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Article

Natural background radiation and population dose in China

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ABSTRACT **On the basis of analyzing the data for the natural background radiation level in China, the typical values for indoor and outdoor terrestrial gamma radiation and effective dose equivalents from radon and thoron daughters are recommended. The annual effective dose equivalent from natural radiation to the inhabitant is estimated to be 2.3 mSv, in which 0.54 mSv is from terrestrial gamma radiation and about 0.8 mSv is from radon and its short-lived daughters.**

RÉSUMÉ **L'analyse des données sur les niveaux de l'irradiation naturelle en Chine a permis de recommander des valeurs types pour l'irradiation gamma terrestre, à l'intérieur et à l'extérieur des habitations, ainsi que l'équivalent de dose efficace pour les produits de filiation du radon et du thoron. On estime à 2,3 mSv l'équivalent de dose efficace annuel dû à l'irradiation naturelle des habitants, dont 0,54 mSv dû au rayonnement gamma terrestre et environ 0,8 mSv dû au radon et à ses descendants à vie courte.**

Introduction

Natural background radiation levels may change with human practice activities and natural evolution. Strictly speaking, natural background radiation level is time-dependent, without any constant level. In contrast to the very slow natural evolution, changes due to human practices, especially the development of modern industries, are quite a fast process that may occur in a brief space of time. The rapid development of nuclear and other industries in China makes it more necessary to investigate the natural radiation level and to determine its baseline so as to discover probable changes quickly.

Natural radiation level measurements began in the late 50s carried out by the predecessor of the China Institute of atomic energy (CIAE). Before its heavy-water reactor commissioning, environmental gamma-ray levels and radon/thoron daughter concentrations in air around the area of the institute

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had been measured. In the 60s and afterwards, before operating a new nuclear installation, routine environmental radiation background investigations were always performed, usually lasting 1-2 years. Systematic measurements of environmental radiation and radionuclide level began in the last 70s and early 80s in a larger scale, initiated by CIAE, firstly in the Beijing region and then in other selected areas of the country [1]. Cooperative groups affiliated to the ministry of public health implemented a nation-wide investigation programme in the early 80s [2, 3]. A more carefully designed programme covering the mainland of China launched in 1983 by the National environmental protection agency acquired, with higher confidence, a set of complete data on natural environmental radiation levels and radionuclide contents in the soils of the country [4, 5].

1. Terrestrial gamma radiation level

1.1 Outdoor gamma radiation level

Natural gamma radiation levels in fields and over roads in mainland of China are summarized in Table I. As shown, values reported by reference [6] are considerably higher. As revealed previously [7], the main reason was that these measurements were carried out by a type of NaI (Tl) scintillation radiometer, model FD-71, which has been proved to have very poor energy dependence [8, 9], though a correction factor of 0.5 had already been suggested for FD-71 higher gamma response [10] that undoubtedly diminished the deviation of the results. It is obvious that a constant factor cannot match the diversification of terrestrial gamma ray spectra over different places of the vast China territory. As a matter of fact, two independent sets of site-to-site comparison measurements with both an FD-71 and a pressurized ion chamber were conducted, which showed that in fields the average values obtained with FD-71 after being corrected with the factor of 0.5 were still 6.7% and 9% higher than the corresponding ion chamber values, and over roads the higher percentage values were as high as 15.9% and 15% [11]. It would not be strange to find that for individual sites the unidirectional departure of FD-71 values from the ion chamber values was even higher than the above average percentages [12]. Comparisons against each province and city were also made between values [2, 4, 5] through which it was found that provinces or cities having higher average gamma level would present higher ratios of soil concentrations of U and Th to ^{40}K. This fact could perfectly be interpreted by the relatively higher energy response of FD-71 to U- and Th-series than to ^{40}K [8].

In view of the significant deviation of the data obtained with FD-71 [2], it is reasonable to use the data listed in Table I for calculating the national average values. As a result, the external gamma radiation dose rates in air are estimated at 62.7 nGy h^{-1} in fields and 59.4 nGy h^{-1} over roads. The typical values recommended in fields and over roads are 65 and 60 nGy h^{-1} respectively.

1.2 Indoor gamma radiation level

The results of indoor gamma radiation dose rates in air (Tab. I) ; just as in fields [2] also imply a higher systematical deviation. The average value derived from Table I, excluding reference [2] data, is 93.4 nGy h^{-1}. This value is close to the value of 92.7 nGy h^{-1}, which was calculated in terms of contents of radionuclides in house structure materials [25] under the assumption that materials were made of brick (46.5%), cement (5.1%), lime (3.2%), sand (34.8%) and broken stone (10.4%) [26]. The typical values of radionuclide contents in various building materials are listed in Table II ; they are the most representative values recommended for each material listed in the table.

Based on the analysis above, the national external gamma radiation dose rate indoors recommended is 95 nGy h^{-1}.

TABLE I

Gamma radiation levels in China
Niveaux d'irradiation gamma en Chine

Region	Sampling sites	Average dose rate (nGy h^{-1})	Detector	Reference
In fields				
mainland	38611	80.3*	NaI(Tl)	[2]
24 prov. & cities	1568	67	TLD ($CaSO_4$: Dy)	[6]
mainland	8813	62.1	PS & PIC	[5]
mainland	1961	59.0*	PS & PIC	[4]
Over roads				
mainland	37727	83	NaI (Tl)	[2]
mainland	8813	61.8	PS & PIC	[5]
mainland	2173	56.9	PS & PIC	[4]
Indoors				
mainland	53952	119.5*	NaI (Tl)	[2]
22 prov. & cities	2452	89*	TLD ($CaSO_4$: Dy)	[6]
mainland	8813	99.1*	PS & PIC	[5]
maintand	2766	92.1*	PS & PIC	[4]

* population weighted average ; PS : plastic scintillator compensated with ZnS ; PIC : pressurized ion chamber.

2. Radon, thoron and their daughters level

2.1 Outdoor concentrations of radon and thoron and their daughters

In Table III, the concentrations of radon and its daughters in outdoor air are presented for provinces and cities of China where the population amounts to 40% of the whole country. The population weighted averages of radon concentrations and its daughter equilibrium radon concentrations (EEC) are 11.2 and 6.1 Bq m^{-3} respectively.

TABLE II

Contents of natural radionuclides in building materials in China
Radionucléides naturels dans les matériaux de construction en Chine

Category	Location	Number of samples	Content (Bq/kg)			Ref.
			^{226}Ra	^{232}Th	^{40}K	
Clay brick	Various regions	79	58.5	73.6	551	[13]
Clay brick	Various regions	26	40	52	698	[14]
Sintered brick	Various regions	173	61.4	63.5	667	[15]
Red & clay brick	Beijing	5	38.0	45.4	748	[16]
Clay brick	Hebei	1	36	48	750	[16]
Red brick	Shenzhen	15	81.8	109	393	[17]
Red brick	Zhejiang	32	62.9	85.1	544	[18]
Red brick	Hubei	22	55.5	62.2	497	[19]
Red brick	Qinchuan, Guangxi	56	78.7	52.7	558	[20]
Red brick	Hunan		42.2	60.9	421	[21]
Red brick	Sichuan	2	57	50	448	[22]
Average for brick		*411*	*54.1*	*63*	*615*	
Recommended for brick			*55*	*65*	*600*	
Broken stone & pebble	Various regions	6	32.9	69.6	1 047.5	[13]
Rock	Zhejiang	5	69	96.2	729	[18]
Recommended for stone and rock			*50*	*80*	*900*	
Portland cement	Whole country	47	44.0	29.6	110.3	[13, 23]
Portland cement	Zhejiang	26	51.8	25.9	104	[18]
Portland cement	Hubei	22	59.2	42.6	218	[19]
Portland cement	Beijing	4	34	28	320	[16]
Portland cement	Qinchuan, Guangxi	11	45	31.6	104	[20]
Portland cement	Shenzhen	16	55.2	36.4	176	[17]
Portland cement	Sichuan	3	46.9	21	116	[22]
Portland cement	Shanxi*	6	63.8	35.7	120	[24]
Average for cement			*47.4*	*30.6*	*137.9*	
Recommended for cement			*50*	*30*	*140*	
Lime	Various regions	8	31.8	9.6	92.9	[13]
Lime	Hubei	5	54.8	5.60	15.8	[19]
Lime	Zhejiang	6	33.3	3.70	11.1	[18]
Lime	Shenzhen	10	25.0	7.12	35.5	[17]
Lime	Beijing	2	3.2	0.4	35	[16]
Lime	Sichuan		0.74	2.6	4.1	[22]
Average for lime			*27.6*	*6.8*	*56.6*	
Recommended for lime			*25*	*7*	*55*	
Sand	Various regions	7	28.1	36.6	905	[13]
Sand	Hubei	4	30.7	18.5	815	[19]
Sand	Zhejiang	7	29.6	37.0	806	[18]
Sand	Shenzhen	15	39.4	47.2	573	[17]
Sand	Beijing	4	10	18	790	[16]
Sand	Shanxi	3	3.3	39.6	1 073	[24]
Average for sand			*25.2*	*34.4*	*868*	
Recommended for sand			*25*	*35*	*850*	

TABLE III

Outdoor concentrations of radon and its daughters (EEC obtained through grab sampling techniques)
Concentration, à l'extérieur, en radon et ses descendants et concentration équivalente à l'équilibre (EEC) obtenue par prélèvements ponctuels

Location (city or province)	Survey date	Radon conc. ($Bq\ m^{-3}$)			EEC ($Bq\ m^{-3}$)			EF	Ref.
		Sampling sites	Average	Range	Sampling sites	Average	Range		
Hubei	1984-1986	70	12.4	2.2-32.7	162	9.4	1.5-48,5	0.62	[27]
Guangdong	1986-1987	110	15.4		110	8.45		0.55	[28]
Hebei					44	5.83	1.34-23		[29]
Liaoning		227	9.7	1.3-103.5	227	5.91		0.61	[30]
Beijing**		15	8.1	0.6-14.1					[31]
Hefei		52	4.67	1.45-11.5					[32]
Zhengzhou*	1984.6-1985				1	11.3			[33]
Lasa*	1982.3-1983.2					9.3			[34]
Shandong	1983-1987	148	4.8						[35]
Taiyuan*	1986-1987	1	10.6		1	6.34		0.66	[36]
Hangzhou*	1986-1987	5	42.3	12.9-66.3	5	6.3	3.9-7.37	0.25	[37]
Baotou*	1984				4	9.16			[38]
Lianyungang		45	9.5		45	5.6		0.59	[39]
Shanghai	1986	4	6.1						[40]
Inner Mongolia	1987	25	11.5	3.7-32.8	21	5.4	3.7-13	0.5	[41]
Heilongjiang	1988.1-5	251	14.7	1.5-66.5					[42]
Zheijiang	1987	8	12.7	2.3-40.0	166	5.90	0.33-28.7		[43]
Yinchuan	1987.5-9	11	6.55	3.44-10.4	10		2.41-78.8		[44]

* Average values refer to annual averages. ** Using charcoal canisters for sampling.
EF : Equilibrium factor. EEC : Equilibrium equivalent concentration.

The data in Table III were obtained by measurements carried out during the last 10 years using grab sampling techniques. Much attention was paid to the effect of seasonal variations of radon concentrations on the annual averages, and efforts were made to arrange the sampling time so as to obtain the best representative results. Nevertheless, these measurements were not performed following one standard procedure ; some of them were reported without clearly describing the sampling techniques and/or analysing time, and others had abnormally low equilibrium factors. Consequently, the representativeness and reliability of the data in Table III are different from one another. For the national typical outdoor concentrations of radon and its daughters, 10 and 6 Bq m^{-3} are respectively recommended.

The data about thoron and its daughters concentrations in outdoor air are fewer, as shown in Table IV. From these data, the average value of the equilibrium equivalent concentration (EEC) for thoron daughters is estimated at 0.39 Bq m^{-3}, and the national typical value of 0.4 Bq m^{-3} is assumed temporally.

TABLE IV

Outdoor concentration of thoron and its daughters
(EEC obtained through grab sampling techniques)
Concentration, à l'extérieur, en thoron et ses descendants
(EEC obtenue par prélèvements ponctuels)

Location (city or province)	Survey date	Thoron conc. (Bq m^{-3})			EEC (Bq m^{-3})			Ref.
		Sampling sites	Average	Range	Sampling sites	Average	Range	
Hubei					43	0.18	0.03-0.82	[27]
Guangdong	1984-1986	110	22.1		110	0.5		[28]
Baoto	1984				4	0.49	0.08-3.6	[38]

2.2 Indoor concentrations of radon and thoron and their daughters

Listed in Table V are the concentrations of radon and its daughters in indoor air in some provinces and cities of China, where the population amounts to 30% of the whole country. The population weighted concentration/EEC of radon and its daughters are estimated at 21.4 and 9.9 Bq m^{-3}, from which typical values of 20 and 10 Bq m^{-3} respectively may be recommended.

Grab sampling techniques were also adopted for most indoor radon investigations. It is well known that indoor radon and its daughters concentrations are closely related with climate and other factors, such as frequency of open-closed doors and windows. In Table VI are collected some ratios of maximum *vs* minimum concentration values which are seasonal or monthly averages in different regions. Inter-seasonal ratios are all greater than, but very close to 2, and the inter-monthly ratios range from 2 to 7 with higher values appearing in the southern part of the country. Owing to consideration of the above factors, the data for various regions in Table V are assumed to be representative to a degree. For the best results, it is better to use instruments giving accumulated radon concentrations, and concentration distributions with locations inside rooms should also be taken into account.

TABLE V

Indoor radon concentration and its daughters
(EEC obtained through grab sampling techniques)
Concentration, à l'intérieur des habitations, en radon et ses descendants
(EEC obtenue par prélèvements ponctuels)

Location (city or province)	Survey date	Radon conc. ($Bq\ m^{-3}$)			EEC ($Bq\ m^{-3}$)			EF	Ref.
		Room number	Average	Range	Room number	Average	Range		
Hubei[1]		380	22.5	2.1-377.9	1920	10.2	1.1-151	0.53	[27]
Guangdong[1]	1984-1986	220	19.0		220	10.3		0.54	[28]
Hubei[1]	1986-1987				44	8.0	1.6-28.5		[29]
Shijiazhuang[1]		47	17.0		47	7.14		0.42	[45]
Liaoning[1]		397	30	1.92-244.2		14.5		0.49	[30]
Beijing[2*]	1984-1985	537	30.3	1.9-259					[31]
Hefei[1]		109	9.66	1.33-36.7					[32]
Three countries of Jiangxi		10	80.7		10	35.2		0.43	[46]
Lianyuangang[1]		45	13.4					0.48	[39]
Shanghai[1]	1986, fall	48	7.8						[40]
Inner Mongolia	1987.3-10	277	31.5	3.8-335.4	45	11.3	1.5-42.2	0.31	[41]
Heilongjiang	1988.1-5	298	24.1	3.3-172.7					[42]
Zhejiang[1]	1987	209	17.2	3.5-91.6	351	7.52	0.6-34.14	0.44	[43]

1 Various constructions.
2 Various residences.
3 Residences.
* Using charcoal canister for sampling.
** Averages are refered to annual averages.
EF Equilibrium factor.

Table VII presents the indoors to outdoors ratios of radon concentrations in different regions, which decrease gradually from North to South, and at the end reach a value a bit higher than 1 in Guangdong province. The reason for this is easily interpreted by different sealings of constructions and different opening time and space of windows and/or doors in various regions. The Guangdong province has more hot and warm days during a year, and consequently the natural air exchange rate of a room is apparently higher than in the North [49].

Data on indoor thoron concentrations/EECs are fewer in Table VIII. The average EEC value of 0.68 Bq m^{-3} for thoron daughters is obtained, which may be rounded to 0.7 Bq m^{-3}, a typical value temporarily recommended.

TABLE VI

Seasonal and monthly indoor radon average concentration, maximum *vs* minimum
Rapport des concentrations moyennes maximales/minimales, par saison et par mois, en radon, à l'intérieur des habitations

	Liaoning [36]	Inner Mongolia [41]	Beijing [39]	Hubei [27]	Guangzhou [48]
Seasonal max. / Seasonal min.	2.07 (Win. / Aut.)		2.15 (Win.&Spr. / Aut.&Sum.)	2.05 (Win. / Sum.)	
Monthly max. / Monthly min.	2.31 (Jan. / Jul.)	3.4 (Feb. / Jul.)	4.5 (Jan. / Jun.–Jul.)		7 (Mar. / May.)

TABLE VII

Indoor *vs* outdoor radon concentration
Rapport des concentrations en radon, intérieur/extérieur

Liaoning [30]	Beijing [31]	Hefei [32]	Hubei [27]	Lianyungang [39]	Shanghai [40]	Zhejiang [43]	Guangdong [28]
3.09	3.74	2.07	1.81	1.41	1.28	1.27	1.23

TABLE VIII

Indoor concentration of thoron and its daughters (EEC obtained through grab sampling techniques)
Concentration, à l'intérieur, en thoron et ses descendants (EEC obtenue par prélèvements ponctuels)

Location (city or province)	Survey date	Thoron conc. (Bq m^{-3})			EEC (Bq m^{-3})			Ref.
		Room number	Average	Range	Room number	Average	Range	
Hubei[1]					37	0.25	0.03-0.6	[27]
Guangdong[1]	1984-1986	220	48.1		220	1.13		[28]
Baotou[2*]					4	0.93		[38]
Baotou[2**]					4	0.36		

1 Various constructions.
2 Office building.
* Sampling with door and window closed.
** Sampling with window open.

3. Dose assessment on natural radiations

3.1 External dose assessment

a) Dose arising from cosmic rays

The reported *per caput* annual dose equivalents at sea level from ionizing components of cosmic rays were very close [2, 5, 50], and the typical value taken here is 250 μSv.

Cosmic neutron measurements performed in China have provided some data of neutron flux density both at sea level and at different altitudes [50, 52]. However, it is hard to take them as a basis for estimating the national population dose. A better approximation is to adopt the value of 55 μSv, recommended by the UNSCEAR 1988 report [54].

b) External dose arising from terrestrial gamma radiation

The *per caput* annual effective dose equivalent H (μSv a^{-1}) resulting from terrestrial gamma radiation is estimated through the following formula :

$$H = 6.132\ (F_i D_i + F_o D_o)$$

where F_i and F_o are the indoor and outdoor occupancy factors, which are 0.8 and 0.2 according to the investigations in Beijing and other regions [53] ; D_i and D_o are the absorbed dose rates in air (nGy h^{-1}), which, as given above, are 95 and 60 nGy h^{-1}. Substituting these values for F_i, F_o, D_i and D_o in the above formula, the estimated H value is estimated at 540 μSv in China.

3.2 Internal dose assessment

a) Dose arising from inhalation of radon and thoron and their short-lived daughters

As aforementioned, the EECs for radon daughters are 6 Bq m^{-3} outdoors and 10 Bq m^{-3} indoors. Adopting the conversion factor of 10 μSv h^{-1} Bq^{-3} suggested by the UNSCEAR 1988 report together with indoor and outdoor occupancy factors of 0.8 and 0.2, the *per caput* annual effective dose equivalent resulting fro radon daughters is estimated at about 800 μSv.

Similar calculation is used for internal exposure to thoron daughters. Using the given EEC values of 0.4 Bq m^{-3} outdoors and 0.7 Bq m^{-3} indoors and adopting the concentration-to-dose conversion factor recommended by UNSCEAR, the annual effective equivalent dose obtained is 230 μSv.

b) Dose arising from internal irradiation of other natural radionuclides

Considering the cumulative data for other radionuclides is not sufficient for an overall dose assessment in China ; relevant data recommended by UNSCEAR are directly adopted as a basis in the following estimations. The main contributor to the internal dose among other radionuclides is ^{40}K, which is assumed to give 180 μSv per year, equal to the UNSCEAR value. This approximation would not result in apparent deviation, if one recognizes that the metabolic properties of ^{40}K are not much different in different human bodies. The total internal annual effective dose equivalent by other radionuclides in China is estimated at 420 μSv, which is a little higher than the value of 356 μSv given by UNSCEAR. The reasons are as follows :

– the contents of natural radionuclides in China soils are apparently higher than the corresponding UNSCEAR typical values ;

– the consequent internal dose arising from intake of foods containing ^{238}U and ^{232}Th series products is estimated at 58 μSv, *i.e.* higher than the UNSCEAR value [55].

3.3 Total dose due to natural exposure

As a preliminary result, the total *per caput* annual effective dose equivalent resulting from natural radiation in China is estimated at 2.3 mSv (Tab. IX) together with the contribution from different sources. ■

TABLE IX

***Per caput* annual effective dose equivalents due to natural radiation in China**
Equivalent de dose efficace, par individu, dû à la radioactivité naturelle en Chine

Source	Effective dose equivalent (μSv a^{-1})
External irradiation	
ioninzing part of cosmic rays	260
neutron of cosmic rays	55
terrestrial gamma rays	540
Terrestrial gamma rays radiation	
radon and its short-lived daughters	800
thoron and its short-lived daughters	230
other natural radionuclides	420
Total	2300

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