http://dx.doi.org/10.5392/IJoC.2012.8.2.060

An analysis of the concentration of radioactivity of natural radionuclides (^{238}U, ^{232}Th, ^{40}K) and gamma-ray emitting artificial radionuclides(^{137}Cs, ^{60}Co) present in the drinking water of the city of Busan, Republic of Korea, and the calculated absorbed dose of the residents

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ABSTRACT

This study was designed to detect and measure the concentration of radioactivity of natural radionuclides (^{238}U, ^{232}Th, ^{40}K) and artificial radionuclides (^{137}Cs, ^{60}Co) present in the drinking water of the city of Busan and surrounding areas in South Korea, and also to measure the absorbed dose of radiation caused by these elements in the residents so as to help better manage the risk that these radionuclides pose in the future. For the purposes of the study, a total of 42 samples of water were collected from three key water sources (19 samples of groundwater, 4 samples of tap water, and 19 samples of surface water) and their contents were analyzed for radioactivity concentration. The results revealed that two natural radionuclides, ^{238}U and ^{232}Th, exist in the groundwater with an average concentration of radioactivity of 3.34 Bq/L and $8.28x10^{-5}$ Bq/L respectively, while the surface water was found to contain the same two radionuclides with mean concentrations of 0.849 Bq/L and $1.103\ x10^{-4}$ Bq/L respectively. In addition, of the 19 samples of the groundwater, ^{137}Cs was found in eight of them and ^{60}Co was detected in ten. Of the four samples of the tap water, ^{137}Cs was detected in all samples and ^{60}Co was detected in three. Both ^{137}Cs and ^{60}Co were detected in all 12 samples of surface water. As far as ^{40}K is concerned, this element was detected in three of the 19 groundwater samples, but was not detected in any surface or tap water sample. In addition, the absorbed dose of ^{238}U from the groundwater was $7.94\ x10^{-8}$ Sv/y, while the absorbed dose of ^{232}Th from the surface water was $9.33\ x10^{-13}$ Sv/y. The absorbed dose of ^{137}Cs from the tap water was $7.33\ x10^{-5}$ Sv/y, while the absorbed dose of ^{60}Co from the surface water was the highest at $4.23\ x10^{-6}$ Sv/y.

Keywords *: Uranium, Thorium, Drinking water, Absorbed dose*

I. INTRODUCTION

Radionuclides that exist in the environment can be largely classified into natural radionuclides found in the Earth's crust and artificial radionuclides that are the result of, for example, nuclear tests or nuclear power plant accidents. The natural radionuclides that exist in soil and rocks are ^{238}U, ^{232}Th and ^{40}K, concentrations of which vary depending on the mix of soil and bedrock in the area. These natural radionuclides dissolve when surface and subsurface water flow over or through the top soil and rock base. The dispersed natural radionuclides flow with the water in particles larger than a colloid [1] [2]. If ingested, water from these contaminated sources can internally expose humans to dangerous levels of radioactivity [3]. Particularly, groundwater is widely used for agricultural irrigation in addition to drinking water because in many countries it is considered cleaner than surface water [4]. However, due to the chemical and radiation toxicity of uranium (^{238}U), if there is a high concentration of this dangerous element in the groundwater, its progeny radionuclide Radon (^{222}Rn) can cause lung cancer to unsuspecting residents; while uranium, if directly absorbed into a body, can cause continual radiation exposure to tissues and organs as well as deterioration of kidney functionality. Thorium (^{232}Th) poses a radiation threat and mainly to the organs it may settle in, but it also endangers surrounding organs due to gamma-ray emission as well as the release of high-LET charged particles as a result of the radioactive decay process [2] [5]. In addition, approximately $4.81x10^{-1}$ Bq of ^{40}K exist in the environment naturally, and it

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Manuscript received Jun. 09, 2012; revised May 29, 2012; accepted Jun 01, 2012

has been reported that each year in America ^{40}K contaminates soil by an additional 1.11 x10^{14} Bq.

The World Health Organization (WHO) recommends that the daily intake of ^{238}U, ^{232}Th and ^{40}K not exceed 15 μg/L, 1 Bq/L and 0.5 Bq/L respectively [6] [7]. ^{137}Cs, one of the artificial radionuclides, has existed as fallout from the hundreds of atmospheric nuclear tests conducted mostly during the cold war era at levels of approximately 3.7 x10^{-3} ~ 3.7 x10^{-2} Bq (mean 1.48 x10^{-2} Bq). Approximately 80% of ^{137}Cs can be ingested through drinking water since its course of intake is similar to that of the natural radionuclides [8].

Assuming an exposure of 3.7x10^{-2} Bq of ^{137}Cs, it has been reported that cancer occurs in approximately six persons per 100,000. The U.S. Nuclear Regulatory Commission recommends that ^{137}Cs not exceed 30 Bq/L in the drinking water. so many countries have been making efforts to minimize the radiation exposure of its citizens by examining the concentration of both natural and artificial radionuclides dispersed in the drinking water [9]. Korea, for example, is now operating environmental radioactivity detection units in major cities to prepare for the possibility of a domestic radiation emergency incident or to cope with a possible massive radiation incident from a neighboring country. Korea is also keeping an eye on the concentration of radionuclides residing within the peninsula by continually analyzing specimens of air, rainfall, foodstuffs and soil. The radionuclides to be analyzed depend on the specimens but are mainly limited to ^{60}Co, ^{137}Cs, ^{40}K, gross-alpha and gross-beta radiation. Additionlly, there have been cases whereby areas surrounding nuclear power plants were monitored for the presence of ^{90}Sr, ^{137}Cs, ^{238}U and ^{238}Pu, while foodstuffs and soil were analyzed for Thorium[10] [11]. There have been, however, only a few cases whereby residents of any particular area were studied for bodily exposure of radiation from the drinking water. For that reason, in addition to studying the existence of natural and artificial radionuclides in the water supplies, we also measured the absorbed dose of these in nearby residents.

II. MATERIALS AND METHODS

1. Sampling and analysis

The city of Busan is a port city that resides in the south-eastern region of the Korean peninsula. It consists of 16 administrative districts which taken together make it Korea's second largest city. For the purpose of collecting samples of the ground and surface water, a single site was selected in each of the 16 districts. However, there is one district that contains a nuclear power plant, so it was decided to select an additional three sites from there. Therefore, a total of 19 sites were selected for the ground and surface water sampling. The metropolitan area of Busan is supplied water from four waterworks facilities, so it was decided to collect a total of 42 drinking water samples from them. The sites are as shown in Fig. 1.

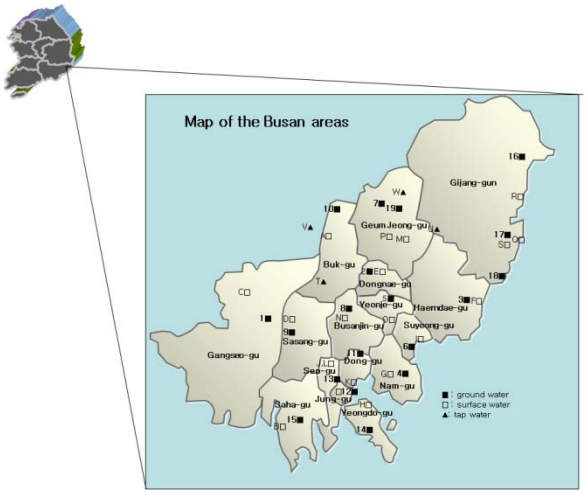

Fig. 1 Drinking water sampling sites

Accurately measured samples of 20 liters were poured into beakers from the collected samples and pre-treated in accordance with ASTM C-1000-05 procedures [12]. After the samples were reduced, they were measured with an Inductively Coupled Plasma Mass Spectrum (ICP-MS).

To minimize contamination of the samples during the sampling process, contaminants around the sampling locations were removed, and to ensure consistent quality, the water was allowed to flow sufficiently for ten minutes or so before being collected.

As part of the pre-treatment process, suspended solids were filtered out, and to minimize absorption and deposition of ions the acidity of the solution was lowered to less than pH 2 by adding 1 ml of concentrated hydrochloric acid for each liter.

Prior to pre-treatment of a sample, 1 ml of 1000 ppm ^{185}Re standard solution was added to check the recovery rate of the treatment process.

In order to be able to measure very small quantities of elements, each sample solution was heated to evaporate most of the water so the contents could be concentrated. Each 20 L sample was slowly heated to between 80 ~ 90℃ until the volume was less than one liter. To prevent any loss of the contents special effort was made to make sure that no sample reached the boiling point, which would cause splattering and potential loss of any contents. Also, while heating each solution, attention was paid to not contaminate it with any surrounding environmental pollutants.

To filter impurities from the concentrated solution, a 0.45 μm micro-filter was used. Because the volume of the final solution was reduced to one liter the sample solution was concentrated by a factor of 20. Samples of the concentrations were then analyzed by an ICP-MS.

2. Analysis of nuclides (^{238}U, ^{232}Th)

To measure ^{238}U and ^{232}Th existing in the soil, alpha spectrometry is generally used, but if the sample is an environmental sample, and the amount of the natural radioactive nuclides in the sample is very small, an ICP-MS is

used because the instrument is capable of analyzing very small amounts of the elements.

The ICP-MS used in this study was the model CCTX-10. Also, for quantitative analysis of the samples, one sample was separated into three portions, and the mean was calculated and used as the resulting value of the natural radioactive nuclides in a region.

3. Analysis of nuclides (^{137}Cs, ^{40}K, ^{60}Co)

An HPGe detector (coaxial Model Gc3019, Canberra Inc.) composed of a cylinder of germanium with an n-type contact on the outer surface and a p-type contact on the surface of the axial well was used to measure each sample. The calibration sample (for reference) for calibrating the gamma-ray energy was a standard 55 ml cylinder (manufactured by the Korea Research Institute of Standards and Science) containing a mixture of ten types of gamma-rays.

For measuring gamma-emitting radionuclides, pre-processed samples were measured along with background emission for 80,000 seconds with a gamma-ray spectrometer composed of a high pure Ge detector and a multi-channel analyzer. Once measurement of the spectrum was completed, the gamma-emitting radionuclides in the samples were analyzed by applying the spectrum whereby the energy resolution power and efficiency were calibrated by the analysis program.

4. Calculation method of absorbed dose

To assess the absorbed dose, this study used the LUDEP 2.07 program. The LUDEP program is currently being used by the IAEA to assess the internal absorbed doses. It was developed by the National Radiological Protection Board (NRPB) of the U.K. The basic configuration complies with the internal absorbed dose assessment model presented by the ICRP. To be more precise, the respirator model is based on ICRP-66, the bio-kinetics model is based on ICRP-30, and excretion is based on ICRP-54.

In general, cumulative activity refers to the time integral in relation to the radioactive decay of the radioactive isotope and can be expressed in the following formula (1)[13] [14],

$$U_s = \int_0^{\infty} A(t)dt \quad (1)$$

Where U_s is the cumulative activity (μCi h or MBq s) and A(t) is the instantaneous radioactivity at time 't.' When the initial radioactivity in the source area is $A_{0,}$ the time function of radioactivity, A(t), is determined by the effective decay constant λ_{eff} of the radioactive isotope and compounds as shown in the following formula (2).

$$A(t) = A_0 e^{-\lambda_{eff} \cdot t} \quad (2)$$

If the above formula is substituted in formula (1), the cumulative activity Us can be simply expressed as shown in formula (3).

$$U_s = \frac{A_0}{\lambda_{eff}} \quad (3)$$

Also, the absorbed dose can be expressed as shown in formula (4) below by means of the above cumulative activity and specific effective energy (SEE),

$$\text{Absorbed Dose} = k \sum_i U_s SEE(T \leftarrow S)_i \quad (4)$$

At this time, constant k is expressed as, $k = 1.602 \times 10^{-10} \frac{\text{Gy}}{\text{MeV/g}}$,

and the SEE of the exposed tissue is defined as shown in formula (5),

$$SEE = \sum_i \frac{E_i \ Y_i AF(T \leftarrow S)_i W_i}{M_i} \quad (5)$$

where Y_i is emissivity of particle 'i' per decay

E_i is average energy of particle 'i'.

$AF(T \leftarrow S)_i$ is absorbed fraction, the proportion of energy of particle 'i' discharged by the source tissue S_i that is absorbed per unit mass of target tissue T_i.

W_i is quality factor of radioactive particle 'i' (radiation weighting factor);

M_t is mass of the target organ.

Ⅲ. RESULTS AND DISCUSSIONS

1. The radioactivity concentration of ^{238}U, ^{232}Th, ^{137}Cs, ^{40}K and ^{60}Co contained in the drinking water

In the 19 groundwater samples, 19 surface water samples and four tap water samples taken from the Busan region, the concentration of the natural radionuclides, ^{238}U and ^{232}Th, were measured to have means of 3.340 Bq/L (range 0.0832~18.86 Bq/L) and 8.279 $x10^{-5}$ Bq/L (range 3.69 $x10^{-6}$ ~ 2.73 $x10^{-4}$ Bq/L) respectively in the groundwater; means of 0.849 Bq/L (range 0.161~ 4.437 Bq/L) and 1.103 $x10^{-4}$ Bq/L (range 8.82 $x10^{-6}$ ~ 8.06 $x10^{-4}$ Bq/L) respectively in the surface water, and means of 7.084 $x10^{-2}$ Bq/L (range 5.28 $x10^{-3}$ ~ 0.126 Bq/L) and 4.499 $x10^{-5}$ Bq/L (range 1.64 $x10^{-6}$ ~ 6.38 $x10^{-5}$ Bq/L) respectively in the tap water. Detailed information is presented in Tables 1 through 3.

Table 1 Activity concentration of ^{238}U, ^{232}Th, ^{137}Cs, ^{40}K and ^{60}Co contained in ground water

Region /Country	^{238}U Bq/L	^{232}Th Bq/ L	^{137}Cs Bq/L		^{40}K Bq/L		^{60}Co Bq/L		Direction
			Radioactivity	MDA	Radioactivity	MDA	Radioactivity	MDA	
1	0.1705	$7.901x10^{-5}$	< MDA	5.370	< MDA	49.90	< MDA	4.870	+35° 12' 5.46", +128° 53' 45.83"
2	0.2195	$1.853 x10^{-4}$	2.196	1.580	< MDA	21.60	1.305	0.728	+35° 12' 29.70", +129° 4' 31.47"
3	0.1008	$9.871 x10^{-5}$	0.581	0.521	< MDA	13.50	< MDA	1.020	+35° 10' 52.36",+129°10' 24.49"
4	18.860	$4.268 x10^{-5}$	< MDA	1.040	< MDA	14.40	1.027	0.469	+35° 8' 13.71", +129° 4' 9.53"
5	0.1869	$1.551 x10^{-4}$	< MDA	0.815	12.01	8.230	< MDA	0.806	+35° 11' 18.49", +129° 3' 14.22"
6	0.1202	$9.378 x10^{-5}$	< MDA	0.812	7.040	0.552	< MDA	0.721	+35° 10' 9.54", +129° 5' 46.86"
7	0.7213	$2.727 x10^{-4}$	< MDA	0.804	6.770	0.229	< MDA	0.697	+35° 13' 50.60", +129° 5' 33.58"
8	6.5240	$4.104 x10^{-5}$	0.638	0.481	< MDA	13.20	< MDA	0.519	+35° 8' 49.84", +129° 1' 32.41"
9	17.020	$9.666 x10^{-5}$	0.760	0.602	< MDA	13.30	< MDA	1.030	+35° 11' 5.11", +128° 59' 31.44"
10	5.2020	$3.140 x10^{-5}$	< MDA	0.834	< MDA	7.09	< MDA	0.717	+35° 14' 39.69", +129° 1' 22.67"
11	1.6080	$4.166 x10^{-5}$	1.384	0.979	< MDA	13.40	0.666	0.477	+35° 7' 35.43", +129° 2' 16.90"
12	0.0832	$4.002 x10^{-5}$	< MDA	1.580	< MDA	22.40	0.998	0.780	+35° 6' 47.66", +129° 2' 9.49"
13	1.7920	$2.709 x10^{-5}$	5.921	5.360	< MDA	157.0	8.786	5.190	+35° 7' 33.15", +129° 2' 15.51"
14	0.2797	$3.694 x10^{-6}$	0.847	0.735	< MDA	19.10	< MDA	0.234	+35° 5' 43.58", +129° 2' 47.96"
15	0.3240	$9.440 x10^{-6}$	< MDA	3.820	< MDA	54.50	2.416	1.890	+35° 6' 46.65", +128° 58' 0.29"
16	0.2688	$1.773 x10^{-4}$	< MDA	0.982	< MDA	14.50	0.563	0.465	+35° 20' 4.79", +129° 17' 19.46"
17	0.4958	$1.432 x10^{-4}$	0.552	0.516	< MDA	13.50	0.901	0.467	+35° 14' 29.97",+129° 12' 36.43"
18	0.7972	$1.375 x10^{-5}$	< MDA	0.567	< MDA	13.50	1.031	0.499	+35° 14' 13.95",+129° 12' 38.13"
19	8.6900	$2.032 x10^{-5}$	< MDA	1.010	< MDA	14.30	1.565	1.060	+35° 14' 39.25", +129° 5' 52.43"
Means	3.3402	$8.279 x10^{-5}$	1.610	1.500	8.610	24.40	1.930	1.190	
SD	5.7064	$7.375 x10^{-5}$	2.820	1.550	2.950	34.90	2.470	1.400	

Table 2 Activity concentration of ^{238}U, ^{232}Th, ^{137}Cs, ^{40}K and ^{60}Co contained in surface water

Region /Country	^{238}U Bq/L	^{232}Th Bq/L	^{137}Cs Bq/L		^{40}K Bq/L		^{60}Co Bq/L		Direction
			Radioactivity	MDA	Radioactivity	MDA	Radioactivity	MDA	
A	1.988	$4.104 x10^{-5}$	5.740	3.700	< MDA	121.0	10.09	8.67	+35° 15' 49.96",+129° 1' 15.26"
B	0.182	$1.108 x10^{-5}$	1.132	0.915	< MDA	13.20	< MDA	0.933	+35° 7' 44.53",+128° 58' 49.57"
C	0.199	$3.304 x10^{-5}$	< MDA	3.710	< MDA	103.0	3.691	3.680	+35° 7' 32.90",+128° 53' 47.22"
D	0.937	$8.824 x10^{-6}$	0.5553	0.509	< MDA	15.10	< MDA	1.140	+35° 7' 44.53",+128° 58' 49.57"
E	2.462	$8.024 x10^{-5}$	0.6473	0.504	< MDA	1500	0.7072	0.548	+35° 12' 55.07",+129° 3' 39.10"
F	0.271	$1.406 x10^{-4}$	< MDA	0.947	< MDA	14.10	1.075	0.482	+35° 11' 1.32", +129° 8' 37.58"
G	0.254	$2.627 x10^{-5}$	1.217	0.830	< MDA	23.10	2.016	0.891	+35° 7' 25.95", +129° 6' 2.62"
H	0.169	$1.116 x10^{-4}$	< MDA	0.458	< MDA	13.90	< MDA	0.971	+35° 4' 56.80", +129° 2' 47.03"
I	0.440	$3.386 x10^{-5}$	0.9558	0.696	< MDA	18.70	< MDA	1.350	+35° 9' 47.19", +129° 6' 20.23"
J	0.325	$3.796 x10^{-5}$	0.8170	0.694	< MDA	15.70	3.312	0.756	+35° 7'21.66"+129° 1' 1.82"
K	0.268	$7.224 x10^{-5}$	0.7964	0.409	< MDA	14.40	1.044	1.030	+35° 7' 19.25", +129° 1' 47.86"
L	0.188	$2.175 x10^{-5}$	0.4283	0.414	< MDA	12.30	< MDA	0.843	+35° 7' 41.24", +129° 0' 24.89"
M	0.161	$3.054 x10^{-4}$	< MDA	0.502	< MDA	13.70	0.6252	0.924	+35° 15'17.85"+129° 5' 0.90"
N	2.763	$2.401 x10^{-5}$	< MDA	1.070	< MDA	13.30	1.860	0.581	+35° 8' 38.73", +129° 1' 39.36"
O	0.243	$1.794 x10^{-4}$	0.5698	0.476	< MDA	13.60	0.8772	0.425	+35° 9' 46.81", +129° 5' 13.96"
P	4.437	$9.686 x10^{-5}$	< MDA	0.874	< MDA	12.80	0.3913	0.866 [4]	+35° 16' 7.37", +129° 4' 31.93"
Q	0.437	$4.884 x10^{-5}$	0.8305	0.457	< MDA	13.30	< MDA	0.429	+35° 11'21.15",+129°13' 24.01"
R	0.216	$8.057 x10^{-4}$	0.7030	0.502	< MDA	14.00	2.026	0.534	+35° 15'51.09",+129° 12' 42.30"
S	0.198	$1.683 x10^{-5}$	< MDA	0.467	< MDA	12.80	< MDA	0.868	+35° 20' 11.85",+129°16' 39.76"
Means	0.849	$1.103 x10^{-4}$	1.200	0.954	-	103.0	2.310	1.360	
SD	1.191	$1.836 x10^{-4}$	1.450	0.991	-	340.0	2.660	1.090	

Table 3 Activity concentration of ^{238}U, ^{232}Th, ^{137}Cs, ^{40}K and ^{60}Co contained in tap water

Region /Country	^{238}U Bq/L	^{232}Th Bq/L	^{137}Cs Bq/L		^{40}K Bq/L		^{60}Co Bq/L	
			Radioactivity	MDA	Radioactivity	MDA	Radioactivity	MDA
T	$5.282 x10^{-3}$	$1.642 x10^{-6}$	0.488	0.457	<MDA	13.30	1.417	0.908
U	$1.260 x10^{-1}$	$6.382 x10^{-5}$	0.648	0.427	< MDA	14.50	< MDA	0.410
V	$6.236 x10^{-2}$	$5.520 x10^{-5}$	1.200	1.010	< MDA	19.30	1.584	0.672
W	$8.965 x10^{-2}$	$5.931 x10^{-5}$	0.663	0.503	< MDA	13.50	0.590	0.497
Means	$7.084 x10^{-2}$	$4.499 x10^{-5}$	0.749	0.599	-	15.20	1.200	0.622
SD			0.310	0.276	-	2.820	0.532	0.220

< MDA, Less than minimum detectable activity

The analysis of gamma-ray emitting radionuclides in the drinking water indicated that ^{137}Cs, ^{40}K and ^{60}Co exist in some the regions.

Observed in detail, of the 19 samples of the groundwater, ^{137}Cs was detected in eight with a mean concentration of radioactivity of 1.61 Bq/L, ^{40}K was detected in three of them with a mean of 8.61 Bq/L, and ^{60}Co was detected in ten with a mean of 1.93 Bq/L.

Of the 19 samples of the surface water, ^{137}Cs and ^{60}Co were detected in 12 with a mean concentration of radioactivity of 1.20 Bq/L and 2.31 Bq/L respectively. However, ^{40}K was not detected.

Of the four samples of the tap water ^{137}Cs was detected in all four and ^{60}Co in three. ^{40}K, however, showed a value less than the MDA (minimum detectable activity) in all four samples.

According to a 1992 U.S. Department of Energy (DOE) report, the radioactivity of ^{137}Cs in the groundwater ranged between 9.99 x10^{-5} Bq/L and 67.70 Bq/L, and according to a 1999 EPA report, the radioactivity of ^{137}Cs in the groundwater of the Carsbad region in New Mexico ranged between 3.66 Bq/L and 25.20 x10^{3} Bq/L. The U.S. Nuclear Regulatory Commission recommends that ^{137}Cs intake through the drinking water should be less than 37 Bq/L. The different levels are suggested because the report states that the allowable ^{137}Cs intake can be adjusted in consideration of the ameliorating effects of co-existing radionuclides being simultaneously ingested [9].

The comparison of radioactivity concentration of ^{137}Cs between the aforementioned results and those of this study showed a similar value. It is, however, necessary to collect data periodically considering that the radioactivity concentration of artificial radionuclides in the drinking water may change due to possible extenuating factors such as a nuclear power plant accident or atmospheric nuclear test.

2. Comparison of radioactivity concentration of ^{238}U and ^{232}Th in drinking water

A comparison of radioactivity concentrations between the values found in the Busan region and those of overseas regions is presented in Table 4.

The table shows that Finland has the highest amount of ^{238}U (0.5-1.5x10^{5} mBq/L) while India has the lowest (0.09-1.5 mBq/L). In addition, the table shows that Egypt has the highest amounts of ^{232}Th in the both tap water (27.37 mBq/L) and groundwater (31.43 mBq/L), whereas Germany has the lowest value for the tap water (5.18 x10^{-4} mBq/L). ^{238}U and ^{232}Th measured in this study belong to the group with a relatively high value.

Radioactivity concentration of natural radionuclides of each region is greatly affected by geologic structure. Korea is located at the far eastern end of the vast Eurasian continental plate and has a geologic structure very similar to those of China and the Japanese archipelago. In addition, Korea is composed of ancient strata that were formed prior to the paleozoic era, with granite strata widely distributed among igneous rocks [15].

According to NCRP Report No. 94, the Colorado region in the United States has a similar granite geological structure with a relatively higher radioactivity concentration of ^{232}Th, ^{238}U and ^{40}K than those in other regions [16]. The radioactivity concentration of ^{238}U and ^{232}Th are also higher than those in other regions due to condensation of ^{238}U and ^{232}Th occurring because the crystal structure of granite becomes larger and harder as magma slowly cools down [17]. In the case of Korea, where there are many strata of granite that were formed long ago, the radioactivity concentration of natural radionuclides is relatively higher than those having a similar geologic structure. As the groundwater and the surface water are able to move natural radionuclides existing in soil and rocks together with inorganic and organic substances, the geologic structure of that particular region can be an important factor in determining the concentration of radionuclides in the drinking water. Based on this, it is speculated that the radioactivity concentration of natural radionuclides (^{232}Th, ^{238}U, ^{40}K) in the drinking water are higher due to the wide distribution of granite strata in the geologic structure of Korea.

Table 4 Activity concentration of ^{238}U and ^{232}Th contained in the drinking water of various countries

Region /Country	^{238}U mBq/L	^{232}Th mBq/L
North America United States[18]	0.3-77	0.058
China[18]	0.1-700	0.04-12
India[18]	0.09-1.5	-
Finland[18]	0.5-150000	-
France[18]	4.4-930	0-4.2
Italy[19]	0.5-130	0.0008
Poland[18]	7.3	0.06
Romania[18]	0.4-37	0.04-9.3
Switzerland[18]	0-1000	-
Spain[18]	3.7-4.4	-
Egypt(tap water)[20]	-	27.37
Egypt(ground water)[20]	-	31.43
Germany(tap water)[18]	-	0.000518
Iran(surface waters+well)[21]	31988	-
Brazil(ground water)[22][23]	0.1-80	0.30
Argentina(Tap water)[24]	88-70460	-
Argentina(wells)[24]	176-146700	-
Greece((ground water)[25]	29.34-29346.94	-
This study(ground water)	83.19-18860	0.00369-0.2727
This study(surface water)	161.4-4437	0.0088-0.8056

3. Absorbed dose assessment

The absorbed dose of residents who ingested drinking water containing ^{238}U, ^{232}Th, ^{40}K, ^{137}Cs and ^{60}Co was evaluated. Table 5 shows the absorbed dose based on the type of the drinking water. For this study. it was assumed that daily intake of water was two liters.

Table 5 Assessment of the absorbed dose according to the daily intake of drinking water [Unit: Sv/y]

	^{238}U	^{232}Th	^{137}Cs	^{40}K	^{60}Co
Ground water	10.85 x10^{-8}	7.06 x10^{-13}	1.57 x10^{-5}	3.22 x10^{-5}	3.53 x10^{-6}
Surface water	2.76 x10^{-8}	9.33 x10^{-13}	1.17 x10^{-5}	-	4.23 x10^{-6}
Tap water	2.30 x10^{-9}	3.81 x10^{-13}	7.33 x10^{-5}	-	2.20 x10^{-6}

The absorbed doses from natural radionuclides ^{238}U and ^{232}Th in the groundwater were 10.85 x10^{-8} Sv/y and 7.06 x10^{-13} Sv/y respectively. In addition, the absorbed dose of the artificial radionuclide ^{137}Cs in the tap water had the highest value of 7.33 x10^{-5} Sv/y, and ^{60}Co in the surface water showed the highest absorbed dose of 4.23 x10^{-6} Sv/y.

IV. CONCLUSIONS

Based on the results of this study, the radioactivity concentration of ^{238}U in the drinking water within the Busan region in Korea did not exceed the recommendations of either the 15 μg/L of the WHO or the 30 μg/L of the USEPA [7] [26]. In addition, the absorbed dose did not exceed the annual intake limit of 1 mSv that is publicly acceptable. It is, however,

necessary to periodically take measurements due to the ease with which the amount of radionuclides appearing in the drinking water can change. In this study, data was measured in a region with 3.5 million inhabitants. It is necessary to conduct an assessment of the harmful effects these radionuclides possess in this region for the healthcare and safety of the residents with regards to the ingestion of drinking water. Previous assessments of the harmful effects of drinking water were mostly limited to heavy metals. Furthermore, it is difficult to set a standard for radionuclides in drinking water in Korea due to a dearth of relevant information. It is hoped that, based on the findings of this study, a more comprehensive management of drinking water may be realized.

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