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EXTENDED SURVEY OF INDOOR AND OUTDOOR TERRESTRIAL GAMMA RADIATION IN GREEK URBAN AREAS BY *IN SITU* GAMMA SPECTROMETRY WITH A PORTABLE Ge DETECTOR

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Abstract — The results obtained from more than 1000 indoor and outdoor *in situ* gamma spectrometry measurements in 41 towns (from all geographic subdivisions) of the Greek mainland (not islands) are presented. From the *in situ* gamma spectra the absorbed dose rate in air due to uranium series, thorium series, ^{40}K and ^{137}Cs are derived and discussed.

INTRODUCTION

Exposure to gamma rays from natural and artificial (e.g. from the Chernobyl accident) radionuclides occurs outdoors and indoors. Surveys by direct measurements of dose rates have been conducted during the past few decades in many countries[1]. The indoor surveys are not quite as complete as outdoor investigations despite the fact that knowledge of radiation levels in buildings is important for the assessment of population exposure. This is because most individuals spend the majority of their time indoors exposed to radiation from the radionuclides (mainly ^{226}Ra, ^{232}Th, their decay products and ^{40}K) in walls, floors and ceilings. The rest of their time is spent outdoor on roads or near buildings, which exposes them to radiation from materials used for construction.

Extended surveys of outdoor gamma dose rates in Greece have been performed[2,3] using gamma spectroscopy measurements of soil samples collected from all Greek provinces. The soil sampling analysis method has a big disadvantage compared to the *in situ* gamma spectrometry method. Most of the Greek population lives in urban areas. The influence of building, road and other construction materials used in urban areas significantly affects the external dose rate. Therefore, the estimations of dose rate based on soil measurements do not apply, generally, to urban areas. Indoor gamma dose rates have been measured in Greece[4] using LiF thermoluminescence dosemeters. This type of measurement has the disadvantage that (a) the absorbed dose rate measured includes the cosmic component of the ionising radiation and (b) it cannot provide information on the relative contribution of the various nuclides to the total exposure rates.

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In the present work the results obtained from more than 1000 indoor and outdoor *in situ* gamma spectrometry measurements in 41 towns (from all geographic subdivisions) of the Greek mainland (not islands) are presented and discussed.

MATERIALS AND METHODS

The portable Ge detector used for the *in situ* measurements is a high purity Ge coaxial cylinder 44 mm in diameter and 41 mm in length, with an efficiency for a point source at 25 cm at 1.33 MeV of 10% relative to a 7.6 × 7.6 cm^2 NaI(Tl) crystal. It is mounted in a small liquid nitrogen cryostat that features an all-attitude capability. The spectrum is collected in a portable multichannel analyser that also provides high voltage and preamplifier power to the detector. The first analysis of the spectra can be performed in a portable computer connected to the multichannel analyser with the use of home-made software. The *in situ* measurements were performed with a downward, tripod-mounted facing detector at 1 m above ground. The duration of each measurement was 2000 s.

The map of Figure 1 illustrates the code numbers of the different towns while Table 1 presents their corresponding names, population and the number of indoor and outdoor measurements performed in each town. The indoor measurements were performed inside workplaces (schools, offices, shops, hospitals etc.) and homes (mainly apartments, where most of the Greek population lives). The outdoor measurements were performed on roads and pavements and over soil (in parks and gardens). The survey was performed during 1994–1999. In most of the towns there was a collaboration with the municipalities for the selection of the houses and workplaces.

Derivation of the gamma dose rates from the *in situ* gamma ray spectra

The methodology used for the derivation of the gamma dose rates from the *in situ* gamma ray spectra is the one introduced by Beck *et al*[5]. Based on this method, Helfer and Miller[6] derived simple calibration factors (for the outdoor measurements) which convert the measured full absorption peak count rate to activity in the soil and dose rate in air. The only parameters that are needed are the efficiency and the crystal dimensions of the Ge detector used. Over the years, a number of investigators have adopted and modified the technique (for a review, see Finck[7] and ICRU report 53[8]). Very recently, Clouvas *et al*[9] extended this technique for measurements in an indoor environment and particularly in the case of masonry structure. A summary of the procedure is presented here; the complete description can be found in the above mentioned publications.

The procedure starts with the measurement of an indoor or outdoor gamma spectrum. A typical spectrum is shown in Figure 2. Different peaks due to different gamma emitters can be observed. All except ^{137}Cs are natural radionuclides (^{137}Cs is due to the Chernobyl accident). What is directly deduced by the *in situ* gamma spectrometry measurement is the number of counts in each photopeak per unit of time (in counts per minute). For each photopeak the dose rate in air $\dot{D}_p(E)$ due to unscattered photons (primary photons of energy E) can be easily deduced from Equation 1

$$\dot{D}_p(E) = E \times (A/\epsilon) \times \mu(E) \quad (1)$$

where $\mu(E)$ is the mass absorption coefficient for air at energy E, A is the number of counts in the photopeak per unit of time (in counts per minute) and ϵ is the peak count rate (in counts per minute) per unit uncollided flux (photons.cm^{-2}.s^{-1}) for a parallel beam of gamma rays of energy E that is incident normally to the detector face. In an *in situ* outdoor or indoor γ spectrometry measurement the incident radiation is not just a parallel flux normal to the detector's face but has all angles of

Figure 1. Code number and location of the 41 towns. Names of the towns shown with a circle appear in Table 1.

incidence. However, it has been shown[10] that the angular response of the detector is not a critical factor, and within 5% it can be considered that the Ge detector has a uniform response over angles at least up to 120° of incidence. The full absorption peak efficiency, ϵ, is detector dependent and can be determined with the use of point sources of known activity and/or Monte Carlo simulations. Alternatively, with a good approximation the generic factors of Helfer and Miller[6] can also be used. The only parameters that are needed are the efficiency and the crystal dimensions of the Ge detector used.

The total absorbed dose rate $\dot{D}_t$ in air from a radionuclide can be expressed as a sum of the absorbed dose rate due to unscattered photons $\dot{D}_p$ and scattered photons $\dot{D}_s$ in the indoor or outdoor environment:

$$\dot{D}_t = \dot{D}_p + \dot{D}_s \quad (2)$$

Relation 2 can be rewritten as

$$\dot{D}_t = \dot{D}_p \times (1 + \dot{D}_s/\dot{D}_p) \quad (3)$$

The expression within the parenthesis is termed the dose build-up factor B:

$$\dot{D}_t = \dot{D}_p \times B \quad (4)$$

Table 1. Code number of the 41 towns presented in Figure 1, their corresponding names, population and the number of indoor and outdoor measurements performed in each town.

No	City	Population	Number of indoor measurements	Number of outdoor measurements
1	Athens	3077846	157	45
2	Thessaloniki	945189	225	78
3	Patra	152570	9	4
4	Larisa	112777	23	7
5	Volos	77192	15	15
6	Ioannina	56699	4	3
7	Kavala	56571	10	7
8	Serres	49380	17	7
9	Trikala	44232	7	4
10	Lamia	44084	10	8
11	Kalamata	43625	3	3
12	Katerini	43613	9	4
13	Veria	37858	17	5
14	Drama	37604	13	7
15	Komotini	37036	6	7
16	Alexandroupoli	36994	9	6
17	Xanthi	34889	11	8
18	Kozani	31553	10	4
19	Karditsa	30067	12	5
20	Pirgos	28465	9	5
21	Korinthos	27412	4	4
22	Ptolemaida	25125	5	4
23	Giannitsa	22504	8	7
24	Tripoli	22429	3	2
25	Naousa	19794	15	3
26	Arta	19087	4	3
27	Levadia	18437	8	5
28	Edessa	17128	10	8
29	Kastoria	14775	12	6
30	Preveza	13341	8	5
31	Sparti	13011	10	7
32	Orestiada	12691	7	6
33	Florina	12355	11	7
34	Kilkis	12139	10	3
35	Nauplio	11897	8	3
36	Mesologgi	10916	8	5
37	Grevena	9345	9	6
38	Amfissa	7189	8	5
39	Igoumenitsa	6807	3	3
40	Karpenisi	5868	9	5
41	Poligyros	4501	6	3

The dimensionless buildup factor B can be calculated if the geometry of the outdoor or indoor geometry is known. In the outdoor environment since the open field source geometry can be fairly well modelled by assuming an infinite half-space with a uniform profile with depth for natural emitters and an exponentially decreasing profile with depth for fallout emitters, the measured fluxes (ratio A/ϵ in Equation 1), can be converted to concentrations or inventories in the air above. The first calculations have been performed by Beck and de Planque[11] and Beck *et al*[5]. They used the polynomial expansion matrix equation method for solving the soil/air transport problem to calculate the exposure rates 1 m above ground level for distributed sources of gamma emitters in soil. Conversion factors have been also calculated by Kocher and Sjoreen[12], Chen[13], Saito and Jacob[14] and by Clouvas *et al*[15].

For the indoor environment the generally unknown source geometry makes the task of converting full absorption peak count rates in a spectrum to dose rate difficult. In a recent work by Clouvas *et al*[9] the dose build-up factor B related to the ratio of primary to scattered gamma radiation in indoor environment was calculated for different indoor geometries and gamma source distributions. From all performed calculations the main conclusion was that the B factor does not depend strongly on different parameters such as dimension of the rooms, the thickness of walls, the density of the building materials, and the gamma source geometry. Therefore, even if a precise 'model' of the indoor geometry and a precise knowledge of the building materials is needed in order to calculate precise dose build-up factors, for a reasonable approximation (uncertainty less than 30%) and in the case of masonry structure the dose build-up factors calculated for a 'typical room'[9] can be used.

Table 2. Photon energies used for the determination of the indoor and outdoor absorbed gamma dose rates, their associated radionuclides as well as the corresponding build-up factor B and the contribution C to the dose rate due to all photon energies of each radionuclide.

Nuclide	Energy (keV)	Outdoor		Indoor	
		B	C	B	C
Uranium series					
^{214}Pb	351.932	3.21	0.57	2.87	0.57
^{214}Bi	609.312	2.57	0.19	2.35	0.20
Thorium series					
^{212}Pb	238.632	3.64	0.90	3.25	0.90
^{208}Tl	583.191	2.62	0.14	2.39	0.16
^{212}Bi	727.33	2.46	0.47	2.23	0.48
^{228}Ac	911.204	2.31	0.28	2.07	0.28
^{137}Cs	661.657	2.52	1.00	2.30	1.00
^{40}K	1460.83	1.99	1.00	1.80	1.00

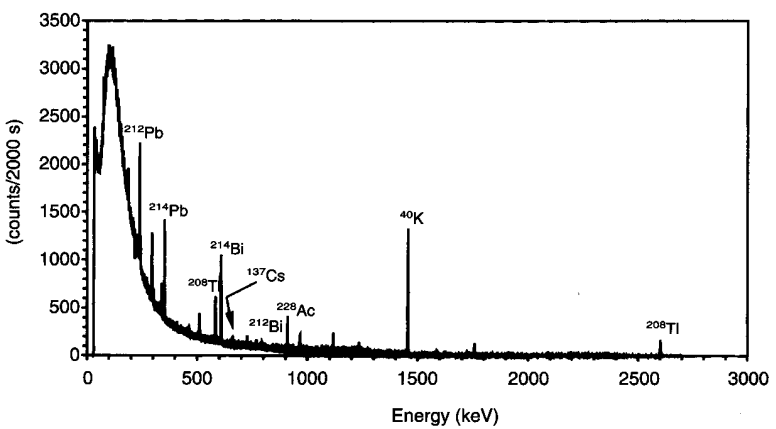

Figure 2. Typical gamma spectrum.

The absorbed gamma dose rate in air is mainly due for the uranium series to ^{214}Pb and ^{214}Bi, and for the thorium series to ^{208}Tl, ^{228}Ac, ^{212}Bi, and ^{212}Pb. Radionuclides like ^{224}Ra and ^{226}Ra can be neglected due to the small fractional yield and relatively low energy of the emitted photons. Each of the above mentioned radionuclides emit photons of different energies. From the Monte Carlo simulations reported in the publications of Clouvas *et al*[9] for the indoor environment and Clouvas *et al*[15] for the outdoor environment the contribution of the dose rate due to one photon energy to the total dose rate due to all photon energies emitted from a specific radionuclide can be easily deduced. Table 2 presents the gamma rays used for the determination of the indoor and outdoor absorbed gamma dose rates as well as the corresponding build-up factor B and the contribution C to the dose rate due to all photon energies of each radionuclide. These factors (B and C) were calculated based on the Monte Carlo simulations reported in the publications by Clouvas *et al*[9] for the indoor environment and Clouvas *et al*[15] for the outdoor environment. However it is important to note that for the outdoor environment in the present work the skyshine was taken into account, whilst in the original publication[15] it was neglected. As in many of the spectra ^{212}Bi could not be directly measured (photon energy 727.3 keV) and as ^{212}Pb at 239 keV has contribution from ^{224}Ra and interference from ^{214}Pb at 242 keV, the dose rate due to the photons emitted by ^{212}Bi and ^{212}Pb were indirectly deduced assuming that ^{212}Bi and ^{212}Pb are in equilibrium with ^{208}Tl. For the uranium series we found unimportant deviations (less than 10%) between the dose rate of the uranium series calculated (a) as a sum of the dose rates due to ^{214}Pb and ^{214}Bi independently or (b) assuming equilibrium between ^{214}Pb and ^{214}Bi; therefore from the measurement of any one gamma ray the dose rate for the entire uranium series is deduced. Table 3 presents for each gamma ray energy the dose rate conversion factor, DRCF, which must multiply the measured unscattered flux (ratio A/ϵ) in order to deduce the dose rate due to the entire series. These values were deduced by Monte Carlo simulations using the MCNP code for the indoor[9] environment. For the outdoor environment these values were deduced considering the skyshine in the original calculations[15]. It must be pointed out that, using this calculation the dose rate for the uranium or thorium series is the *average* for the different dose rates deduced by the different gamma lines belonging to each series and not the *sum*. Indeed for ^{137}Cs and ^{40}K the *DRCF* factors presented in Table 3

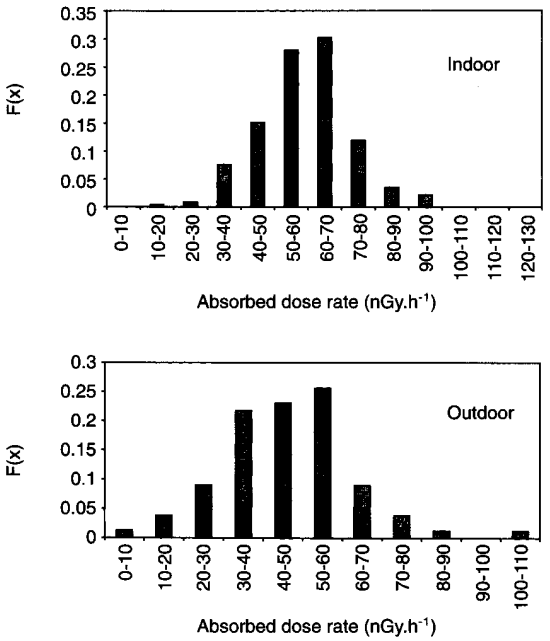

Figure 3. Frequency distribution F(x) of the total indoor and outdoor absorbed dose rates in air measured in Thessaloniki.

Table 3. Dose rate conversion factor DRCF (see text).

Nuclide	Energy (keV)	Outdoor DRCF (nGy.h^{-1} per gamma$_{unscattered}$ cm^{-2}.s^{-1})	Indoor DRCF (nGy.h^{-1} per gamma$_{unscattered}$ cm^{-2}.s^{-1})
Uranium series			
^{214}Pb	351.932	267	219
^{214}Bi	609.312	165	143
Thorium series			
^{212}Pb	238.632	368	288
^{208}Tl	583.191	342	287
^{212}Bi	727.33	1443	1212
^{228}Ac	911.204	332	281
^{137}Cs	661.657	28	26
^{40}K	1460.83	43	39

are simply the values which must multiply the measured unscattered fluxes at the energies of 662 keV and 1460 keV in order to deduce the dose rates due to ^{137}Cs and ^{40}K. Table 3 is useful due to the fact that the DRCF factors are not detector dependent. The full absorption peak efficiency, ϵ, which is detector dependent, can be deduced with a good approximation using the generic factors of Helfer and Miller[6]. The only parameters that are needed are the efficiency and the crystal dimensions of the Ge detector used. In this way it is very easy to deduce the contribution to the dose rate in an indoor or outdoor environment of the uranium series, thorium series and ^{40}K.

RESULTS AND DISCUSSION

The mean indoor and outdoor absorbed gamma dose rates in air due to the uranium series, thorium series, ^{40}K, ^{137}Cs and the sum of them (total) as well as their corresponding minimum and maximum values for each of the 41 towns investigated are presented in Table 4. The first considerations that can be deduced from this table are:

(1) The mean total outdoor and indoor absorbed gamma dose rate in air for the different towns varies between 17 and 88 nGy.h^{-1} and 20 and 101 nGy.h^{-1} respectively. The cities with relatively higher mean total absorbed dose rates are located in Northern Greece. On the contrary in Southern Greece and particularly in Athens and surroundings, where 33% of the Greek population lives, the values of the mean total outdoor and indoor dose rates are (22 and 24 nGy.h^{-1}) one of the smallest mean values measured in the Greek towns. The Greek population-weighted average for the outdoor and indoor gamma dose rates is 31 and 36 nGy.h^{-1} respectively. In the UNSCEAR report[1] the mean national averages of the gamma dose rates are reported. They range from 24 to 160 nGy.h^{-1} and 20 to 190 nGy.h^{-1} for the outdoor and indoor environment respectively. The world population-weighted average for the outdoor and indoor gamma dose rates is 57 and 80 nGy.h^{-1} respectively.

(2) By comparison of the mean indoor and outdoor averages of the total dose rates for the different Greek towns it is seen that the indoor dose rate is almost always higher than the outdoor dose rate. Building materials are usually of local origin and therefore radionuclide concentrations are similar to local soil. The building materials act as sources of radiation and also as shields against outdoor radiation. Most of the buildings and houses of Greece are made of brick and concrete. In this case the gamma rays emitted outdoors are efficiently absorbed by the walls, and the indoor absorbed dose rate depends mainly on the activity concentrations of natural radionuclides in the building materials. Under these circumstances, the indoor-outdoor ratio of absorbed dose rates in air is higher than 1 as a result of the change in source geometry.

(3) The indoor and outdoor absorbed dose rates in air are mainly due to natural emitters. The mean contribution of ^{137}Cs from the Chernobyl accident to the total indoor dose rate for the different Greek towns is negligible (always smaller than 1%). Conversely, the mean contribution of ^{137}Cs to the total outdoor dose rate for the different Greek towns is small (less than 24%) but not negligible. The mean contributions of the uranium series, thorium series ^{40}K and ^{137}Cs to the total dose rate are 28.5% (U), 34% (Th), 37% (^{40}K), 0.5% (^{137}Cs) for the indoor measurements and 28% (U), 33% (Th), 31.5% (^{40}K), 7.5% (^{137}Cs) for the outdoor measurements respectively.

In the following we will focus our attention only on the measurements performed in Athens and Thessaloniki as 50% of the measurements were performed in

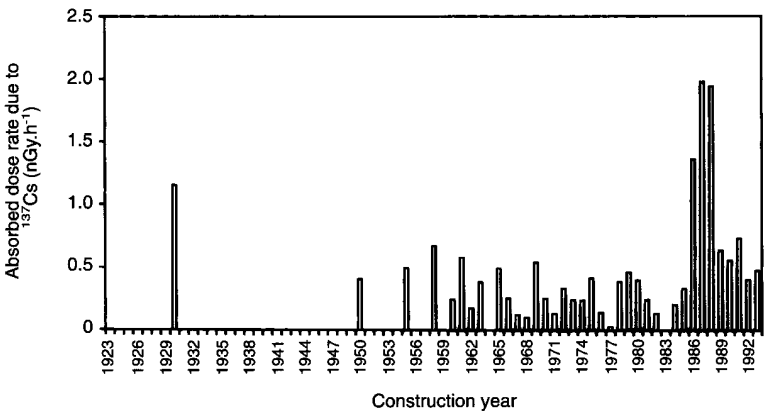

Figure 4. Indoor dose rate due to ^{137}Cs as function of the construction year of the house or building.

Table 4. Mean outdoor and indoor absorbed gamma dose rates in air due to uranium series, thorium series, ^{40}K, ^{137}Cs and the sum of them (total) as well as their corresponding minimum and maximum values for each of the 41 towns investigated.

			Indoor measurements											
No.	Total dose rate ($nGy.h^{-1}$)	Range	U series			Th series			^{40}K			^{137}Cs		
			($nGy.h^{-1}$)	Range	Contribution (%)	($nGy.h^{-1}$)	Range	Contribution (%)	($nGy.h^{-1}$)	Range	Contribution (%)	($nGy.h^{-1}$)	Range	Contribution (%)
1	23.9 ± 7.2	7.8–53.7	7.4 ± 2.5	1.9–17.0	30.8	8.0 ± 2.9	2.3–19.0	33.6	8.4 ± 3.0	2.2–19.9	35.3	0.1 ± 0.3	0.0–1.9	0.3
2	59.2 ± 13.3	18.1–98.7	15.0 ± 4.0	4.7–27.6	25.4	20.6 ± 5.2	6.2–36.1	34.9	23.1 ± 5.2	5.2–35.3	39.0	0.5 ± 0.8	0.0–7.2	0.8
3	24.7 ± 5.0	17.7–33.3	8.2 ± 1.5	5.9–10.8	33.2	7.3 ± 2.4	4.6–12.4	29.8	9.1 ± 2.6	6.7–13.7	36.7	0.1 ± 0.2	0.0–0.5	0.2
4	49.3 ± 9.4	30.9–72.9	11.0 ± 2.1	7.3–15.2	22.4	16.6 ± 3.5	10.5–24.6	33.6	21.6 ± 4.7	11.6 – 33.2	43.7	0.2 ± 0.3	0.0–1.0	0.4
5	31.9 ± 14.4	12.6–71.6	12.7 ± 4.3	6.4–26.3	39.9	8.6 ± 5.8	1.8–22.4	27.0	10.4 ± 5.2	3.6–22.9	32.8	0.1 ± 0.1	0.0–0.4	0.3
6	20.6 ± 5.7	16.0–30.3	9.7 ± 2.6	5.9–12.8	46.9	5.1 ± 1.7	3.4–7.7	24.6	5.9 ± 2.4	3.7–9.8	28.5	0.0 ± 0.0	0.0–0.0	0.0
7	82.5 ± 25.8	34.0–120.4	19.8 ± 7.2	9.6–32.2	23.9	28.9 ± 10.6	10.1–47.3	35.1	33.8 ± 9.4	14.2–48.4	41.0	0.0 ± 0.0	0.0–0.0	0.0
8	100.7 ± 31.1	57.0–155.7	25.3 ± 7.3	15.2–39.8	25.1	38.1 ± 15.7	15.8–66.1	37.8	37.2 ± 8.9	24.3–49.8	36.9	0.1 ± 0.4	0.0–1.8	0.1
9	36.8 ± 9.0	20.6–50.0	8.5 ± 1.8	5.9–11.9	23.2	12.2 ± 3.4	6.0–16.2	33.2	15.6 ± 5.2	8.7–24.9	42.2	0.5 ± 0.6	0.0–1.6	1.4
10	34.7 ± 9.4	20.2–54.2	13.4 ± 5.0	8.7–24.3	38.8	9.8 ± 3.0	5.3–14.4	28.1	11.5 ± 4.1	6.2–17.4	33.1	0.0 ± 0.0	0.0–0.0	0.0
11	38.7 ± 6.0	32.7–46.9	25.7 ± 7.6	16.5–35.0	66.3	5.9 ± 1.1	4.4–6.9	15.1	7.2 ± 1.6	5.7–9.3	18.5	0.0 ± 0.0	0.0–0.0	0.0
12	60.5 ± 9.2	48.6–78.6	19.8 ± 3.1	13.8–24.7	32.7	20.7 ± 4.6	13.9–28.9	34.3	19.8 ± 3.1	15.1–25.0	32.8	0.1 ± 0.4	0.0–1.3	0.2
13	60.3 ± 9.0	47.5–79.4	15.3 ± 2.3	12.2–20.1	25.4	20.1 ± 4.2	13.4–30.0	33.4	24.6 ± 3.0	20.0–30.7	40.8	0.3 ± 0.6	0.0–1.6	0.5
14	52.3 ± 7.3	41.7–62.3	12.1 ± 2.1	8.8–16.6	23.1	18.6 ± 3.8	11.9–24.6	35.6	21.3 ± 2.8	16.6–25.5	40.8	0.3 ± 0.6	0.0–2.2	0.6
15	69.9 ± 17.0	51.3–104.0	17.8 ± 4.7	13.5–26.9	25.4	21.8 ± 5.8	15.5–32.9	31.1	30.3 ± 7.3	21.2–44.2	43.3	0.2 ± 0.3	0.0–0.9	0.2
16	48.4 ± 12.8	29.9–68.7	12.9 ± 3.2	7.2–18.7	26.6	15.8 ± 5.5	7.4–23.8	32.6	19.8 ± 4.9	15.1–29.7	40.9	0.0 ± 0.0	0.0–0.0	0.0
17	81.9 ± 19.0	40.1–121.0	18.4 ± 4.8	8.3–28.9	22.5	30.3 ± 7.5	14.3–44.3	37.0	33.2 ± 7.1	17.5–47.8	40.5	0.0 ± 0.0	0.0–0.0	0.0
18	36.7 ± 11.6	16.2–56.9	11.4 ± 4.3	4.9–20.1	31.2	11.2 ± 4.2	5.3–18.4	30.4	13.8 ± 4.5	6.0–22.7	37.7	0.2 ± 0.3	0.0–0.7	0.6
19	39.8 ± 11.2	24.4–69.3	10.3 ± 2.9	6.2–17.3	25.9	13.9 ± 4.7	6.9–24.0	34.8	15.5 ± 4.3	10.8–28.0	39.0	0.1 ± 0.3	0.0–1.0	0.4
20	30.8 ± 6.3	20.8–42.5	10.6 ± 2.9	6.6–15.3	34.4	9.4 ± 1.9	6.2–12.8	30.5	10.8 ± 2.2	7.4–14.4	35.1	0.0 ± 0.1	0.0–0.1	0.1
21	21.9 ± 8.1	15.2–35.6	9.6 ± 3.5	6.3–15.4	43.8	6.0 ± 2.6	3.9–10.4	27.6	6.3 ± 2.1	4.5–9.8	28.6	0.0 ± 0.0	0.0–0.0	0.0
22	41.0 ± 9.0	26.4–51.3	11.8 ± 3.3	6.4–16.6	28.9	12.4 ± 3.8	7.7–16.8	30.4	16.4 ± 3.3	12.4–20.2	40.0	0.3 ± 0.4	0.0–1.0	0.8
23	68.7 ± 9.3	55.6–86.7	21.0 ± 2.8	15.4–25.8	30.6	23.4 ± 4.6	18.3–31.1	34.1	24.3 ± 3.2	19.2–29.8	35.3	0.0 ± 0.0	0.0–0.0	0.0
24	45.7 ± 3.2	41.7–49.5	21.9 ± 1.2	20.7–23.5	47.9	13.0 ± 1.3	11.9–14.8	28.3	10.6 ± 1.7	8.3–12.2	23.1	0.3 ± 0.4	0.0–0.8	0.6
25	65.5 ± 19.5	36.1–114.9	18.1 ± 6.1	10.3–34.1	27.7	22.3 ± 8.2	9.4–43.3	34.0	24.4 ± 6.0	12.2–37.5	37.2	0.7 ± 1.0	0.0–2.9	1.1
26	26.4 ± 4.9	21.9–34.6	9.3 ± 1.5	8.0–11.8	35.4	7.3 ± 2.4	4.3–10.5	27.8	9.5 ± 3.2	7.2–15.0	36.1	0.2 ± 0.2	0.0–0.6	0.7
27	32.6 ± 9.7	22.2–52.8	13.6 ± 3.1	9.0–19.9	41.7	9.7 ± 4.4	5.2–19.3	29.8	9.3 ± 3.0	5.5–13.7	28.5	0.0 ± 0.0	0.0–0.0	0.0
28	83.3 ± 16.0	63.7–114.6	26.3 ± 6.0	17.3–36.2	31.5	31.8 ± 7.0	25.2–46.5	38.2	25.3 ± 4.0	20.7–32.0	30.3	0.0 ± 0.0	0.0–0.0	0.0
29	59.5 ± 12.1	29.9–75.2	14.4 ± 2.6	8.7–17.7	24.2	17.6 ± 4.2	9.4–23.9	29.5	27.1 ± 6.6	11.3–36.8	45.6	0.4 ± 0.3	0.0–1.5	0.7
30	22.4 ± 8.6	10.8–36.2	7.5 ± 3.4	2.5–12.9	33.4	6.7 ± 3.2	1.7–11.8	30.0	8.2 ± 2.6	3.5–11.5	36.6	0.0 ± 0.0	0.0–0.1	0.1
31	41.7 ± 8.7	29.9–56.3	15.4 ± 5.7	9.7–27.6	36.8	13.7 ± 4.0	5.1–18.3	32.7	12.7 ± 3.5	6.9–19.0	30.5	0.0 ± 0.0	0.0–0.0	0.0
32	63.3 ± 12.3	48.1–79.1	15.0 ± 2.5	11.9–20.3	23.7	19.7 ± 4.7	13.0–25.9	31.1	28.6 ± 5.8	20.2–35.9	45.2	0.0 ± 0.0	0.0–0.0	0.0

Table 4. Continued.

Indoor measurements

No.	Total dose rate (nGy.h^{-1})	Range	U series			Th series			^{40}K			^{137}Cs		
			(nGy.h^{-1})	Range	Contribution (%)	(nGy.h^{-1})	Range	Contribution (%)	(nGy.h^{-1})	Range	Contribution	(nGy.h^{-1})	Range	Contribution (%)
33	85.0 ± 29.0	46.9–139.2	19.4 ± 4.7	11.8–28.0	22.8	30.2 ± 12.3	14.7–54.9	35.6	35.4 ± 12.6	19.2–57.3	41.7	0.0 ± 0.0	0.0–0.0	0.0
34	59.6 ± 12.8	33.6–76.8	15.9 ± 3.7	9.0–21.7	26.7	20.1 ± 5.6	9.7–27.3	33.7	23.4 ± 4.6	14.7–29.2	39.2	0.2 ± 0.3	0.0–1.1	0.4
35	25.6 ± 6.5	16.3–37.9	9.8 ± 2.7	6.8–14.6	38.3	7.4 ± 2.2	4.7–11.3	29.0	8.3 ± 2.2	4.8–12.0	32.3	0.1 ± 0.2	0.0–0.7	0.4
36	30.5 ± 5.4	23.3–38.2	9.0 ± 2.2	6.8–14.3	29.6	10.5 ± 2.0	7.4–14.1	34.4	10.9 ± 2.4	7.0–14.8	35.8	0.1 ± 0.2	0.0–0.6	0.2
37	48.6 ± 5.3	39.9–57.4	12.0 ± 1.5	10.2–14.5	24.8	14.5 ± 1.8	11.9–17.5	29.7	21.7 ± 4.2	14.2–27.7	44.7	0.4 ± 0.6	0.0–1.6	0.8
38	28.6 ± 10.8	17.9–54.4	13.9 ± 4.8	6.4–19.4	48.6	6.7 ± 3.0	3.8–14.4	23.5	7.8 ± 5.1	4.0–20.6	27.3	0.2 ± 0.3	0.0–1.0	0.6
39	19.5 ± 3.3	14.8–22.5	7.1 ± 1.1	5.6–8.1	36.6	5.2 ± 1.6	3.1–6.9	26.8	7.1 ± 0.8	6.1–8.0	36.7	0.0 ± 0.0	0.0–0.0	0.0
40	33.5 ± 8.7	21.3–47.9	12.5 ± 5.3	5.9–23.6	37.3	9.8 ± 3.2	3.5–13.8	29.3	11.0 ± 3.3	7.0–17.4	32.8	0.2 ± 0.3	0.0–0.8	0.7
41	45.5 ± 8.1	39.2–62.9	11.1 ± 2.8	7.8–16.5	24.3	16.9 ± 2.5	14.0–22.1	37.2	17.5 ± 3.6	13.1–24.4	38.5	0.0 ± 0.1	0.0–0.3	0.1

Outdoor measurements

No.	Total dose rate (nGy.h^{-1})	Range	U series			Th series			^{40}K			^{137}Cs		
			(nGy.h^{-1})	Range	Contribution (%)	(nGy.h^{-1})	Range	Contribution (%)	(nGy.h^{-1})	Range	Contribution (%)	(nGy.h^{-1})	Range	Contribution (%)
1	21.9 ± 9.7	6.6–39.7	6.8 ± 2.6	1.6–16.6	31.0	7.3 ± 4.0	1.6–15.4	33.1	7.0 ± 3.5	1.1–14.6	31.9	0.9 ± 1.3	0.0–5.2	4.0
2	46.2 ± 16.1	9.6–107.1	10.2 ± 3.2	4.7–21.6	22.1	15.3 ± 6.8	1.2–36.5	33.1	14.4 ± 6.5	1.5–42.4	31.1	6.5 ± 6.5	0.0–28.3	14.0
3	25.5 ± 5.5	18.5–33.4	7.7 ± 2.0	5.8–10.8	30.2	8.7 ± 2.0	5.9–10.8	34.1	8.5 ± 2.1	6.8–12.2	33.5	0.5 ± 0.6	0.0–1.4	2.1
4	42.0 ± 19.7	13.0–68.5	9.8 ± 4.9	2.1–16.3	23.3	15.2 ± 8.4	3.2–28.5	36.1	15.8 ± 6.9	6.1–27.0	37.5	1.3 ± 0.7	0.7–2.9	3.1
5	29.5 ± 13.3	6.7–57.8	10.3 ± 3.3	3.9–15.2	35.1	7.5 ± 5.1	1.1–20.0	25.6	10.2 ± 6.2	1.4–22.6	34.4	1.5 ± 1.9	0.0–6.4	5.0
6	26.7 ± 7.5	17.5–35.9	8.4 ± 0.9	7.3–9.5	31.4	8.5 ± 3.4	4.7–12.9	31.8	7.8 ± 2.0	5.2–10.1	29.3	2.0 ± 1.8	0.4–4.4	7.4
7	81.0 ± 30.9	56.0–153.0	19.9 ± 9.4	14.3–42.4	24.6	30.1 ± 11.5	19.3–56.5	37.1	30.5 ± 10.7	19.2–54.0	37.6	0.5 ± 0.6	0.0–1.6	0.7
8	80.8 ± 16.5	62.6–107.7	20.0 ± 5.0	13.5–28.5	24.7	31.2 ± 7.0	21.2–40.8	38.7	27.4 ± 4.3	22.7–34.8	33.9	2.2 ± 2.7	0.0–7.9	2.7
9	36.3 ± 13.2	19.7–52.5	10.0 ± 2.6	7.4–13.8	27.4	11.6 ± 6.4	3.0–19.1	31.8	12.4 ± 4.6	6.7–19.6	34.1	2.4 ± 0.8	1.1–3.2	6.7
10	22.4 ± 3.8	16.8–30.7	11.3 ± 2.9	6.0–14.8	50.6	4.5 ± 2.2	2.5–8.3	20.1	4.9 ± 2.5	2.3–11.1	22.0	2.2 ± 2.5	0.0–8.1	9.9
11	30.3 ± 11.6	15.6–44.0	11.9 ± 4.1	6.6–16.6	39.2	10.1 ± 5.6	4.9–18.0	33.4	7.1 ± 3.2	4.2–11.6	23.3	1.2 ± 0.9	0.0–2.1	4.1
12	59.2 ± 6.7	51.9–69.9	28.7 ± 1.9	26.4–31.1	48.5	16.5 ± 3.9	12.1–22.7	27.9	14.0 ± 1.6	11.8–16.2	23.6	0.0 ± 0.0	0.0–0.0	0.0
13	46.2 ± 7.0	38.1–59.1	10.8 ± 3.2	6.0–14.5	23.4	12.1 ± 3.9	5.1–16.4	26.1	15.6 ± 3.0	10.7–20.0	33.6	7.8 ± 7.7	1.4–18.2	16.9
14	53.5 ± 15.1	30.3–70.6	13.0 ± 3.0	9.4–17.5	24.4	20.5 ± 7.4	10.0–29.1	38.3	18.3 ± 5.1	10.8–27.9	34.2	1.6 ± 2.1	0.0–6.5	3.1
15	49.6 ± 18.5	10.5–71.8	12.5 ± 3.7	5.1–16.7	25.1	18.4 ± 2.5	14.3–22.9	37.0	20.6 ± 8.6	4.9–33.4	41.5	0.8 ± 0.7	0.0–1.8	1.6
16	37.5 ± 8.1	27.3–52.4	9.5 ± 1.9	7.3–11.8	25.3	12.4 ± 3.1	9.0–18.3	33.0	13.9 ± 3.9	9.6–20.5	37.1	1.7 ± 2.1	0.0–6.1	4.6

Table 4. Continued.

Outdoor measurements

No.	Total dose rate ($nGy.h^{-1}$)	Range	U series			Th series			^{40}K			^{137}Cs		
			($nGy.h^{-1}$)	Range	Contribution (%)	($nGy.h^{-1}$)	Range	Contribution (%)	($nGy.h^{-1}$)	Range	Contribution (%)	($nGy.h^{-1}$)	Range	Contribution (%)
17	84.7 ± 37.1	34.0–149.2	20.2 ± 8.7	7.2–37.1	23.8	33.5 ± 16.9	11.6–62.9	39.5	31.0 ± 12.0	15.1–49.2	36.6	0.1 ± 0.2	0.0–0.7	0.1
18	37.9 ± 19.8	14.4–59.6	10.4 ± 5.0	5.1–18.6	27.3	9.6 ± 5.4	3.3–17.4	25.4	10.8 ± 7.2	4.5–22.7	28.4	7.2 ± 10.4	0.9–25.2	18.9
19	32.1 ± 13.8	12.9–48.6	7.3 ± 2.6	3.8–10.2	22.6	10.9 ± 5.1	3.4–16.6	33.8	10.7 ± 4.6	5.2–16.1	33.4	3.3 ± 2.1	0.5–5.9	10.2
20	23.7 ± 4.9	16.6–31.5	8.9 ± 1.0	7.5–10.1	37.4	6.3 ± 1.7	4.2–8.8	26.8	8.0 ± 2.5	4.8–12.3	33.8	0.5 ± 0.2	0.1–0.7	2.0
21	17.3 ± 4.8	9.5–21.6	6.8 ± 1.6	4.9–8.5	39.3	6.0 ± 2.0	3.2–8.6	34.6	4.5 ± 2.1	1.3–6.6	26.1	0.0 ± 0.0	0.0–0.0	0.0
22	48.0 ± 17.0	24.2–66.1	11.9 ± 2.7	8.4–14.6	24.8	12.3 ± 4.8	6.3–18.2	25.6	14.2 ± 3.4	9.0–17.4	29.5	9.6 ± 9.0	0.5–23.4	20.1
23	62.6 ± 18.9	40.8–94.6	19.5 ± 3.7	15.2–24.5	31.2	23.1 ± 9.8	10.9–37.2	36.9	16.7 ± 7.2	6.2–29.0	26.7	3.3 ± 4.6	0.0–12.8	5.2
24	35.1 ± 0.8	34.4–35.9	19.1 ± 1.1	18.0–20.2	54.4	10.2 ± 2.6	7.6–12.8	29.0	4.6 ± 1.5	3.0–6.1	13.0	1.3 ± 0.7	0.6–2.0	3.7
25	64.5 ± 9.0	52.4–74.1	12.7 ± 1.4	11.1–14.6	19.6	23.9 ± 5.1	17.4–29.8	37.0	12.5 ± 2.1	10.7–15.4	19.4	15.5 ± 7.5	4.9–21.9	24.0
26	33.8 ± 12.7	18.4–49.4	16.4 ± 3.4	12.3–20.6	48.4	8.0 ± 4.8	2.1–13.8	23.7	9.1 ± 4.5	3.7–14.7	26.9	0.3 ± 0.1	0.2–0.4	1.0
27	34.7 ± 14.1	13.6–55.7	10.1 ± 4.0	6.4–17.3	29.2	12.0 ± 5.3	4.0–19.8	34.5	10.5 ± 5.4	2.5–17.6	30.4	2.1 ± 1.4	0.7–4.4	6.0
28	66.1 ± 14.3	41.8–86.1	21.0 ± 3.9	15.5–28.2	31.8	24.5 ± 6.0	14.0–33.5	37.1	18.0 ± 4.6	8.7–22.9	27.2	2.6 ± 2.4	0.0–7.8	4.0
29	55.9 ± 29.3	27.4–107.4	13.4 ± 7.0	5.5–23.0	24.1	17.4 ± 10.6	8.4–36.2	31.1	23.0 ± 13.2	9.9–48.2	41.3	2.0 ± 1.4	0.0–3.9	3.5
30	20.2 ± 8.9	11.2–31.3	6.6 ± 1.3	4.4–8.1	32.9	7.4 ± 4.6	2.9–14.4	36.5	7.3 ± 4.0	2.8–13.8	36.1	0.4 ± 0.4	0.0–0.9	1.8
31	30.3 ± 9.3	17.8–45.3	10.0 ± 2.2	5.4–13.5	33.0	10.0 ± 4.3	5.1–17.3	33.0	8.2 ± 2.9	4.4–13.3	27.1	2.1 ± 1.8	0.0–5.3	6.9
32	60.6 ± 20.0	22.9–81.3	14.6 ± 3.2	7.9–17.6	24.0	21.8 ± 9.9	5.1–32.5	36.0	22.8 ± 6.8	9.8–30.3	37.6	1.4 ± 1.4	0.0–3.5	2.3
33	88.0 ± 47.3	40.5–173.4	17.8 ± 5.3	12.4–25.9	20.3	28.5 ± 14.8	14.0–50.5	32.4	29.9 ± 12.6	11.3–46.7	34.0	11.8 ± 17.2	1.5–50.3	13.4
34	28.3 ± 4.3	23.9–34.2	8.2 ± 0.9	6.9–8.9	29.0	7.9 ± 1.9	6.4–10.5	27.9	9.6 ± 1.0	8.8–11.0	33.8	2.6 ± 1.0	1.4–3.9	9.4
35	33.4 ± 4.3	29.7–39.5	9.4 ± 0.7	8.4–9.8	28.0	11.8 ± 2.0	10.3–14.7	35.4	11.2 ± 1.6	9.5–13.4	33.5	1.0 ± 0.7	0.0–1.6	3.1
36	29.8 ± 7.0	20.0–37.7	6.2 ± 1.1	4.2–7.4	20.8	11.5 ± 2.6	7.8–15.1	38.6	10.7 ± 3.3	6.2–14.2	36.1	1.3 ± 0.8	0.0–2.1	4.5
37	30.6 ± 13.3	10.1–48.3	7.8 ± 2.8	3.4–12.1	25.4	8.4 ± 4.8	2.5–15.7	27.5	11.2 ± 5.7	2.8–19.7	36.7	3.2 ± 5.3	0.0–15.1	10.4
38	27.4 ± 11.4	13.3–46.5	11.7 ± 6.8	4.1–23.9	42.6	7.9 ± 5.0	4.4–17.4	28.9	7.1 ± 5.3	3.2–16.9	25.9	0.7 ± 0.7	0.0–2.1	2.6
39	22.3 ± 7.3	13.0–30.7	7.3 ± 1.3	5.9–9.1	32.9	7.6 ± 4.6	1.8–13.2	34.1	5.7 ± 2.9	1.8–8.9	25.7	1.6 ± 1.1	0.3–2.9	7.3
40	23.3 ± 9.1	15.2–39.2	7.8 ± 2.3	5.1–10.6	33.4	6.4 ± 3.2	3.8–12.2	27.7	6.8 ± 4.3	2.8–14.7	29.3	2.3 ± 2.6	0.5–7.3	9.7
41	37.8 ± 8.3	28.8–48.9	9.3 ± 0.8	8.5–10.4	24.5	12.9 ± 4.3	9.3–19.0	34.1	13.5 ± 2.2	11.0–16.3	35.7	2.2 ± 1.5	0.0–3.3	5.7

these two cities where about 40% of the Greek population lives.

Measurements in Thessaloniki

In Thessaloniki (second town of Greece) and its surroundings, 225 indoor measurements and 78 outdoor measurements (56 over soil and 22 on roads and pavements) were performed. The frequency distribution of the total indoor and outdoor absorbed dose rates in air is shown in Figure 3. It seems to follow a normal type distribution. In order to study the spatial variability of the indoor and outdoor gamma dose rates the town of Thessaloniki was divided in six subdivisions. The difference between the mean dose rates in the different subdivisions were within the standard deviations.

The minimum, maximum and mean total indoor dose rate in air due to gamma radiation is 18 nGy.h^{-1}, 99 nGy.h^{-1} and 59 nGy.h^{-1} respectively. The contribution of the different radionuclides to the total indoor gamma dose rate in air is 39% due to ^{40}K, 35% due to thorium series, 25% due to uranium series and about 1% due to ^{137}Cs from the Chernobyl accident.

For the buildings and houses constructed before the Chernobyl accident the actual indoor ^{137}Cs gamma radiation is only due to the presence of ^{137}Cs from the Chernobyl accident in the nearby outdoor environment. Conversely for buildings and houses constructed after the Chernobyl accident the indoor ^{137}Cs gamma radiation can be also due to possible radiocesium contamination of the building materials. Figure 4 presents the indoor dose rate due to ^{137}Cs as function of the construction year of the house or building. A pronounced peak appears at the year 1986 where the Chernobyl accident occurred. This fact indicates that for houses and buildings that were under construction in 1986, ^{137}Cs acted also as an indoor source term, however with a small contribution to the total dose rate. Finally the relatively high value of the indoor dose rate due to ^{137}Cs for the house constructed in 1930 can be explained from the fact that the specific house was reconstructed in 1986. The fact that for the houses and buildings constructed before 1986 the actual indoor ^{137}Cs gamma radiation is only due to the presence of ^{137}Cs in the nearby outdoor environment, gave the opportunity to measure in real conditions the attenuation of the gamma radiation by the building materials. For such buildings the dose rate due to ^{137}Cs was determined outdoors, in the vicinity of the building, as well as inside the building. Most values gave dose attenuations, due to the shielding of the buildings, between 90% and 100%.

For the indoor gamma dose rates due to natural emitters, no dependence was found on the construction year of the house. As an example, Figure 5 shows the indoor dose rate due to ^{40}K as a function of the construction year of the house or building. The same result was also found for the uranium and thorium series. The indoor dose rate was also measured in different floors of the same building. Figure 6 presents the total indoor dose rate as a function of the floor number in a 9 storey building. It is clear that there is no dependence of the total indoor dose rate on the floor number.

From the 78 outdoor measurements in Thessaloniki, 56 were performed over soil and 22 on roads and pavements. The mean outdoor absorbed gamma dose rates in air due to the uranium series, thorium series, ^{40}K, ^{137}Cs and the sum of them (total) are presented in Table 5. The only difference between the measurements performed over soil and on roads and pavements is the dose rate due to ^{137}Cs which as expected is higher over soil than on roads and pavements.

Measurements in Athens

In the extended Athens (capital of Greece) region, 157 indoor and 45 outdoor *in situ* gamma spectrometry measurements were performed. The extended Athens region is relatively a large area with a population of more than 3 millions (more than 30% of the Greek population). The mean indoor and outdoor absorbed gamma dose rates in air due to the uranium series, thorium series, ^{40}K, ^{137}Cs and the sum of them (total)

Table 5. Mean outdoor absorbed gamma dose rates in air due to uranium series, thorium series, ^{40}K, ^{137}Cs and the sum of them (total) measured in Thessaloniki.

	Tilled soil	Asphalt	Concrete, Flagstone	Grass, Soil	Total
Number of measurements	19	7	15	37	78
Average of total dose (nGy.h^{-1})	51.5	23.4	43.4	49.0	46.2
Standard deviation (nGy.h^{-1})	12.4	13.2	16.5	14.2	16.1
Min (nGy.h^{-1})	25.4	9.6	23.5	24.9	9.6
Max (nGy.h^{-1})	73.0	43.7	87.3	107.1	107.1
Contribution uranium series	20.6%	35.3%	28.2%	19.6%	22.1%
Contribution thorium series	36.0%	26.9%	33.0%	32.1%	33.1%
Contribution ^{40}K	31.2%	31.1%	34.4%	29.8%	31.1%
Contribution ^{137}Cs	12.2%	6.6%	4.4%	19.0%	14.0%

as well as their corresponding minimum and maximum values is presented in Table 4 and are among the smallest mean values measured in the Greek towns. The important question is if these values, and particularly the number of the *in situ* gamma spectrometry measurements performed, are sufficient in order to deduce representative values of mean dose rates for the Athens region. In our opinion the answer is positive due to the following facts:

(1) The frequency distribution of the total indoor absorbed gamma dose rates in air follows a normal type distribution (Figure 7).
(2) The extended Athens region was divided in five subdivisions. The difference between the mean dose rates in the different subdivisions was small and within the standard deviations (Table 6).

CONCLUSIONS

In the present paper the results obtained from more than 1000 indoor and outdoor *in situ* gamma spectrometry measurements in 41 towns (from all geographic subdivisions) of the Greek mainland (not islands) were presented and discussed. To our knowledge this is the first national ground survey in urban areas performed in the world based on high resolution gamma spectrometry with a portable Ge detector. From the *in situ* gamma spectra the absorbed dose rate in air due to the uranium series, thorium series, ^{40}K, and ^{137}Cs could be derived.

The mean total outdoor and indoor absorbed gamma dose rate in air for the different towns varies between 17 and 88 $nGy.h^{-1}$ and 20 and 101 $nGy.h^{-1}$ respectively. The cities with relatively higher mean total absorbed dose rates are located in Northern Greece. In Southern Greece, and particularly in Athens and its surroundings, where 33% of the Greek population lives, the values of the mean total outdoor and indoor dose rates are 22 and 24 $nGy.h^{-1}$ among the smallest mean values measured in the Greek towns. The Greek population-weighted average for the outdoor and indoor gamma dose rates is 31 and 36 $nGy.h^{-1}$ respectively. Assuming that 80% of people's time is spent indoors a mean annual equivalent dose of 0.54 mSv from the gamma radiation can be deduced.

The indoor dose rate is almost always higher than the outdoor dose rate. This is due to the fact that most of the buildings and houses of Greece are made of brick and concrete. In this case the gamma rays emitted outdoors are efficiently absorbed by the walls, and the indoor absorbed dose rate depends mainly on the activity concentrations of natural radionuclides in the building materials. Under these circumstances, the indoor-outdoor ratio of absorbed dose rates in air is higher than 1 as a result of the change in source geometry.

The indoor and outdoor absorbed dose rates in air are mainly due to natural emitters. The mean contributions

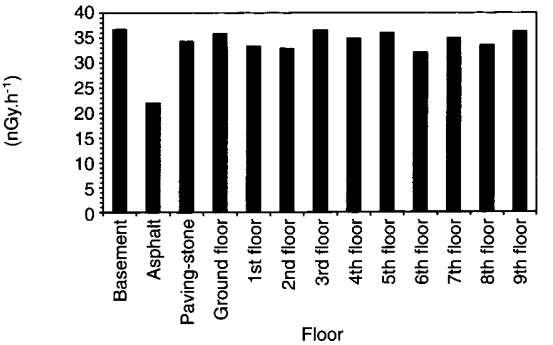

Figure 6. Total indoor dose rate as function of the floor number in a 9 storey building.

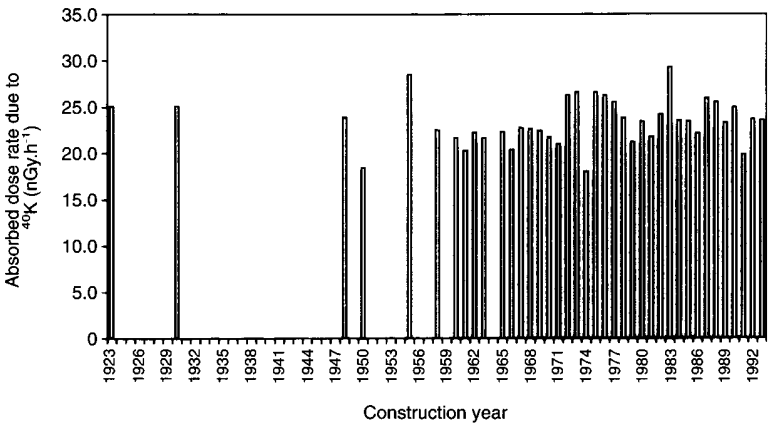

Figure 5. Indoor dose rate due to ^{40}K as function of the construction year of the house or building.

Table 6. Mean outdoor and indoor absorbed gamma dose rates in air in the 5 subdivisions of Athens.

Division	No measurements	Average dose ($nGy.h^{-1}$)	STD ($nGy.h^{-1}$)	Min ($nGy.h^{-1}$)	Max ($nGy.h^{-1}$)	**Indoor measurements** U series		Th series		^{40}K		^{137}Cs	
						($nGy.h^{-1}$)	%	($nGy.h^{-1}$)	%	($nGy.h^{-1}$)	%	($nGy.h^{-1}$)	%
Centre	75	23.9	6.0	14.5	43.3	6.8	28.6%	8.3	34.6%	8.7	36.5%	0.1	0.2%
West district	21	20.4	7.0	11.5	41.6	7.1	34.6%	6.6	32.4%	6.5	31.9%	0.2	1.1%
Piraeus	35	26.2	8.6	10.2	53.7	8.2	31.5%	8.7	33.1%	9.2	35.1%	0.1	0.3%
North district	21	22.8	7.9	7.8	42.5	7.6	33.3%	7.3	31.8%	7.9	34.8%	0.0	0.1%
South district	5	26.6	5.8	20.6	37.5	9.5	35.6%	8.6	32.5%	8.5	31.9%	0.0	0.0%
Total	157	23.9	7.2	7.8	53.7	7.4	30.8%	8.0	33.6%	8.4	35.3%	0.1	0.3%

Division	No measurements	Average dose ($nGy.h^{-1}$)	STD ($nGy.h^{-1}$)	Min ($nGy.h^{-1}$)	Max ($nGy.h^{-1}$)	**Outdoor measurements** U series		Th series		^{40}K		^{137}Cs	
						($nGy.h^{-1}$)	%	($nGy.h^{-1}$)	%	($nGy.h^{-1}$)	%	($nGy.h^{-1}$)	%
Centre	10	21.3	6.5	13.2	34.7	6.1	28.6%	7.3	34.1%	7.5	35.0%	0.4	1.8%
West district	10	18.8	9.3	8.3	31.8	6.2	32.8%	6.3	33.5%	5.3	28.1%	1.6	8.4%
Piraeus	5	24.8	8.6	9.6	32.8	7.1	28.7%	9.2	37.2%	7.6	30.7%	0.8	3.2%
North district	10	21.9	10.9	6.7	39.7	7.3	33.5%	6.7	30.5%	7.3	33.3%	0.3	1.4%
South district	10	24.3	11.1	6.6	39.4	7.5	30.8%	9.0	37.1%	7.6	31.3%	1.3	5.4%
Total	45	21.9	9.7	6.6	39.7	6.8	31.0%	7.6	34.5%	7.0	31.9%	0.9	4.0%

of the uranium series, thorium series ^{40}K and ^{137}Cs to the total dose rate are 28.5% (U), 34% (Th), 37% (^{40}K), 0.5% (^{137}Cs) for the indoor measurements and 28% (U), 33% (Th), 31.5% (^{40}K), 7.5% (^{137}Cs) for the outdoor measurements respectively. The mean contribution of ^{137}Cs from the Chernobyl accident to the total indoor dose rate for the different Greek towns is negligible (always smaller than 1%). Conversely, the mean contribution of ^{137}Cs to the total outdoor dose rate for the different Greek towns is small but not negligible. For the buildings and houses constructed before the Chernobyl accident the actual indoor ^{137}Cs gamma radiation is only due to the presence of ^{137}Cs from the Chernobyl accident in the nearby outdoor environment. The attenuation of the outdoor radiation (661.6 keV) observed due to the shielding of the houses was at least 90% up to 100%. For houses and buildings that were under construction in 1986, ^{137}Cs acts also as an indoor source term, however with a small contribution to the total dose rate.

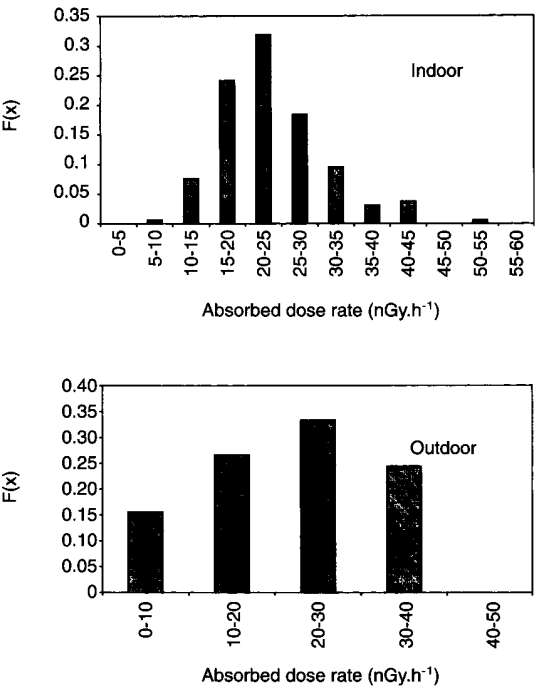

Figure 7. Frequency distribution F(x) of the total indoor and outdoor absorbed dose rates in air measured in Athens.

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