; 2. servicing personnel, including the Karstic Water Research Station staff in the upper cave system.

Let us assume concentration values of $1.1 \cdot 10^{-11}$ Ci/litre for the estimation of radiation exposure, and a radioactive equilibrium between radon and its short-lived daughters.

Persons in the first group spend a few days in the thermal caves (1—2 hours a day), thereby the radiation exposure endured is negligible.

Persons in the second group are in a worse situation. Since these working places not rated officially and are endangered by radiation, workers occupy them during 48 hours a week, hence data in Table 8 are to be multiplied by a 1.2 factor. Based on the results by HACQUE and COLLINSON, lungs of those constantly working in the caves are affected by doses of 165 rem in a year, superior by an order to the permissible maximum suggested by ICRP for the lung. However, even regarding other values, respiratory organs of those working in the cave are seen to be affected by a radiation exposure of the order of permissible maximum.

Summary

The most significant component of the natural radioactivity of atmosphere is radon (^{222}Rn) and its decay products. The radon concentration in air is of the order of 10^{-13} Ci/litre in general, but in closed spaces it may be higher, depending on the radium in enviroment. ICRP recommended $1 \cdot 10^{-11}$ Ci/litre for the MPC value of radon concentration, but since it is usual to consider its thirtieth for the population, it is advisable to estimate radiation exposure in every case where the specific radon content of air is above the average value.

The Radiation Protection Group of the Atomic Reactor of the Budapest Polytechnical University, and the Health Physics Department of Budapest Hygiene and Epidemiology Institute made common tests in the cave system of the Gellért-hill, Budapest, housing the Karsting Water Research Station of the Research Institute for Water Resourches, and where thermal caves are being developed.

The determination method of radon concentration has been based on the so-called "Tsivoglou-method". Several types of aerosol samplers have been tried out, such as the sampler

FH-422 operating by electrostatic condensation. A simple method has been applied to determine the filtering efficiency of this latter, which proved to be about 17 per cent because of the high vapour content in caves.

Test values of radon concentration involved efficiency of ventilation and concentration determinations at different spots. Maximum concentration was found to be $1.1 \cdot 10^{-11}$ Ci/litre, and because of poor ventilation conditions, one had to reckon practically with radioactive equilibrium.

In spite of rather diverging literature data, radiation exposure assessments showed that pulmonary doses of regular cave workers are likely to reach or exceed the maximum permissible dose.

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