J Radioanal Nucl Chem
DOI 10.1007/s10967-014-3881-8

Estimation of effective dose rates caused by radon and thoron for inhabitants living in rare earth field in northwestern Vietnam (Lai Chau province)

Le Khanh Phon · Bui Dac Dung · Nguyen Dinh Chau · Tibor Kovacs · Nguyen Van Nam · Duong Van Hao · Nguyen Thai Son · Vu Thi Minh Luan

Received: 19 August 2014

Abstract Forty six houses at three typical inhabitant villages that are located in the rare earth field in northwestern Vietnam were surveyed for radon and thoron concentrations. The measurements were conducted by exposing alpha track detectors CR-39 inside and outside of dwellings for 4 months. The results showed that houses adjacent to the rare earth ore bodies have significantly elevated radon concentrations. Annual committed effective doses originated from the inhalation of radon and thoron were estimated. The results showed that people living in the ore bodies areas would be exposed to the dose that could be 10 times higher than the world average.

Keywords Rare earth · Ore bodies area · Radon · Thoron · Annual effective dose

Introduction

It has been known that in some inhabited areas around the world people may live in dwellings with high levels of natural radiation, 100 times higher than the global average. Yangjiang in China, Kerala in India, Guarapari in Brazil and Ramsar in northern Iran are among the world's well-known areas with high levels of natural radiation [1–4]. The possible impact of natural radiation on humans has been of serious concern for the society. Areas with high levels of natural radiation have been under study to assess the risks and long-term exposure effects [3, 4].

People living in rare earth deposits areas could be exposed to high levels of natural radiation [5–8]. Because of similar chemical properties and under similar physico-chemical condition of formation, rare earth elements (REE)

L. K. Phon · D. Van Hao
Hanoi University of Mining and Geology, Dong Ngac – Tu Liem, Hanoi, Vietnam
e-mail: lekhanhphon.humg@gmail.com

D. Van Hao
e-mail: haodnth@gmail.com

B. D. Dung (✉)
Institute for Nuclear Science and Technology, 179 Hoang Quoc Viet, Nghia Do - Cau Giay, Hanoi, Vietnam
e-mail: buidacdung.jrnc@gmail.com

N. D. Chau
AGH University of Science and Technology, Krakow, Poland
e-mail: nguyen.chau@fis.agh.edu.pl

T. Kovacs
Institute of Radiochemistry and Radioecology, University of Pannonia, Veszprem Egyetem str. 10, Veszprem 8200, Hungary
e-mail: kt@almos.vein.hu

N. Van Nam
General Department of Geology and Minerals of Vietnam (GDGMV), Hanoi, Vietnam
e-mail: nguyenvannam180165@gmail.com

N. T. Son
Geological Division for Radioactive and Rare Elements, GDGMV, Hanoi, Vietnam
e-mail: nguyenthaisondvl@gmail.com

V. T. M. Luan
Academy of Development and Policy, Ministry of Planning and Investment, Hanoi, Vietnam
e-mail: vuminhluan@gmail.com

Published online: 14 January 2015

are often found in conjunction with uranium and thorium [4–6].

Rare earth deposits have been found in northern Vietnam and are concentrated in northwestern metallogeny zone [9]. Rare earths present potential economic opportunities as well as health and environmental risks. Results of natural radioactive environment survey in northwestern Vietnam showed that the gamma radioactive doses vary from 0.2 to 3.0 μSv h^{-1} [10, 11]. In all rare earth deposits areas the gamma dose level exceeds the safety limit of 0.6 μSv h^{-1} [10].

The biggest rare earth field in northwestern Vietnam is located in Lai Chau province [9, 10]. It has been suspected that inhabitants living in the ore deposits areas could be suffered by exposing to high external and internal effective dose rates due to high levels of uranium and thorium and their decay progenies as well as high radon and thoron levels in their dwellings [10–12]. This paper reports on the findings of a survey for radon and thoron concentrations, inside and outside of local dwellings in three typical inhabitant villages situated on and near the ore bodies areas.

Materials and methods

The study areas

Ban Mau and Ban Mo

Ban Mau and Ban Mo are two villages located in the North Nam Xe rare earth field, Nam Xe commune, Phong Tho district, Lai Chau province (coordinates: 103°27′E, 22°31′N). These are high, rugged mountains where the ore bodies are found in erupting bedrock of the Vien Nam (T_1i *vn*) formations, from the left bank of the Nam Xe stream with elevation of 450 m up to the high peaks of 1,200 m (Fig. 1).

In the mine field, original hard rocks are rarely exposed and outcrops are only found in streams. Quaternary rocks have thickness from 1 to 7.5 m, averaging about 4–5 m. North Nam Xe rare earth field has both original and weathered ore bodies [10, 12]. Original ore bodies were created under two types of hydrothermal filling and metasomatic. Weathered ore bodies have the thickness range of 10–90 m, commonly of about 20–40 m. The thickness of weathering increases from northwest to southeast with sudden changes [10, 12].

The composition of REE in North Nam Xe rare earth field is mainly of light group (cerium–lanthanum group). Weathered ore has average content of 4–5 % rare-earth oxides (REOs) and the original ore has average content of 1.4 % REOs. The proven reserves were estimated to be 940,000 t of REOs and the possible reserves were estimated to be 3.135 Mt of REOs [12, 13]. In addition, there were proven reserves of 76,000 t of U_3O_8, 59,000 t of ThO_2, and 38,000 t of Nb_2O_5 [13].

Ban Tham

Ban Tham is a village located in the Dong Pao rare earth field (coordinates: 103°33′E, 22°18′N) and belong to Tam Duong commune, Tam Duong District, Lai Chau province (Fig. 2). Dong Pao rare earth field has rugged mountainous terrain with heights of 500–2,000 m above-sea-level (ASL). The center of the mine in the south has height of 1,138 m ASL. Mountains have slopes of 40°–50°, sometimes with steep cliff. The topography is in the form of weathering denudation. In the limestone areas like Ban Giang and Dong Pao there is also karst topography with caves, karst sinkholes [10, 12].

As reported in [12], there are about 60 ore bodies in the Dong Pao rare earth field. The majority of ore bodies are usually distributed along the edge of syenite blocks (Fig. 2). Dong Pao rare earth field contains mainly rare earth minerals like bastnaesite, fewer parisite, and lantanite. The ore bodies are under strong weathering, and have content of 0.3–12.0 % REOs. The proven reserves were estimated to be 645,000 t of REOs [12, 13].

Measuring technique

RADUET chambers made by Radosys Ltd.—Hungary were used for the survey. A chamber pair with two CR-39 track etch detectors is dedicated to detect the radon and thoron activity [14]. The main chamber is selective for detecting only radon and the secondary chamber is sensitive for both radon and thoron. A simple linear calculation separates radon and thoron activity data results [15, 16].

At each dwelling, two pairs of RADUET chambers were deployed, one pair was hung inside the house and the other pair was hung outside the house. The list of the surveyed dwellings is given in Table 1. A total of 46 houses were surveyed, including 15 houses in Ban Mau village, 16 houses in Ban Mo village, and 15 houses in Ban Tham village.

The measurements were conducted in the winter–spring time (December to April). The annual average radon and thoron concentrations were estimated by averaging measured concentrations in this time period. This could be a reasonable estimation as the area has tropical climate, and, as it was reported in [17], tropical climate areas could have no seasonal changes in radon concentration. Also, December to April is the winter–spring time, the only time of the year people tend to close windows at cold nights. The total exposure time was 132 days. During exposure

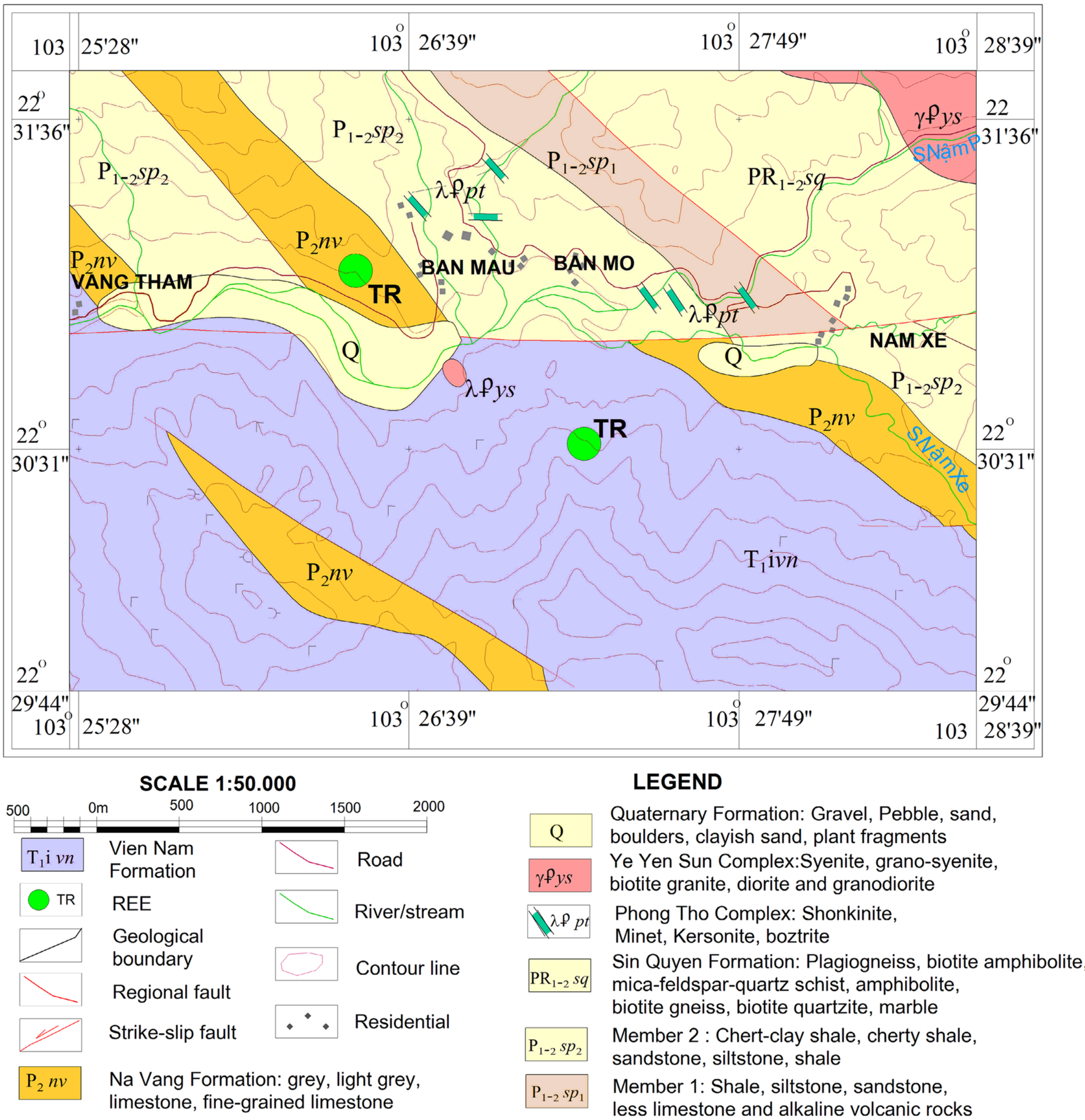

Fig. 1 Geological map showing Ban Mau and Ban Mo villages in the North Nam Xe rare earth field (adapted from [12])

time, the detectors were hung on a stable rod, 20 cm away from any wall, at the height of 1.5–2 m from the floor. At the end of the exposure time the detector pairs were recovered and transferred to the laboratory for processing. Five detector pairs were removed from the original locations by the house owners and so they were not used for data evaluation.

In the laboratory the CR-39 chips were etched at 80 °C in 6 M NaOH solution for the duration of 4 h. The tracks caused by the radon and thoron exposure were counted up with the help of OLIMPUS CX21 microscope. The calibration factors were determined as a result of test exposure in radon and thoron calibration chambers, as described in [16].

Dose assessment

The annual committed effective doses originated from the inhalation of radon or thoron, inside and outside of the dwellings were calculated using the following Eqs. (1), (2), and (3):

$$E_{\mathrm{Rn/Tn}} = Ein_{\mathrm{Rn/Tn}} + Eout_{\mathrm{Rn/Tn}} \tag{1}$$

where $E_{\mathrm{Rn/Tn}}$ is annual committed effective dose from radon (Rn) or thoron (Tn);

$$Ein_{\mathrm{Rn/Tn}} = Cin_{\mathrm{Rn/Tn}} \times Fin_{\mathrm{Rn/Tn}} \times t_{in} \times K_{\mathrm{Rn/Tn}} \tag{2}$$

$$Eout_{\mathrm{Rn/Tn}} = Cout_{\mathrm{Rn/Tn}} \times Fout_{\mathrm{Rn/Tn}} \times t_{out} \times K_{\mathrm{Rn/Tn}} \tag{3}$$

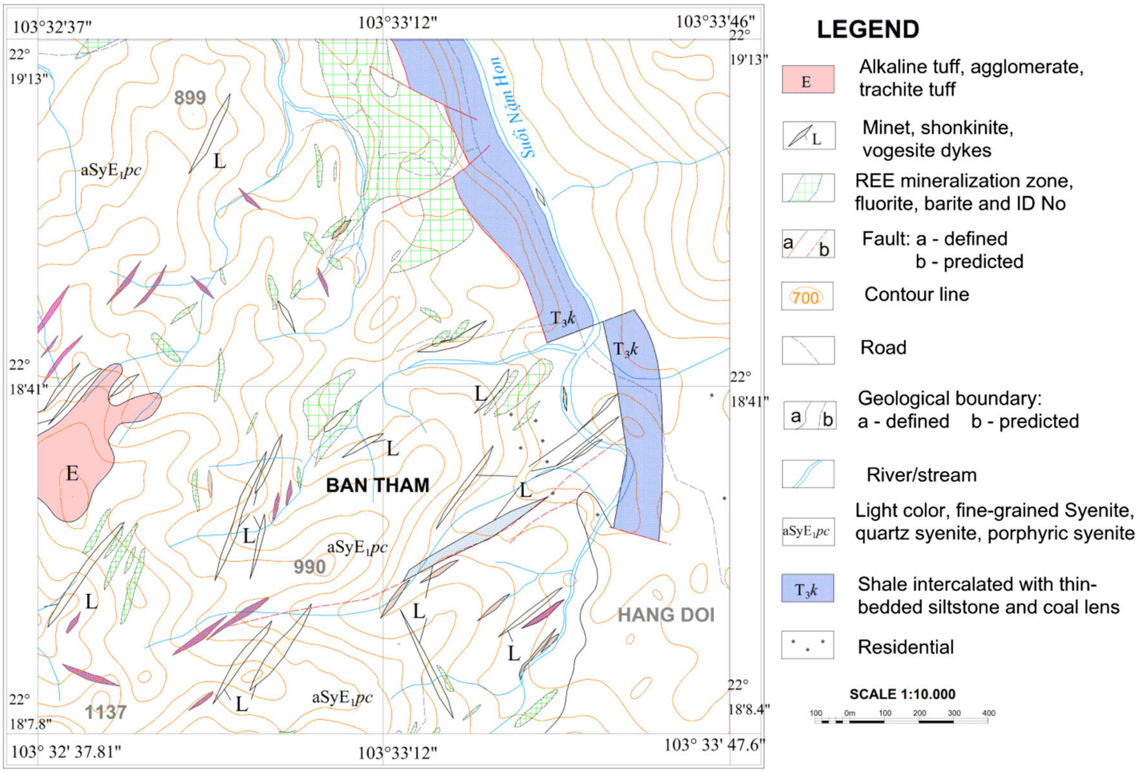

Fig. 2 Geological map showing Ban Tham village in the Dong Pao rare earth field (adapted from [10])

$Cin_{Rn/Tn}$ and $Cout_{Rn/Tn}$ is annual average radon or thoron concentration (Bq m^{-3}) inside (Cin_{Rn} or Cin_{Tn}) and outside ($Cout_{Rn}$ or $Cout_{Tn}$) of the dwellings. $Fin_{Rn/Tn}$ and $Fout_{Rn/Tn}$ is the inside and outside equilibrium factors for radon and its progenies or thoron and its progenies. These values were taken from UNSCEAR 2000 [18] with $Fin_{Rn} = 0.4$ and $Fout_{Rn} = 0.6$ for radon, and $Fin_{Tn} = 0.02$ and $Fout_{Tn} = 0.003$ for thoron; t_{in} and t_{out} is annual spending hours inside (7,000 h) and outside (1,760 h); $K_{Rn/Tn}$ is USCEAR 2000 recommended dose conversion factors, with $K_{Rn} = 9$ nSv per unit integrated radon concentration (Bq h m^{-3}) and $K_{Tn} = 40$ nSv per unit integrated thoron concentration (Bq h m^{-3}).

In this survey, the annual average radon and thoron concentrations were estimated by averaging measured concentrations from December to April. It was also understood that thoron concentration would be strongly dependent on the distance from the source due to its short haft-life, and the determination of the equilibrium equivalent thoron concentration (EETC) would be very important in estimating thoron dose for inhabitants. In this survey the EETC was not measured. To estimate the risk caused by the inhalation of thoron, the EETC was calculated by multiplying measured thoron concentration with the equilibrium factor for thoron and its progenies, taken from UNSCEAR 2000 [18].

Result and discussion

Radon and thoron concentrations

The results of the measurements of radon and thoron concentrations in the rare earth field of Lai Chau province are given in Table 1. Houses in the Ban Mau village have the highest radon concentrations, both inside and outside. The indoor radon concentrations are ranging from 84 to 634 Bq m^{-3} with geometric mean (GM) of 308 Bq m^{-3} (Geometric standard deviation—GSD 1.7). Comparing to worldwide GM value of 37 Bq m^{-3} (GSD 2.2) reported in UNSCEAR 2000 [18], the indoor radon level in the Ban Mau village is nearly 10 times higher than the world average. The outdoor radon concentrations in the Ban Mau village are ranging from 90 to 920 Bq m^{-3} with GM of 363 Bq m^{-3} (GSD 1.9), and that level is more than 30 times higher than the world average value of 10 Bq m^{-3} reported in UNSCEAR 2000 [18]. This could be due to the fact that the Ban Mau village is located adjacent to the ore bodies of North Nam Xe rare earth field (Fig. 1).

The Ban Mo village is located about 500–700 m from the ore bodies of North Nam Xe rare earth field (Fig. 1). This could be the reason the radon concentrations in this village are about 3 times lower than that in the Ban Mau village, with inside GM of 132 Bq m^{-3} (GSD 1.7) and

Table 1 Annual average radon and thoron concentrations

No.	House's code	Inside concentration (Bq m^{-3})		Outside concentration (Bq m^{-3})	
		Rn	Tn	Rn	Tn
Ban Mau village					
1	BMau1	ND		920 ± 29	32 ± 14
2	BMau2	352 ± 18	59 ± 9	420 ± 19	60 ± 10
3	BMau3	84 ± 9	95 ± 7	245 ± 15	98 ± 9
4	BMau4	199 ± 13	15 ± 7	222 ± 14	13 ± 7
5	BMau5	241 ± 15	50 ± 8	ND	
6	BMau6	229 ± 14	54 ± 8	90 ± 9	208 ± 10
7	BMau7	493 ± 21	87 ± 11	378 ± 18	10 ± 8
8	BMau8	273 ± 16	43 ± 8	320 ± 17	65 ± 9
9	BMau9	220 ± 14	72 ± 8	332 ± 17	18 ± 8
10	BMau10	516 ± 22	66 ± 11	516 ± 22	33 ± 10
11	BMau11	499 ± 21	17 ± 10	ND	
12	BMau12	634 ± 24	10 ± 11	621 ± 24	72 ± 12
13	BMau13	512 ± 21	27 ± 10	859 ± 28	15 ± 13
14	BMau14	295 ± 16	23 ± 8	351 ± 18	15 ± 8
15	BMau15	295 ± 16	23 ± 8	261 ± 15	41 ± 8
Min		84 ± 9	10 ± 11	90 ± 9	10 ± 8
Max		634 ± 24	95 ± 7	920 ± 29	208 ± 10
AM ± ASD		346 ± 158	46 ± 28	426 ± 245	52 ± 54
GM ×/÷ GSD)		308 ×/÷ 1.7	37 ×/÷ 2.0	363 ×/÷ 1.9	35 ×/÷ 2.5
Ban Mo village					
1	BMo1	129 ± 11	22 ± 6	69 ± 8	10 ± 4
2	BMo2	227 ± 14	16 ± 7	118 ± 10	27 ± 6
3	BMo3	163 ± 12	16 ± 6	ND	
4	BMo4	80 ± 9	22 ± 5	96 ± 9	20 ± 5
5	BMo5	98 ± 9	13 ± 4	123 ± 11	13 ± 5
6	BMo6	168 ± 12	23 ± 6	99 ± 9	15 ± 5
7	BMo7	104 ± 10	18 ± 5	186 ± 13	20 ± 7
8	BMo8	520 ± 22	16 ± 10	209 ± 14	17 ± 7
9	BMo9	135 ± 11	29 ± 6	111 ± 10	94 ± 8
10	BMo10	107 ± 10	83 ± 7	112 ± 10	25 ± 6
11	BMo11	99 ± 9	16 ± 5	28 ± 5	93 ± 7
12	BMo12	108 ± 10	23 ± 5	134 ± 11	13 ± 5
13	BMo13	46 ± 6	31 ± 5	134 ± 11	20 ± 6
14	BMo14	135 ± 11	27 ± 6	94 ± 9	19 ± 5
15	BMo15	117 ± 10	44 ± 6	66 ± 8	67 ± 6
16	BMo16	213 ± 14	14 ± 7	43 ± 6	70 ± 6
Min		46 ± 6	13 ± 4	28 ± 5	10 ± 4
Max		520 ± 22	83 ± 7	209 ± 14	94 ± 8
AM ± ASD		153 ± 108	26 ± 17	108 ± 48	35 ± 30
GM ×/÷ GSD		132 ×/÷ 1.7	23 ×/÷ 1.6	97 ×/÷ 1.7	26 ×/÷ 2.1
Ban Tham village					
1	BTham1	74 ± 9	52 ± 7	85 ± 10	90 ± 8
2	BTham2	74 ± 9	52 ± 7	85 ± 10	61 ± 7
3	BTham3	105 ± 11	71 ± 8	62 ± 9	77 ± 8
4	BTham4	113 ± 12	45 ± 7	157 ± 14	17 ± 7
5	BTham5	63 ± 9	73 ± 7	114 ± 12	12 ± 5

Table 1 continued

No.	House's code	Inside concentration (Bq m^{-3})		Outside concentration (Bq m^{-3})	
		Rn	Tn	Rn	Tn
6	BTham6	68 ± 9	68 ± 7	67 ± 9	266 ± 12
7	BTham7	111 ± 11	45 ± 7	62 ± 9	72 ± 7
8	BTham8	62 ± 9	72 ± 7	48 ± 7	78 ± 7
9	BTham9	48 ± 7	71 ± 7	145 ± 13	35 ± 7
10	BTham10	60 ± 8	99 ± 8	55 ± 8	84 ± 8
11	BTham11	69 ± 9	49 ± 6	79 ± 10	70 ± 7
12	BTham12	48 ± 7	90 ± 8	118 ± 12	108 ± 9
13	BTham13	124 ± 12	97 ± 9	ND	
14	BTham14	117 ± 12	29 ± 6	62 ± 9	63 ± 7
15	BTham15	82 ± 10	27 ± 6	85 ± 10	29 ± 6
Min		48 ± 7	27 ± 6	48 ± 7	12 ± 5
Max		124 ± 12	99 ± 8	157 ± 14	266 ± 12
AM ± ASD		81 ± 26	63 ± 22	87 ± 33	76 ± 62
GM ×/÷ GSD		77 ×/÷ 1.4	59 ×/÷ 1.5	82 ×/÷ 1.4	58 ×/÷ 2.2

ND no data available because the detector pair was removed from the original location, *AM* arithmetic mean, *ASD* arithmetic standard deviation, *GM* geometric mean, *GSD* geometric standard deviation

Table 2 Annual committed effective doses originated from the inhalation of radon and thoron

	Effective dose from radon (mSv year^{-1})		Effective dose from thoron (mSv year^{-1})		Total dose from Rn and Tn (mSv year^{-1})
	Inside	Outside	Inside	Outside	
Ban Mau village					
Min	2.1 ± 0.2	0.9 ± 0.1	0.1 ± 0.1	<0.1	5.0 ± 0.4
Max	16.0 ± 0.6	8.7 ± 0.3	0.5 ± 0.1	<0.1	22.0 ± 0.9
AM ± ASD	8.7 ± 4.0	4.1 ± 2.3	0.3 ± 0.2	<0.1	12.6 ± 5.7
GM ×/÷ GSD	7.8 ×/÷ 1.7	3.5 ×/÷ 1.9	0.2 ×/÷ 2.0	<0.1	11.4 ×/÷ 1.6
Ban Mo village					
Min	1.2 ± 0.2	0.3 ± 0.1	0.1 ± 0.1	<0.1	2.6 ± 0.3
Max	13.1 ± 0.6	2.0 ± 0.1	0.5 ± 0.1	<0.1	15.2 ± 0.7
AM ± ASD	3.9 ± 2.7	1.0 ± 0.5	0.1 ± 0.1	<0.1	5.0 ± 3.0
GM ×/÷ GSD	3.3 ×/÷ 1.7	0.9 ×/÷ 1.7	0.1 ×/÷ 1.6	<0.1	4.5 ×/÷ 1.5
Ban Tham village					
Min	1.2 ± 0.2	0.5 ± 0.1	0.2 ± 0.1	<0.1	2.4 ± 0.3
Max	3.1 ± 0.3	1.5 ± 0.1	0.6 ± 0.1	0.1 ± 0.1	4.6 ± 0.5
AM ± ASD	2.0 ± 0.7	0.8 ± 0.3	0.4 ± 0.1	<0.1	3.2 ± 0.6
GM ×/÷ GSD	2.0 ×/÷ 1.4	0.8 ×/÷ 1.4	0.3 ×/÷ 1.5	<0.1	3.1 ×/÷ 1.2

outside GM of 97 Bq m^{-3} (GSD 1.7). Houses in the Ban Tham village (Fig. 2) have similar level of radon concentrations as in the Ban Mo village, with inside GM of 77 Bq m^{-3} (GSD 1.4) and outside GM of 82 Bq m^{-3} (GSD 1.4). The outdoor radon levels in the Ban Mo and Ban Tham villages are about 8–9 times higher than the world average value of 10 Bq m^{-3} [18]. The indoor radon levels in the Ban Mo and Ban Tham villages are about 3–4 times higher than that in the US with GM of 25 Bq m^{-3} (GSD 3.1) [19], in China with GM of 34.4 Bq m^{-3} (GSD 1.95) [18], and in the world with GM of 37 Bq m^{-3} (GSD 2.2) [18].

Thoron concentrations in Ban Mau and Ban Mo villages are not high with inside GM of 37 Bq m^{-3} (GSD 2.0) and outside GM of 35 Bq m^{-3} (GSD 2.5) in Ban Mau, inside GM of 23 Bq m^{-3} (GSD 1.6) and outside GM of 26 Bq m^{-3} (GSD 2.1) in Ban Mo, and are equivalent to an average concentration of the world [18]. This could be due to the fact that thorium concentration in North Nam Xe rare earth field is not high [10–12]. However, the thoron concentrations in the Ban Tham village are about 2 times higher than that in the Ban Mau and Ban Mo villages, with inside GM of 59 Bq m^{-3} (GSD 1.5) and outside GM of 58 Bq m^{-3} (GSD 2.2). This could be due to the higher thorium concentrations in soil in this area [10–12].

There is also an interesting point to note that the indoor radon and thoron concentrations are not statistically different from the outdoor concentrations. The reason could be because of the fact that the area has tropical climate and most dwellings are simple houses with open door and windows that allow fresh air to exchange freely through the house. Similar phenomena were observed in Thailand where average indoor and outdoor radon levels are the same in Bangkok and are not statistically different in Chiang Mai because of rapid air exchange [17].

Based on the measured outdoor and indoor radon and thoron levels it could be concluded that the investigated rare earth field of Lai Chau province would be considered as elevated radon and thoron level area, similar to the areas with elevated uranium mineralization in south–west England where about 30 % of the houses have indoor radon level of up to 300 Bq m^{-3} [20].

Annual doses

The results of estimation of annual committed effective doses (Eqs. 1–3) originated from the inhalation of radon and thoron in the rare earth field of Lai Chau province are given in Table 2. It could be seen that all inhabitants in the investigated areas may have been exposed to high annual effective doses. Comparing to the worldwide average values of 1.25 mSv $year^{-1}$ (1.15 mSv $year^{-1}$ for radon and 0.1 mSv $year^{-1}$ for thoron) reported by UNSCEAR 2000 [18], people in the Ban Mau village may be exposed to GM dose of 11.4 mSv $year^{-1}$ (GSD 1.6), nearly 10 times higher than the world average. Inhabitants in the Ban Mo village may be exposed to GM dose of 4.5 mSv $year^{-1}$ (GSD 1.5), nearly 4 times higher than the world average. The people in the Ban Tham village may also be exposed to GM dose of 3.1 mSv $year^{-1}$ (GSD 1.2).

Conclusion

The results of radon and thoron investigation at the rare earth field in northwestern Vietnam have shown that this is an elevated natural radiation area. Indoor radon and thoron concentrations are not statistically different from the outdoor concentrations. Both outdoor and indoor radon concentrations are higher than the world average. Houses in the Ban Mau village, located adjacent to the ore bodies of North Nam Xe rare earth field, have the highest average radon concentration of more than 300 Bq m^{-3}. Houses in the Ban Mo village, located about 500–700 m from the ore bodies of North Nam Xe rare earth field, and in the Ban Tham village have radon level of about 100 Bq m^{-3}.

Thoron concentrations in the Ban Mau and Ban Mo villages are not high and are equivalent to average concentration of the world. However, the thoron level in the Ban Tham village is about 2 times higher than that in the Ban Mau and Ban Mo villages, averaging about 60 Bq m^{-3}.

Results of estimation of annual committed effective doses originated from the inhalation of radon and thoron showed that people in the Ban Mau village may be exposed to average dose of 11.4 mSv $year^{-1}$, nearly 10 times higher than the world average of 1.25 mSv $year^{-1}$ [18]. Inhabitants in the Ban Mo and Ban Tham villages may receive average dose of 4.5 and 3.1 mSv $year^{-1}$, respectively. It was concluded that inhabitants living in the rare earth field in northwestern Vietnam may have been exposed to high effective dose rates due to high radon and thoron concentrations in the air.

The risks and possible effects of long-term exposure of the inhabitants in the Ban Mau village need to be evaluated and intervention needs to be taken in order to reduce the radon level since the radon level is beyond the action level of 200 Bq m^{-3} set by Vietnam [21] and ICRP [22].

Acknowledgments This work was funded by the Vietnam Ministry of Education and Training (MOET) through research project of bilateral cooperation with Poland (Project Code: 01/2012/HĐ-HTQTSP) and by Vietnam Ministry of Science and Technology (MOST) through research project of bilateral cooperation with Hungary (Project Code: 19/2011/HĐ-NĐT), implemented in the years 2011–2012.

References

1. Abdollahi H (2013) World high background natural radiation areas and public life: letter to the editor. Radiat Meas 59:288–289
2. Ahmed JU (1991) High levels of natural radiation: report of an international conference in Ramsar. IAEA Bulletin 2:36–38
3. IAEA (2003) Extent of environmental contamination by naturally occurring radioactive material (NORM) and technological options for mitigation. IAEA, Vienna
4. Derin MT, Vijayagopal P, Venkatraman B, Chaubey RC, Gopinathan A (2012) Radionuclides and radiation indices of high background radiation area in Chavara-Neendakara placer deposits (Kerala, India). PLoS One 7(11):e50468. doi:10.1371/journal.pone.0050468
5. Naturally-Occurring Radioactive Materials (NORM), World Nuclear Association. http://www.world-nuclear.org/info/Safety-and-Security/Radiation-and-Health/Naturally-Occurring-Radioactive-Materials-NORM/. Assessed 02 Aug 2014
6. Uranium from rare earths deposits, World Nuclear Association. http://www.world-nuclear.org/info/Nuclear-Fuel-Cycle/Uranium-Resources/Uranium-From-Rare-Earths-Deposits/. Assessed 16 Oct 2014

7. Ali SH (2014) Social and environmental impact of the rare earth industries. Resources 3:123–134. doi:10.3390/resources3010123
8. Ives M (2013) Boom in mining rare earths poses mounting toxic risks, Yale Environment 360. http://e360.yale.edu/feature/boom_in_mining_rare_earths_poses_mounting_toxic_risks/2614/. Assessed 16 Oct 2014
9. Tu CM, Huan TD, Hoa NV, Ton ND, Long ND, Phong DH (2013) Characteristics of rare earth ore mineralization in South Nam Xe Area, Lai Chau Province. J Geol A 335: 67–76 (in Vietnamese with abstract in English). http://idm.gov.vn/Data/TapChi/2013/A335/a76.htm. Assessed 16 Oct 2014
10. Nam NV, Hai DV, Son NT, Long LT (2013) Rare earth deposits in the Northwest of Vietnam considered from the perspective of radioactive environment. J Geol A 335: 47–55 (in Vietnamese with abstract in English). http://idm.gov.vn/Data/TapChi/2013/A335/a55.htm. Assessed 16 Oct 2014
11. Nam NV, Son NT, Vinh NQ (2010) Studying on the characteristics of natural radiation field for the assessment of radioactive pollution over rare earth mines in the North Vietnam. J Geol A 320: 9–10 (in Vietnamese with abstract in English). http://idm.gov.vn/Data/TapChi/2010/A320/A270.htm. Assessed 16 Oct 2014. http://www.dgmv.gov.vn/index.php?option=com_k2&view=item&task=download&id=278_964cb2203a87417c1d65a2e078749a9d&Itemid=379&lang=en. Assessed 16 Oct 2014
12. Phuong N, Dung NV, Phon LK, Dong NP, Anh VTL, Huan TD, Chau TL, Hai DV (2013) A study on the increase of natural radiation field due to the exploration of rare earth ores in the Dong Pao and Nam Xe areas - Lai Chau Province. J Geol A 335: 56–62 (in Vietnamese with abstract in English). http://idm.gov.vn/Data/TapChi/2013/A335/a62.htm. Assessed 16 Oct 2014
13. Yolanda FS (2013) The mineral industry of Vietnam. U.S. geological survey minerals yearbook 2011. http://minerals.usgs.gov/minerals/pubs/country/2011/myb3-2011-vn.pdf. Assessed 02 Aug 2014
14. Tokonami S, Takahashi H, Kobayashi Y, Zhuo W, Hulber E (2005) Up-to-date radon-thoron discriminative detector for a large scale survey. Rev Sci Instrum 76:113505–113509
15. RADOSYS (2008) User Manual RS_Man63-080316
16. Dung BD, Van Giap T, Kovacs T, Toan TN, Cuong LD, Minh TK, Quyet NH, Van Khanh N (2014) Estimation of radon and thoron caused dose at extraction and processing sites of mineral sand mining area in Vietnam (HA TINH province). J Radioanal Nucl Chem 299:1943–1948
17. Chittaporn P, Harley NH (2000) Indoor and outdoor ^{222}Rn measurements in Bangkok and Chiang Mai, Thailand. Technology 7:491–495
18. UNSCEAR Report Volume II, Annex E (2000) Sources-to-effects assessment for Rn in homes and workplaces, United Nations, Vienna
19. Marcinowski F, Lucas RM, Yeager WM (1994) National and regional distributions of airborne radon concentrations in U.S. homes. Health Phys 66(6):699–706
20. Wrixon AD, Green BMR, Lomas OR, Miles JCH, Cliff KD, Francis EA et al (1988) Natural radiation in UK dwellings. National Radiological Protection Board Report R190. NRPB, Chilton
21. Vietnam standard TCVN 7889:2008 (2008) Natural radon activity in buildings—levels and general requirements of measuring methods
22. ICRP (1993) Protection against radon-222 at home and at work. ICRP Publication 65. Ann. ICRP 23 (2)