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CONTRIBUTION OF COSMIC RAYS TO RADIATION EXPOSURE OF THE POPULATION*

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To evaluate the exposure of the Hungarian population to cosmic rays, the absorbed dose rate in air of cosmic radiation was directly measured by high pressure ionization chamber at ground level on the surface of different bodies of water and at various altitudes on board an aircraft. From the dose rates measured in this way, the outdoor dose equivalent rate from the ionizing components of cosmic radiation to people living at sea level would be 300—325 μSv per year. Taking into account the altitude distribution of the population, the average weighted dose equivalent is about 320, μSv per year. At Kékestető, the highest peak of the Mátra Mountains, (the highest altitude in Hungary), the annual dose equivalent is about 50 per cent higher than on the Great Hungarian Plain.

Introduction

Radiation in the environment from natural sources is the major contributor to radiation exposure of man. It is frequently used, therefore, as a standard of comparison for exposures to man-made sources of ionizing radiation, in particular, for those due to nuclear power generation. It is for this reason that interest in the knowledge and evaluation of exposure of the population to natural background radiation has increased during the last quarter of the century. Several reports have been published on nation-wide surveys in various countries [1—5] and on global averages of natural radiation exposure of mankind. The most comprehensive have been the 1972 and 1977 reports of the United Nations Scientific Committee on the Effects of Atomic Radiation UNSCEAR [6—7].

In the mid-70s, after the decision to develop nuclear power in Hungary had been taken, our Institute embarked on a research programme to examine and evaluate the studies performed by the various institutions and scientists in our country [8], and to initiate additional investigations regarding sources of ionizing radiation in the environment that may contribute to the overall exposure of the population. This paper, the first in a series of publications envisaged under this programme, is concerned with assessing the dose to the population from cosmic rays. Preliminary results have already been published at various national and international meetings [9—10].

* Dedicated to Prof. I. Tarján on his 70th birthday.

1. Cosmic radiation

The term cosmic radiation refers both to the high energy particles that enter the earth's atmosphere from outer space (primary cosmic rays), and to the particles and electromagnetic radiation generated by the interactions of primary particles with target atoms in the atmosphere (secondary cosmic rays). By virtue of these interactions, the atmosphere serves as a shield against cosmic radiation. The primary particles are almost completely absorbed in the upper atmosphere, so that the cosmic radiation detected at ground level consists mainly of the highly penetrating muon and associated decay and collision electron components of secondary radiation. There are also some smaller components such as neutrons and gamma photons. The composition and intensity of the cosmic radiation field within the atmosphere vary markedly with altitude, and there is a less important variation with geomagnetic latitude and solar cycle.

The ionization rate per unit volume in free air is a measure of the flux density of the total charged-particle component of the cosmic ray field and is usually expressed as the number of ion pairs formed per second in each cubic centimetre of air at normal temperature and pressure (NTP). The values of the sea level cosmic ray ionization rate reported after 1960 show a relatively good agreement and scatter between 1.9 and 2.6 $cm^{-3}\,s^{-1}$. Assuming that each ion pair requires 33.7 eV to be produced in air, the absorbed dose rate for an ionization rate of 1 $cm^{-3}\,s^{-1}$ is $1.50 \cdot 10^{-8}$ $Gy \cdot h^{-1}$. Using the values of the ionization rate at sea level, the absorbed dose rate in air is between 2.85 and $3.90 \cdot 10^{-8}$ $Gy \cdot h^{-1}$. For the average, a value of $3.2 \cdot 10^{-8}$ $Gy \cdot h^{-1}$ has been accepted by UNSCEAR [7].

About 75 per cent of the dose is from muon collision electrons, 15 per cent from muon decay electrons and 10 per cent from other electron, proton and neutron processes. Flux density data of cosmic ray neutrons at ground level are in serious disagreement [2]. A value of $8 \cdot 10^{-3}$ $cm^{-2}\,s^{-1}$ has been adopted for the purpose of estimating dose rates at sea level and latitudes above 40°. Using a conversion factor from neutron flux density to absorbed dose rate of $5 \cdot 10^{-8}$ $Gy \cdot h^{-1}\,cm^2\,s$, the absorbed dose rate would be $4 \cdot 10^{-10}$ $Gy \cdot h^{-1}$ [7]. Apparently, the neutron absorbed dose rate in air is negligible in comparison with that from charged particles.

The extensive and traditional cosmic ray studies performed in Hungary have been mainly directed to characterizing particular components and little attention has been paid to determining their ionizing properties and none to their dose rates produced either in air or in human tissues [11—13]. It is intended that this gap be filled by our measurements.

2. Equipment and methods

Ionization chamber and thermoluminescence dosimeters have been used to measure the absorbed dose rate in air of the ionizing components of cosmic rays. Since the expectable neutron dose rate is about two orders of magnitude lower than that of the charged particles and since we had no neutron detector of appropriate sensitivity, no neutron component measurements were made.

2.1. High pressure ionization chamber

Field measurements, especially those that take longer than a few hours, are best performed with systems which operate on selfcontaining battery packs, maintain their characteristics over long periods, and are relatively insensitive to climatic conditions. With these features in mind, the Area Monitor Model RSS-111 (Reuter-Stokes Instruments, Inc. Cleveland, Ohio, USA) was chosen as the basic instrument for our dose rate measurements.

The standard detector of the instrument is a spherical, 25.4 cm diameter, high pressure ionization chamber (HPIC). The gas filling is ultra high purity argon at a pressure of 25 atmospheres. The 2.4 $g \cdot cm^{-2}$ thick chamber shell is made of stainless steel. The spherical shape of the chamber provides an essentially omnidirectional response to the incident radiation, and the spherical collecting electrode ensures a more uniform electric field configuration than the usual rod electrodes.

A 300 V battery connected between the guard ring and the outer shell is routinely used for all measurements. Saturation studies have shown that the ionization chamber exhibits essentially complete collection of ionization currents in fields up to $1 \cdot 10^{-5}$ $Gy \cdot h^{-1}$ with the 300 V polarizing potential.

The ionization chamber is connected electrically and mechanically to an electrometer designed to give a temperature-compensated signal. This system with digital display, strip chart recorder and magnetic tape recorder is capable of resolving changes of less than $1 \cdot 10^{-9}$ $Gy \cdot h^{-1}$ in the field, using a computer technique [14].

2.2. Thermoluminescence dosimeters

Thermoluminescence dosimeters (TLD's) are widely used for environmental radiation monitoring, personnel dosimetry of professional radiation workers and special dosimetry studies. Processing techniques and procedures have been developed that make measurements of radiation exposures at environmental levels ($1-10 \cdot 10^{-5}$ Gy per week) accomplishable with an accuracy better than 5 per cent [15].

Various possible phosphors were checked regarding sensitivity, stability and fading, energy and directional response, manageability, etc. On the basis of the suitability for our environmental monitoring, LiF:Mg/Ti phosphor designated TLD-700 (Harshaw Chemical Co., USA) and $CaSO_4$:Dy/Tm phosphor (made in Hungary) [16] were selected and used in powder form throughout the programme. The phosphors were put into waterproof and light-tight capsules made of teflon and copper. Dosimeter readout was by a commercial reader (Harshaw 2000 AB).

For calibration of the dosimeters, different known exposures from ^{60}Co and ^{137}Cs sources were given, measured with a secondary standard dosimeter.

Field measurements with HPIC at a particular location provide quick information on exposure rate and its variations within minutes; measurements with TLD's give total exposure data integrated over an extended period. The advantages of environmental monitoring with TLD's are their relatively low price and applicability in large numbers over an extensive area.

3. Results of measurements

3.1. Measurements at ground level

At ground level, man is subjected simultaneously to all types of natural radiation. The contribution of the individual components of radiation to overall exposure can only be established if these components are measured separately. This is why a major part of our measurements of the cosmic ray absorbed dose rate have been carried out on the surface of bodies of water whose depth is sufficient to absorb radiation emitted by the radionuclides present in the earth's crust. A water layer of 2 m reduces the intensity of this radiation by about three orders of magnitude, while a layer of 4 m by more than six orders of magnitude [17].

Measurements were performed on the surface of Lake Balaton with HPIC at two points and with TLD's at one point (Fig. 1). Additional measurements were made on Lake Szelidi and on the River Danube with HPIC at one point on each. The most

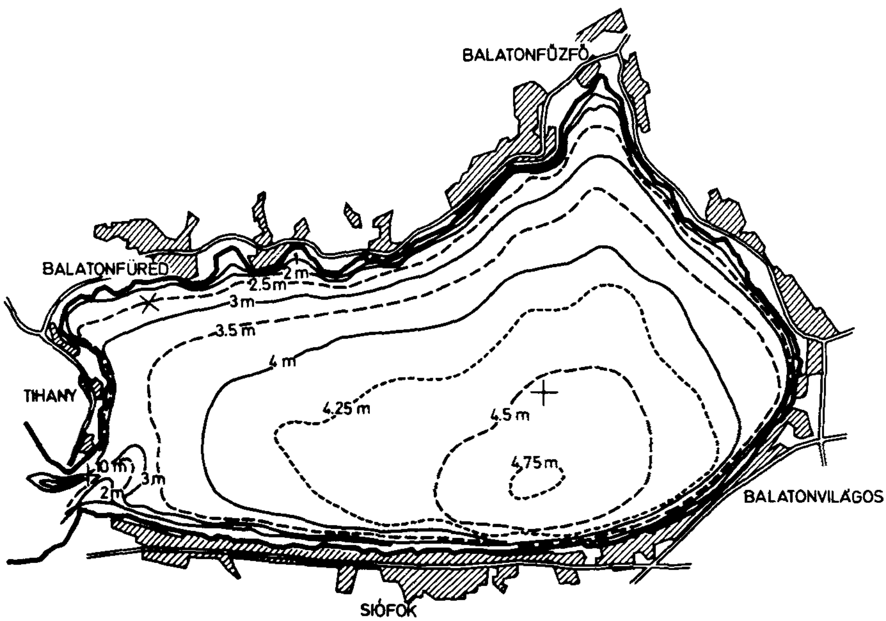

Fig. 1. Sketch of the northern basin of Lake Balaton showing water depths and the points of measurement with HPIC (+) and TLD's (×)

Table I
Absorbed dose rates in air measured at different locations

Location of measurements	Approximate distance from shore [km]	Average depth of water [m]	Overall duration of measurements [h]	Absorbed dose rate measured [nGy · h⁻¹]
Lake Balaton (Tihany)	0.4	9.5—10.5	35.2	36.7 ± 3.7
Lake Balaton (Siófok)	4	4.6	27.5	37.7 ± 3.6
Lake Balaton (Füred)	0.25	2.5	1008	36.0 ± 2.9
Lake Szelidi	0.2	5	24	40.4 ± 3.6
River Danube (Tétény)	0.2	6	1	35.6 ± 3.4

Note: All measurements were carried out with HPIC except the one at Balatonfüred that was performed with TLD's. The measured values are corrected to sea level.

important characteristics of these points, the total duration of measurements at each point and the absorbed dose rates, can be seen in Table I.

Measurements have been carried out both in summer and winter, and under various conditions (Fig. 2). It might be interesting, therefore, to see the results of individual series of measurements separately (Table II). It appears from these data that there might be a moderate seasonal variation in cosmic ray absorbed dose rate. The values obtained in winter time (28.8 ± 4.5 nGy · h^{-1}) are somewhat lower than those in summer (37.6 ± 3.6 nGy · h^{-1}). We should be cautious, however, concerning this conclusion, since the total time of measurements in winter (3.67 h) is about 16 times shorter than that in summer (59 h).

The overall average of cosmic ray absorbed dose rate in air measured with HPIC on water surface and extrapolated to sea level is found to be 37.1 ± 3.6 nGy · h^{-1}. This is about 15 per cent higher than the value assumed by UNSCEAR [7] as the world average, but it is still within the range measured and published by several authors [18—20]. Nonetheless, a potential interference of radiation from naturally occurring radionuclides should also be analysed and excluded.

Activity concentration of ^{40}K in Balaton water varied between 0.24 and 0.59 Bq · l^{-1} during the last few years [21]. This may result in an increment of absorbed dose rate in air of 0.010—0.025 nGy · h^{-1}, that is negligible.

The contribution to the absorbed dose rate in air of all the radionuclides produced by cosmic rays (cosmogenic radionuclides) is of the order of 0.20 nGy · h^{-1}; this is also insignificant compared with the direct contribution of cosmic rays [7].

More significant changes with time of the absorbed dose rate in air might be associated with variations in the atmosphere concentrations of ^{222}Rn decay products. As a result of variations in stability conditions of the lower atmosphere, the night-time concentrations of ^{222}Rn decay products in air near the ground are usually a few times higher than those existing during the day. It is believed that the absorbed dose rate

Fig. 2. Measurements of cosmic ray absorbed dose rate with HPIC on the surface of Lake Balaton

Table II
Dose rates measured with HPIC on the surface of Lake Balaton

Date of measurement	Placing of instrument	Location of measurements			
		Tihany		Siófok	
		Duration, [h]	Dose rate [$nGy \cdot h^{-1}$]	Duration, [h]	Dose rate [$nGy \cdot h^{-1}$]
23.01	ice	2	27.4 ± 5.4	–	–
15—17.08	pier	6	36.6 ± 3.4	–	–
15—17.08	boat	1	37.7 ± 3.9	11	37.2 ± 3.9
10—11.09	boat	25	37.7 ± 3.6	16	38.2 ± 3.4
20.12	boat	0.5	28.9 ± 2.0	0.5	39.4 ± 2.8
20.12	ship	0.67	32.3 ± 5.1	–	–
	average		36.7 ± 3.7		37.7 ± 3.6
overall average			37.1 ± 3.6		

Note: All measured values are corrected to sea level.

in air from atmospheric ^{222}Rn decay products might usually be approximately 1—2 $nGy \cdot h^{-1}$ [7]. Our long term measurements with HPIC at Tihany and Siófok (Lake Balaton) have indeed shown a diurnal variation of the dose rate in air ranging from about 36 to 43 $nGy \cdot h^{-1}$. Maximum values have been observed in the early morning and minimum values in the early afternoon. In order to clarify the role of this factor, parallel radon concentration and dose rate measurements have been initiated.

It should also be mentioned that the absorbed dose rate obtained with TLD's is corrected according to O'Brien. This author has established that TLD's, if calibrated with gamma-ray sources such as ^{60}Co, ^{137}Cs and radium in air, register 0.83 of the muon produced ionization. The ratio between the total cosmic ray ionization and the ionization inferred from the TLD calibration is 0.865 ± 0.017 [22]. Therefore the dose rate of 31.1 ± 2.5 $nGy \cdot h^{-1}$ measured with TLD's at Balatonfüred has been corrected with this factor (Table I).

3.2. *Measurements at various altitudes*

Alteration of the cosmic ray absorbed dose rate with altitude above sea level (i.e. with atmosphere depth) has been measured on board a JAK-40 type aircraft of the Hungarian Airlines MALÉV (Fig. 3). For these measurements, flights were made above Lake Balaton, in the air-space of the first Hungarian nuclear power station under

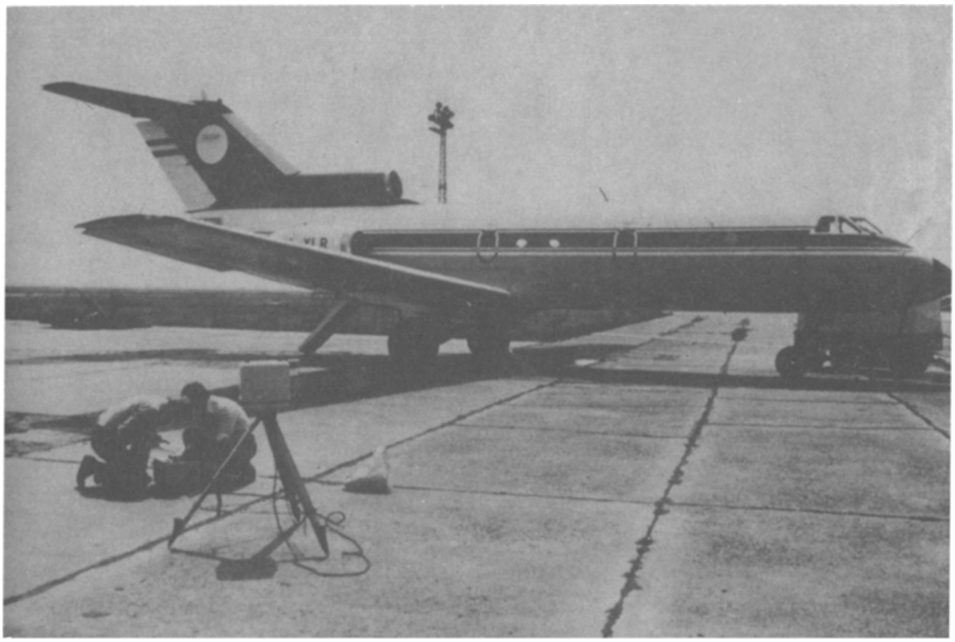

Fig. 3. HPIC in position of field measurement in front of the aircraft used for measuring cosmic dose rates in air at various altitudes

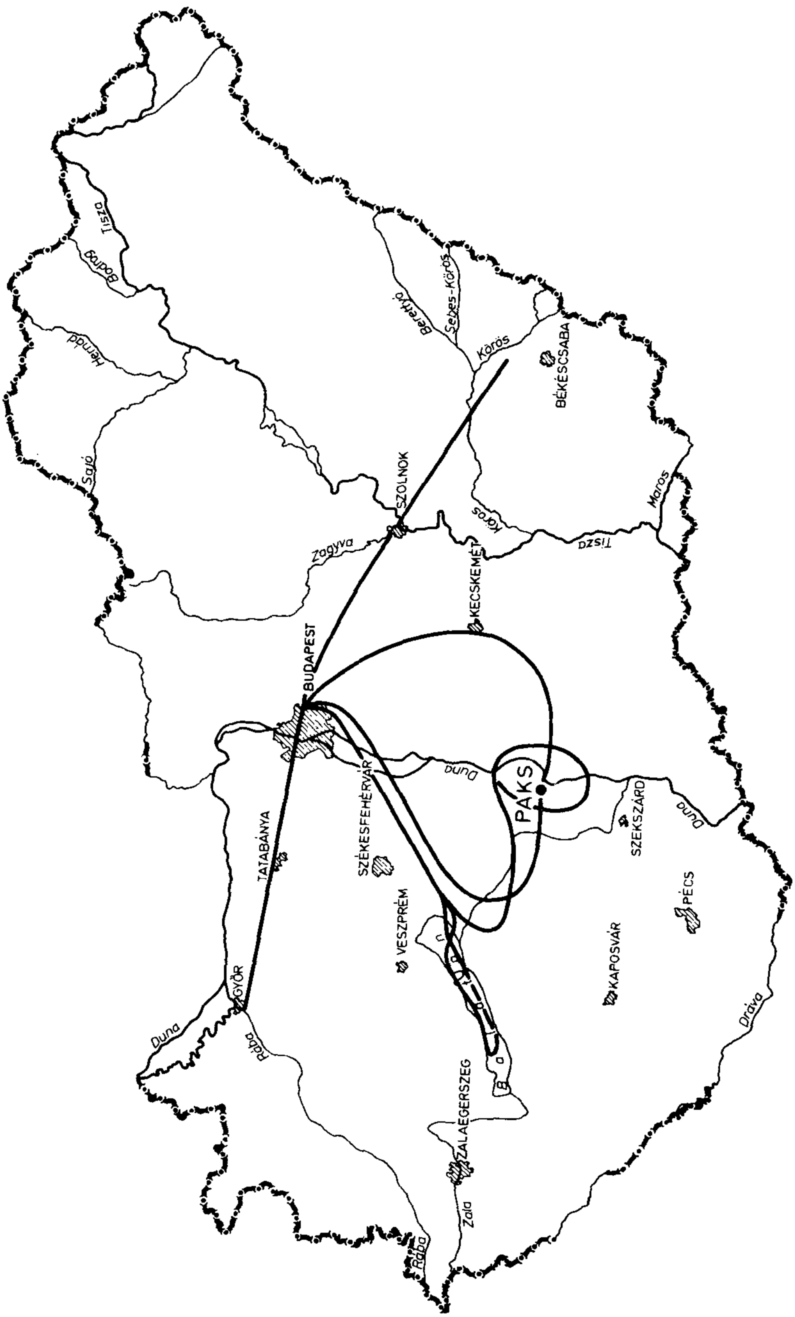

Fig. 4. Map of the country with the routes of the aircraft flown during the measurements of cosmic dose rates in air

Table III

Variation of cosmic dose rate with altitude in the lower atmosphere*

Height above sea level [m]	Number of data registered	Dose rate in air, measured [nGy · h⁻¹]	Dose rate obtained from regression curve [nGy · h⁻¹]
0		37.1 ± 3.6**	34.2
900	200	52.5 ± 4.3	50.3
1 110	750	56.5 ± 2.9	55.0
1 910	200	72.4 ± 4.5	77.3
2 940	900	114.1 ± 5.8	119.9
4 100	250	200.5 ± 3.2	196.6
4 600	750	251.4 ± 11.5	243.3
4 750	200	257.7 ± 11.2	259.4

Notes:

* These measurements were performed with HPIC on board an aircraft on 9th and 15th April, and 26th July 1979.

** Overall average of dose rates measured on the surface of Lake Balaton in 1978 and 1979. This value was omitted when fitting the data.

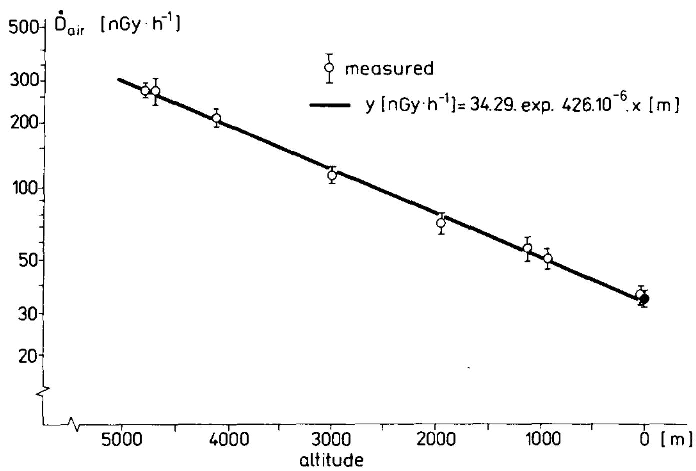

Fig. 5. Change of cosmic ray absorbed dose rate in air with altitude

construction at Paks, and along the main civil air travel service (ATS) routes of our country (Fig. 4). The measurements were performed with HPIC at altitudes between 900 and 4750 m (Table III). No additional radiation from the structural elements of the aircraft could be detected on board at the point the HPIC was fixed. The absorbed dose rate values measured have been fitted and a regression curve obtained (Fig. 5). The correlation coefficient of this curve is 0.99. It is worth noting that the absorbed dose value obtained from the regression curve for sea level is 34.3 $nGy \cdot h^{-1}$, that is, somewhat below the measured average.

4. Average dose equivalent rate to the population from cosmic rays

The stopping power of muons and associated fast electrons in the body is barely different from that in air. Therefore, the air absorbed dose rate can be taken without modification to infer the absorbed dose rate of cosmic radiation to a person in the outdoor environment. The mean quality factor of muons and electrons is also close to unity, so that the same figures may be used for calculating the cosmic ray charged particle dose equivalent rate. Protons constitute less than one per cent of the charged particles in the lower atmosphere [2].

Assuming that the outdoor absorbed dose rate at sea level varies between 34.3 $nGy \cdot h^{-1}$ (as a lower bound value that follows from the regression curve of dose rates measured at various altitudes) and 37.1 $nGy \cdot h^{-1}$ (as an upper bound value which is the overall average of HPIC measurements on the surface of Lake Balaton), the annual absorbed dose equivalent in human tissues from ionizing components of cosmic rays at sea level is 300—325 μSv.

The average annual dose equivalent to the population from cosmic radiation can be estimated by combining the data on the absorbed dose rate in air (or rather the dose equivalent rates) at various altitudes with the altitudinal distribution of the population. Unfortunately, the latter is not readily available in our country. Therefore, the rough fractional distribution of the national territory has been used as first approximation (Table IV). The annual dose equivalent from cosmic radiation averaged over the whole population is found to be 320 μSv. Citizens living in the highest part of the country (Kékestető, Mt. Mátra) receive about 50 per cent higher doses from cosmic rays annually than those who live on the Great Hungarian Plain.

In reality, the average annual dose equivalent is somewhat higher than given above, due to the contribution of cosmic ray neutrons. Taking the quality factor of these neutrons to be 5 or 6 as given in the literature [2, 7], the annual dose equivalent is to be increased by 18—21 μSv (that is 5—7 per cent). On the other hand, there is another factor which results in a decrease of the actual exposure. Individuals spending a large part of their time in buildings are exposed to lower cosmic radiation levels than the outdoor exposure level, because of the effect of structural shielding. A 10 per cent or higher structural attenuation factor should be applied depending on the thickness of

Table IV

Cosmic ray dose rates at various altitudes and approximate fractions of the national territory affected

Height above sea level [m]	Average cosmic ray dose rate in air or tissue		Approximate fraction of the national territory [%]
	[nGy·h^{-1}]	[μGy·y^{-1}]	
0—200	35.8	313	79
200—400	39.0	341	18
400—600	42.2	371	2
600—800	46.2	405	0.5
800—1000	50.3	441	0.3

overhead shielding. This effect is due to be considered for a future publication dealing with exposure of the population to natural radiation sources inside and outside buildings.

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