Artificial and Natural Radioactivity Measurements and Radiation Dose Assessment in the Vicinity of Ghana Nuclear Research Reactor-1 (GHARR-1).

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Abstract

Radioactivity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in soil samples and water sources around the Ghana Research Reactor-1 (GHARR-1) and the immediate surroundings have been measured using gamma spectrometry. The primary aim of the study was to establish baseline radioactivity levels in the environs of GHARR-1. The average activity concentration of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs were 22.3 ± 1.12 Bq kg^{-1}, 49.8 ± 1.60 Bq kg^{-1}, 99.60 ± 5.81 Bq kg^{-1} and 1.48 ± 0.25 Bq kg^{-1} for soil and 0.60 ± 0.11 Bq l^{-1}, 2.13 ± 0.21 Bq l^{-1}, 10.75 ± 0.84 Bq l^{-1} and 0.47 ± 0.05 Bq l^{-1} for the water, respectively. The ^{226}Ra and ^{232}Th concentrations compare quite well with world averages, whilst the ^{40}K concentration was lower than the world average. The levels of ^{137}Cs observed in the samples are within the range of 'background' concentrations. The estimated average annual effective doses from external exposure to soil and ingestion of water samples were calculated to be 0.06 mSv and 0.53 mSv, respectively. The estimated outdoor external gamma dose rate measured in air ranged from 20-430 nGy h^{-1} with an average value of 100 nGy h^{-1}, which is higher than the world average value of 59 nGy h^{-1}. In the case of water samples, the average value was higher than the guidance level of 0.1 mSv y^{-1}, as recommended by the European Union and the World Health Organization.

Introduction

The International Basic Safety Standards (BSS) [IAEA, 1996] specify the basic requirements for the protection of health and the environment from ionizing radiation. These are based on the latest recommendations of the International Commission on Radiological Protection, (ICRP) [ICRP, 1990] on the regulation of Practices and Interventions. The BSS is applied to both natural and artificial sources of radiation in the environment and the consequences on human and other species. The environment is defined within the framework of national laws and international legal instruments, and may be considered to include man, biota (living), abiota (non-living), physical surroundings and their interactions [IAEA, 2002].

Radiation and radioactive materials occur naturally and are ubiquitous in the environment. Artificial or man-made sources of radiation are used extensively in industry and medicine with substantial benefits for the economy and health care. These diverse sources, including radionuclides, originating from the generation of nuclear energy, result in the exposure of people, both in workplaces and in the general environment, through various means. By far, the largest contribution to the exposure of the population is from natural sources while exposure from artificial sources is largely due to the use of radiation and radioactive materials in medicine. Other sources of potential exposure are of cosmic rays and terrestrial origin to which all organisms are exposed, at differing levels, according to their habitat. Natural and artificial radionuclides may enter the food chain and expose to man. They can also be concentrated during their transfer through the environment (bio-accumulation), resulting in higher exposures of some people (critical groups).

Studies on the levels of artificial and natural radionuclides have been reported in a number of published articles (Matiullah *et al*., 2004; Darko & Faanu, 2007; Darko *et al*., 2008; Merdanoglu *et al.*, 2006). This has helped in the formulation of guidelines for radiation protection of the worker, the general public and the environment. In addition, the study of the background level of ^{137}Cs in soil is important as it is the main source of inventory of radionuclides from nuclear fission into the food chain. Its presence in soil indicates that an area under study might have received some fallout radioactivity from past activities such as nuclear weapons testing (Matiullah *et al*., 2004). The concentration of ^{137}Cs in surface soil from fallout ranges from 3.7 to 37 Bq kg^{-1}, averaging less than 14 Bq kg^{-1}, and it has been reported that the 'background' ^{137}Cs in soils is estimated to be 4.81 ± 2.96 Bq kg^{-1} (Hamilton, 1997). Studies by Yeboah *et al.* (2001) concentrated on natural radioactivity in soils and rocks within the Greater Accra Region of Ghana.

The present study was aimed at determining the levels of ^{226}Ra (^{238}U), ^{40}K and artificial radionuclides such as ^{137}Cs in soil and water samples within the environs of the Ghana Research Reactor (GHARR-1). The Ghana Atomic Energy Commission (GAEC) has, in addition, a number of nuclear facilities which are used for research and training. It is, therefore, important to undertake periodic surveys to find out if there has been any negative impact on the surrounding environment, and to establish a baseline radioactivity data for comparison in the event of an emergency.

Material and methods

Description of the study area

Ghana's first Research Reactor is installed at the site of Ghana Atomic Energy Commission. The study covered GAEC and its immediate surroundings up to 10 km from the main laboratories of the Commission. The GAEC is located at the north-western part of Accra, the capital city of Ghana at longitude 5° 40' N and latitude 0° 13' W. Fig. 1 shows the location of GAEC and its surrounding communities where the study was carried out. The GAEC has a number of nuclear facilities, which are used for research and training purposes for the socio-economic development of Ghana. These include a 30 kW miniature research reactor, 50 kCi gamma irradiator, variety of radiation sources in storage at the Radioactive Waste Management Centre, sources for calibration in a Secondary Standard Dosimetry laboratory and a host of other sources used in the laboratories of GAEC. The Ghana Research Reactor-1 is also surrounded by a number of communities, including Dome, Kwabenya, Narhman, Haatso and Taifa. The

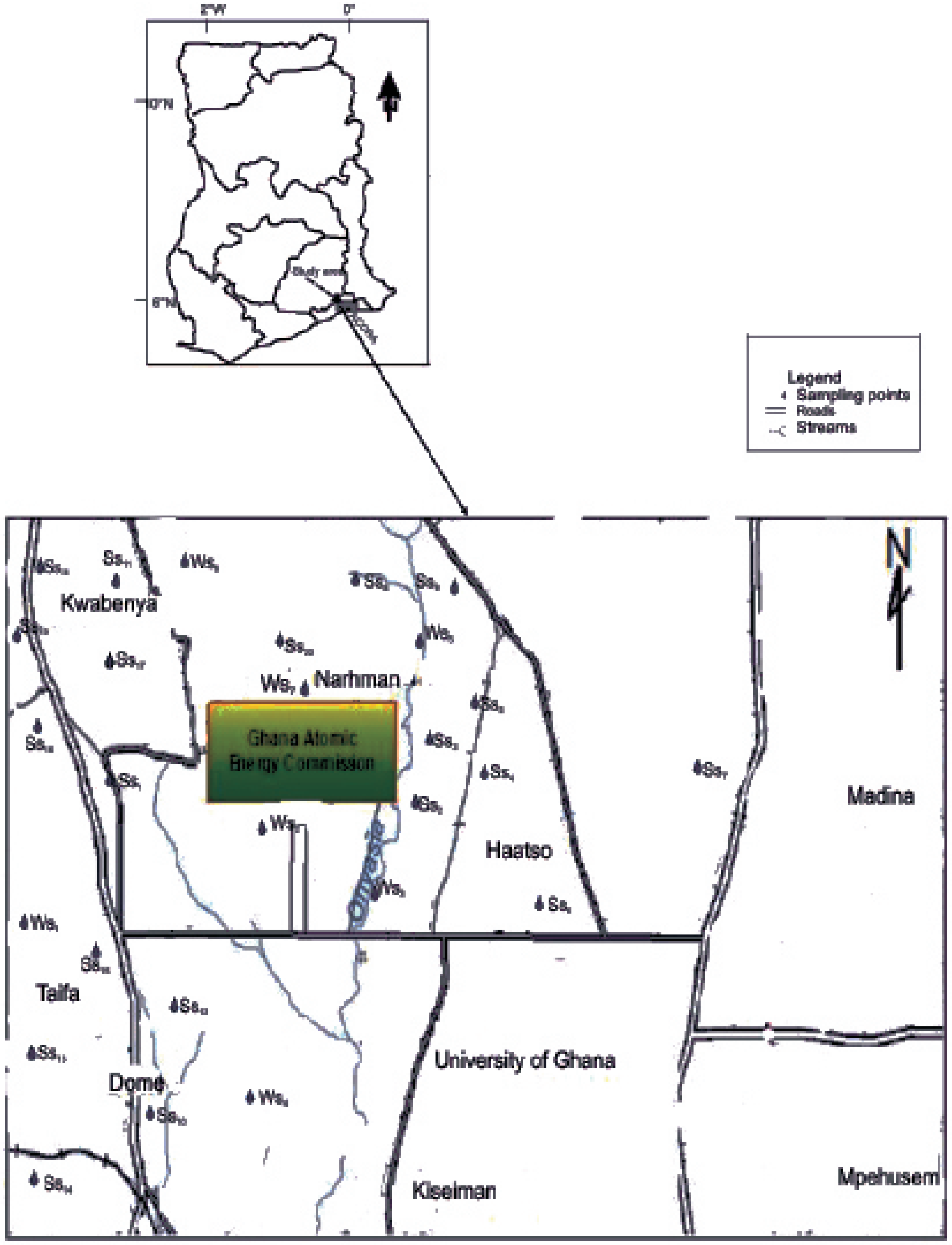

Fig. 1. Map of Ghana Atomic Energy Commission showing sampling areas in the Greater Accra Region of Ghana

main occupation of the inhabitants is farming. The sampling points for both water and soil are shown in Table 1.

TABLE 1

Sampling locations for the soil and water samples

Location code	*Description of sampling location*
SS1	Ghana Research Reactor Centre, GAEC
SS2	Chemistry Building, GAEC
SS3	Waste Management Centre, GAEC
SS4	Gamma Irradiation Facility, GAEC
SS5	Farm, GAEC
SS6	Farm, Haatso
SS7	Farm, Haatso
SS8	Farm, Narhman
SS9	Farm, Narhman
SS10	Residential Area, Dome
SS11	Residential Area, Kwabenya
SS12	Church Premises, Dome
SS13	Residential Area, Taifa
SS14	Offices, Taifa
SS15	Hotel Premises, Taifa
SS16	Car Washing Bay, Kwabenya
SS17	Metal Works Company, Kwabenya
SS18	Residential Area, Kwabenya
SS19	Block Factory, Kwabenya
SS20	Residential Area, Narhman
WS1	Tap Water, Taifa
WS2	Fish Pond, GAEC
WS3	Stream Water, Haatso
WS4	Tap Water, Dome
WS5	Well Water, Narhman
WS6	Well Water, Kwabenya
WS7	Tap Water, GAEC

SS = Soil sample; WS = water sample.

The geology of the surrounding rocks consists of the Akwapim-Togo series and the Dahomeyan systems [Amedofu *et al*., 2008]. The Akwapim-Togo series extend from the north-eastern part of Ghana and the coastline on the western part of Accra through Kpong and Anum to the Republic of Togo. The main rocks include phyllites, schists, and quartzite, and in some places unaltered shales and sandstones [Amedofu *et al.*, 2008]. The Dahomeyan system consists of four alternate belts of acid and basic gneisses stretching south-south west (SSW) to north-north east (NNE) from the coastal plains, east of the Togo series. The types of rocks here are quartz-schists, metamicrogabbos forming dykes and sills (Amedofu *et al*., 2008). The predominant rock type of the GAEC and its environs is metamorphic, which are formed as a result of changes in temperature and pressure, as well as changes in the chemistry of the fluids in their pores [Press & Siever, 1986].

Sample collection, preparation and analysis

Soil and water samples were collected within the site of the GAEC and the surrounding communities. Table 1 shows the sampling points in the study area. Soil samples were taken from farms around GAEC with a coring tool to a depth of about 5-20 cm into polyethyhene bags, labelled and transported to the laboratory for further preparation. The water samples were taken from fish ponds, streams, water hydrants, tap water and wells used for irrigation, domestic and other purposes within the study area. A total of 100 composite soil samples and 35 water samples were taken within the study area for analysis. At each location five subsamples were collected and homogenized to make a composite sample.

In the laboratory, the soil samples were air-dried for 1 week and oven-dried at a temperature of 75 °C for 4-5 h until all the moisture in the soil samples had evaporated. The dried soil samples were ground into fine powder and sieved through a 2-mm particle size into 1 litre Marinelli beakers. The Marinelli beakers with the soil samples were then sealed using a paper tape to prevent the escape of gaseous radionuclides in the sample. In all cases the samples were stored for at least 30 days for secular equilibrium to be established between the long-lived parent nuclides of ^{226}Ra (^{238}U) and ^{232}Th, and their short-lived daughters.

The method of the -ray analysis reported in published research works [Darko & Faanu, 2007; Matiullah *et al.*, 2004; Merdanoglu & Altinsoy, 2006] was adopted for this study. The gamma spectrometer used for the analysis consists of an ORTEC GEM Coaxial n-type HPGE gamma-ray detector with ORTEC Multichannel Analyzer (MCA) and MAESTRO-32 evaluation software for spectrum acquisition and processing. The detector is located inside a cylindrical lead shield of 5 cm thickness with internal diameter of 24 cm and height of 60 cm. The lead shield is lined with various layers of copper, cadmium and plexilglass each of 3 mm thick. The relative efficiency of the detector was 25% with energy resolution of 1.8 keV at gamma ray energy of 1332 keV of ^{60}Co. The gamma lines 609.31 and 1764.49 keV of ^{214}Bi were used to determine ^{226}Ra. The gamma lines 583.19 keV and 2614.53 keV of ^{208}Tl were used to determine ^{232}Th, and that of ^{40}K was determined from the gamma line of 1460.83 keV. Cesium-137 (^{137}Cs) was determined from the gamma line 662.0 keV.

Similarly, the water samples were collected into plastic bottles and acidified on site with 1*M* HCl to prevent radionuclides adhering to the sides of the container. The bottles were filled to the brim without any head space to prevent trapping of CO_2 gas. The water samples were also transported to the laboratory and prepared into 1 litre Marinelli beakers and stored prior to measurements. The samples were not filtered prior to preparation and measurements. The *p*H of the water samples were measured *in-situ* using a multi-parameter instrument, model *p*H/Cond 340i and serial number 05470077. The *p*H probe was calibrated using buffer solutions with 4.01 and 7.00. The samples were counted for 36,000 seconds (10 h). The energy and efficiency calibrations were performed using mixed radionuclide calibration standard in the form of solid water, serial number NW 146 with approximate volume 1000 ml and density 1.0 g cm^{-3} in a 1.0-l Marinelli beaker. The standard was supplied by Deutscher Kalibrierdienst (DKD-3), QSA Global GmBH, Germany. Background measurements were made for the same period. Density corrections were also made where appropriate.

Calculation of the specific activity concentrations and the doses

The specific activity concentrations (A_{sp}) of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in Bq kg^{-1} for the soil and Bq l^{-1} for the water samples, respectively, were determined using the following expression [Uosif *et al.*, 2008; Darko & Faanu, 2007; Darko *et al.*, 2008] after decay correction.

$$A_{sp} \quad \frac{N_{sam}}{P_E \cdot \ .T_c.M} \qquad (1)$$

where; N_{sam} = net counts of the radionuclide in the sample, P_E = gamma ray emission probability (gamma yield), = total counting efficiency of the detector system, T_c = sample counting time, and M = mass of sample (kg) or volume (l)

The background spectra were determined using an empty Marinelli beaker and used to correct the net peak area of gamma rays of measured isotopes. The minimum detectable activity was determined from the back-ground measurements and obtained as 0.12 $Bqkg^{-1}$, 0.11 $Bqkg^{-1}$, and 0.9 $Bqkg^{-1}$ for ^{226}Ra, ^{232}Th, and ^{40}K, respectively.

The absorbed dose rates, *D* ($nGy\,h^{-1}$), at 1 m above the ground for soil was calculated as follows (Uosif, *et al.*, 2008).

$$D(nGyh^{-1}) = 0.0417A_k + 0.462A_{Ra} + 0.604A_{Th} \qquad (2)$$

where the coefficients in equation 2 are the dose conversion factors for ^{40}K, ^{226}Ra and ^{232}Th, respectively [UNSCEAR, 2000], and A_K, A_{Ra} and A_{Th} are the specific activities for ^{40}K, ^{226}Ra and ^{232}Th, respectively.

For the soil samples, the effective dose was calculated from the absorbed dose by applying the conversion factor of 0.7 $Sv\,Gy^{-1}$ [UNSCEAR, 2000]. Thus, for dose assessment to the public, the effective doses were calculated from Equation 3 below.

Annual Effective Dose = D.T.F. (3)

where D is the calculated dose rate ($nGyh^{-1}$), *T* is the outdoor occupancy time (0.2 × 24 × 365.25 ~1753 hy^{-1}) and F is the conversion factor (0.7 $Sv\,Gy^{-1}$) for the conversion of absorbed dose in air to effective dose.

For the water samples, the annual committed equivalent dose, H_{ing} (W), was computed from the expression below.

$$H_{ing}(W) \quad \overset{3}{\underset{j\ 1}{}} \ DCF_{ing}(Ra,Th,K).A_{sp}.I \qquad (4)$$

where DCF_{ing} = Dose conversion coefficients of the radionuclides in Sv Bq^{-1} from ICRP 72 (ICRP, 1996). A_{sp} = Specific activity concentrations of radionuclides in the water samples in Bq l^{-1}. I = Radionuclide intake in litres per year, assuming 2 l average water intake per day for 365 days y^{-1} will be 730 l y^{-1}.

Uncertainty estimation

In this study, the uncertainties associated with the determination of activity concentrations of each radionuclide was estimated from the following equation.

$$A_{SP} \quad \frac{N}{\ .\ .M.\ c} \qquad (5)$$

where A_{sp} is the specific activity in Bq kg^{-1}, N is the background corrected net peak area, is the absolute detector efficiency, Y is the gamma yield, Tc is the counting time of the sample, M is the mass of the sample in kg.

Neglecting the uncertainties in the counting time and the gamma emission probability, the following expression was used to determine the overall uncertainty in the activity.

$$dA_{sp} \quad A_{sp}\{(\frac{N}{N})^2 \quad (\text{—})^2 \quad (\frac{M}{M})^2\}^{\frac{1}{2}} \qquad (6)$$

where dN is determined from the uncertainty in the integration of the peak area of each full energy event; dM is the standard uncertainty on the weighing balance used to weigh the samples and the standard uncertainty was quoted to be 0.1 mg; d is the uncertainty in the efficiency.

Estimation of the annual equivalent dose from dose rate measurements

The outdoor external gamma dose rate was measured using RDS-200 Universal Radiation Survey Meter, which had been calibrated at the Secondary Standard Dosimetry Laboratory (SSDL) at the Radiation Protection Institute of the GAEC. At each sampling point more than five measurements were taken at 1 m above the ground surface and the average value calculated in ìGy h^{-1}. The estimated annual equivalent dose, $H_{\tilde{a},ext}$, is given by the expression:

$$H_{,ext} \quad D_{,ext}.T_{\exp}.DCF_{ext} \qquad (7)$$

where $D_{\tilde{a},ext}$ = Dose rate in ìGy h^{-1} (measured by the dose rate meter), T_{exp} = duration of exposure per year (8,760 h) and with outdoor occupancy of 0.2, DCF_{ext} = the conversion coefficient (0.70 Sv Gy^{-1}) from absorbed dose in air to effective dose.

Estimation of total effective dose

The total effective dose, E_T, is calculated by summing the individual equivalent doses due to external irradiation from the soil and ingestion of water according to ICRP publication 60 [ICRP, 1991; Vennart, 1991].

$$E_T = H_{\tilde{a},\,ext}(Ra, Th, K) + H_{mg}(W) \qquad (8)$$

where $H_{\tilde{a},ext}$(Ra, Th, K) = annual external equivalent dose from external gamma radiation from the soil.

H_{mg} (W) = annual equivalent dose from ingestion of Ra, Th and K in the water samples.

Results and discussion

Tables 2 and 3 show the results of the calculated activity concentrations of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in the soil and water samples, respectively. The results of the outdoor external gamma dose rate measured in air at 1 m above the ground ranged from 20 to 430 nGy h^{-1} with an average value of 100 nGy h^{-1} as shown in Tables 4 and 5. The Tables also show the calculated gamma dose rates from the activity concentrations of the radionuclides in soil at 1 m above ground and the corresponding annual effective doses for the soil and water samples. The average dose rate obtained is about two times higher than the outdoor global level of 60 nGy h^{-1} [UNSCEAR, 2000]. The average outdoor external gamma dose rate calculated from the soil samples was 47 nGy h^{-1}, and this is two times lower than that measured directly in air from the sampling locations.

Caesium-137 (^{137}Cs) was the only artificial radionuclide that was detected in the samples. The activity concentrations of ^{137}Cs varied in a range of 0.24–4.87 Bq kg^{-1} and 0.24–1.20 Bq l^{-1} in soil and water, respectively, with the average of 1.48 ± 0.25 Bq kg^{-1} and 0.47 ± 0.05 Bq l^{-1} in soil and water, respectively. The activity concentrations of ^{137}Cs in this study are lower than the maximum acceptable concentration of 10 Bq l^{-1} in drinking water recommended by WHO [WHO, 2004]. Caesium-137 is an important fission product due to its relatively high yield, and its ability to bioconcentrate in the food chain, and high fixation by sediments in aquatic environment reduces its concentration in water bodies. The exemptions level of ^{137}Cs in any material as recommended in the BSS [IAEA, 1996] is 10 Bq g^{-1}. The activity concentrations of ^{137}Cs in all the soil samples studied are below the exemption levels.

The calculated specific activity concentrations of ^{226}Ra, ^{232}Th and ^{40}K in the soil samples were 22.3 ± 1.1 Bq kg^{-1}, 49.8 ±

TABLE 2

The average specific activities of ^{226}Ra, ^{232}Th, ^{40}K, and ^{137}Cs in the soil samples

Location code	*Specific activity (Bq kg^{-1})*			
	^{226}*Ra*	^{232}*Th*	^{40}*K*	^{137}*Cs*
SS1	31.25 ± 2.08	107.14 ± 1.58	129.86 ± 6.13	4.87 ± 0.19
SS2	53.18 ± 1.39	183.41 ± 1.72	105.09 ± 9.37	1.47 ± 0.35
SS3	52.06 ± 1.60	181.12 ± 1.32	88.04 ± 11.06	1.16 ± 0.33
SS4	72.61 ± 1.18	136.09 ± 1.87	170.64 ± 7.68	0.85 ± 0.38
SS5	44.08 ± 1.38	63.21 ± 2.14	166.26 ± 9.26	2.77 ± 0.22
SS6	26.07 ± 0.89	25.41 ± 1.68	66.74 ± 5.27	1.39 ± 0.26
SS7	3.39 ± 1.38	38.12 ± 1.76	169.65 ± 5.76	1.88 ± 0.29
SS8	22.52 ± 0.69	28.34 ± 1.16	52.75 ± 4.30	1.27 ± 0.20
SS9	17.14 ± 0.77	26.52 ± 1.27	260.76 ± 3.40	0.30 ± 0.18
SS10	13.62 ± 0.66	13.08 ± 1.67	54.43 ± 3.89	1.71 ± 0.35
SS11	17.48 ± 0.74	16.36 ± 1.20	66.57 ± 4.02	0.52 ± 0.09
SS12	7.54 ± 0.63	12.43 ± 1.02	23.44 ± 4.08	4.87 ± 0.22
SS13	20.19 ± 0.81	15.09 ± 1.80	59.05 ± 4.97	0.61 ± 0.15
SS14	9.61 ± 1.66	25.73 ± 2.01	50.21 ± 7.36	0.24 ± 0.15
SS15	12.37 ± 1.21	21.37 ± 1.68	88.89 ± 5.63	0.28 ± 0.09
SS16	8.26 ± 0.74	2.13 ± 1.38	47.09 ± 3.80	0.98 ± 0.26
SS17	10.47 ± 1.01	24.93 ± 1.66	92.19 ± 5.09	0.74 ± 0.29
SS18	12.50 ± 0.99	30.31 ± 1.45	135.66 ± 4.94	1.80 ± 0.25
SS19	6.88 ± 1.05	12.14 ± 1.99	82.39 ± 4.99	0.91 ± 0.32
SS20	14.25 ± 0.96	23.36 ± 1.57	82.27 ± 5.24	0.71 ± 0.48
Ave ± SD	22.27 ± 1.12	49.81 ± 1.60	99.60 ± 5.81	1.48 ± 0.25

TABLE 3

Average specific activities of ^{226}Ra, ^{232}Th, ^{40}K and ^{137}Cs in the water samples

Location code	*Specific activity (Bql^{-1})*			
	^{226}*Ra*	^{232}*Th*	^{40}*K*	^{137}*Cs*
WS1	20.23 ± 0.06	2.18 ± 0.23	9.77 ± 0.80	0.43 ± 0.08
WS	30.83 ± 0.18	2.12 ± 0.21	14.1 ± 1.10	0.75 ± 0.06
WS	41.81 ± 0.14	2.77 ± 0.26	14.14 ± 0.96	1.20 ± 0.14
WS	50.55 ± 0.15	3.24 ± 0.28	17.81 ± 1.18	0.23 ± 0.01
WS	60.22 ± 0.06	1.79 ± 0.15	7.32 ± 0.60	0.30 ± 0.01
WS	70.17 ± 0.02	0.19 ± 0.05	1.97 ± 0.33	0.11 ± 0.03
WS	0.49 ± 0.16	2.76 ± 0.27	10.17 ± 0.92	0.24 ± 0.05
AVE±SD	0.60 ± 0.11	2.13 ± 0.21	10.75 ± 0.84	0.47 ± 0.05

TABLE 4

The measured and calculated average absorbed dose rate and annual effective dose at 1 m above the ground at the soil sampling points

Location code	*Measured ambient dose equivalent rate (Gy h^{-1})*		*Calculated absorbed dose rate (Gy h^{-1})*	*Estimated annual effective dose (mSv y^{-1})*	
	Range	*Average*	*Calculated*	*Measured*	*Calculated*
Ss_1	0.03–0.22	0.13	0.090	0.16	0.111
SS_2	0.08–0.31	0.18	0.149	0.22	0.183
SS_3	0.11–0.43	0.27	0.147	0.33	0.180
SS_4	0.07–0.26	0.17	0.129	0.21	0.158
SS_5	0.04–0.14	0.09	0.068	0.11	0.083
SS_6	0.09–0.14	0.12	0.031	0.15	0.038
SS_7	0.03–0.15	0.15	0.034	0.18	0.042
SS_8	0.04–0.09	0.07	0.031	0.09	0.038
SS_9	0.11–0.14	0.13	0.036	0.16	0.044
SS_{10}	0.04–0.06	0.05	0.017	0.06	0.021
SS_{11}	0.06–0.10	0.08	0.021	0.10	0.026
SS_{12}	0.07–0.15	0.11	0.013	0.13	0.015
SS_{13}	0.05–0.08	0.06	0.021	0.07	0.026
SS_{14}	0.03–0.11	0.08	0.023	0.10	0.029
SS_{15}	0.04–0.12	0.08	0.023	0.10	0.029
SS_{16}	0.02–0.04	0.03	0.014	0.04	0.017
SS_{17}	0.02–0.05	0.04	0.025	0.05	0.031
SS_{18}	0.07–0.11	0.09	0.031	0.11	0.038
SS_{19}	0.04–0.08	0.07	0.015	0.09	0.018
SS_{20}	0.06–0.16	0.11	0.025	0.14	0.031
Average±SD		0.11 ± 0.04	0.047±	0.13 ± 0.05	0.06

SD-Standard deviation

TABLE 5

The measured and calculated average absorbed dose rate and annual effective doses at 1 m above the ground at the water sampling points

Location code	p*H*	*Measured ambient dose equivalent rate (μGyh^{-1})*		*Estimated annual effective dose (mSv y^{-1})*	
		Range	*Average*	*Measured*	*Calculated*
WS_1	6.70	0.03–0.15	0.15	0.18	0.46
WS_2	8.48	0.02–0.05	0.04	0.05	0.60
WS_3	6.90	0.08–0.13	0.11	0.13	0.90
WS_4	8.26	0.08–0.13	0.11	0.13	0.74
WS_5	7.14	0.02–0.05	0.04	0.05	0.38
$\mathbf{WS_6}$	7.28	0.08–0.11	0.08	0.10	0.02
$\mathbf{WS_7}$	7.80	0.06–0.10	0.08	0.10	0.61
AVE±SD	*7.51 ± 0.58*	*0.09 ± 0.03*	*0.11 ± 0.04*	*0.53*	

SD-Standard deviation

1.6 Bq kg^{-1} and 99.6 ± 5.8 Bq kg^{-1}, respectively, as shown in Table 2. The corresponding calculated average outdoor annual effective dose due to all the radionuclides is 0.06 mSv. This value is below the outdoor component of the world-wide average value of 0.07 mSv y^{-1} [UNSCEAR, 2000]. The water samples also recorded average specific activity concentrations of 0.60 ± 0.11 Bq l^{-1}, 2.13 ± 0.21 Bq l^{-1} and 10.75 ± 0.84 Bq l^{-1} for ^{226}Ra, ^{232}Th and ^{40}K, respectively. The average activity concentrations of ^{226}Ra and ^{232}Th are above the WHO maximum acceptable concentrations of 0.5 and 0.6 Bq l^{-1}, respectively [WHO, 2004]. It has been observed from Fig. 2 and 3 that communities such as Haatso, Narhman and Dome, which are close to GAEC, have relatively high activity concentrations in soil and water.

The measured and calculated annual effective doses from the different communities in the study area are shown in Fig. 4. The annual effective dose to an adult from the radionuclides was calculated to be 0.53 mSv y^{-1}; this value is about five times higher than the WHO and the European Union guidance level of 0.1 mSv y^{-1} [WHO, 2004]. The reasons for this could be attributed to geological considerations and other factors. The previous study by Yeboah *et al*. (2001) had established that the predominant rock type in the study area was granitic igneous rocks, which are known to contain significant levels of NORM. The water samples, with the exception of the tap waters, were from underground water with *p*H values in the range of 6.70–8.48.

The world average concentration of these radionuclides in soil samples are 35 Bq kg^{-1} (^{226}Ra), 45 Bq kg^{-1} (^{232}Th) and 420 Bq kg^{-1}

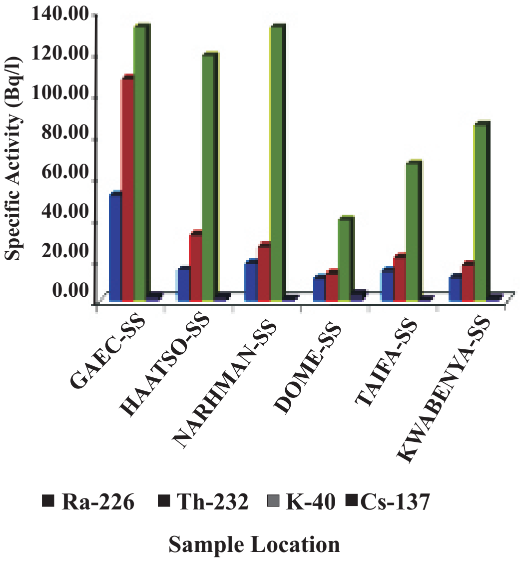

Fig. 2. Specific activity of soil samples collected from different locations.

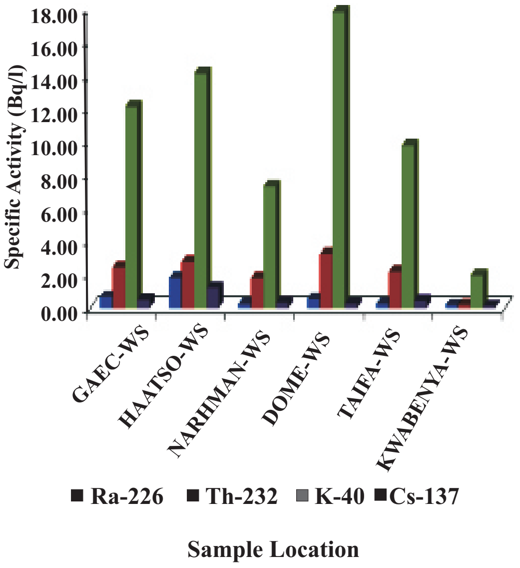

Fig. 3. Specific activity of water samples collected from different locations

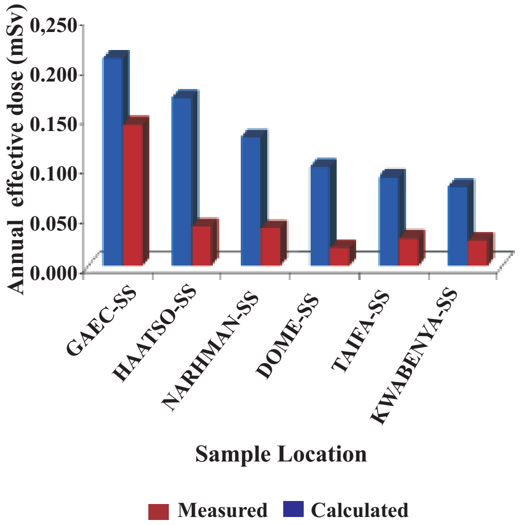

Fig. 4. Measured and calculated annual effective dose from soil samples collected from different communities.

(^{40}K) [UNSCEAR, 2000]. The average concentrations of ^{226}Ra from the study are lower than the world average. The results also showed that the activity concentration of the ^{232}Th compares quite well with the world average, and that of ^{40}K is far below the world average by a factor of about four. The soil samples recorded values lower than that of the previous study by Yeboah *et al*. (2001). The total annual effective dose, which includes the contribution from ingestion of water and external irradiation due to U, Th and K in soil, was calculated to be 0.59 mSv y^{-}

From radiation protection point of view, the calculated doses from the soil and water samples, as well as the terrestrial gamma radiation, might not pose any radiological health hazards to the public within and around GAEC since these doses are below the recommended public annual dose limit of 1 mSv. It is also an indication that the GHARR-1 and the other radiation facilities within the GAEC are not impacting negatively on the immediate surroundings.

Conclusion

Measurement of the levels of natural and artificial radionuclides within GAEC and its immediate surroundings has been carried out. The estimated annual effective doses from exposure to the natural radionuclides in soil and water samples were found to be 0.06 mSv and 0.53 mSv, respectively. The levels in the water samples were about five times higher than that of the European Union and WHO guidance levels. The ^{226}Ra levels in the soil, however, compared quite well with the world average. On the other hand, the levels of ^{232}Th were slightly higher than the world average whilst the levels of ^{40}K were lower than the world average. Even though the estimated average annual effective dose for water samples is higher than the European Union and WHO guidance levels, it is still lower than the ICRP recommended public dose limit of 1 mSv per year for practices. Also, the average activity concentrations of ^{137}Cs in the soil and water sources studied were below the exemption levels and the maximum acceptable concentration levels, respectively. These results will further serve as a baseline data for future studies.

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