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ARTICLE

Natural Radionuclides in Bottled Drinking Water in Jordan and their Committed Effective Doses

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Abstract: Natural radioactivity in bottled drinking water marketed in Jordan was measured. High purity germanium (HPGe) spectrometer system coupled to a PC was used to analyze the obtained gamma-ray spectra. The activity in Bq/l for each of eighteen samples of bottled drinking water and one drinking tap water was obtained and corrected for efficiency and background. For example, we found that the maximum measured activity of ^{226}Ra was 5.5 Bq/l. Gross alpha and beta activities were also estimated from the isotopes identified in the samples. Concentrations of isotopes and their parent nuclides were calculated in g/l. For example, the concentrations were in the range of 0 mg/l to 0.103 mg/l for ^{40}K. The committed effective dose due to ingestion of radionuclide from the consumption of bottled waters for adults and children were estimated. The range was found to be 1.9 mSv/y for children and 1.7 mSv/y for adults. No artificial or fission products were detected in any one of the samples.
Keywords: HPGe, Bottled water, Radioactivity, Concentration, Effective dose.

Introduction

Natural radioactivity is always present in the environment. Water**,** especially ground water, is not free of radioactive isotopes from naturally decaying series of ^{235}U, ^{238}U, ^{232}Th and ^{40}K.

The local market of Jordan is flooded with domestic and imported marketing brands of bottled drinking water. Some of which were imported from countries with no natural resources of natural water except ground water. Domestic and imported waters were purified using physical and chemical methods to remove solid particles, some low Z value salts such as NO_3, Ca and Mg were also used to control the acidity pH of water. UV and Cl_2 were used to kill the pseudomonas, Ecoli and other biological objects such as bacteria, fungi,... etc.

The international regulation for quality control with regards to limit values for gross alpha and beta radioactivity concentration in potable water are 0.5 Bq/l for alpha and 1.0 Bq/l for beta [1]. These limits are applicable in Jordan, too. The kind of treatment applied to purify bottled water in Jordan and possibly in imported brands does not touch the problem of radioactivity, except in the case of vaporization of sea water.

The earth's crust in Jordan is covered by sedimentary sequence with some interruption of sandstone that contains iron-uranium. The upper part of the sequence consists of phosphorite beds and limestone that contains ^{238}U and its daughter products which may be dissolved or suspended in water. Concentration of ^{238}U in phosphorite beds is up to 100 – 200 mg/kg [2].

Several authors in different countries tackled this problem. Da'vila et al studied radioactivity in bottled water in Mexico using liquid scintillator and found that (50%) of the examined samples exhibited alpha radioactivity in excess of the limit value of

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0.1 Bq/l.[3,4]. Cooper et al. determined the activity of some natural radioactive materials and came to the same conclusion that some bottled mineral water in Australian market contain radioactivity in excess of the limits recommended by Australian authority [5]. Martin Sanchez, et al. determined alpha and beta concentration in bottled mineral water [6]. Their results showed that some brands had high values surpassing the reference level established by the Spanish regulatory organization. Total activities of the natural radionuclides in hot mineral waters in Jordan ranged between 0.14 to 34.8 Bq/l [7]. Somlai et al. studied the concentration of ^{226}Ra in Hungarian bottled water and soft drinks produced from bottled water [8]. They found that six out of twenty eight cases contain ^{226}Ra concentration exceeded the 100 mBq/l and in one case it reached 3 Bq/l. In case of soft drinks they found doses up to 1.4 mSv/y. T. Kov'acs and co-workers studied ^{238}U, ^{226}Ra and ^{210}Po concentration in bottled mineral waters in Hungary [9]. The maximum concentration of ^{226}Ra they found was in agreement with Somlai et al. [8] and it was found to be 2.94 ±7.4% Bq/l. Vesterbacka et al. studied natural radioactivity in drinking water in private wells in Finland [10]. The mean concentrations of ^{222}Rn, ^{226}Ra, ^{234}U, ^{238}U, ^{210}Pb and ^{210}Po in drilled wells were found to be 460, 0.05, 0.35, 0.26, 0.04 and 0.05 Bq/l, while the maximum activities were found to be 8600, 1.3, 12.1, 9.9, 0.54 and 2.0 Bq/l successively. The concentrations in the dug wells were found to be less than that of the drilled ones. Age dependent dose assessment of ^{226}Rn from bottled water intake was studied by M. Bronzovic and G. Marovic [11]. They found that the ^{226}Ra concentration in samples of Croatian bottled water brands range from 6 – 412 mBq/l. Ben Fredj et al. used GeLi gamma spectrometer to measure the natural radionuclides in eight brands of bottled water in Tunisia [12]. In some samples, the total activity concentration was up to 10 Bq/l. Doses due to ingestion of some brands were up to 13.2 mSv/y for babies. Fatima et al. used HPGe gamma spectrometer to measure natural radioactivity in bottled drinking water in Pakistan [13]. The mean concentrations of ^{226}Ra, ^{232}Th and ^{40}K were found to be 11.3, 5.2, and 140.9 mBq/l, respectively. Somlai et al. measured the ^{222}Rn concentration of mains water in 120 settlements in Hungary [14]. The concentration was in the range 0 – 24.3 Bq/l. They also found that the concentrations in mains water were less than those in spring water within the same region. Bronzovic et al. investigated the effect of ^{226}Ra concentration in drinking water in Croatia [15]. They found that teenagers (13-17) consume more water than other ages; the effective dose was higher for this group. Compared to other research groups they found a small concentration of ^{226}Ra.

In this work, the radiological qualities of almost all the brands of bottled drinking water that are available in the Jordanian markets were tested. HPGe gamma spectrometer of high resolution was used. This is because most of the daughter products of the naturally radioactive series of ^{235}U, ^{238}U and ^{232}Th are gamma emitters such as ^{226}Ra, ^{228}Th, ^{228}Ac, ^{214}Pb, ^{210}Pb, ^{214}Bi… etc.

Experimental Work

Eighteen brands of bottled drinking water marketed in Jordan of domestic and imported origins were purchased from the local market. All samples were of purified ground water, except one sample believed to be evaporated from sea water. Each sample had been given a coded name. The samples stored for more than three months to reach secular equilibrium. The storage of the samples was only considered to substitute for the radon gas escaping during the purification process, since the isotopes considered for dose and activity calculations were those with short half-lives. Furthermore, the Marinelli beakers used in our study were completely filled with water samples and tightly sealed with no head space during both storage and counting. Purification methods of ground water carried out by producers don't disturb the equilibrium of heavy nuclei in the samples.

Spectral analysis of radionuclide was carried out using a direct gamma-ray spectrometer with high purity germanium detector (HPGe) of high resolution (1.73 keV at 1.33 MeV) connected via a spectrum master (EG&G) to a multi channel analyzer (MCA) installed in a PC computer. The spectrometer is shielded against the background radiation. A software called Gamma Vision was used to accumulate and

analyze the data, with the help of a gamma library that includes over 300 nuclides and about 1900 gamma lines.

The system was calibrated for energy and efficiency using standard sources (Amersham Buchler GmbH & Co. KG, Braunschweig, Germany) of known energies and activities distributed uniformly in multi element Marinelli beaker standard (1000 ml in volume, with no head space). The standard sources contained several isotopes: ^{54}Mn, ^{57}Co, ^{88}Y, ^{133}Ba and ^{137}Cs which had been calibrated and tested by the calibration laboratory for measurements of radioactivity (Deutscher Kalibrierdienst). To achieve the right efficiency calibration curve, the activities of these standard isotopes were entered into the GammaVision software along with their date of manufacture. Water from samples was placed in empty Marinelli beaker and the spectrum was acquired for 24 hours. The accumulated activity was automatically corrected for background and efficiency. Data and spectra were obtained for all of the samples. A gamma-ray spectrum obtained for one of the samples (HT) is shown in Fig.1.

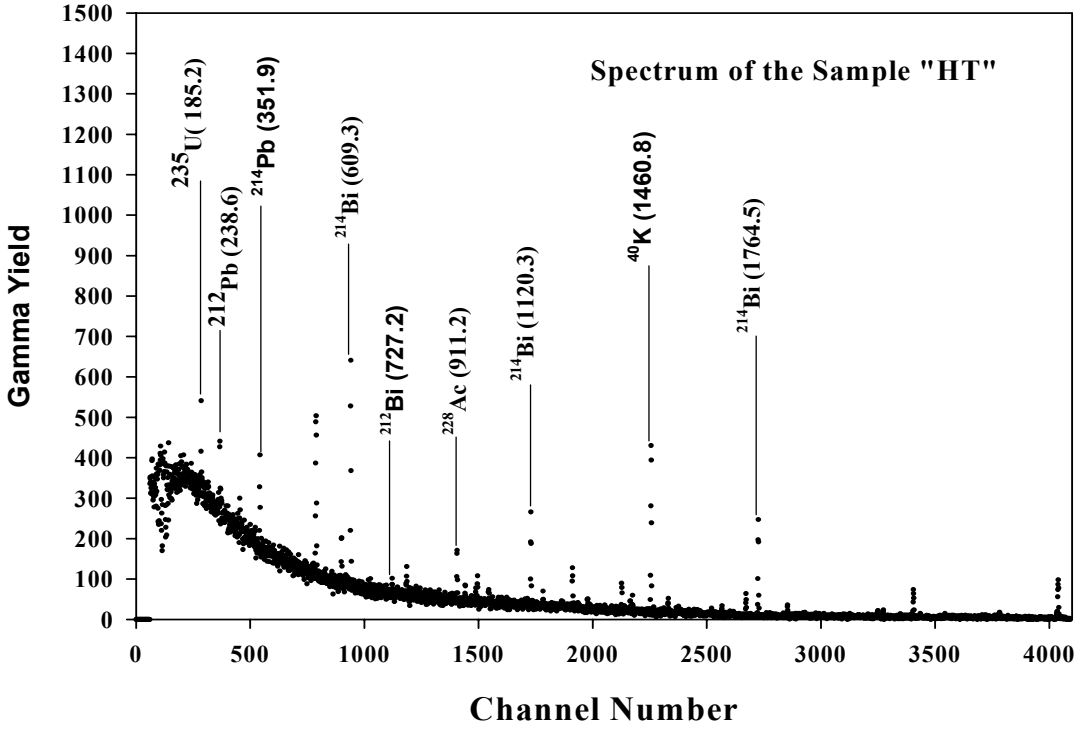

FIG.1. A typical gamma spectrum for one of the samples.

Results and Discussion

Evaluation of the Measurement Data

The eighteen samples of bottled water were analyzed, and for a comparison purpose, another sample taken from a drinking tap water (TW) from Irbid was also analyzed. The concentration of the parents can be calculated using the following relation; if secular equilibrium conditions are satisfied, then

$$A_d = A_p \qquad (1)$$

holds for any daughter product, where A_p and A_d are the activities of parent and daughter nuclei in secular equilibrium. If the secular equilibrium does not exist, the calculation of concentration of parent will be extremely difficult.

The activity of parent nuclide A_p can be resolved from relation 2:

$$A_p = N_p \lambda_p = N_d \lambda_d \qquad (2)$$

where N and λ is the number of particles and the decay constant, respectively, of the parent (p) and daughter (d) in a given sample.

Then we can calculate the concentration of the parent from the relation 3:

$$m_p = \frac{N_p A_{w_p}}{A_{\alpha v}} \quad (3)$$

where $A_{\alpha v}$ is Avogadro's number and A_{w_p} is the mass number of the parent nucleus.

Corrections due to coincidence summing were not considered because a standard source of the same size and geometry was used to carry out the efficiency calibration. Random summing was also ignored because of the very low count rate and there was no pileup or losses from the energy peaks [7].

Tables (1a) and (1b) summarize the measured activities in all samples expressed in Bq/l, where we found that the isotopes ^{214}Pb, ^{214}Bi, ^{228}Ac, ^{208}Tl, ^{212}Pb, ^{212}Bi, and ^{40}K were almost present in all samples. Each isotope was approximately present in the same order for almost all of the samples and that indicates that all of the bottled waters are coming from similar geological regions. On the other hand, the sample of coded-brand TS seems to be evaporated from sea water because the values of the activities of the observed radionuclide were less than the minimum detection activity (MDA).

We calculated the concentration of radionuclides expressed in g/l, for all samples (Table 2). For example, the calculated concentrations of 40 K from the measured activities ranged from 0 up to 0.103×10^{-3} g/l.

Furthermore, we estimated the gross alpha and beta radioactivity concentrations (Table 3) based on the measured activities presented in Tables (1a) and (1b). Alpha activity varied between 0.29 and 31.46 Bq/l while beta activity varied between 0 and 50.14 Bq/l. The calculated values far much exceeded the limit of 0.1 Bq/l for alpha and 1.0 Bq/l for beta. The total activity in drinking tap water TW (43.95 ± 7.5 Bq/l) is the third highest in total activity just after that of the NB (53.98 ± 4.8 Bq/l) and HA (53.64 ± 7.0 Bq/l) samples. Some of the radionuclides from natural radioactive series were not included in the estimation of gross beta and alpha emitters and the subsequent dose estimation because their gamma activities were not detected by the HPGe spectrometer (^{220}Rn, ^{216}Po, ^{210}Po, ^{218}Po, and ^{222}Rn) or their activities were below the detection limits (^{227}Th, ^{223}Ra, and ^{219}Rn).

The isotopes ^{228}Th, ^{235}U, ^{230}Th, ^{226}Ra, ^{224}Ra and ^{212}Bi (with emission rate 36%) were considered as alpha emitters, while the beta activity in the samples was due to the following isotopes: ^{40}K, ^{210}Pb, ^{234}Th, ^{231}Th, ^{109}Cd, ^{228}Ac, ^{214}Pb, ^{214}Bi, ^{212}Pb, ^{212}Bi (with emission rate 64%) and ^{208}Tl. Other isotopes of alpha and beta emitters that had been identified in our samples by the spectrometer were omitted from our consideration because either their activities were less than the minimum detectable limit or their peaks were of bad shapes.

Dose Calculation

Radionuclide may reach the gastrointestinal tract directly by ingestion or indirectly by transfer from the respiratory tract. From small intestine (S1) the radionuclide can be absorbed to the body fluids.

Tables (A.8.7), (A.9.7), and (A.10.7) in ICRP publication 78 give the predicted values (Bq/Bq) for ingested Ra, Th and U for the first (10) days after ingestion, that is, the values (in Bq) of the remained activities after 10 days of ingestion per each ingested Bq [16, 17]. Such tables show that the predicted values are very small (ranging from 2.9×10^{-2} for Ra down to 1.9×10^{-4} for U). This means that the effective half-lives of the above radionuclide and their daughter products are small. The committed quantities, because of small effective half-lives, are practically realized within one year after intake [18].

In this work, the effective dose over one year was calculated using the following relation.

$$E = I\,A\,C \times 365 \quad (4)$$

Where I is the daily water consumption in l/day, A is the activity/l; C is a dose conversion factor in Sv/Bq. Dose conversion factors used to calculate the internal radiation exposure by ingestion of radionuclide by IAEA [19] were considered, see Table (4).

On average, adults are considered to consume two litres of water per day, while children are considered to consume only one

litre per day. This is a conservative estimation in a hot summer in Jordan. The values of the effective dose for adults varied from 0.0 to 3.9 mSv/y with an average value of 1.7 mSv/y. But, for children, the effective dose values varied from 0.0 to 4.4 mSv/y with an average value of 1.9 mSv/y. These values are greater than the allowed dose contributed from water which was estimated to be less than 0.1 mSv/y [4]. Table (5) shows the annual effective dose calculated from the activities of the detected radionuclide only, it may slightly underestimate the real intake dose because it does not include all radionuclide in the natural series. According to these results, it seems that the purification technique is not efficient at all and it does not touch the heavy radionuclide, while the evaporation of water appears to be the best way for the purification of water in this region of the world, this is because the earth's crust in this region is rich in ^{238}U and ^{232}Th and their daughters' isotopes. It is worth mentioning that none of the fission products such as ^{137}Cs, ^{134}Cs, ^{90}Sr, etc were found in our samples, even though these isotopes were detected in Jordanian soil [20].

The uncertainties given in all tables were evaluated from the counting uncertainties reported along the count rate by the used software (GammaVision) as one sigma (one standard deviation), which depend on the distribution of the peak area of each detected radionuclide. The total uncertainties in Table (3) were the sum of all uncertainties in the activities.

Conclusion

In this study, we measured the natural radioactivity in eighteen samples of bottled drinking water and one sample of tap water (TW) by using the HPGe gamma-ray. Also, we estimated the gross alpha and beta activity values and found that they are very much higher than the limit of 0.1 Bq/l for alpha and 1.0 Bq/l for beta. In addition to that, we estimated the annual effective dose for adults and children; we found that the average values were 1.7 and 1.9 mSv/y for adults and children, respectively. These values are greater than the allowed dose contributed from water which is estimated to be less than 0.1 mSv/y. Finally, we could say that the gamma spectrometry technique may not be an efficient one for the estimation of the gross alpha and beta or the effective dose because some of the daughter products from the natural radioactive series could not be detected by HPGe spectrometer. Other techniques, such as liquid scintillator or chemical analysis, may give more accurate results.

References

[1]WHO, World Health Organization. "Guidelines for drinking water quality", (Geneva-Switzerland, 2004).

[2]Smith, B., Powell, J., Bradley, A., Gedeon, R. and Armo, H., Mining Environmental Management, 3 (1995) 7.

[3]Dávila Rangel, J.I, López del Rio, H., Rodriguez B.L. and Solache-Rios, B.M., J. Radioanal. Nucl. Chem. 247(2) (2001) 425.

[4]Dávila Rangel, J.I., López del Rio, H., Mireles Garcia, F., Quirino Torres, L.L., Villalba, M.L, Colmenero Sujo., L. and Montero Cabrera, M.E., Appl. Radiat. Isotopes, 56 (2002) 931.

[5]Cooper, M.B., Ralph, B.J. and Wilks, M.J., Australian Radiation Laboratory. ARL-TR-063 (1981).

[6]Martin Sanchez, A., Rubio Montero, M.P., Go'mez Escobar, V. and Jurado Vargas, M., Appl. Radiat. Isotopes, 50 (1999) 1049.

[7]Saqan, S.A., Kullab, M.K. and Ismail, A.M., J. Environmental Radioactivity, 52 (2001) 99.

[8]Somlai, J., Horváth, G., Kanyár, B., Kovács, T, Bodrogi, E. and Kavási, N., J. Environmental Radioactivity, 62(3) (2002) 235.

[9]Kovács, T., Bodrogi, E., Dombovari, J., Somlai, J., Németh, Cs., Capote, A. and Tarján, S., Radiation Protection Dosimetry, 108(2) (2004) 175.

[10]Vesterbacka, P., Makelainen, I. and Arvela, H., Radiation Protection Dosimetry, 113(2) (2005) 223.

[11]Bronzovic, M. and Marovic, G., Health Physics, 88(5) (2005) 480.

[12]Ben Fredj, A., Hizem, N., Chelbi, M. and Ghedira, L., Radiation Protection Dosimetry, 117(4) (2005) 419.

[13]Fatima, I., Zaidi, J., Arif, M. and Tahir, S., Radiation Protection Dosimetry, 123(2) (2007) 234.

[14]Somlai, K., Tokonami, S., Ishikawa, T., Vancsura, P., Gaìspaìr, M., Jobbagy, V., Somlai, J. and Kovács, T., Radiation Measurements, 42 (2007) 491.

[15]Bronzovic, M., Marovic, G., Vrtar, M. and Bituh, T., J. Environmental Science and Health Part A, 42 (2007) 817.

[16]ICRP Publication 78. "Individual Monitoring for Internal Exposure of Workers", (1997).

[17]Kovács, T., Bodrogi, E., Somlai, J., Jobbagy, V., Patak, G. and Németh, Cs., J. Radioanalytical and Nuclear Chem. 258(1) (2003) 191.

[18]Turner, J.E., "Atoms, Radiation and Radiation Protection", 2nd Ed. (John Wiley and Sons Ltd, 1995).

[19]IAEA. "International Basic Safety Standards for Protection Against Ionizing Radiation and for the Safety of Radiation Sources", No. 115 (IAEA, Vienna, 2003).

[20]Al-Hamarneh, I., Wreikat, A. and Toukan, K., J. Environmental Radioactivity, 67 (2003) 53.

TABLE 1a. Natural Radioactivity in Bq/l (±1 standard deviation).

	AA	FT	GR	HA	HT	HW	KR	KZ	MY	NB
^{234}Th	3.70±0.7			3.85±0.71						
^{234m}Pa				15.02±2.20						
^{231}Th				5.70±0.50						
^{230}Th										
^{226}Ra		5.30±1.8		3.52±0.70				4.20±0.90		
^{214}Pb	0.58±0.10	0.79±0.20	1.19±0.20	1.01±0.15	1.15±0.20	1.16±0.20	1.21±0.20	1.10±0.20	1.15±0.20	1.09±0.20
^{214}Bi	2.30±0.11	2.00±0.10	3.00±0.20	2.69±0.13	2.90±0.10	2.90±0.10	3.00±0.20	2.80±0.20	2.90±0.20	2.80±0.20
^{210}Pb		2.20±0.90				1.90±0.80			1.80±0.80	
^{235}U	0.29±0.04		0.50±0.10		0.40±0.10	0.40±0.10	0.30±0.10	0.20±0.10	0.30±0.10	0.30±0.10
^{228}Ac		0.40±0.20	1.70±0.20		1.80±0.20	2.40±0.20	1.50±0.20		1.60±0.20	1.90±0.20
^{228}Th			30.5±4.10				25.2±2.20	16.70±2.30	29.6±3.70	17.9±1.70
^{224}Ra					1.70±0.80	1.60±0.80				1.70±0.80
^{212}Pb	0.44±0.04	0.40±0.10	0.51±0.10	0.44±0.04	0.42±0.10	0.60±0.10	0.60±0.10	0.60±0.10	0.60±0.10	0.50±0.10
^{212}Bi			1.29±0.40		1.06±0.70	1.52±0.70	1.49±0.70	1.52±0.50	1.51±0.70	1.28±0.70
^{208}Tl	0.89±0.10			1.18±0.12		1.90±0.10				1.80±0.10
^{40}K	16.20±2.0			18.1±2.20	25.8±0.80	26.7±1.0				24.7±0.80
^{109}Cd	2.98±0.70			2.13±0.25						

TABLE 1b. Natural Radioactivity in Bq/l (±1 standard deviation).

	NQ	PD	QS	RA	RE	RM	TS*	TW	UA
^{234}Th		2.68±0.50		3.44±0.65		3.67±0.70		1.69±0.50	2.87±0.52
^{234m}Pa		16.65±2.40							
^{231}Th				4.96±0.70					5.81±0.52
^{230}Th	25.5±9.50								
^{226}Ra					5.50±1.80				3.77±0.75
^{214}Pb		0.78±0.12	1.10±0.20	0.80±0.13		0.86±0.13		0.63±0.40	0.61±0.10
^{214}Bi		2.46±0.12	2.80±0.10	2.25±0.11		2.13±0.10		1.60±0.20	2.63±0.13
^{210}Pb			2.00±0.80						
^{235}U		0.34±0.04	0.50±0.10	0.33±0.04		0.26±0.03		0.30±0.10	
^{228}Ac			1.60±0.20					1.20±0.30	
^{228}Th			28.6±3.60					12.2±3.20	
^{224}Ra									
^{212}Pb		0.36±0.04	0.50±0.10	0.35±0.03		0.46±0.04		0.47±0.10	0.45±0.04
^{212}Bi		0.44±0.26	1.29±1.00	0.39±0.17				1.20±0.40	
^{208}Tl		0.91±0.11		0.74±0.09		0.67±0.08		0.20±0.10	1.02±0.11
^{40}K		7.31±1.00			2.50±1.00	5.73±1.90		24.5±2.20	16.9±2.10
^{109}Cd		2.33±0.60		2.60±0.60		3.10±0.70			3.14±0.70

* The activities of all the identified radionuclides were less than the minimum detectable activity (MDA).

TABLE 2. Concentrations of natural radionuclides in g/l.

	^{234}Th $\times10^{-15}$	^{234m}Pa $\times10^{-19}$	^{231}Th $\times10^{-16}$	^{230}Th $\times10^{-8}$	^{226}Ra $\times10^{-10}$	^{214}Pb $\times10^{-19}$	^{214}Bi $\times10^{-18}$	^{210}Pb $\times10^{-13}$	^{235}U $\times10^{-6}$	^{228}Ac $\times10^{-17}$	^{228}Th $\times10^{-13}$	^{224}Ra $\times10^{-16}$	^{212}Pb $\times10^{-18}$	^{212}Bi $\times10^{-18}$	^{208}Tl $\times10^{-19}$	^{40}K $\times10^{-5}$	^{109}Cd $\times10^{-14}$
AA	4.31					4.79	1.41		3.63				8.56		0.83	6.25	3.14
FT					1.45	6.52	1.23	7.79		0.50			7.78				
GR						9.82	1.85		6.25	2.11	10.05		9.92	2.38			
HA	4.49	5.91	2.90		0.96	8.34	1.66						8.56		1.09	6.99	2.24
HT						9.49	1.78	7.09	5.00	2.23		2.88	8.17	1.95		9.96	
HW						9.58	1.78	6.38	5.00	2.98		2.71	11.67	2.80	1.76	10.30	
KR						9.99	1.85		3.75	1.86	8.30		11.67	2.75			
KZ					1.15	9.08	1.72		2.50		5.50		11.67	2.80			
MY						9.49	1.78		3.75	1.98	9.75		11.67	2.78			
NB						9.00	1.72		3.75	2.36	5.90	2.88	9.73	2.36	1.67	9.53	
NQ				3.34													
PD	3.13	6.55				6.44	1.51		4.25				7.00	0.81	0.84	2.82	2.45
QS						9.08	1.72	6.73	6.25	1.98	9.42		9.73	2.38			
RA	4.01		2.52			6.60	1.38		4.13				6.81	0.72	0.69		2.74
RE					1.50											0.96	
RM	4.28					7.10	1.31		3.25				8.95		0.62	6.07	3.26
TS*																	
TW	1.92					5.20	0.98		3.75	1.49	4.02		9.14	2.21	0.19	9.46	
UA	3.35		2.96		1.03	5.04	1.62						8.76	0.95		6.52	3.30

* The activities of all the identified radionuclides were less than the minimum detectable activity (MDA).

TABLE 3. Alpha and beta activities in Bq/l (±1 standard deviation)

Sample	Total Activity	Total Alpha	Total beta
AA	27.38±3.8	0.29±0.04	27.09±3.76
FT	11.09±3.3	5.3±1.8	5.79±1.5
GR	38.69±5.26	31.46±4.34	7.23±0.92
HA	53.64±7.0	3.52±0.7	50.14±6.3
HT	35.23±3.0	2.48±1.15	32.75±1.85
HW	41.08±4.2	2.55±1.15	38.53±3.05
KR	32.3±3.7	26.04±2.55	6.26±1.15
KZ	27.12±5.3	21.65±3.9	5.47±1.4
MY	39.57±5.9	30.55±4.05	9.02±1.85
NB	53.97±4.8	20.08±2.85	33.89±1.95
NQ	25.5±9.5	25.5±9.5	0.0
PD	34.26±5.19	0.50±0.15	33.76±5.04
QS	38.59±6.1	29.56±4.06	9.03±2.04
RA	15.83±3.52	0.47±0.10	15.36±3.42
RE	8.0±2.8	5.5±1.8	2.5±1.0
RM	26.88±3.68	2.5±1.3	24.38±2.38
TS	< MDA	< MDA	< MDA
TW	43.95±7.5	12.93±3.44	31.02±4.06
UA	37.2±4.97	3.77±0.75	33.43±4.72

TABLE 4. Ingestion: Committed Effective Dose per Unit Intake Via Ingestion (Sv/Bq) For Members of the Public.

Nuclide	Physical half-life	Age g ≤ 1 a	Age 1-2 a	Age 2-7 a	Age 7-12 a	Age 12-17a	Age >17 a
K-40	1.28 E+09 a	6.2 E-08	4.2 E-08	2.1 E-08	1.3 E-08	7.6 E-09	6.2 E-09
Pb-210	22.3 a	8.4 E-06	3.6 E-06	2.2 E-06	1.9 E-06	1.9 E-06	6.9 E-07
Pb-212	10.6 h	1.5 E-07	6.3 E-08	3.3 E-08	2.0 E-08	1.3 E-08	6.0 E-09
Pb-214	0.447 h	2.7 E-09	1.0 E-09	5.2 E-10	3.1 E-10	2.0 E-10	1.4 E-10
Ra-224	3.66 d	2.7 E-06	6.6 E-07	3.5 E-07	2.6 E-07	2.0 E-07	6.5 E-08
Ra-226	1.60 E+03 a	4.7 E-06	9.6 E-07	6.2 E-07	8.0 E-07	1.5 E-06	2.8 E-07
Ac-228	6.13 h	7.4 E-09	2.8 E-09	1.4 E-09	8.7 E-10	5.3 E-10	4.3 E-10
Th-228	1.91 a	3.7 E-06	3.7 E-07	2.2 E-07	1.5 E-07	9.4 E-08	7.2 E-08
Th-230	7.70 E+04 a	4.1 E-06	4.1 E-07	3.1 E-07	2.4 E-07	2.2 E-07	2.1 E-07
Th-231	1.06 d	3.9 E-09	2.5 E-09	1.2 E-09	7.4 E-10	4.2 E-10	3.4 E-10
Th-234	24.1 d	4.0 E-08	2.5 E-08	1.3 E-08	7.4 E-09	8.0 E-07	7.1 E-07
U-235	7.04 E+08 a	3.5 E-07	1.3 E-07	8.5 E-08	7.1 E-08	7.0 E-08	4.7 E-08
Bi-212	1.01 h	3.2 E-09	1.8 E-09	8.7 E-10	5.0 E-10	3.3 E-10	2.6 E-10
Bi-214	0.332 h	1.4 E-09	7.4 E-10	3.6 E-10	2.1 E-10	1.4 E-10	1.1 E-10
Cd-109	1.27 a	2.1 E-08	9.5 E-09	5.5 E-09	3.5 E-09	2.4 E-09	2.0 E-09

TABLE 5. Committed effective dose (±1 standard deviation) (mSv/y).

	Age groups in years			
Sample	2-7	7-12	12-17	17>
AA	0.16239945	0.1305459	0.06286322	0.09896902
FT	2.97142485	3.0765923	4.42958525	2.193577
GR	2.47281335	1.68915795	1.06237411	1.62360979
HA	0. 96605645	1.129935975	1.98619787	0. 81773724
HT	0.4342332	0.29830063	0.20858655	0.21414112
HW	1.956693095	1.6123218	1.5224515	1.17153685
KR	2.04196695	1.39271225	0.8757956	1.3385645
KZ	2.30594955	2.15090485	2.88083915	1.7463425
MY	3.84068987	2.882191475	2.27510997	2.4764958
NB	1.861144855	1.27115557	0.81753795	1.14694826
NQ	2.885325	2.2338	2.04765	3.90915
PD	0.08871325	0.0566553	0.037011365	0.05673706
QS	3.92591445	2.97053936	2.38410043	2.53060705
RA	0.0387119	0.02527625	0.01860405	0.02675158
RE	1.2638125	1.6178625	3.018185	1.135515
RM	0.1581983	0.098696	0.0609696	0.0958782
TS	-	-	-	-
TW	1.1915863	0.80065305	0.49694239	0.76936014
UA	1.0108675	1.1979081	2.12127415	0.86246215