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ORIGINAL PAPER

Indoor and outdoor ^{222}Rn and ^{220}Rn and their progeny levels surrounding Bayan Obo mine, China

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Abstract. More than half of the total natural ionizing radiation dose received by the human population is caused by radon and thoron (Rn and Tn) and their progeny. To estimate the level of radiation due to radon and thoron and their progeny, an investigation was conducted in a residential area near the world's largest open-pit mine of Bayan Obo in Inner Mongolia, China. The concentration of Rn, Tn, and their decay products in air and soil were studied by using AlphaGUARD, RAD7, and ERS-RDM-2S for a discrete period of time in three different locations. The average indoor concentration of radon and thoron was 62.6 ± 44.6 Bq/m^3 and 108.3 ± 94.5 Bq/m^3 respectively, and the outdoor concentration was 12.9 ± 6.3 Bq/m^3 and 55.8 ± 18.5 Bq/m^3, respectively. Relatively high concentrations were recorded in the area near to the mine, with a significant increasing trend observed in indoor thoron concentration. A prominent hotspot in thoron concentration was found in a single-story house with values 747 ± 150 Bq/m^3. The equilibrium equivalent thoron concentration (EEC_{Tn}) varies from 0.48 Bq/m^3 to 2.36 Bq/m^3 with an arithmetic mean of 1.37 ± 0.64 Bq/m^3, and comparatively higher than EEC_{Rn}. Concluding that the mining activity at Bayan Obo mine is significantly increasing the level of indoor thoron and its progeny in surroundings. It is suggested to further systematically investigate the indoor Rn and Tn progeny concentrations in the residential dwellings of the Bayan Obo mining area, and ^{232}Th content of the building materials, to provide a basis for calculating the radiation dose.

Keywords: Radon • Thoron • Radon and thoron progeny • Equilibrium equivalent thoron concentration • Rn equilibrium factor • Bayan Obo

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Introduction

The Bayan Obo Fe-RE-Nb deposit is a world-renowned super-large rare-earth iron ore located in Baotou City, Inner Mongolia of China, covering an area of about 48 km^2. The main ore body is an open-pit mine that has been mining iron ore since the 1950s. The Bayan Obo iron deposit is mainly produced in the dolomite, and fine-grained monazite, which is rich in thorium (Th), is a crack filler in the dolomite [1].

At the end of 2006, the storage capacity of tailings in the tailings dam in the Kundulun District of Baotou City was 1.49 × 108 t, where the Th content reached 8.8 × 104 t and the activity was about 2.11 × 10^{14} Bq [2]. Therefore, the impact of Bayan Obo mining on the environment and human health is an issue of concern.

Since the 1980s, Chinese scholars have performed investigations of indoor and outdoor gamma absorbed dose rates, the specific radioactivity concentration of U and Th in soil, and indoor Rn and Tn concentrations around Bayan Obo mine. The results show that except for the tailings dam area, the absorbed dose rate has not increased significantly in other regions, but the Th content in the soil around the tailings dam was enriched slowly [3, 4]. The Th content in the soil around the Bayan Obo mining area is twice as high as that in the normal background areas [4]. Studies of lung burden of workers in different workplaces for inhaling thorium-containing dust show that dust-carrying radioactive contamination is an important source of air pollution in some areas of Bayan Obo [5].

There are only two articles reported the surveyed results of indoor Rn and Tn in the Bayan Obo mine. The Rn and Tn concentrations, when the RAD7 was put at the distance of 20 cm from the wall, ranged from 11 Bq/m^3 to 63 Bq/m^3 and 0 to 450 Bq/m^3, respectively [6]. The indoor Rn concentration in Bayan Obo District varied from 19.6 Bq/m^3 to 125.3 Bq/m^3 with an average value of 48.2 Bq/m^3 by the solid-state nuclear track detector, while the indoor Tn concentration changed from 31 Bq/m^3 to 153.3 Bq/m^3 with an average value of 64.7 Bq/m^3 [7].

A nationwide survey of the Tn exhalation rate and its progenies levels was conducted in the Netherlands in 2015 [8]. Indoor Tn levels were measured using RAD7 in Serbia, Australia, and Italy [9–11].

Therefore, to understand the indoor Rn and Tn levels of residential houses near the Bayan Obo mining area, we carried out an investigation of Rn and Tn and their progeny concentrations indoor and outdoor, and in soil gas using AlphaGUARD, RAD7, and a radon monitor of ERS-RDM-2S.

Instruments and methods

Radon and thoron measurements with active sampling

The active sampling methods were mainly used to determine the Rn and Tn concentrations in the survey with an AlphaGUARD (PQ2000) and a semiconductor radon detector RAD7, made by Durridge, USA. The AlphaGUARD (Saphymo, Germany) was set in flow mode with 10 min cycle time during the measurements. It detects alpha particles from Rn and their progenies to calculate the Rn concentration. This equipment was calibrated in the Rn chamber in the National Institute of Metrology, China.

For the measurements of Rn and Tn concentration in the air and soil gas, the RAD7 radon monitor was used. The RAD7 was set to "thoron" mode with a small drying tube and with a cycle time of 30 min and 2 h. The procedure and method using RAD7 to determine the concentrations of Rn and Tn in soil gas were as described in the article [12]. The RAD7 was calibrated in the Rn chamber in the National Institute of Metrology, China every year. The RAD7 was calibrated for thoron measurement in the thoron chamber in Nanhua University, China. Thoron gas was produced by the solid thoron sources made of $Th(NO_3)_4$. The thoron emanation coefficient of the thoron sources is 96.5 ± 3% and the thoron gas yield is constant with a relative standard deviation below 2.5%. The uncertainty of the thoron source should be about 3.5% [13].

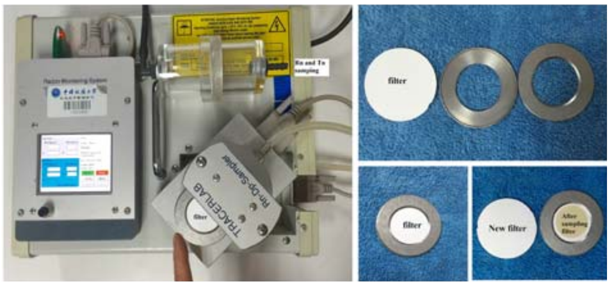

Fig. 1. A photo of Rn and Tn progeny monitor ERS-RDM-2S.

Rn and Tn progeny measurements with active sampling

An active, real-time, and direct detecting Rn and Tn, and Rn and Tn progeny monitor ERS-RDM-2S was also used in the radon investigation in Bayan Obo. The device was built with two silicon alpha sensitive detectors (Canberra PIPS Sensitive Detector) and two alpha spectroscopy systems, MCA with 256 channels. It is designed to collect the alpha particles of ^{218}Po and ^{216}Po for the determination of the concentration of Rn and Tn, using the diffusion mode or pump mode. For the determination of the Rn and Tn progeny concentration, ambient air is sucked by the internal air-suction pump with an air flow-rate of approx. 100 l/h through the membrane filter (0.8 μm pore-size) of the removable progeny filter (Fig. 1). There is the collection of ^{218}Po/^{214}Po for the determination of the radon progenies and ^{212}Po (a decay product of ^{216}Po) for the determination of the Tn progenies, shown as "Rn Dp-sampler" in Fig. 1 [14], which was calibrated in Physikalisch-Technische Bundesanstalt, the National Metrology Institute of Germany.

Measured results and discussion

The Bayan Obo Iron-Rare Earth-Niobium Deposit is located 150 km north of Baotou City, about 18 km long from east to west and 3 km wide from north to south. The Bayan Obo living district is located about 2 km south of the main mine of the Bayan Obo iron mine, which area is about 3 km^2. In 1997, the town had a population of about 30 000, but now less than 20 000. We selected three types of build-

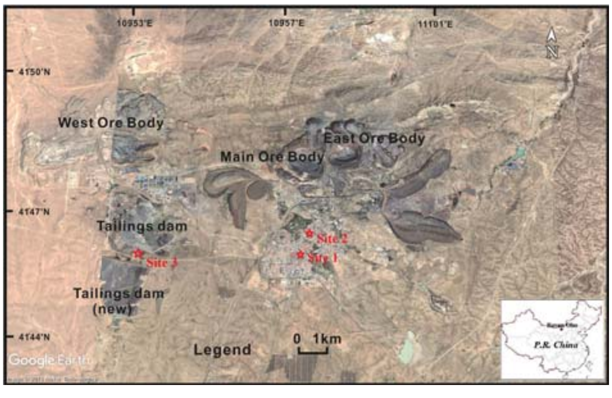

Fig. 2. The survey locations map of Bayan Obo District.

Table 1. Results of indoor and outdoor Rn and Tn concentrations (in Bq/m³)

Date	Outdoor Rn		Outdoor Tn	Indoor Rn		Indoor Tn
	AlphaGUARD	RAD7	RAD7	AlphaGUARD	RAD7	RAD7
In 2018 (30 min)*	34.2 ± 10.1 (22.1–52.6)	12.9 ± 6.3 (7.0–24.3)	55.8 ± 18.5 (34.4–93.5)	63.7 ± 30.0 (17.8–105.7)	73.0 ± 42.9 (22.3–166.0)	124.7 ± 122.5 (28.2–439.9)
In 2019 (2 h)*	/	/	/	/	52.2 ± 46.1 (18.7–215.5)	91.8 ± 66.5 (11.4–260.0)
Background area	16 ± 9	**	**/	/	25.1 ± 11.7 (11.9–43.3)	47.2 ± 30.7 (15.4–87.7)

Notes: *RAD7 sampling time. **Outdoor Rn and Tn concentrations measured by RAD7 in the background area were not listed because the errors were too large. "()" showing the range of radon and thoron values and "/" symbol used to represent that there was no data at this specific time period.

Table 2. The average of Rn and Tn indoor and in soil gas in Bayan Obo District (by RAD7)

Location	Indoor Rn and Tn [Bq/m³]		Rn and Tn in soil gas [kBq/m³]	
	Rn	Tn	Rn	Tn
Living area (Site 1)	49.3 ± 23.7	79.6 ± 57.3	68.9 ± 0.28	68.0 ± 14.7
Near mining area (Site 2)	21.2 ± 18.3	149.8 ± 72.9	2.2 ± 1.0	38.0 ± 4.6
Near tailings dam (Site 3)	31.1 ± 8.9	143.4 ± 81.4	4.1 ± 1.2	35.9 ± 4.4
Background area	25.1 ± 11.7	47.2 ± 30.7	6.4 ± 0.5	15.8 ± 1.7

ings for measurements: the first was located in the center of the town (Site 1), the second was near the open-pit mining area (Site 2), and the third one was near the tailings dam (Site 3), as shown in Fig. 2. In addition, the Saihan Tara Park (SHTL) in Baotou City was selected as a reference site in the background area.

Indoor and outdoor Rn and Tn

Table 1 shows the average values of the outdoor and indoor Rn and Tn concentrations around the Bayan Obo Mining District and SHTL Park in Baotou City. Key points in Table 1 are: (1) the average indoor Rn and Tn concentrations in the Bayan Obo mining area were twice as high as in the background area and (2) the indoor Rn concentration measured by RAD7 was approximately equal to the measurements by AlphaGUARD.

Table 2 shows the Rn and Tn concentration indoor and in soil gas at different measurement locations. Key points in Table 2 are: (1) nominal variations were recorded in indoor Rn concentration in the Bayan Obo mining area compared with that in the background area, but a significant variation in indoor Tn concentration was observed. The average Tn concentration in the living area is about twice as high as that in the background area and (2) near the mining area and near the tailings dam, the soil Rn concentration was very low, while the Tn concentration was high. The reason for the low Rn concentration in soil gas is due to the poor soil and vegetation.

Figure 3 displays the variation of indoor Rn and Tn concentrations of a "hot spot" found in a residential building. The building is a one-story house, and the walls were made of clay bricks and concrete. During the measurement period, the door and the window were closed, and indoor and outdoor air exchange rates were very low. At a distance of 10 cm from the wall, the average Rn and Tn concentrations were

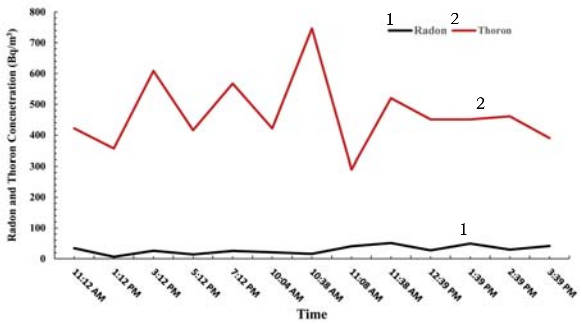

Fig. 3. Variations of Rn (1) and Tn (2) concentration in a "hot-spot" room in a dwelling.

28.3 ± 15.3 Bq/m³ and 469.3 ± 118.3 Bq/m³, respectively. The Tn maximum value was 747 Bq/m³, but it was about 200 Bq/m³ at the center of the room. Indoor Tn "hot spot" shows that the Tn concentration depends on the building materials.

Indoor Rn and Tn progeny

Table 3 shows the average values of Rn and Tn daughter concentration and Rn equilibrium factor at 12 locations of the Bayan Obo mining area measured by the ERS-RDM-2S monitor. (1) The indoor EEC_{Tn} value in this area is relatively high, the arithmetic average is 1.37 ± 0.64 Bq/m³, ranged from 0.48 Bq/m³ to 2.36 Bq/m³. The highest observed values occurred at points 8 and 11, with EEC_{Tn} of

Table 3. The results of EEC_{Rn}, EEC_{Th} and Rn equilibrium factor using ERS-RDM-2S

Parameters	EEC_{Rn}	F_{Rn}	EEC_{Th}
Number of dwellings	12	12	12
Mean	12.28	0.21	1.37
Standard deviation	4.92	0.17	0.64
Min	3.18	0.08	0.48
Max	19.80	0.72	2.36

2.34 Bq/m^3 and 2.36 Bq/m^3, respectively. Point 8 is located near the tailings dam, and Point 11 is located at the center of the town of Bayan Obo; (2) the concentration of EEC_{Rn} in this area is very low, with an average value of 12.3 ± 4.9 Bq/m^3; and (3) the indoor Rn equilibrium factor (F_{Rn}) is low with an average value of 0.21 ± 0.17.

Conclusions and suggestions

Based on our surveyed data, the effect of the mining activity of Bayan Obo mine on the high indoor Tn and its progeny concentration is significant. The Rn and Tn concentrations indoor and outdoor, as well as in soil gas, at the sites near Bayan Obo mine are about twice as high as that in the background area in Baotou City. Near the mine, the indoor Tn concentration varies drastically and shows regional distribution characteristics, while the indoor Rn change is not obvious.

Due to several factors affecting the distribution and changes of Rn and Tn progeny, it is suggested to further systematically investigate the indoor Rn and Tn progeny concentrations in the residential dwellings of the Bayan Obo mining area, and ^{232}Th content of the building materials, to provide a basis for calculating the radiation dose to the public.

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