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An Assessment of Natural Radioactivity in the Namxe Rare Earth Deposit, Laichau Province, Vietnam

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Abstract: The Namxe rare earth deposit belongs to Namxe commune, Phongtho district, Laichau province, which has a large resource of rare earth metals in Vietnam. The case study presents an assessment of the naturally occurring radioactivity for the rare earth prospect Namxe for future monitoring purpose, especially for the case of an actual mine in the area. The investigation included determination of radioactivity in the air, soil, water, and plants. The results showed that although the water usage is harmless, radioactive materials were found in soils and plants in considerable amounts. The mapping of these features revealed two zones of elevated radioactivity, one of which even bearing health risks according to several health standards. These zones correspond well with the rare earth deposit area. From the study, safety, health, and environmental issues could be deduced, including a risk assessment for the area and the intended mining site.

Keywords: rare earth mine; Namxe deposit; radioactive monitoring; radioactive pollution

1. Introduction

The Namxe rare earth deposit belongs to Namxe commune, Phongtho district, Laichau province, which has a large resource of rare earth metals in Vietnam (Figure 1). The deposit is divided by the east–west striking Ban Pan-Phong Tho fault into a northern and a southern part, situated on both sides of the Nam Xe river valley. The northern deposit consists of a deeply weathered lateritic ore with thickness up to 40 m on top of a Permian limestone. The southern part, on the other hand, comprises carbonatitic dyke-like structures in a triassic trachyandesitic host rock [1]. The geological exploration results have shown that the potential resource of Namxe rare earth deposit is about 8 Million Tons of TRE₂O₃ [2,3]. Former studies have indicated that the rare earth deposit contents include about 80 different minerals [4]. Besides rare earth elements, the Namxe deposit even contains some radioactive elements such as uranium and thorium.

The population in the deposit area is mostly the ethnic minorities [5]. The deposit area has a mountain topographic with steep slopes, which makes it a challenge to collect samples and measure radioactive elements [6].

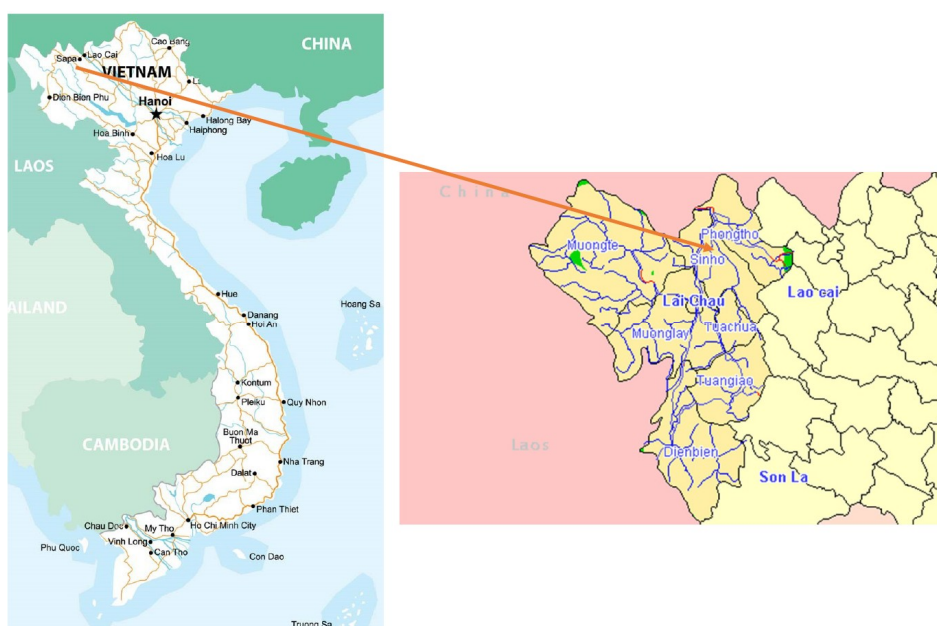


Figure 1. Location of Namxe rare earth deposit [7,8].

The monitoring activities of the natural radioactive environmental investigation at the deposit area included measuring the natural radioactive gases and sampling of soil, water, and flora for further analysis in the labs [9]. On the basis of the analyzed data and on-site measurements, the map of natural radiation in the local area will be established.

2. Materials and Methods

Radioactive exposure is represented by the equivalent dose H (mSv/year). In order to assess the natural radioactive environment in the mineral deposit, it needs to combine the equivalent dose with other data of airborne radiation, radioactive element concentration, and intensive radiation from radioactive sources, and so on.

2.1. Calculation of Natural Radioactive Environmental Elements in the Mineral Deposit

According to national standards of the geological environmental investigation and National Commission for Sanitary Inspection of Russian Epidemiology [10,11], as well as the studies of the Geological Division of Radioactive and Rare Minerals belonging to the General Department of Geology and Minerals of Vietnam [12–14], the radioactive environmental impact is determined as follows:

2.1.1. The Equivalent Dose (or Effective Dose)

Equivalent dose H , is the sum of external dose and internal dose, as in the following expression:

$$H = H_n + H_t, \text{ (mSv/year)} \quad (1)$$

where H_n is the external dose, which is calculated from measured data of the ambient gamma at the 1 m from ground land, which determinates as:

$$H_n = 6.13 \times DN, \text{ (mSv/year)} \quad (2)$$

in which DN is an equivalent absorbed dose in ambient, ($\mu\text{Sv/h}$); H_t is the internal dose due to inhalation (H_p) and ingestion of food and water (H_d), in mSv per year and is given by:

$$H_p = H_{Rn} + H_{Tn}, \text{ (mSv/year)} \quad (3)$$

The inhalation H_p equivalented with an average adult breathing 7280 m^3 air per year. Where: $H_{Rn} = 0.047 \cdot C_{Rn}$ (Bq/m^3), $H_{Tn} = 0.007 \cdot C_{Tn}$ (Bq/m^3); and C_{Rn} is ^{222}Rn 's concentration of outdoor air; C_{Tn} is Tn 's (^{220}Rn for convenience called Tn —Thoron—hereafter) concentration of outdoor air.

H_d is the effective dose in food crops samples and it is given by:

$$H_d = (6.2 \times 10^{-6}K + 2.8 \times 10^{-4}Ra + 2.3 \times 10^{-4}Th + 4.4 \times 10^{-5}U) \times m_d, \text{ (mSv/year)} \quad (4)$$

where K, Ra, Th, U are activities of potassium, radium, thorium, uranium in one liter of water or one kilogram of food (Bq per kg), respectively; m_d is the average amount of water or food consumed by a person per year (800 liters of water and 650 kg of food).

2.1.2. Activity Radiation in the Soil Samples

The radiation activity in any soil is determined by:

$$A = A_{Ra} + 1.3A_{Th} + 0.085A_K \leq 370, \text{ (Bq/kg)} \quad (5)$$

with A_{Ra} , A_{Th} , A_K are activities of Ra, Th, K, respectively.

2.2. Calibration Method

In order to assess the natural radioactive environment, this study used methods of radioactive sampling according to Vietnamese Standards such as TCVN 9414:2012; TCVN 9416: 2012; TCVN 9419:2012 [15–17]. Whereby it required to determine the radioactive components in ambient air which include: i) Measurement of gamma dose to determine the external dose of gamma radiation in the studied area; ii) measurement of radioactive gas to determinate the radon concentration in the ambient air, thus calculating the internal dose by inhalation; iii) measurement of gamma spectrum to determinate the concentration of uranium, thorium, and potassium in the soil, rock, and so forth. On the basis of the measured data, the existence and dispersion of radioactive elements in the studied area will be determined.

Error calculating from repetition measurements is determined by the expressions:

$$\text{For the absolute error: } \sigma = \sqrt{\frac{\sum_{i=1}^n (X_i - Y_i)^2}{2n}} \quad (6)$$

and for the relative error $\partial = \frac{\sigma}{R} \cdot 100\%$ with $R = \frac{1}{2n} \sum_{i=1}^n (X_i + Y_i)$.

The indexes X_i and Y_i are the measured and repeated measured values at the i , and n is the number of repetition.

2.3. Measuring Methods of Natural Radiation

2.3.1. Measuring the Gamma Dose

The environmental gamma dose was measured in the studied area, directly on the ground and in a vertical distance of 0.1 m above the ground surface with a DKS-96 gamma dosimeter (Doza co.—Moscow, Russia), according to the Vietnamese Standard TCVN 9414:2012 [15].

2.3.2. Measuring the Radon Concentration

In order to determine the radon concentration in the air, a RAD-7 (DurrIDGE co.—Billerica, USA) was used, and data acquisition was conducted according to the TCVN 9416:2012 [16]. Radon was measured on the deposit area, in confined rooms and close to the site.

2.3.3. The Measurement of Gamma Spectrum

In order to determine the exiting and dispersion of radioactive elements at the deposit area, the gamma spectrum was measured to determine the concentration of ^{238}U , ^{232}Th , and ^{40}K in the surface soil. ^{238}U was measured using the peak with energy of gamma-quant 1764 keV (^{214}Bi). ^{232}Th and ^{40}K were measured using the peak with energy of gamma-quant 2614 keV (^{208}Tl) and 1460 keV, respectively. It was conducted by using a GAD-6 spectrometer (Scintrex Ltd., Concord, ON, Canada), following the procedure described in TCVN 9419:2012 [17].

2.4. Sampling Method of the Radioactivity in the Soil, Water, and Flora

Soils and waters were sampled according to the national and international standards TCVN 7538-1:2006 (ISO 10381-1:2002), TCVN 7538-1:2006 (ISO 10381-1:2002), and TCVN 6663-1:2011 (ISO 5667-1:2006), respectively [18–20], the flora (food crops) samples and analysis according to international standard of International Atomic Energy Agency (IAEA's standard) [21].

The position of sampling has been distributed on the deposit area evenly to ensure that the samples cover areas from both the ore deposit area as well as the nearest vicinity.

2.4.1. Water Sampling

The water sampling and analyses were done according to Vietnamese Standard of TCVN 6663-1:2011 (ISO 5667-1:2006), which is described shortly, as followed [20]:

The water samples were collected at the streams and the points of outfalls following the direction of dispersing radioactive substances in water sources, to evaluate the influence of the radioactive environment on households.

Water samples were taken at depths of 0.2 m and packed in 2 liter plastic canes after they have been rinsed with water at the sampling site. The sampling locations were determined by the GPS positioning method. The water samples were acidified with HNO_3 at 0.3% concentration to prevent precipitation.

Analysis of water samples was focused on the determination of total activity α , β and indicators ^{226}Ra , ^{238}U , ^{232}Th , ^{137}Cs , ^7Be , and ^{40}K .

2.4.2. Soil Sampling

The soil sampling and analyzing methods were implemented according to Vietnamese Standard TCVN 7538-1:2006 (ISO 10381-1:2002) [18]. Samples of soils were preferably taken at the sampling sites of plants (food crops). The sampling area was 2.0×2.0 m, and the distance of sampling points was 0.5 m. Samples were taken at a depth of 15 cm. Each sample weighed 1 kg. The sampling location was documented by GPS coordinates.

The samples were dried and ground to the grain size of 0.74 mm. Each sample weight was 600 g, which was homogenized and split into 300 g samples for the analysis in a standardized manner.

Analysis of soil samples was focused on ^{226}Ra , ^{238}U , ^{232}Th , ^{137}Cs , ^7Be , and ^{40}K .

2.4.3. Flora Sampling

The flora sampling and analyzing methods were implemented according to international standard of IAEA [21]:

The flora samples were collected from some of the food crops planted, such as rice grains and cassava roots, which are the staple food of the residents in the villages in the vicinity of the ore deposit area. The average weight of each sample was 3.0 kg. The sampling locations were documented by GPS.

The food crops samples were collected and rinsed by the water on site, and then processed by slicing and drying for cassava. The samples were prepared by drying at $105\text{ }^\circ\text{C}$ for 48 h, and then they were weighted, and moisture content was determined. The specimens were then heated to temperatures below $450\text{ }^\circ\text{C}$ for 48 h to achieve the ash specimens. Weight of ash and ash factor were determined and sent to

labs for the analysis. Analysis of food crops samples was undertaken to fully determine the presence of uranium and thorium in plants by analyzing ^{226}Ra , ^{238}U , ^{232}Th , ^{137}Cs , ^7Be , and ^{40}K .

3. Results and Discussion

3.1. Determination of Environmental Radioactive Gas Positions

3.1.1. Measurement Localities of the Gamma Radiation

The gamma dose measurement positions were defined by a network measuring along the geological exploration route with a distance of 20 m/point in both the residential and planned future mining area. Outside the mine area, measurement points were set at a distance of 40 m/point, and a total distance measuring line of 200 m was achieved. The total number of completed points was 2165.

3.1.2. Measurement Points for Radon Determination

The data point network for radon measurements was set along the geological exploration route, with special focus on radon concentrations in residential areas. Therefore, the investigation on the North Namxe deposit followed data acquisition positions from geological exploration routes of T1 to T11 with the measurement interval of 120 m and 240 m for T12 to T19, respectively (see Figure 2). The data point distance for the South Namxe deposit was determined to be 120 m within populated and exploration area, and 240 m in the other areas. The total of measured points was 309.

3.1.3. Measurement Points of Environmental Gamma Spectrum

Measurements were carried out along the geological exploration route. The data points were distributed denser in the residential and future mining areas. Specifically, in the North Namxe district, the data points followed the T1 to T11 exploration route with a point interval of 120 m and route T12 to T19 of 240 m, respectively (see Figure 2). For the South Namxe deposit, again in populated and exploration area, the distance between the data points was 120 m, and in the remaining areas 240 m, respectively. The total number of measured points was 306.

3.2. The Natural Radioactive Environmental Components

After measuring and analyzing data treatment, the results of error assessment are summarized in the Table 1.

Table 1. Error assessment of measured results in site.

Measured Method	Number of Points	Relative Error (%)	Absolute Error		Tolerance (%)
			Value	Unit	
Gamma Dose Measurement					
At the measured point of 0 m	180	2.14	0.01	μSv per hour	≤ 10
At the measured point of 1 m	180	2.64	0.02	μSv per hour	≤ 10
Radon Gas Measurement					
Rn	34	14.19	8.41	Bq per m^3	≤ 30
Tn	34	8.54	26.22	Bq per m^3	≤ 30
Gamma Spectrum Measurement					
Potassium channel	30	5.44	0.17	%	≤ 10
Uranium channel	30	7.64	1.52	ppm	≤ 10
Thorium channel	30	2.74	3.09	ppm	≤ 10

The data assessment of the measured and analyzed data has revealed that they meet current standard criteria. Therefore, the collection data meet the required reliability.

3.2.1. Characterization of Gamma Dose

The gamma dose data have been collected by the net measuring from the whole Namxe rare earth deposit exploration area. Summarized results have shown that the gamma dose at the 0 m position varied from 0.11 to 3.28 μSv per hour, with an average value of 0.69 μSv per hour, and at the 1 m position, varied from 0.10 to 2.46 μSv per hour, with an average value of 0.63 μSv per hour (Table 2).

Table 2. Statistic of gamma dose characterization.

Parameters	Gamma Dose Value Measured (μSv per Hour) at Point Position of	
	0 m	1 m
Min	0.11	0.10
Max	3.28	2.46
Average	0.69	0.63
Standard deviation	0.43	0.40
Coefficient of variation (%)	62.31	63.49
Amount of measured points	2 165	2 165

The gamma dose level smaller than 0.3 μSv per hour was found in only smaller areas which were close to the border of the area of investigation.

The gamma dose level from 0.3 to 0.6 μSv was found in the transition area between the ore body and the non-ore area, revealing elevated gamma dose rates due to the close distance to the ore body. Respectively, the highest values, ranging from 0.6 to >1.0 μSv per hour were found in the close vicinity of the ore bodies. According to the standard of NRB-96 and NRB-99 [10,11], this distribution area is exceeding the secondary class safety standard of gamma dose [22].

3.2.2. Characterization of Radioactive Gas Concentration

The measured radon gas contribution varied from 6.7 to 465 Bq per air cubic meter, and the mean value was 76.29 Bq per air cubic meter (Table 3). The positions of high radon concentration were not only depending on the distribution area of ore bodies, but also the areas of limited natural ventilation. In the investigated places of high population density, such as the villages of Mau, Man, Mo, and Namxe, the radon concentration was considerably higher.

Table 3. Statistic of characterization of radioactive gas concentration.

Parameters	Radioactive Gas Concentration (Bq per Air Cubic Meter)	
	Rn	^{220}Rn
Min	6.7	3.9
Max	465	1,123
Average	76.29	129.59
Standard deviation	66.47	179.78
Coefficient of variation (%)	87.13	138.73
Number of measured points	309	309

According to the standard of TCVN 7889: 2008 [19], it is not recommended to construct new houses in areas where the Rn's concentration exceeds 100 Bq per cubic meter, which is, unfortunately, the case in the region.

3.2.3. Characterization of Gamma Spectra in the Soil of the Deposit Area

The results of the gamma spectra measurements in the soils of the deposit area revealed details of the radioactive substances' concentrations. Table 4 summarizes the measured data with the respective highest and lowest measured values and averages.

Table 4. Statistic of characterization of gamma spectra in the soil.

Parameters	Concentration Values of		
	K (%)	U (ppm)	Th (ppm)
Min	0.41	0.7	9.0
Max	10.08	147.8	629.2
Average	3.58	30.71	169.83
Standard deviation	2.22	24.75	124.51
Coefficient of variation (%)	62.01	80.59	75.54
Number of measured points	306	306	306

These results have shown that the concentration of thorium and uranium is high, with Th exceeding the U contents.

3.2.4. Alpha and Beta Activity in the Water

The analysis results of alpha and beta activity in the water have shown that the alpha activity value ranged from 0.021 to 0.090 Bq per liter water, with the average value of 0.04 Bq/L, and beta activity ranged from 0.210 to 0.819 Bq/L, with the average value of 0.486 Bq/L. Comparing with the Vietnamese standard of QCVN 08-MT:2015/BTNMT [23], the threshold limit value of the alpha activity was 0.1 Bq/L and for beta 1.0 Bq/L, respectively. Alpha and beta activity levels in the study are therefore not exceeding the national threshold limit values (Table 5).

Table 5. Statistic of characterization of alpha and beta concentration in water.

Parameters	Values of Activity (Bq per Water Liter)	
	Alpha	Beta
Min	0.021	0.219
Max	0.090	0.819
Average	0.046	0.490
Standard deviation	0.018	0.154
Coefficient of variation (%)	39.13	31.43
Number of samples	30	30

Thus, the radioactivity in the local water environment is generally considered normal (i.e., within the national restrictions). The analysis results of total alpha and beta activity in water in the streams as well as in some nearby localities have shown that there were not any samples exceeding the threshold limit values. Therefore, the water use in the study area is still safe.

3.2.5. Activity of Radioactive Elements in Food Crops

The statistic results of radioactive elements in samples of food crops have shown that the radionuclides of ^{226}Ra , ^{238}U , ^{232}Th , ^{137}Cs , ^7Be , and ^{40}K were present in most of the plant samples from Namxe area (Table 6).

Table 6. Statistic of characterization of radioactivity in food crops.

Parameters	Radioactivity (Bq/kg)					
	^{226}Ra	^{238}U	^{232}Th	^{137}Cs	^7Be	^{40}K
Min	0.0	0.22	1.21	0.0	0.98	109.32
Max	39.54	18.32	36.02	0.51	11.23	402.12
Average	6.32	5.3	7.49	0.18	4.09	221.9
Standard deviation	10.68	4.86	10.27	0.14	3.08	62.26
Coefficient of variation (%)	168.99	91.70	137.12	77.78	75.31	28.06
Number of samples	80	80	80	80	80	80

Compared with the standard of NRB-96 [10], the radioactivity in plant samples exceeded the permitted limitation ($H_d \leq 0.2$ mSv per year), which means that the staple food in the Namxe rare

earth deposit has incorporated radioactive ingredients in high doses. The samples had higher H_d concentrated in the North Namxe, the village of Mau and the regions around the rare earth ore bodies.

3.2.6. The Activity of Radioactive Elements in the Soil

Statistical analysis of the activity of radioactive elements in soils has shown that radioactive isotopes such as ^{226}Ra , ^{238}U , ^{232}Th , ^{137}Cs , ^7Be , and ^{40}K were present in most of the soil samples at the Namxe rare earth deposit area (Table 7).

Table 7. Statistic of characterization of radioactivity in the soil.

Parameters	Radioactivity (Bq/kg)					
	^{226}Ra	^{238}U	^{232}Th	^{137}Cs	^7Be	^{40}K
Min	17.98	9.33	10.32	0.0	0.0	47.34
Max	2173.45	1399.09	848.32	2.59	9.75	848.17
Average	338.02	208.51	199.11	0.19	1.84	220.58
Standard Deviation	566.04	326.74	252.62	0.37	2.38	164.38
Coefficient of Variation (%)	167.46	156.70	126.88	194.74	129.35	74.52
Number of samples	80	80	80	80	80	80

Analyzes of the soil samples have shown that some soil samples exceeded the 1.000 Bq per kg limit (cf. NRB-96). Those soil samples were taken out from the North Namxe area, which has the use of land to plant the food crop. Figure 2 shows the distribution of areas with soil samples of high radioactivity (red color)—mainly located in North Namxe. It can be summarized therefore that most of the soil on the surface land of North Namxe is contaminated with radioactive material. According to the threshold limit values of radioactive substances in construction materials, the soil and rock in the North Namxe deposit are not granted to make permanent settlements, or use for landfill, construction of civil works, and so forth.

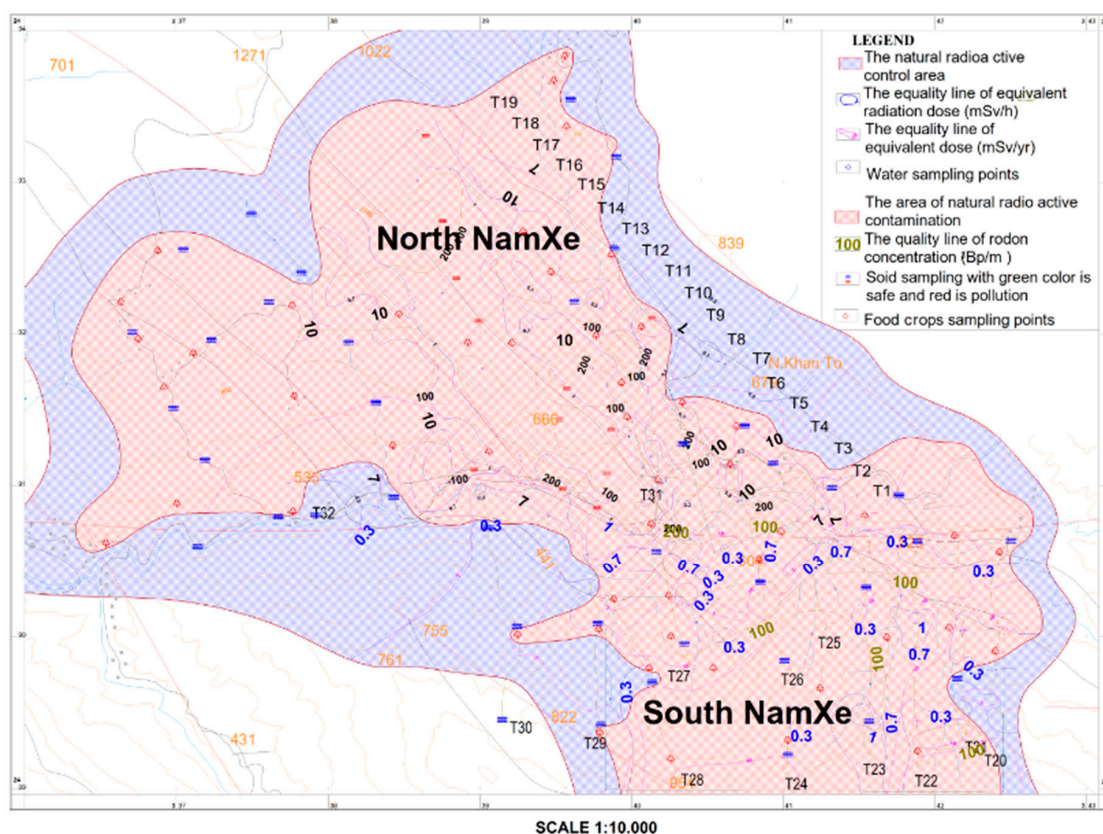


Figure 2. Map of delineating area contaminated by natural radiation in Nam Xe rare earth deposit.

3.3. Radiation Pollution Partition for the Namxe Rare Earth Deposit

3.3.1. Basic of Radiation Pollution Definition

On the basis of Vietnamese regulations and standards for the environmental protection, the radiation pollution areas in Namxe rare earth deposit were determined. However, some radionuclides have not been regulated in the Vietnamese standards, so they have been applied by the references of the international standards (e.g. IAEA [21], ICRP, [24,25]).

Main standard applied

The recommendations of ICRP have been used for the health safety and environmental protection of the natural radiation. Figure 3 shows a perspective on the recommended levels for the individual dose restrictions in terms of additional annual dose can be gained by presenting them vis à vis values of existing annual doses due to natural background radiation [24].

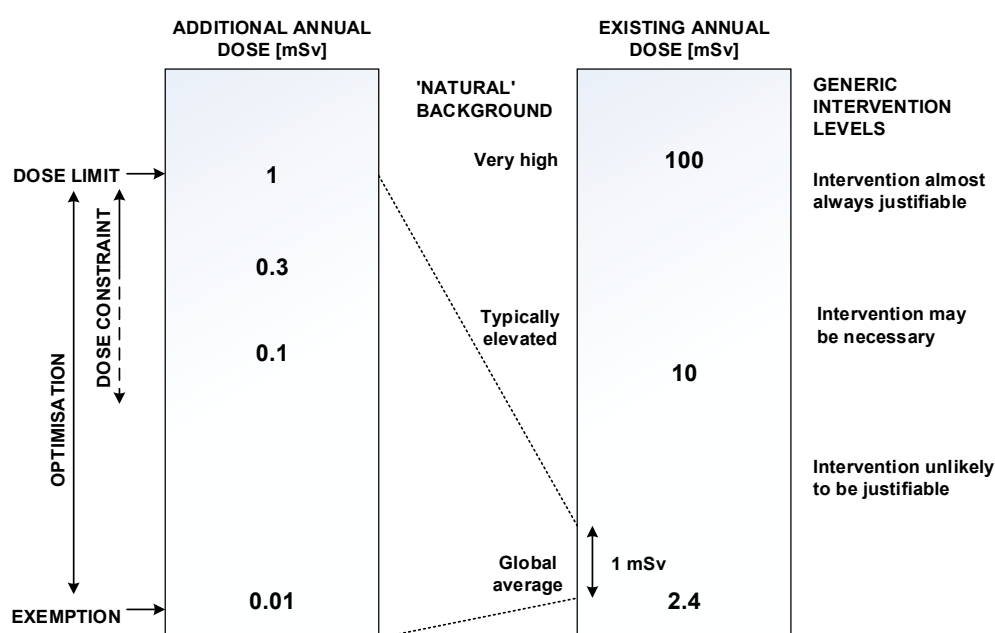


Figure 3. Schematic representation of the individual dose restrictions in terms of additional annual dose vis à vis the reported levels of natural background exposure in terms of existing annual dose.

For the existing annual dose of natural radiation, the average value is 2.4 mSv, if this value is from 2.4 mSv to 10 mSv, then the intervention is not needed, but if it is higher than 10 mSv, then actions have to be applied.

Secondary standards

According to several Vietnamese standards (Vietn. Standard), the limiting concentration is the highest concentration of radioactive material in a volume unit of drinking water or breathing air for the subjects, so that the annual infiltration of radioactive materials into the body does not exceed the regulated limited threshold [19]. Table 8 compiles the limiting radioactivity of some main elements which penetrate into the human body by the digestive tract and by inhalation.

Total of alpha radioactivity (α) is ≤ 0.1 Bq/L (according to QCVN 08:2008/BTNMT).

Total of beta radioactivity (β) is ≤ 1.0 Bq/L (according to QCVN 08:2008/BTNMT).

The radon concentration limit in the air where new houses are being built is ≤ 100 Bq/m³ and for using existing buildings, ≤ 200 Bq/m³ (according to TCVN 7889:2008).

The gamma dose rate of outdoor radiation does not exceed 0.3 μ Sv/h (according to NRB-96).

Radioactivity in the flora sampling ≤ 0.2 mSv per year (according to NRB-96).

When all of the radionuclides are concurrently present in drinking water and food, the total condition must be satisfying the following expression:

$$\sum_{i=0}^n \frac{A_i}{A_i^{gh}} \leq 1 \quad (7)$$

where: A_i is the specific activity of the radionuclides in the sample; and A_i^{gh} is the limited activity of radioactive nuclei.

Table 8. Limiting radioactivity in the air, water, and food.

Elements	Penetrating by the Digestive Tract				Penetrating by the Inhalation		
	Vietn. Standard	IAEA's standard			IAEA's Standard		
	Limited Radioactivity (Bq/kg)	Dose Factor E (Sv/Bq)	Annual Limiting (Bq/year)	Radioactive Threshold (Bq/kg)	Dose factor E (Sv/Bq)	Annual Limiting (Bq/year)	Active Volume Threshold (Bq/m ³)
⁴⁰ K	9.25×10^3	6.2×10^{-9}	1.6×10^5	2.0×10^2	2.1×10^{-9}	4.8×10^5	6.5×10
²²⁶ Ra	19.9×10^{-1}	2.8×10^{-7}	3.6×10^3	4.5×10	1.6×10^{-5}	6.3×10	8.6×10^{-3}
²³² Th	7.40×10^{-1}	2.3×10^{-7}	4.3×10^3	5.4×10	4.2×10^{-5}	2.4×10	3.3×10^{-3}
²³⁸ U	2.17×10	4.4×10^{-8}	6.0×10^2	7.3×10^{-1}	4.9×10^{-7}	2.0×10^3	2.8×10^{-1}

3.3.2. Principle of Delineating Area Contaminated by Radiative Environment

Delineating expected area contaminated by natural radiation

Expected area contaminated by natural radiation happens when it satisfies one of following conditions [26]:

- i. An area has a total of equivalent radiation dose of >10.0 mSv/year;
- ii. An area has a radon concentration of >200.0 Bq/m³;
- iii. An area with a screening rate of >0.6 μ Sv/h, delineating an area with a total equivalent radiation dose of >7.0 mSv/year;
- iv. Total of alpha activity of >0.1 Bq/L water, or total of beta activity of >1.0 Bq/L water;
- v. Radioactivity in the soil of >370.0 Bq/kg;
- vi. Radioactivity in the flora samples of >0.2 mSv/year.

Delineating controlled area contaminated by natural radiation

Controlled area contaminated by natural radiation happens when it has one of following conditions [26]:

- i. An area with an equivalent radioactive dose of gamma of >0.3 μ Sv/h, which equals to a total equivalent radioactive dose of >7.0 mSv/year;
- ii. An area with the radon concentration of >100.0 Bq/m³.

3.3.3. Local Definition of the Radioactive Areas in the Namxe Rare Earth Region

Based on the threshold values above, two areas in the Namxe ore deposit region were defined: A region of actual high radioactive contamination, exceeding several limit values, and a region with elevated radioactivity, where special control and monitoring efforts should be applied to (Figure 2).

The area of natural radioactive contamination extends from the South, according to the Namxe stream to the North of Namxe deposit, with an area of 14.33 square kilometers, covering the whole area of the Namxe rare earth deposit and the villages Mau, Mo, Pa Chai, and Bo Cha. In this area, people are advised not to move to or settle permanently.

The natural radioactive control area is covering the area of natural radioactive contamination with an additional area of 8.33 square kilometers.

4. Conclusions

Several methods were applied to monitor the premining state of an area surrounding the Nam Xe rare earth deposit. The analytical work included air, soil, water, and crop samples and their activity due to the incorporation of radioactive elements such as Th, Rn, and K.

Analysis results of radioactivity from floras on the Namxe deposit area showed that staple food, planted in the vicinity of the area, has included radioactive active contents in high doses. The samples had higher H_d concentrated in the North Namxe region, village of Mau, and the area directly above the rare earth ore bodies.

The results presented in this study are the basis for monitoring the environmental impact of planned mine work in the near future, but may have a direct influence on the inhabitants in the area, with recommendations on the current agriculture.

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References

1. Heinig, T.; Burisch, M.; Möckel, R.; Phan, Q.V.; Ebert, D. *Gutzmer: Mineralogy, Petrography and Genesis of REE Bearing Carbonatite Dykes, NamXE Deposit, Vietnam*; (in preparation)
2. Dzien, D.V. Rare Earth Deposits. In *Geology and Mineral Resources of Vietnam*; Xinh, L.T., Tri, T.V., Dzung, D.H., Dzung, N.T., Chien, L.T., Chau, D.M., Hai, T.H., Eds.; Mineral Development Co: Hanoi, Vietnam, 1990; pp. 144–147.
3. Hedrick, J.B. Rare Earths. USGS Minerals Yearbook. 1996. Available online: http://minerals.usgs.gov/minerals/pubs/commodity/rare_earth/740496.pdf (accessed on 6 August 2013).
4. Bui, T.H.; Trinh, D.H.; Nguyen, P. Overview of rare earth in Vietnam. *Geol. J. Ser. A* **2010**, 447–456.
5. People’s Committee of Nam Xe commune (2015): Report on the socio-economic development in order to ensure national defense and security in 2015 and the key tasks of socio-economic development to ensure national defense and security in 2016. No. 215/BC-UBND. Nam Xe, 2015.
6. Trinh, D.H.; Nguyen, P. Develop a methodology for investigating and assessing the environment related to toxic minerals on the basis of existing equipment in Vietnam. *J. Geol. Ser. A* **2013**, 30–38.
7. Vietnam Map. Available online: <http://www.vietnamtours.ws/Map.html> (accessed on 28 August 2019).
8. LaiChau Map. Available online: <http://vietnamtravels.vn/Vietnam-travel-information/Lai-Chau.htm> (accessed on 28 August 2019).
9. Paiva, I.; Marques, R.; Santos, M.; Reis, M.; Prudêncio, M.I.; Waerenborgh, J.C.; Dias, M.I.; Russo, D.; Cardoso, G.; Vieira, B.J.C.; et al. Naturally occurring radioactive material and risk assessment of tailings of polymetallic and Ra/U mines from legacy sites. *Chemosphere* **2019**, 223, 171–179. [CrossRef] [PubMed]
10. Ryabukhin, Y.S. Radiation Safety Standards (NRB-96). *Meditinskaya Radiologiya i Radiatsionnaya Bezopasnost* **1997**, 42, 70–73.
11. National Commission for Sanitary Inspection of Russian Epidemiology. *Radiation Safety Standards (NRB-99)*; Minzdrav Rossii: Moscow, Russia, 1999.

12. Nguyen, V.N. *To Study the Scientific Basis to Determine the Level of Environmental Pollution of Natural Radioactive Sources in Order to Develop Technological Process for Detailed Assessment of Radioactive Contamination Areas*; Archives in Science and Technology Information Center; Ministry of Science and Technology of Vietnam: Hanoi, Vietnam, 2009.
13. Dao, V.T.; Nguyen, P.D.; Vu, H.L.; Chu, V.N.; Vu, V.N.; Bui, V.T.; Nguyen, T.T.; Tran, B.T. *Temporary Guidance on Environmental Geological Survey and Geological Disasters*; Archives in Geological Archives Information Center: Hanoi, Vietnam, 2004.
14. Trong, T.B. *Investigating the State of the Radioactive Environment, Its Ability to Influence and Remedial Measures on Some Radioactive Mines, Mines Containing Radioactivity in Lai Chau, Cao Bang and Quang Nam*; Archive in Geological Archives Information Center: Hanoi, Vietnam, 2003.
15. TCVN 9414:2012: Investigation, Assessment of Geological Environment—Gamma Method. Available online: <https://vanbanphapluat.co/tcvn-9414-2012-dieu-tra-danh-gia-dia-chat-moi-truong-phuong-phap-gamma> (accessed on 28 September 2019).
16. TCVN 9416: 2012: Investigation, Assessment of Geological Environment—Radioactive Air Method. Available online: <https://vanbanphapluat.co/tcvn-9416-2012-dieu-tra-danh-gia-dia-chat-moi-truong-phuong-phap-khi-phong-xa> (accessed on 28 September 2019).
17. TCVN 9419:2012: Investigation, Evaluation and Exploration of Minerals—Gamma Spectrometric Method. Available online: <https://vanbanphapluat.co/tcvn-9419-2012-dieu-tra-danh-gia-tham-do-khoang-san-phuong-phap-pho-gamma> (accessed on 28 September 2019).
18. TCVN 7538-1:2006 (ISO 10381-1:2002): Soil Quality—Sampling—Part 1: Guidance on the Design of Sampling Programmes. Available online: <https://vanbanphapluat.co/tcvn-7538-1-2006-chat-luong-dat-phan-1-huong-dan-lap-chuong-trinh-lay-mau> (accessed on 28 September 2019).
19. TCVN 7889:2008: Natural Radon activity in Buildings—Levels and General Requirements of Measuring Methods. Available online: <http://luattrongtay.vn/ViewFullText/Id/b294e192-e2fe-440e-86df-bac4c4bbd75b> (accessed on 28 September 2019).
20. TCVN 6663-1:2011 (ISO 5667-1:2006): Water Quality—Sampling—Part 1: Guidance on the Design of Sampling Programmes and Sampling Techniques. Available online: <https://www.iso.org/obp/ui/#iso:std:iso:5667:-1:ed-2:v1:en> (accessed on 28 September 2019).
21. International Atomic Energy Agency (IAEA). Technical Reports Series No.295. Measurement of Radionuclides in Food and the Environment. A Guidebook. Available online: <https://www.iaea.org/publications/1398/measurement-of-radionuclides-in-food-and-the-environment> (accessed on 28 September 2019).
22. Phuong, N. *Study on the Methodology for Environmental Impact Assessment and Integration of Mineral Resource Protection with Environmental Protection of Uranium and Rare Earth Mines in Northwest of Vietnam*; Bulletin No. B2001-36-13; Library of Hanoi University of Mining and Geology: Hanoi, Vietnam, 2003.
23. QCVN 08-MT:2015/BTNMT. *National Technical Regulation on Surface Water Quality*; Socialist Republic of Vietnam: Hanoi, Vietnam, 2015.
24. ICRP Publication 82. *Protection of the Public in Situations of Prolonged Radiation Exposure*; Elsevier Science Ltd.: Amsterdam, The Netherlands, 2000.
25. ICRP Publication 103. *The 2007 Recommendations of the International Commission on Radiological Protection*; Elsevier Science Ltd.: Amsterdam, The Netherlands, 2007.
26. Nguyen Van Nam. *Research on the Scientific and Practical Basis for Determining the Level of Natural Irradiation Potentially Harmful to Human Beings*; Project of Ministry Level; Archives of Science and Technology Information Center, Ministry of Science and Technology Vietnam: Hanoi, Vietnam, 2011.

