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Radon-222 Concentration and Potential Risk to Workers of Al-Jalamid Phosphate Mines, North Province, Saudi Arabia

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Abstract**—**Usually, phosphate deposits contain ^{238}U and ^{232}Th in addition to their decay products. Due to their different pathways in the environment, the $^{238}U/^{232}Th$ activity concentration ratio usually found to be greater than unity in phosphate sediments. The presence of these radionuclides creates a potential need to control exposure of workers in the mining and processing activities of the phosphate minerals in accordance with IAEA safety standards. The greatest dose to workers comes from exposure to radon, especially ^{222}Rn from the uranium series, and has to be controlled. In this regard, radon (^{222}Rn) was measured in the atmosphere (indoor and outdoor) of Al-Jalamid phosphate-mines working area using a portable radon-measurement instrument RAD7, in a purpose of radiation protection. Radon was measured in 61 sites inside the open phosphate mines, the phosphate upgrading facility (offices and rooms of the workers, and in some open-air sites) and in the dwellings of the workers residence-village that lies at about 3 km from the mines working area. The obtained results indicated that the average indoor radon concentration was about 48.4 Bq/m^3. Inside the upgrading facility, the average outdoor concentrations were 10.8 and 9.7 Bq/m^3 in the concentrate piles and crushing areas, respectively. It was 12.3 Bq/m^3 in the atmosphere of the open mines. These values are comparable with the global average values. Based on the average values, the annual effective dose due to radon inhalation was calculated and risk estimates have been done. The average annual effective dose to workers due to the radon inhalation was estimated by 1.32 mSv. The potential excess risk of lung cancer mortality that could be attributed to radon, when considering the lifetime exposure, was estimated by 53.0x10^{-4}. The results have been discussed in detail.

Keywords**—**Dosimetry, environmental monitoring, phosphate deposits, radiation protection, radon-22.

I. Introduction

USUALLY phosphate deposits contain the naturally occurring radionuclides ^{238}U and ^{232}Th together with their decay products [1]-[3]. ^{232}Th usually occurs in lower concentrations in phosphate deposits of sedimentary origin due to its poor mobility in the environment [2], [3]. Uranium can substitute for calcium in the phosphate rock structure, and over a period accumulates in the phosphate reserves due to similarity in ionic sizes between U^{4+} and Ca^{2+} [4]. Therefore, uranium and its decay products are present in phosphate rocks in levels can be differing from one rock to another depending upon the rock constitution. However, usually phosphate mining and processing activities result in radiation exposure to workers. In northern Saudi Arabia lies one of the largest reserves of phosphate mineral worldwide, where its exploitation is recently started in Al-Jalamid site. It is the first site where phosphate mining is started. Such activities must be subjected to radiometric investigation to evaluate the radiation hazards to workers and the environment, and provide appropriate recommendations to mitigate the potential risk. Preliminary examination based on analyzing few raw phosphate rock samples by α-spectrometry indicated ^{238}U and ^{232}Th concentrations of about 350±50 and 2±0.4 Bq/kg, respectively. Fast screening of five groundwater wells of the same water reservoir in the mining area showed average activity concentration of 0.57±0.08 and 2.42±0.7 Bq/L for gross α and gross β particle activities, respectively. On considering the radiation exposure of phosphate miners in the working places, radon and its decay products in the atmosphere are the most important contributors [5], where about 60% of the global average total annual effective dose (2.4 mSv) is related to radon and its decay products. Radon emanates from the uranium bearing rock and tends to accumulate in closed places, where its inhalation increases the risk of lung cancer [6]. According to the US Environmental Protection Agency [7], epidemiological studies showed clear link between lung cancer and atmospheric radon levels, and estimated the lifetime risk of lung cancer mortality, due to exposure to 150 Bq/m^3, by about 2.3% for public.

The prospective of this work was to provide radiological data about indoor and outdoor radon concentrations in Al-Jalamid phosphate mining area, to be helpful for estimating the potential risk to workers due to radon inhalation and submitting the proper recommendations to reducing exposure rate of workers to radon.

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II. Experimental

A. Description of the Study Area

Al-Jalamid phosphate mining area is located inside Hazm Al-Jalamid Quadrangle (bounded by lat 31° 00’ and 32° 00’ N and long 39° 00' and 40°30' E), Northwest of Saudi Arabia (Fig. 1). The topography of the Quadrangle is dominated by a high land in the southwestern part, by a northwest-trending elongate through in the western part, and by a flat, mostly featureless, gravel-covered plain that encompasses most of the Quadrangle including the mines working site [8]. The center of the mine working area is located nearly at 31° 50' 171" N and 39° 92' 143" E.

Fig. 1 Map of Saudi Arabia showing the location of the phosphate mining and processing areas; Al-Jalamid mines area (A), the phosphate processing complex (B) and the export marine port (C).

According to [8], Al-Jalamid formation is divided into two members, the Thaniyat phosphorite member at the base and the Kuwaykabah member at the top. Al-Jalamid phosphorite district occurs in the Thaniyat phosphorite member in two ore zones. The lower ore zone has a P2O5 concentration of less than 20% and the upper ore zone has a P_2O_5 concentration of 16-22%.

B. Equipment

A portable radon detection equipment (RAD7), manufactured by DURRIDGE Company, Inc., USA, can measure radon activity concentration in the field. It forms a basis of a comprehensive radon measurement system, which can be used in different modes for different purposes. RAD7 can measure radon activity concentration in air and water in remote areas using the proper 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 [9]. 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 σ level.

C. Measurement of Radon Concentration in the Atmosphere

The activity concentration of radon was measured in air by following the standard operating procedure of the RAD7 instrument manual [9]. Briefly, the instrument was connected to the appropriate accessories (air filter, drying station and dry-stick) to guarantee dry particulate-free inlet air, and fixed in the site of interest at 1 m above the floor at equal distance from the sidewalls. The instrument is controlled through the CAPTURE software and a four-key menu driven interface. The four keys allow to looking at the commands and operating the instrument to collect the required data. After the counting period, the result of radon activity concentration is automatically printed in a unit of Bq/m^3 of air, with the statistical error. Radon concentration measurements in the outer atmosphere were performed by fixing the instrument in specific sites to avoid fast winds and direct sunlight.

D. Dose Due to Radon

The annual effective dose, (D_E) due to indoor radon inhalation, which corresponds to the value of the average activity concentration of radon in indoor air, was calculated using [5]:

$$D_E = A_{Rn} \text{ x } E_f \text{ x } T \text{ x } 9 \text{ nSv/(Bq h m}^{-3}) \quad (1)$$

where A_{Rn} is the average activity concentration of indoor radon in Bq/m^3, E_f is the indoor equilibrium factor between radon and its progeny (estimated by 0.4); T is the exposure time to this concentration in hours (assumed to be equal to 7000 h/y), and 9 nSv/(Bq h m^{-3}) is the estimated dose conversion factor. Following this equation, inhalation of 1 Bq/m^3 of indoor radon causes an annual effective dose of about 25.2 µSv.

The above equation was used to calculate D_E due to outdoor radon inhalation, assuming that the exposure time to this concentration, in this case, is 1760 hours and E_f is estimated by 0.6 [5]. Accordingly, inhalation of 1 Bq/m^3 of outdoor radon causes an effective dose of about 9.45 µSv.

E. Risk Assessment

For estimating the risk of lung cancer mortality associated with lifetime inhalation of radon in air at a unit concentration (1 Bq/m^3), the National Research Council report [10] developed a risk projection of 1.3x10-4 per this unit concentration in air for a mixed population of smokers and nonsmokers. This risk projection is used in this work to calculating the risk of lung cancer mortality for the phosphate miners.

III. Results and Discussion

A. Radon Concentration in the Atmosphere

Radon concentration was measured in the atmosphere of the working area of Al-Jalamid phosphate mines. A set of 61 indoor and outdoor measurements in different sites scattered in the area have been achieved, and the results are given in Table I. The results in Table I indicated a wide range of variation in the indoor radon concentration ranging from 19.3 to 83.9 Bq/m^3, with an average value of 48.4±14.6 Bq/m^3. This variation may be related to various geological aspects affecting the local radon migration to air as rock porosity, fractures and depth of the bearing rock [11]-[14]. Home ventilation and the used building materials are additional factors contributing this variation [15], [16]. The average indoor radon concentration was about 1.2 times greater than the global average value of 40 Bq/m^3 [5]. These results propose a slight remediation action based on more enhancement of the ventilation condition in the closed places. No extreme values are detected, likely due to the normal ventilation conditions. The overall results did not show much significant indoor ^{222}Rn levels where all values of the indoor radon concentration in the mine working area were below the U.S. EPA recommended action level of 148 Bq/m^3 [17], whereas 7 sites (about 11% of the examined sites) exceeded the encourage action starting at 74 Bq/m^3. The World Health Organization (WHO) recommended a reference level of 300 Bq/m^3 [18] should not exceeded for indoor radon, otherwise mitigation programs, basically, aeration codes have to be planned. All values of the present data comply with this reference level. Othman et al. [19] reported higher values for indoor radon in open phosphate mining area in Syria ranging from 100-720 Bq/m^3, with an average value of about 200 Bq/m^3. Other workers reported much higher values (4187±650 and 5772±550 Bq/m^3) for radon concentration in the atmosphere inside tunnels of underground phosphate mines due to inconvenient ventilation [20], [21].

TABLE I
RADON CONCENTRATION IN THE ATMOSPHERE OF THE WORKING AREA OF AL-JALAMID MINES

Site	Measured Rn	No. of sites	Concentration, Bq/m^3 (average and range)
1. Upgrading Facility of low grade ore			
Offices	Indoor	10	50.9±9.9 (29.9-83.9)
Technician rooms	Indoor	10	42.5±7.2 (19.3-79.1)
Crushing area	Outdoor	6	9.7±1.6 (< 5.8-13.3)
Concentrate piles area	Outdoor	6	10.8±1.2 (< 5.8-13.4)
2. Upgrading the high grade ore			
sizing zone	Outdoor	5	9.1±1.7 (< 5.8-13.6)
Concentrate piles zone	Outdoor	4	9.4±1.9 (< 5.8-13.3)
3. Open mines area	Outdoor	6	12.3± 1.5 (7.1-15.4)
4. Residence homes	Indoor	14	46.6±8.1 (28.5-78.6)

The outdoor radon concentration in the working areas was lower, ranging from < 5.8 to 15.4 Bq/m^3, with an average value of 10.3 Bq/m^3. This average outdoor radon concentration value was almost normal and in consistent with the global average value of 10 Bq/m^3 [5]. The indoor radon concentration usually found to be greater than that of the outdoor due to the accumulation of radon gas in closed places and the outdoor air dilution by the wind action. The average indoor radon concentration was almost 4.7 times greater than the average outdoor concentration. This ratio may range from 1.5 to 5.0, depending on the radon emanation rate and the effect of wind action [22]-[24].

B. The Annual Effective Dose and Potential Risk

The obtained average indoor and outdoor radon concentrations were used to calculate the average annual effective dose to the mine-workers due to radon inhalation. The results are given in Table II. In addition, the probability of lung cancer mortality that could be attributed to lifetime exposure to radon in the mining area was estimated and included in the table. It is worthy to mention that the later estimate, generally, has a large number of unavoidable uncertainties due to uncertainties in the other estimates as the used averages in occupancy factors, equilibrium factor of radon/radon daughters and radon concentration.

TABLE II
ANNUAL EFFECTIVE DOSE AND POTENTIAL RISK ESTIMATES BASED ON INHALATION OF THE AVERAGE RADON CONCENTRATION IN THE ATMOSPHERE OF THE MINING AREA

Inhaled Rn	Average Rn concentration, Bq/m^3	Effective dose, mSv/y	Lifetime excess risk
Indoor	48.4	1.220	50.34x10^{-4}
Outdoor	10.3	0.097	2.68x10^{-4}
Total		1.317	53.02x10^{-4}

The results in Table II showed that the estimated annual effective doses due to indoor and outdoor radon inhalation were estimated by 1.220 and 0.097 mSv, respectively. The total average annual effective dose due to radon only, was estimated by 1.32 mSv However, the contribution of phosphate deposits to the annual dose due to radon inhalation only represents about 55% of the average global annual effective dose of 2.4 mSv. Because the major part (about 95%) of the dose was due to exposure to indoor radon in the study area, enhancement in aeration conditions is recommended to reduce indoor radon exposure.

The risk of lung cancer mortality for the mine-workers, posed by lifetime exposure based on inhalation of the average indoor and outdoor radon concentration was estimated by 50.34x10^{-4} and 2.68x10^{-4}, respectively, with a total risk of 53.02x10^{-4} (Table II). The later value means that per 189 individuals working and residing permanently in the field, a lung cancer case due to exposure to radon may occur along their lifetime.

IV. CONCLUSIONS AND RECOMMENDATIONS

Based on the obtained results, the following conclusions could be presented:

- The average ^{222}Rn concentration in the dwellings of the workers and office rooms of the buildings of the upgrading facility was almost 20% greater than the global average concentration.
- A slight increase (about 20%) in the average indoor radon concentrations, compared to the global average, due to the indoor air change and/or quenching effect of the surface waste layer overlain the upper phosphate deposit layer to radon emanation.
- The average outdoor radon concentration was in consistence with the global average due to the impact of air dilution by wind action in a remote area of vast plain desert.
- Although the results do not show much significant radiological risk for the mine workers due to radon inhalation, a slight remediation action based on more

enhancement of the ventilation condition in the closed places is recommended.

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