Author's Accepted Manuscript

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PII: S0969-8043(11)00550-1
DOI: doi:10.1016/j.apradiso.2011.11.015
Reference: ARI5569

To appear in: *Applied Radiation and Isotopes*

Received date: 26 June 2011
Accepted date: 4 November 2011

Cite this article as: Huda Al-Sulaiti, Tabassum Nasir, K.S. Al Mugren, N. Alkhomashi, N. Al-Dahan, M. Al-Dosari, D.A. Bradley, S. Bukhari, M. Matthews, P.H. Regan, T. Santawamaitre, D. Malain and A. Habib, Determination of the Natural Radioactivity Levels in North West of Dukhan, Qatar Using High-Resolution Gamma-ray Spectrometry, *Applied Radiation and Isotopes*, doi:10.1016/j.apradiso.2011.11.015

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4 Determination of the Natural Radioactivity Levels in North West 6 of Dukhan, Qatar Using High-Resolution Gamma-ray 8 Spectrometry

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18 ABSTRACT

This study is aimed at the determination of the activity concentrations of naturally occurring and technologically enhanced levels of radiation in 34 representative soil samples that been collected from an inshore oil field area which was found to have, in a previous study, the highest observed value of ^{226}Ra concentration among 129 soil samples. The activity concentrations of ^{238}U and ^{226}Ra have been inferred from gamma-ray transitions associated with their decay progenies, measured using a hyper-pure germanium detector. Details of the sample preparation and the gamma-ray spectroscopic analysis techniques are presented, together with the values of the activity concentrations associated with the naturally occurring radionuclide chains for all the samples collected from NW Dukhan. Discrete-line, gamma-ray energy transitions from spectral lines ranging in energy from ~100 keV up to 2.6 MeV have been associated with characteristic decays of the various decay products within the $^{235,8}\text{U}$ and ^{232}Th radioactive decay chains. These data have been analyzed, under the assumption of secular equilibrium for the U and Th decay chains. Details of the sample preparation and the gamma-ray spectroscopic analysis techniques are presented. The weighted mean value of the activity concentrations of ^{226}Ra in one of the samples was found to be around a factor of 2 higher than the values obtained in the previous study and approximately a factor of 10 higher than the accepted worldwide average value of 35 Bq/kg. The weighted mean values of the activity concentrations of ^{232}Th and ^{40}K were also deduced and found to be within the worldwide average values of 30 and 400 Bq/kg respectively. Our previous study reported a value of $201.9 \pm 1.5_{\text{Stat.}} \pm 13_{\text{Syst.}}$ Bq/kg for ^{226}Ra in one sample and further investigation in the current work determined a measured value for ^{226}Ra of $342.00 \pm 1.9_{\text{Stat.}} \pm 25_{\text{Syst.}}$ Bq/kg in a sample taken from the same locality. This is significantly higher than all the other investigated soil samples in the current and previous work. Notably, the Th levels in the same sample are within the worldwide average expectations, implying that the increased ^{226}Ra concentration arises from TENORM processes.

Keywords

Soil radioactivity, HPGe detector, Gamma spectrometry, Activity concentrations, NORM, ^{238}U , ^{226}Ra .

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1. Introduction

Oil and gas production and processing operations sometimes accumulate naturally occurring radioactive materials (NORM) at elevated concentrations in by-product waste streams. The primary radionuclides associated with clear gamma-ray decay signatures of concern in NORM wastes are ^{226}Ra (from the ^{238}U decay series) and its decay progeny ^{214}Pb and ^{214}Bi [1]. The current study was conducted in NW

Dukhan in the State of Qatar, an area known for its oil fields, with the original aim of investigating the correlation between the underlying geological background and any measured elevation in the activity concentration of ^{226}Ra . An anomalously high value for ^{226}Ra activity had been observed for a number of measured samples from this region in our earlier work, in this particular area [2] and in particular.

2. Experimental Arrangements

2.1 Soil Sampling and Preparation

The regular distance between sampling points was chosen to be 1 km. Thus soil samples were collected from sampling points located at regular intervals of a 1 per 1 km² square grid, using the Qatar National Grid (QNG) system. The total number of the representative sampling points which were required to cover this particular area (NW Dukhan) corresponded to 34 individual soil samples. Approximately 1.5 – 2 kg of soil was collected at 5 to 15 cm depth levels at each sample point. Each sample was then transferred to a 2 mm sieve fitted in a collecting pan. The post-sieved samples were then filled into labelled polyethylene bags, sealed, packed in a box and shipped to the UK for analysis. The final sample preparation and all the gamma-ray measurements to determine the sample radioactivities were performed in the low-background radiation detection laboratories of the Centre for Nuclear and Radiation Physics, situated within the Department of Physics at the University of Surrey.

Prior to final measurement in the laboratories in Guildford, all of the samples were placed in a drying oven. The drying temperature was set to 60°C for 24 hours to ensure that any significant moisture was removed from the samples. A 500 µm mesh was then used to sieve the samples which were then weighed and transferred to 500 ml labeled Marinelli beakers. The samples were then stored and kept sealed for about one month in order to reach radioactive secular equilibrium (> 7 half-lives of ^{222}Rn and ^{220}Rn).

2.2 Detector Calibration

The soil samples in the current study were analysed using a high-resolution, low-background gamma-ray spectrometry system based on a coaxial hyper-pure germanium detector (HPGe). A crystal of 50 mm diameter was operated under a high voltage, bias of +3000 V (DC). The unwanted ambient radioactivity from room background sources was reduced by surrounding the detector with a cylindrical passive lead shield of about 10 cm thickness. The Pb shield incorporated an internal copper layer on the inner surface of the shield which significantly reduced the effects from photo-fluorescence of the Pb (i.e. absorbed the Pb K_{α} and K_{β} X-rays) from gamma rays emitted from the source material.

The gamma-ray spectra which were analysed were created through converting the event energy into a pulse height spectrum. The signal processing was done by connecting the detector to a preamplifier and a standard spectroscopy shaping amplifier (Canberra 2022). The selected shaping time was 4 µs. The applied coarse gain and fine gain were 10 and 0.5 respectively. Finally, the resultant spectral data was taken directly to the PC to be introduced using Canberra Genie software [3].

The performance of the HPGe detector used in the current work was characterized by the energy calibration and its absolute full energy peak detection efficiency. The initial energy calibration of the detector was carried out using full-energy peaks from a standard source (^{152}Eu) with an activity of 3.02 kBq. The spectrum was acquired for 1200 seconds. The range of energies included 121.78 keV, 344.27 keV, 778.90 keV, 1112.05 keV and 1407.92 keV were selected to calibrate the initial energy scale of the program. In order to avoid any drift in the later soil samples measurements, the system was recalibrated on a weekly basis during the sample measurements [4].

The absolute efficiency calibration of the detector were carried out using full energy peaks from four standard sources of ^{226}Ra , ^{232}Th , ^{152}Eu and NG3 (a mixed source containing ^{241}Am , ^{57}Co , ^{60}Co , ^{85}Sr , ^{88}Y , ^{109}Cd , ^{137}Cs , ^{139}Ce , and ^{203}Hg). The sources were placed surrounding the germanium detector with the radionuclides dispersed in gel matrices within marinelli beakers of geometries identical to that of the evaluated samples. The source activities of ^{226}Ra , ^{232}Th and ^{152}Eu were 3.10, 1.08, 3.02 kBq respectively for active volumes of 550 ml each and were spread homogeneously in gel matrices of densities 1.1, 1.1, and 1.6 g/cm³ respectively. These were taken to be representative of the density of the samples measured and therefore, corrections for gamma-ray self-attenuation within the samples were accounted for in the initial efficiency measurements using these marinelli-housed sources. The efficiency calibration spectra were acquired for 86,400 seconds (= 1 day) each. A range of discrete gamma-ray energies from 0.059 MeV (from the decay of ^{241}Am) up to 2.614 MeV (from the decay of

²⁰⁸Tl) were covered using these standard sources. A marinelli beaker with the same geometry, filled with de-ionized water, was used on a weekly basis during the measurements period to determine the background spectrum observed by the germanium detector. The counting time of the ambient background spectrum was also 86,400s and was used to determine the minimum detectable activity (MDA) in the system.

62.3 Samples Analysis

The samples were placed directly over the front face of the detector. The acquisition time for each sample was 1 day. The counting geometry of the samples and the standard sources used for efficiency calibration were kept constant. A range of different gamma-ray energy transition lines ranging from 10<100 keV up to 2.614 MeV, associated with the decay products of the ^{235,8}U and ²³²Th decay chains were analyzed independently to obtain more statistically significant overall results. These data were analyzed under the assumption of secular equilibrium of the radionuclides within these samples. Several transitions from decays of shorter-lived radionuclides in the ²³⁸U decay chain, such as ²²⁶Ra, ²¹⁴Pb and ²¹⁴Bi (which can be thought of as ²²⁶Ra indicators), were used to estimate the weighted mean of the activity concentration of ²²⁶Ra. The activity concentration of ²³²Th was determined using gamma-ray transitions associated with the decays of ²²⁸Ac, ²¹²Pb and ²⁰⁸Tl. The gamma-ray peaks associated with decays from ⁴⁰K and ¹³⁷Cs at 1461 and 662 keV respectively, were used to determine the activity concentrations for these nuclei. Background contributions were subtracted from the peak areas for the measured samples.

The activity concentration of ²²⁶Ra present in the samples was estimated using two methods. The first method was to deduce the activity concentration of ²²⁶Ra indirectly from one of the reference peaks in radium indicators. The contribution of ²²⁶Ra through its (3.59 % branching ratio) gamma ray at the energy of 186.1 keV was calculated by employing the spectral interference correction method [5] using the least spectrally disturbed peak (reference peak) at 295.2 keV from the decay of ²¹⁴Pb. The net peak area of ²²⁶Ra at the line 186.1 keV was then estimated by employing the following equation [6] taking into consideration gamma-ray intensities I_γ and peak detection efficiencies ϵ_p of the reference peak:

$$N_p[186.1\text{keV}, ^{226}\text{Ra}] = \frac{[I_\gamma \epsilon_p F_{\text{COI}} F_s]_{186.1\text{keV}}}{[I_\gamma \epsilon_p F_{\text{COI}} F_s]_{295.2\text{keV, Ref}}} \times N_p[295.2\text{keV}, ^{214}\text{Pb}]_{\text{Ref}} \quad (1)$$

where N_p is the net counts, I_γ is gamma-ray emission probability, ϵ_p is the full-energy peak efficiency. F_{COI} and F_s are the correction factors of the true coincidence summing peak and self-absorption. The effect of the true coincidence summing peak and self-absorption were considered to be negligible in the current work. The activity concentration of the "indirectly" deduced ²²⁶Ra using this method will be expressed by the label ²²⁶Ra_(pb-214). This method may lead to underestimated values for ²²⁶Ra if secular equilibrium was not achieved at the time of measurement. It might also include a significant contribution from the decay of the gaseous parent ²²²Rn, which is present in the air surrounding the detector in the lead castle if the gas is not flushed with nitrogen gas [5]. The deduced values may not reflect the real values of ²²⁶Ra if the equilibrium in the Th and U decay series was disturbed during geological times.

In order to obtain additional information on the possible disturbance in radioactive equilibrium in the investigated areas, two measurements were conducted; firstly, the direct measurement of ²²⁶Ra from its single line 186.2 keV was applied in the current work, taking into account that this line has a potential contaminant from the direct decay of ²³⁵U to ²³¹Th in NORM at 185.7 keV (with a contribution of 34 % to the measured sum peak assuming natural abundances for ²³⁵U and secular equilibrium between the ²³⁸U parent and the decaying ²²⁶Ra) [5]. This method can however lead to large systematic uncertainties if the correction for the spectral interference was not taken into account, because this line is heavily interfered with the most intense line from the ²³⁵U decay series. It should therefore be corrected in the relative gamma intensity, according the uranium isotopic ratios in the investigated samples. The deduced ²²⁶Ra activity using this second method was given the label ²²⁶Ra_(u-235) in the current work. The second measurement can be used to indicate if there has been disequilibrium in the U decay series during geological times. This uses an indirect measurement of the activity concentration of ²³⁸U which is derived by assuming a natural uranium abundance ratio between the ²³⁵U and ²³⁸U isotopes (of 0.7 and 99.3% respectively) and by the direct measurement of the activity concentration of ²³⁵U from the decay transitions at the lines 143.76 and 163.36 keV associated with transitions in the decay scheme for

²³¹Th. An alternative value can be obtained assuming secular equilibrium, from measurements of the intensity of the decay progeny ²²³Ra via its 154.21 keV signature gamma ray. Both measurements were deduced by employing equation (2) and assuming natural abundance of uranium:

$$N = \frac{A \times T_{1/2}}{\ln 2} \quad (2)$$

where A is the activity, $T_{1/2}$ is the half-life of the specific radionuclide and N is the number of nuclei.

2.4 Measurements of Activity Concentration

The activity concentration of the radionuclides found in the soil samples were determined using Equation (3), and expressed in Bq/kg:

$$Ac = C_{net} / \gamma \times \varepsilon(E_\gamma) \times m \quad (3)$$

where C_{net} are the net peak counts, γ is absolute gamma decay intensity for the specific energy photopeak, $\varepsilon(E_\gamma)$ is the absolute photopeak efficiency of the germanium detector at this energy and m is the mass of the sample in kg.

The outdoor air-absorbed dose rates due to terrestrial gamma rays at 1m above the ground level are calculated from ²²⁶Ra, ²³²Th and ⁴⁰K concentration values in soil assuming that the other radionuclides, such as ¹³⁷Cs, ⁹⁰Sr and the ²³⁵U decay series can be ignored as their contributions are expected to be negligible to the total dose from environmental background [7] and [8, 9]. The gamma dose rate (D) in the outdoor air at 1 m above the ground level can be calculated by Eq. (4):

$$D = \sum A_x \times C_x \quad (4)$$

where A_x (Bq/kg) is the mean activity of ²²⁶Ra, ²³²Th or ⁴⁰K, and C_x (in units of nGy h⁻¹/ Bq.kg⁻¹) is the corresponding dose conversion factor. In the current work, the considered dose rate conversion factors for the ²³⁸U and ²³²Th series and for ⁴⁰K, used in all dose rate calculations are those determined by Saito et al. (1990) [8]. These have been used previously for related calculations in the UNSCEAR (1993) report [9]. The dose conversion factors used in the calculation for ²²⁶Ra, ²³²Th and ⁴⁰K were 0.461, 0.623 and 0.0414, respectively [9]. These factors were originally derived from Monte Carlo calculation using mathematical phantoms [10]. In the above conversion factors, it is assumed that all the decay products of ²²⁶Ra and ²³²Th are in radioactive equilibrium [9]. The published maximal admissible (permissible) dose rate is 51 nGy/h [10].

Radium equivalent activity (Ra_{eq}) is used to assess the hazards associated with materials that contain ²²⁶Ra, ²³²Th and ⁴⁰K in Bq/kg [11], which is, calculated on the assumption that 370 Bq/kg ²²⁶Ra or 260 Bq/kg ²³²Th or 4810 Bq/kg ⁴⁰K produce the same γ dose rate [12], [13] and [14]. The Ra_{eq} of the sample in (Bq/kg) can be achieved using the following equation [12]:

$$Ra_{eq} = (A_K \times 0.077) + (A_U) + (A_{Th} \times 1.43) \quad (5)$$

The published maximal admissible (permissible) Ra_{eq} is 370 Bq/kg [11].

The external hazard index is an evaluation of the hazard of the natural gamma radiation [15]. The prime objective of this index is to limit the radiation dose to the permissible dose equivalent limit of 1mSv.y⁻¹ [16] and [17]. In order to evaluate this index, a model proposed by Beretka and Mathew in 1985 [13], [14] and [18] was used in the current study which is illustrated in the following equation:

$$H_{ex} = (A_u/370) + (A_{Th}/259) + (A_K/4810) \leq 1 \quad (6)$$

The criterion of this model considers that the external hazard due to gamma-rays corresponds to a maximum radium-equivalent activity of 370 Bq/kg for the material [12, 18]. The external hazard index should be below the unity [17].

In order to estimate the annual effective dose rate in air the conversion coefficient from absorbed dose in air to effective dose received by an adult has to be taken into consideration. This value is published in UNSCEAR 2000, and UNSCEAR 1993, to be 0.7 SvGy⁻¹ for environmental exposure to gamma rays of moderate energy [11, 19]. The outdoor occupancy factor is about 0.2 [11]. The annual effective dose equivalent is given by the following equation [20]:

$$AEDE(\mu Sv/y) = D(nGy/h \times 8760(h/y) \times 0.2 \times 0.7(Sv/Gy) \times 10^{-3} \quad (7)$$

The world average annual effective dose equivalent (AEDE) from outdoor terrestrial gamma radiation is 460 $\mu Sv/year$ [11].

43. Results and Discussion

This area has previously reported a value of $201.9 \pm 1.5_{Stat.} \pm 13_{Syst.}$ Bq/kg (sample no. X228) for the 6weighted mean activity concentration of ^{226}Ra , ^{214}Pb and ^{214}Bi [2]. Another elevated soil sample (no. 29-X228) was found in this area with values of $208.8 \pm 5.6_{Stat.} \pm 15_{Syst.}$ and $327.4 \pm 8.8_{Stat.} \pm 2_{Syst.}$ Bq/kg for $^{226}Ra_{(U-235)}$ and $^{226}Ra_{(Pb-214)}$ respectively. The weighted mean of the activity concentration of ^{226}Ra , ^{214}Pb and ^{214}Bi was approximately a factor of two higher than the highest value reported previously in sample 10no. X228. Two more soil samples (23-X228 and 27-X228) were found to exhibit values just above the world wide average value of 35 Bq/kg [11]. Only a single sample (27-X228), among the elevated 12samples, showed clear gamma-ray spectral lines associated with the decay of ^{235}U at 163.36 keV. From these data, and using the assumed natural $^{235}U/^{238}U$ abundance ratio as discussed previously, the activity 14concentration of ^{238}U was deduced to be $32 \pm 18_{Stat.} \pm 2_{Syst.}$ Bq/kg. The $^{226}Ra_{(U-235)}$ and $^{226}Ra_{(Pb-214)}$ deduced values for the activity concentration were $39.5 \pm 2.2_{Stat.} \pm 2.9_{Syst.}$ and $48.5 \pm 2.8_{Stat.} \pm 3.5_{Syst.}$ Bq/kg 16respectively. Since the deduced activity concentration of ^{238}U in this sample is close to $^{226}Ra_{(U-235)}$ value, it is suggested that any apparent elevation in ^{226}Ra activity concentration may come from the parent 18 ^{238}U . The activity concentrations of $^{226}Ra_{(U-235)}$ and $^{226}Ra_{(Pb-214)}$ along with the values obtained using the gamma-ray transitions associated with decays of (a) ^{214}Pb , and ^{214}Bi from the ^{238}U series, (b) ^{228}Ac , 20 ^{212}Pb and ^{208}Tl from the ^{232}Th series, (c) ^{40}K and (d) ^{137}Cs in sample no. 29-X228 are presented in Figure 1.

22

Figure 1: The individual activity concentrations of the observed gamma-ray transitions from $^{226}Ra_{(U-235)}$, $^{226}Ra_{(Pb-214)}$, ^{214}Pb , and ^{214}Bi from the ^{238}U series, ^{228}Ac , ^{212}Pb and ^{208}Tl decay lines associated with the ^{232}Th series, ^{40}K and ^{137}Cs in sample no. 29-X228. The weighted means of these individual data points are the dashed lines.

The activity concentrations of ^{238}U (estimated from the measured ^{235}U activity and assuming the natural abundance ratio), ^{226}Ra , ^{232}Th and ^{40}K for all the samples in the investigated area are plotted in Figure 2. 28The mean value of ^{238}U , ^{226}Ra , ^{232}Th and ^{40}K of these individual data points are the dashed lines. This figure shows that the obtained values for ^{238}U are comparable with the results measured directly from 30the gamma transition lines of ^{226}Ra and its decay products with the exception of sample no. 29-X228 (the sample with the highest measured ^{226}Ra specific activity) which did not contain any visible lines 32associated with the decay of ^{235}U .

34Figure 2: Comparison of the measured activity concentration distributions for ^{238}U and ^{226}Ra , for the area of elevated activity, in NW Dukhan. The mean values of these individual data points are the dashed lines. The sample no in the plot refers to the 36first two numbers of the sample number.

Figure 3 shows the distribution of the activity concentrations of ^{226}Ra , ^{228}Ac and ^{40}K . It is clear that the 38 ^{226}Ra distribution extends with a tails toward higher concentrations for samples no. 27-X228, 23-X228 and 29-X228 while the values for ^{232}Th and ^{40}K showed more typical distributions.

40

Figure 3: Distributions of activity concentration of ^{226}Ra , ^{228}Ac and ^{40}K .

42Figure 4 shows the ratio of ^{232}Th to ^{238}U (assuming equilibrium with ^{228}Ac and ^{226}Ra respectively) in the soil samples that were collected from NW Dukhan. The slope of the trend line in this plot was used to 44find out the activity ratio of ^{232}Th to ^{238}U , which was about 0.34. This group of 31 samples have different soil profiles and hence may have different chemical behaviours because they belong to 46different geological formations [21] (see Figure 5). Nevertheless, their activity ratios were similar, which indicates that they had similar geochemical behaviour regardless of their geological background. 48On the other hand, the other three odd samples had different ratios although they were collected from the same area. This variation supports a hypothesis that the elevation of ^{226}Ra in these three samples is 50due to ^{226}Ra in the oil-field rocks which replaced Ca, Sr and/or Ba in the formation water, released with the production waste of an oil field in this area, disposed of to the ground and finally contaminated the 52soil where these samples were collected.

2

Figure 4: The weighted mean of activity concentration for ^{232}Th versus the weighted mean of activity concentration for ^{238}U for 4soil samples collected from NW Dukhan.

The activity concentration of ^{226}Ra in sample 29-X228 which had the highest observed value of ^{226}Ra among the 34 investigated samples in this area is significantly higher than the value determined previously for X228 in this area and clearly does not support a hypothesis of elevated ^{238}U co-precipitated with phosphates due to vertebrate remains in this area. Notably, this area contains an old inshore oil well. Therefore, it is likely that the high values obtained for samples X228 and 29-X228 are a result of technically enhanced NORM (TENORM) in this region. We note that it is possible that such elevated levels in the TENORM might arise due to the mobility of ^{226}Ra in the oil-field rocks.

The activity concentration of ^{226}Ra is likely to be a heterogeneous distribution since there is a weak correlation between the levels of activity concentrations of ^{226}Ra and the type of soil in this area (see Figure 5) which consists of two types of geology background (dammam formation, middle Eocene and rus formation, lower Eocene). The activity concentration of ^{226}Ra in samples no. 24-X228 and 28-X228 which were collected from the same type of soil (see Figure 5) had normal levels of ^{226}Ra compared with the other two highly elevated samples (X228 and 29-X228). Our highest values of ^{226}Ra which were observed for samples collected from NW Dukhan, are from rus formations, which consist of dolomite and limestone and not from sabkha deposits of Dukhan area which consists of sand and silt flats (celestite crystals) as stated by I.A. El-Kassas [22]. Indeed, the obtained levels of ^{226}Ra for Dukhan's sabkha were found to be in the normal world average range. The elevation of ^{226}Ra in sample numbers X228 and 29-X228 ($201.9 \pm 1.5_{\text{Stat.}} \pm 12.9_{\text{Syst.}}$ and $342 \pm 2_{\text{Stat.}} \pm 25_{\text{Syst.}}$ Bq/kg respectively) may be due to the mobility of ^{226}Ra in the oil-field rocks.

24

Figure 5: The geology profiles in NW Dukhan on the left [23]. The sampling point in this area showing the ^{226}Ra elevated samples.

The activity levels of ^{238}U with the high standard deviation that been estimated from the activity concentration of ^{235}U and especially in the concerned area support the hypothesis that this elevation in this area is from the daughter ^{226}Ra and not from ^{238}U since there is disequilibrium in $^{226}\text{Ra}/^{238}\text{U}$ ratio with high concentration of ^{226}Ra in the area where samples X228 and 29-X228 were collected.

4. Conclusions

It is likely that the elevated values of ^{226}Ra observed from sample no. X228 and 29-X228 are a result of technically enhanced NORM (TENORM) in this region. The activity concentration of ^{226}Ra was likely to be in a heterogeneous distribution, since there was a weak correlation between the levels of activity concentration of ^{226}Ra and the type of soil in this area. The activity concentration of ^{226}Ra in sample numbers 24-X228 and 28-X228, which were collected from the same type of soil and close to the elevated samples, had normal levels of ^{226}Ra compared with the other two highly elevated samples (X228 and 29-X228). The activity levels of ^{238}U that been estimated from the activity concentration of ^{235}U support the hypothesis that this elevation in this area is from an enhanced (daughter) ^{226}Ra activity and not from ^{238}U directly, since there is notable disequilibrium in $^{226}\text{Ra}/^{238}\text{U}$ ratio with high concentration of ^{226}Ra in the area where samples X228 and 29-X228 were collected.

The mean value of the activity concentration of ^{226}Ra was 29.5 ± 9.7 Bq/kg, within the 'normal level' of radiation and is below the world wide averaged value. The mean value of gamma dose rate, D, was found to be 24.2 ± 4.3 nGy/h. This value is in the normal expected region and well below the published maximal admissible (permissible) dose rate of 51 nGy/h [10]. Sample numbers X228 and 29-X228 were both found to be higher than the permissible value with values of $92.8 \pm 6.7_{\text{Stat.}} \pm 10.2_{\text{Syst.}}$ and $160.3 \pm 11.5_{\text{Stat.}} \pm 18.1_{\text{Syst.}}$ nGy/h respectively. The mean value of radium equivalent activities (Ra_{eq}) of gamma dose rate was determined to be 50.4 ± 9.9 Bq/kg. These values are also considered to be normal.

The highest activity samples, which were collected from NW Dukhan (samples no. X228 and 29-X228) were both found to have values less than the permissible value of Ra_{eq} of 370 Bq/kg [11] (which corresponds to an annual effective dose of 1 mSv). They had measured values of $213.9 \pm 15.5_{\text{Stat.}} \pm 23.6_{\text{Syst.}}$ and $367.5 \pm 26.4_{\text{Stat.}} \pm 41.5_{\text{Syst.}}$ Bq/kg respectively. The mean value of the external hazard index (H_{ex}) for the samples taken from the region of NW Dukhan were found to be in the normal

range and below unity [17]. The mean values of the annual effective dose equivalent (AEDE) due to terrestrial gamma radiation outdoors obtained was found to be less than the average external annual effective dose of 460 $\mu\text{Sv/year}$ from natural outdoor radiation sources of terrestrial origin [11].

4 Acknowledgments

This work is funded by the Ministry of Environment, Doha-Qatar. Huda AL-Sulaiti would like to acknowledge the minister of environment, H.E. Abdulla bin Mubarak Al Moadhadi for his support. T. Nasir acknowledges the financial support from the Higher Education Commission Islamabad, Pakistan through "HEC Post Doctoral Fellowship Program Phase-II (Batch-IV-2009)". TS and DM acknowledge financial support from the Royal Thai Government.

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2

Fig. 1

4

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4 Fig. 2

2 Fig. 3

fig. 4

Research Highlights:

- 2 • Aims to determine the A_c of NORM levels in 34 soil samples collected from an inshore oil field area.
- 4 • In a previous study, this area found to have the highest value of ^{226}Ra levels among 129 samples.
- 6 • The A_c of ^{238}U and ^{226}Ra have been measured using a HPGe detector.
- 8 • ^{226}Ra level was around a factor of 2 higher than the previous one and 10 higher than the world average.
- 10 • The highest value reported in our study for ^{226}Ra was about $342.00 \pm 1.9_{\text{Stat.}} \pm 25_{\text{Syst.}}$ Bq/kg.