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RESEARCH ARTICLE - CIVIL ENGINEERING

Evaluation of Radiation Hazards Due to Mining Activities in Al Jalamid Mining Area, North Province, Saudi Arabia

El-Said Ibrahim Shabana[1] · Essam Mohammed Banoqitah[1] · Maher Mohammad Taher Qutub[1] · Mohammad Sami Tayeb[2] · Abdulraheem Abdulrahman Kinsara[1]

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Abstract

Radiometric investigation has been conducted in Al Jalamid phosphate mining area, for purposes of radiation protection. A car-borne monitoring system was used for area monitoring, whereas thermoluminescence dosimeters were used for personal dose rate measurements. Natural radioactivity has been analyzed in groundwater by α-spectrometry and liquid scintillation counting. The occupational exposure dose rate inside the open mines and the physical beneficiation site was the highest, ranging from 0.08–0.50 μSv/h, compared to the normal background values (0.04–0.06 μSv/h) recorded on roads and undisturbed topsoil surface. The dose rate was ranging from 0.04–0.1 μSv/h inside the chemical beneficiation plant. The personal exposure dose rate measurements indicated that a worker would receive, on average, an occupational radiation dose of about 0.214 μSv/h inside the mine sites. It was lowest (about 0.06 μSv/h) in the offices located outside the mining and ore beneficiation sites. Gross α and gross β measurements in groundwater showed activity concentrations ranging from 0.61 to 0.96 Bq/L and from 2.08 to 3.03 Bq/L, with average values of 0.78 ± 0.08 and 2.44 ± 037 Bq/L, respectively. All samples have activity levels exceeding the national regulation limit values. Detailed analysis showed that this water contains uranium and radium with average concentrations of 0.12 ± 0.04, 0.33 ± 0.04, 0.14 ± 0.3 and 21 ± 1.5 Bq/L, for ^{238}U, ^{226}Ra, ^{228}Ra and ^{222}Rn, respectively. The obtained results have been discussed in detail.

Keywords Dosimetry · Dose rate measurements · Phosphate deposits · Radiation protection · Radiation monitoring · Groundwater · Water pollution · Uranium · Radium · Radon

1 Introduction

The concentration of ^{238}U and its decay products tends to be elevated in phosphate ores of sedimentary origin (e.g., [1–5]). Groundwater is likely contaminated with these natural radionuclides. This enhanced concentration results in radiological impacts on the workers and the environment during phosphate mining and processing activities [6]. In addition, inhabitants residing in areas of phosphate deposits may be exposed to extra fraction of terrestrial γ-radiation. In such sites, area monitoring and personal dose rate measurements have to be of interest for miners and other occupants for the purpose of radiation protection. The global average annual human exposure from natural sources is 2.4 mSv/year, where about 21% of this dose is related to external exposure to terrestrial γ-radiation [7]. Most of the world's population (about 95%) is assumed to live in areas of normal background radiation with outdoor exposure ranging from 0.3 to 0.6 mSv/year [8]. Therefore, it is crucial to determine the baseline of natural terrestrial γ-radiation in the mining area and nearby residential sites where values outside this range would be assumed to be related to spatial sources. A number of studies have been done to evaluate the occupational exposure in phosphate mines [9–12]. In a phosphate deposit region located in the northeast of Brazil, the inhabitants are exposed to natural radioactivity levels higher than the normal background values recorded in the literature [9]. Population doses from external terrestrial γ-radiation in areas near a Jordanian phosphate mine were found to exceed normal radiation background [10], where the absorbed dose rate in air due to ^{238}U varied

✉ El-Said Ibrahim Shabana
eishabana@kau.edu.sa

[1] Faculty of Engineering, Nuclear Engineering Department, King Abdulaziz University, P.O. Box 80204, Jeddah 21589, Saudi Arabia

[2] Radiation Protection and Training Centre, King Abdulaziz University, P.O. Box 80204, Jeddah 21589, Saudi Arabia

from 20.6 to 223.4 nGy/h. Therefore, exposure of workers and the public to radiation in such areas is of interest. The European commission has issued a draft proposal aiming at revising the Basic Safety Standards for more safety to workers and the public against effects of ionizing radiation [13].

In this context, exploitation of Al Jalamid phosphate deposits, north province, Saudi Arabia, is ongoing by open mining of this surficial deposit. Workers and the public in the mining area are likely to be affected by direct external radiation arising from the phosphate rocks. Beneficiation processes of the ore are proceeding through physical and chemical methods. The present work aims at studying personal exposure dose rates due to terrestrial γ-radiation in the mining area to demonstrate whether proper operational radiation protection measures exist or whether further measures have to be considered.

2 Experimental

2.1 Area Dose Rate Measurements

A car-borne monitoring system was used for radiometric surveying of the working area (raw rock mining sites, the beneficiation plant site and the physical beneficiation site which contains concentrate and piles of rejected) to estimate the exposure dose rate due to the arising terrestrial γ-radiation. For the method of taking measurements by car-borne, movable radiation monitoring system, SPIR-Ident Mobile, from Mirion international, France (www.mirion.com), was placed in the car in the opposite direction of the oil tank and connected by cables to a laptop. When making a radiation survey for a specific area, the speed of the car carrying the radiation survey device did not exceed 60 km/h. Measurements were taken from January 25, 2016 to January 29, 2016 and were done in daylight hours from 8 a.m. to 12 noon. Figure 1 shows the monitoring system device that was used in the field. The surveyed area was immediately mapped. The recorded exposure dose rate values were due to terrestrial γ-radiation, where the software program automatically corrects the reading for standard detector height (1 m above the ground) and for cosmic radiation interference. The movable monitoring system records the exposure dose rate within the car track of 40 meters width during the car movement. However, the change in dose rate within the car track is due to the influence of the change in terrestrial γ-radiation emissions because cosmic radiation is supposed to be uniform (0.035 µSv/h) in this small area and already subtracted. Higher radiation levels inside the mines or near the concentrate piles are expected to be due to the contribution of the spatial terrestrial γ-radiation mostly emitted from phosphate ore and surface soil.

Fig. 1 Monitoring system device used in the field

2.2 Personal Dose Rate Measurements

Radiological personal dose rate measurements were conducted to estimate the dose that workers would receive due to exposure to γ-radiation in different working sites. Thermoluminescence detectors (TLDs) were distributed to the workers to fix in their pockets, via TLD holders, at the beginning of the working time, and collected at the end of the day. Each dosimeter measures the external exposure dose rate to a worker, at site, due to exposure to natural γ-radiation during working hours.

2.3 Radioanalysis

Groundwater samples were collected from wells outside the parameter of the mining area. Water in these wells is meant for cooling and rinsing purposes. Samples were screened for gross α and gross β activities using liquid scintillation counter. The obtained results shown in Table 2 exceeded the national regulation limit for gross α and gross β in drinking water, which are 0.55 Bq/L and 1.85 Bq/L, respectively [14,15]. Regulators may recommend further analysis to identify the origin of the additional radioactivity in these water samples in case water in these wells is accidently used for drinking purposes. Detailed analysis of gross α and gross β activity measurements in addition to uranium, radium and radon determinations was discussed by Shabana et al. [14].

2.4 Equipment

Car-borne, movable radiation monitoring system, SPIR-Ident Mobile, from MIRION international, France (www.mirion.com), was used. It is a ragged and easily deployable equipment with higher capability for both detection and identification of radiation sources. It has a 2-L NaI (Tl) detector which is very sensitive to radiation detection in exposure dose rate measurements. It has a rugged detection case and wireless tablet PC, global positioning system (GPS) and immediate mapping function.

TL Dosimeters (LiF:Mg, Ti) were used for personal dose estimation. The doses were calculated using Harshaw 4500 Manual Reader.

An ultra-low-level liquid scintillation spectrometer, Quantulus, 1220, from PerkinElmer (www.perkinelmer.com), was used for measuring gross α and gross β activities in addition to radium isotopes. The minimum detectable activity (MDA) was 0.06 Bq/L for the gross α activity and 0.17 Bq/L for gross β activity, at 500 min count time and 8 mL sample size. The MDA value was 0.03 Bq/L for ^{226}Ra. For ^{228}Ra determinations, the MDA was 0.05 Bq/L for 60 min counting time and 1 L sample size. These MDA values were within the limit requirements of the national guideline values specified for natural radioactivity in drinking water [15].

A high-resolution alpha-spectrometry system, Octete Plus, from ORTEC (www.ortec.online.com) of eight silicon surface barrier detectors (450 mm^2) with efficiencies ranging from 20 to 21.5%, located in separate chambers and connected to a vacuum pump, was used to measure uranium isotopes. The detectors have very low count rates (0.9×10^{-3} to 1.85×10^{-3} counts/s) under each of the energy peaks of ^{238}U and ^{234}U, producing an ultra-low detection limit of about 0.01 Bq/L.

A portable radon measurement instrument (RAD7), from Durridge Company, Inc., USA (www.durridge.com), was used to measure radon activity concentration in the field. Following the instrument manual, RAD7 can measure radon activity concentration in water in remote areas using the RADH2O accessory. It contains internal sample cell of a hemisphere shape of volume 0.7 L and coated on the inside with an electrical conductor. A solid-state, ion-implanted, planar, silicon alpha detector is at the center of the hemisphere. The accuracy of RAD7 measurements, as reported in the calibration certificate, claims only 5%, and the results are reported with the normal statistical error in 2-sigma level.

Duplicate determinations for each sample were conducted and averaged.

2.5 Radiotracers

^{226}Ra standard reference material (SRM A7197), purchased from North America Scientific, USA, and ^{228}Ra (SRM 4339b), purchased from the National Institute of Standards and Technology (NIST), USA, were diluted and used to prepare ^{226}Ra and ^{228}Ra standard solutions, respectively. ^{241}Am (SRM 4322C) and ^{90}Sr (SRM 4239) were also purchased from NIST, USA, and used to prepare a mixed standard for controlling the gross α and gross β determinations. A ^{232}U standard reference material (SRM 4324), purchased from NIST, was also used as a spiking radiotracer in uranium determinations.

3 Results and Discussion

3.1 Area Dose Rate Measurements

A working area of about 49 km^2 (https://www.maaden) was monitored for terrestrial γ-radiation, and the exposure dose rate is mapped in Fig. 2. The radiation dose rate in the colored car track is estimated, by comparison with the color-indicator bar on the figure, to observe the spatial variations in the intensity of the emitted γ-radiation.

The surveying results in Fig. 2 show that the dose rate was higher inside the open mines and the physical beneficiation site, where the dose rate ranged from 0.08 to 0.50 and from 0.09 to 0.50 μSv/h, respectively. The physical beneficiation site contains the piles of the high-grade (about 25%) raw ore and the produced concentrate. These values are two to ten times higher than the average global normal background level [16]. Surveys inside the chemical beneficiation plant of beneficiating the low-grade (about 20%) ore showed lower radiation dose rate ranging from 0.04 to 0.1 μSv/h. Surveys on the overburden layer (surface soil layer) indicated almost normal dose rate (0.04 to 0.06 μSv/h) on roads and in some zones inside the beneficiation plant due to the shielding effect of the overburden layer (average thickness is about 18 m) on γ-radiation emission from the upper phosphate zone. Car track segments of yellow color on roads inside the working area in Fig. 2 showed higher radiation dose levels (0.08 to 0.09 μSv/h) than the normal background level due to the use of the reject material produced from the beneficiation processes in road pavement. The little yellow segment inside the plant is due to the phosphate stockpile in the crushing zone.

3.2 Personal Dose Rate Measurements

Spatial variation in radiation intensity within workplaces results in different radiation doses to workers and the public (office workers) depending upon the character of the working zone. Therefore, personal dose rate measurements have been conducted and the obtained results are given in Table 1.

The results in Table 1 showed that a worker in the beneficiation plant would receive, on average, an occupational radiation dose of about 0.137 μSv/h and a higher dose (about 0.181 μSv/h) in the site of physical beneficiation processes. The personal dose rate was comparatively the highest inside the mine sites, where a mineworker would receive, on average, an occupational radiation dose of about 0.214 μSv/h. Workers in the underground phosphate mines usually receive

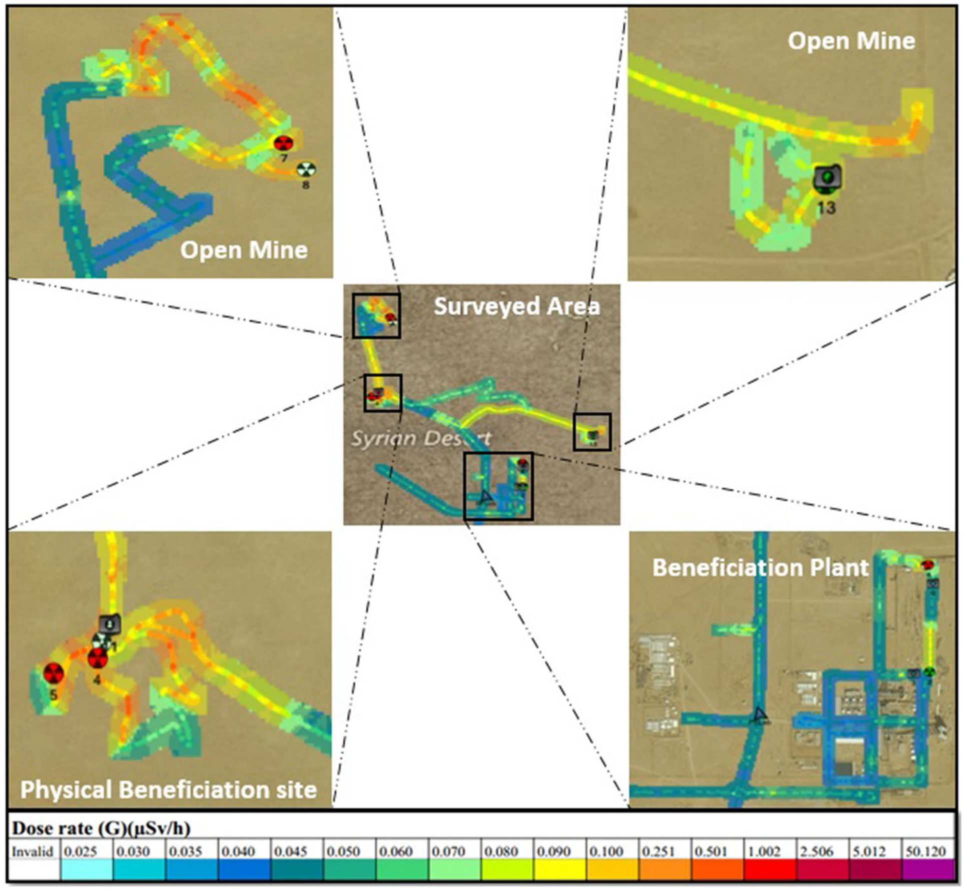

Fig. 2 Ground surveying of the working area of Al Jalamid open phosphate mines

higher doses [17]. It may be due to radiation emissions from all directions and accumulation of the emanated radon gas, which is usually diluted by wind action in open mines [18]. However, the current results have to be compared with data of workers in another open phosphate mine. Data from an open phosphate mine in Minjingu, Tanzania [3], showed that a worker would receive, on average, exposure radiation dose of 1.40 mSv/month (7 μSv/h) in places where handling of the rock phosphate is done manually. This higher value may be related to the higher radioactivity content in Tanzania phosphate deposits (about 4000 Bq/kg) compared to the present phosphate deposits (400–500 Bq/kg).

Table 1 also shows that the average exposure dose rate to the workers in the workplaces follows this sequence: mines zone > physical beneficiation zone > the beneficiation plant zone. These exposure dose rates exceeded the global average dose rate of 0.46 mSv/year (0.05 μSv/h) for normal background areas reported by UNSCEAR [7]. Despite this difference, the calculated external γ-radiation dose received by the mineworker, based on 8 h/day as working time and 5 days/week, resulted in annual occupational dose of about 0.45 mSv/year, which is far below the limit value (alarming value) of 20 mSv/year recommended by the International Commission on Radiological Protection [19].

The dosimeters, which were fixed in the pockets of office workers for control, showed that in such places, workers would receive an average exposure radiation dose of about 0.06 μSv/h, which is about 6.7 times lower, compared with the respective value of 0.4 mSv/month (0.55 μSv/h) in the Tanzanian open mine [20].

3.3 Natural Radioactivity in the Groundwater

Investigation of natural radioactivity in groundwater was performed using fast screening procedure. The fast screening procedure is performed by measuring gross α and gross β activities using an advanced liquid scintillation counter with α / β discrimination capability. Samples of gross α or gross β activities that do not exceed the national regulation limit values for drinking water (0.55 and 1.85 Bq/L, respectively) [14,15] are excluded from further investigation and considered as safe water with regard to radio-toxicity. If samples exceed the limit, they are subject to additional detailed isotopic analysis to identify the radiation source. Gross α and gross β activities were measured in all wells around the working area (11 wells), and the results are given in Table 2.

The data in Table 2 show that the gross α and gross β activities ranged from 0.61 to 0.96 Bq/L and from 2.08 to

Table 1 External exposure dose rate to workers due to γ-radiation during working hours

Site	Worker position	No. of distributed dosimeters	Dose rate, μSv/h Average (Range)
Chemical beneficiation plant	Crushing zone	10	0.152 (0.074–0.332)
	Chemical treatment zone	6	0.126 (0.058–0.272)
	Floatation zone	6	0.135 (0.086–0.197)
	Filtration zone	6	0.122 (0.072–0.210)
	Drying and handling zone	3	0.143 (0.061–0.311)
	Total average		0.137
Mines	Mine 1	8	0.232 (0.084–0.505)
	Mine 2	8	0.196 (0.077–0.486)
	Total average		0.214
Physical beneficiation	Sizing zone	6	0.188 (0.078–0.422)
	Concentrate piles zone	6	0.174 (0.065–0.389)
	Total average		0.181
Office workers		9	0.062 (0.047–0.096)

Table 2 Activity concentration of natural radionuclides in the groundwater of Al Jalamid phosphate mining area

Well no.	Activity concentration (Bq/L)						
	Gross α	Gross β	^{238}U	^{234}U	^{226}Ra	^{228}Ra	^{222}Rn
1	0.67 ± 0.07	2.08 ± 0.39	0.12 ± 0.05	0.14 ± 0.04	0.32 ± 0.03	0.10 ± 0.02	23.7 ± 1.6
2	0.78 ± 0.07	2.64 ± 0.37	0.14 ± 0.05	0.15 ± 0.04	0.35 ± 0.03	0.11 ± 0.02	22.1 ± 1.6
3	0.68 ± 0.07	2.18 ± 0.36	0.11 ± 0.04	0.13 ± 0.04	0.29 ± 0.03	0.16 ± 0.03	20.5 ± 1.5
4	0.91 ± 0.08	2.62 ± 0.37	0.15 ± 0.03	0.19 ± 0.05	0.36 ± 0.03	0.13 ± 0.04	19.8 ± 1.5
5	0.96 ± 0.09	3.03 ± 0.38	0.11 ± 0.02	0.16 ± 0.04	0.41 ± 0.04	0.21 ± 0.04	19.9 ± 1.5
6	0.81 ± 0.08	2.24 ± 0.39	0.14 ± 0.04	0.17 ± 0.03	0.29 ± 0.03	0.17 ± 0.03	23.1 ± 1.6
7	0.78 ± 0.07	2.17 ± 0.38	0.14 ± 0.04	0.14 ± 0.03	0.31 ± 0.04	0.13 ± 0.04	18.9 ± 1.4
8	0.73 ± 0.07	2.16 ± 0.37	0.10 ± 0.04	0.13 ± 0.03	0.33 ± 0.03	0.12 ± 0.03	21.6 ± 1.6
9	0.68 ± 0.08	2.52 ± 0.37	0.13 ± 0.03	0.14 ± 0.02	0.26 ± 0.04	0.13 ± 0.04	24.1 ± 1.6
10	0.92 ± 0.09	2.93 ± 0.38	0.12 ± 0.02	0.16 ± 0.03	0.42 ± 0.05	0.19 ± 0.03	19.8 ± 1.5
11	0.61 ± 0.07	2.28 ± 0.36	0.10 ± 0.04	0.11 ± 0.03	0.28 ± 0.06	0.10 ± 0.02	21.0 ± 1.6
Average	0.78 ± 0.08	2.44 ± 0.37	0.12 ± 0.04	0.15 ± 0.03	0.33 ± 0.04	0.14 ± 0.03	21.3 ± 1.5

3.03 Bq/L, with average values of 0.78±0.08 and 2.44±0.37 Bq/L, respectively. These values indicated that all samples had gross activity levels exceeding the national regulation limit values, justifying the need for detailed analysis. Detailed analysis showed that the radiation comes mainly from ^{226}Ra and ^{228}Ra, where the national regulations recommend 0.185 Bq/L as a limit value for combined radium ($^{226}Ra + ^{228}Ra$) due to their high toxicity. This value is exceeded in all samples (Table 2).

Radon-222 was measured in all samples, and the obtained results are included in Table 2. Radon-222 concentration was ranging from 18.9 to 23.7 Bq/L, with an average value of 21.3 ± 1.5 Bq/L. These values exceeded the national limit (11.1 Bq/L) set out for ^{222}Rn in drinking water [15]. It is also observed that the results of the activity concentrations and the isotopic ratios between the different samples varied in a narrow range, indicating that the water in these wells could be coming from the same water table. It is recommended that this water should be treated before being used for drinking or restricted to other usages.

4 Conclusions and Recommendations

From the radiation dose measurements in the phosphate mining area, the following conclusions and recommendations could be drawn:

Normal dose rate was observed on the sites of undisturbed topsoil and buildings.

The use of the reject material in road reclamation enhanced the exposure rate.

The highest dose rate recorded was found in the mine (0.214 μSv/h) and the physical beneficiation sites (0.181 μSv/h).
Although this dose rate is several times higher than the normal level (0.04 to 0.06μSv/h), it is not high enough to cause alarm at 20 mSv/year (11.11 μSv/h).
Groundwater must be treated before being used for drinking or restricted to other usages.

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