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Assessment of dose rate of detected gamma emitting nuclides using a carborne survey with a large volume NaI(Tl) detector

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ABSTRACT

A carborne survey system based on a hexahedral 4″ × 4" × 16″ NaI(Tl) detector was developed to assess the dose rate from ground deposited radionuclides over a wide area. A concept based on dose rate spectroscopy was introduced to the carborne survey to simply and directly calculate the ambient dose rate and dose rates of detected gamma emitting nuclides. In addition, an attenuation correction to account for loading the survey system in a vehicle was established, by calculating the count rate of several ROIs and the dose rate of natural radionuclides at diverse sites with different dose rates levels. All of the results from the carborne survey were then corrected to a dose rate 1 m above the ground in the air, to provide data consistency between diverse survey platforms. An experimental verification was conducted by comparing the dose rates of nuclides measured at the same site from the carborne survey and from in situ gamma-ray spectrometry at a fixed position using a portable HPGe detector. Finally, the developed method of a carborne survey was successfully applied to the evaluation of dose rate around the construction site of a nuclear facility. It is anticipated this result can be used to make a baseline of background radiations in the site before operating the nuclear facility currently under construction.

1. Introduction

The importance of environmental radiation surveys has increased after the nuclear accident at the Fukushima Daiichi nuclear power plant (FDNPP). Determining the dose rate from radionuclides deposited from radioactive fallout can provide information useful to an efficient response and appropriate risk management. In general, high pressure ion chamber (HPIC) and NaI(Tl) detectors have been widely used as environmental radiation monitors to assess the ambient dose rate at fixed positions around nuclear facilities in Korea. Mobile gamma-ray spectrometry based on carborne surveys has also been performed to rapidly monitor the dose rate in widely areas and to build dose rate maps. Various ground-based survey platforms (Andoh et al., 2018; Sanada et al., 2016; Tsuda et al., 2015), such as the backpack and carborne survey systems have also been employed to measure dose rates around contaminated areas at different accident phases, the early, intermediate, and recovery phases.

A carborne survey system based on a large volume NaI(Tl) detector and global positioning system (GPS) was developed to assess the ambient dose rate as well as dose rate induced from detected gamma emitting nuclides. The reliability of the results of the mobile survey system is based on a well-established survey algorithm used to calculate the dose rate from the measured energy spectrum for count rate. Several methods can be used to make a spectrometric determination of the ambient dose rate, including the energy band (HASL, 1972) and G-factor methods (Cho et al., 1998; Moriuchi and Miyanaga, 1966; Tsuda and Saito, 2017). In this study, dose rate spectroscopy (Ji et al., 2014, 2015; 2016) based on the G-factor method was applied to a carborne survey system to determine the ambient dose rate and dose rate due to ground deposits of radionuclides.

Because the carborne survey has a short acquisition time to link the dose rate with GPS data, it was difficult to identify the full energy absorption peaks to calculate dose rates for detected gamma emitting nuclides. A new approach to directly calculate the dose rate by the nuclide using the carborne survey was then introduced by merging all measured energy spectra with a short live time to represent the survey site. Therefore, one energy spectrum merged during the carborne survey could be directly applied to the calculation of dose rates of deposited nuclides in the ground through the peak analysis. All of the carborne survey results were then converted into a dose rate 1 m above the ground in the air with the help of an attenuation correction factor. The calculated results were experimentally verified by comparing them with the

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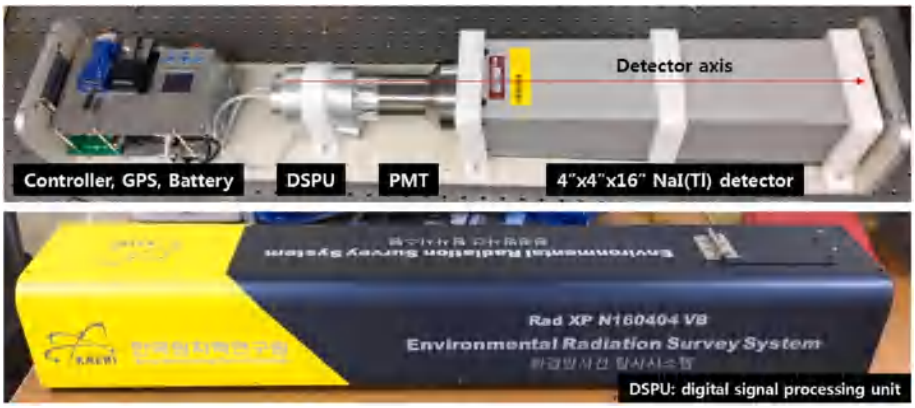

Fig. 1. The carborne survey system based on a large volume NaI(Tl) detector.

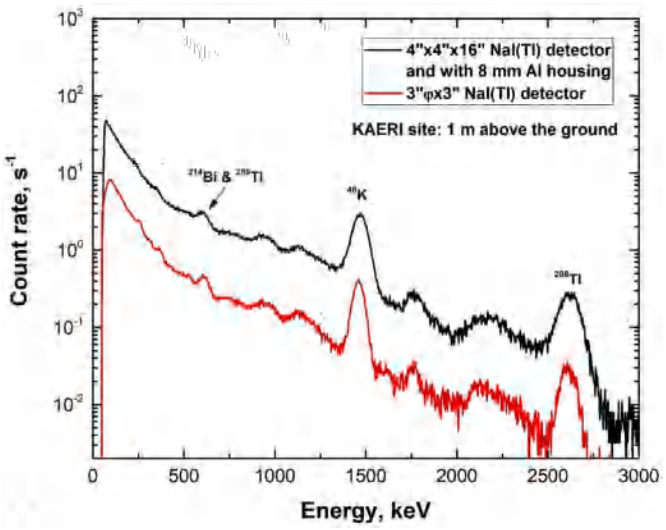

Fig. 2. Measured energy spectra from the developed carborne survey system and a 3″ϕx3″ NaI(Tl) detector at 1 m above the ground in the same site.

results from a portable HPGe detector at the same site. Finally, a carborne survey was successfully conducted in the construction site of a research reactor in Busan, Korea to build the baselines for the dose rate induced from natural radionuclides, before its construction.

2. Material and method

2.1. Carborne survey system

The high counting efficiency carborne survey system based on a large volume NaI(Tl) detector was developed for dose rate mapping on the ground in the environment. This system consists of a hexahedral 4″ × 4" × 16″ NaI(Tl) detector and photomultiplier (PMT) package (SCIONIX Inc., V102 AR 406, NLD), a digital signal processing unit (SI Detection Co. Ltd., HAMPack MCA 527, KOR), controller, GPS, and internal battery in the Al housing, as shown in Fig. 1. The signal processing unit includes a HV power supplier, preamplifier, amplifier and multichannel analyzer (MCA) with 1024 channels. The counting time of incident gamma-rays can be changed by intervals of 1 s from the minimum live time of 1 s. The measured energy spectra and GPS data during the dedicated counting period are then transferred to a PC through a Bluetooth interface.

Fig. 2 shows a comparison of the energy spectrum measured by the developed carborne survey system and a 3″ϕx3″ NaI(Tl) detector at 1 m above the ground for the same site. The total count rate from 50 to 3000 keV in the large volume NaI(Tl) detector was about five times that of the 3 inch NaI(Tl) detector. In the peak analysis, the net count rate was calculated using three peak ROIs, the multiplet of 583 and 609 keV from ^{208}Tl and ^{214}Bi, and two singlets of 1461 and 2615 keV from ^{40}K and ^{208}Tl, for both spectra. The results are shown in Table 1. For the clear peaks of the two singlets, about ten times higher net count rate was achieved in the developed carborne survey system, because of the relatively low Compton continuum compared with the net peak area. On the other hand, about five times higher net count rate was achieved in the weak peak, such as the multiplet of 583 and 609 keV, due to the relatively high Compton continuum.

Table 1
Comparison of measured net count rates using survey system based on 4″ × 4" × 16″ and 3″ϕx3″ NaI(Tl) detectors at the same site.

Peak	Major Nuclide	Photon energy (keV)	Net count rate (s^{-1})		Ratio
			4″ × 4" × 16″ NaI(Tl)	3″ϕx3″ NaI(Tl)	
1	^{214}Bi and ^{208}Tl	609 and 583	12.8 ± 0.7	2.41 ± 0.20	5.3
2	^{40}K	1461	79.9 ± 0.6	8.73 ± 0.14	9.2
3	^{208}Tl	2615	9.87 ± 0.21	0.95 ± 0.04	10.4

2.2. Dose rate spectroscopy

2.2.1. Ambient dose rate

To estimate the dose rate from the measured energy spectrum for counts using a gamma-ray spectrometer, the dose rate calculation method should be prepared for the gamma-ray spectrometer used. In this study, the G-factor, which is the dose conversion factor from the measured count rate (s^{-1}), of the developed carborne survey system was calculated from a Monte Carlo simulation. According to Eq. (1), the ambient dose rate can be simply calculated from the measured count rate and G-factor by integrating their multiplication for all energy bins.

$$\dot{X} = \int n(E)G(E)dE \quad (1)$$

where $\dot{X}$ is the ambient dose rate, E means the photon energy, n(E) is the measured count rate, and G(E) is the dose conversion factor in the unit of nGy·h^{-1}·s.

First, the MCNP (Monte Carlo N-Particles) code was used to calculate the theoretical energy spectra for count rate by simulating the vertically incident photon fluence to the detector axis with an energy from 50 to 3000 keV. Fig. 3 shows the simulation process for both cases, with and without the Al housing. The detector response matrix of a large volume

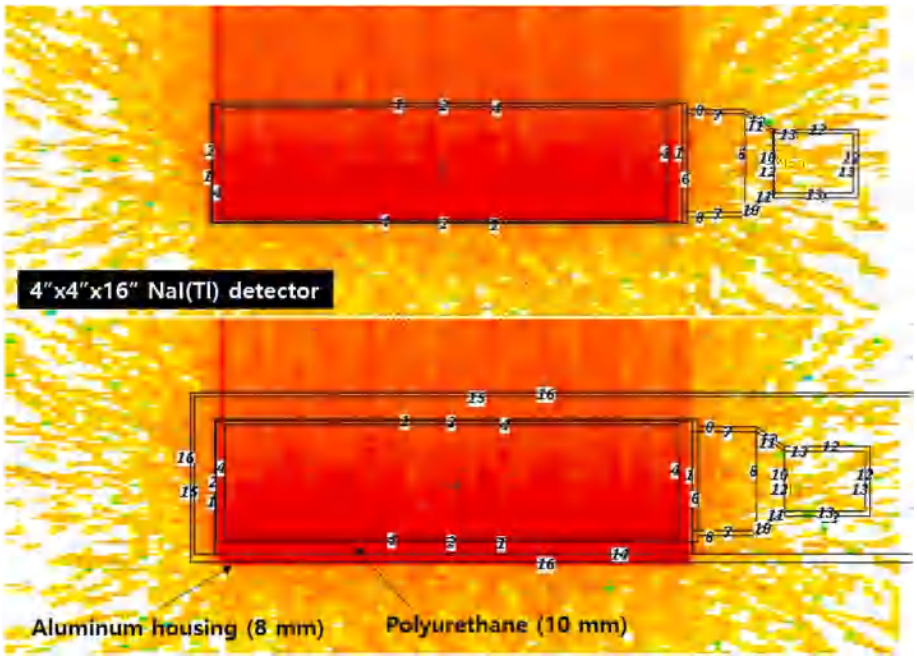

Fig. 3. The MCNP simulation process used to calculate the detector response.

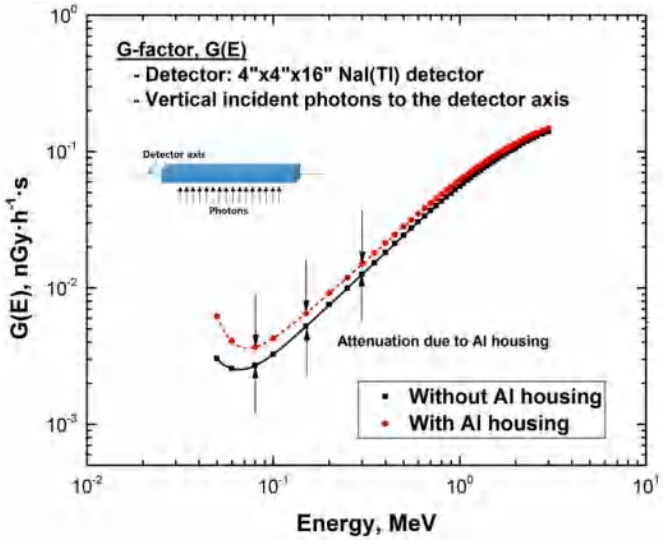

Fig. 4. The G-factor of the developed carborne survey system equipped with a 4″ × 4" × 16″ NaI(Tl) detector.

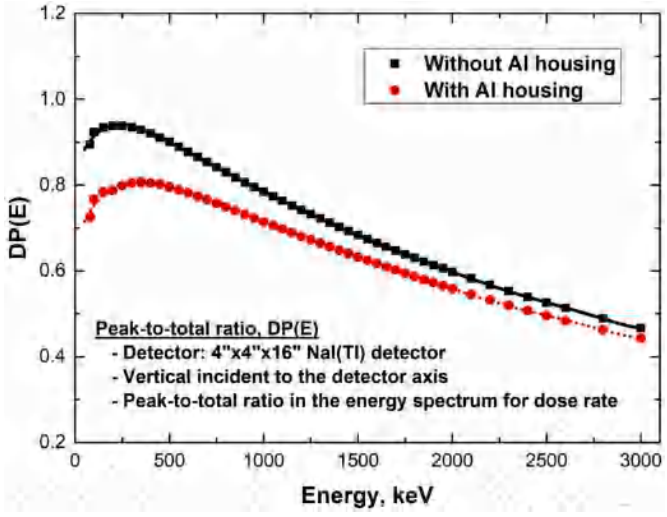

Fig. 5. The peak-to-total ratio in the energy spectrum for dose rate using the developed carborne survey system.

NaI(Tl) detector was made by arranging and dividing theoretical energy spectra for count rate into the same energy bins. The G-factor of the developed carborne survey system was then obtained from the matrix calculation of calculated detector response and conversion coefficient of the photon fluence into the dose rate, as shown in Fig. 4, by employing a previous calculation procedure (Ji et al., 2014). The difference between the two cases, meaning the G-factors without and with Al housing, is the dose rate attenuation due to the housing materials.

2.2.2. Dose rate of a detected gamma emitting nuclide

According to the dose rate spectroscopy, the dose rate of a detected gamma emitting nuclide can be calculated from the measured net count rate of gamma-rays emanating from a nuclide by using Eq. (2).

$$\dot{X}_i = \frac{\dot{n}(E)}{W(E)} \frac{G(E)}{DP(E)} \frac{1}{CR_i(E)} = \frac{\dot{X}(E)}{W(E)DP(E)} \frac{1}{CR_i(E)} \quad (2)$$

where, $\dot{X}_i$ is the dose rate of a detected gamma emitting nuclide, $\dot{n}(E)$ is the measured net count rate in the real geometry of incident gamma-rays with diverse angles, $\dot{X}(E)$ means the net dose rate and can be made by multiplying measured net count rate and value of G-factor in the same photon energy, W(E) means the angular correction factor (Helfer and Miller, 1988; ICRU, 1994; ISO, 2013) in the form of the ratio of net count rate with diverse incident angles at a given geometry to one for the vertical incidence to the detector axis, which is the same incident direction of the simulation process to calculate a G-factor, DP(E) is the peak-to-total ratio with respect to the net dose rate, and finally, $CR_i(E)$ is the contribution ratio of one gamma-ray to the dose rate of nuclide i.

First, the peak-to-total ratio of the carborne survey system was

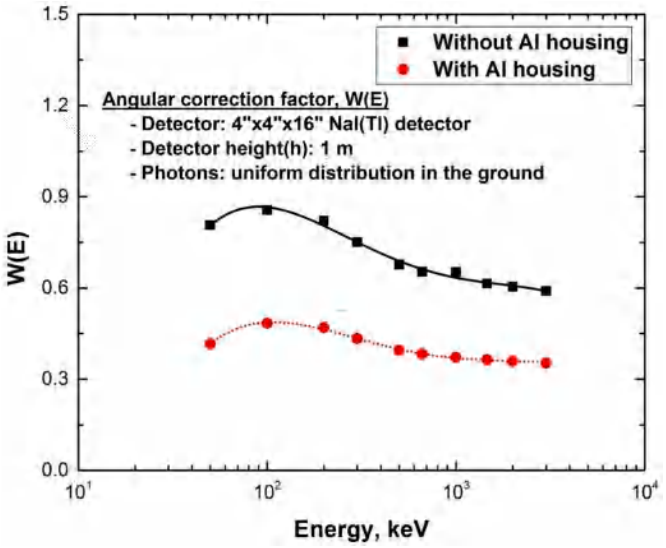

Fig. 6. The angular correction factor for the measured net count rate using the carborne survey system.

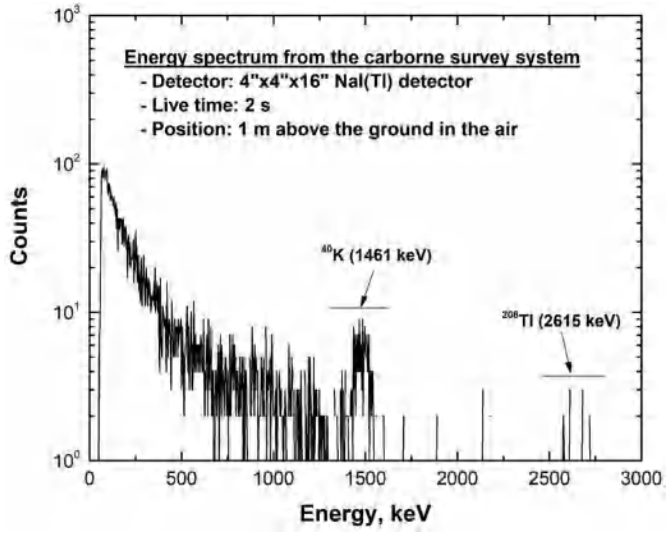

Fig. 7. An example of the measured energy spectrum from the carborne survey system during a live time of 2 s.

calculated using theoretical energy spectra for count rate. In the calculation of a G-factor, fifty energy spectra for count rate were made by simulating the incident photon fluence to carborne survey system with an energy from 50 to 3000 keV, respectively. All theoretical energy spectra for count rate were then converted into those of dose rate by multiplying the energy spectrum for count rate and G-factor. The net peak and total areas were finally calculated through all theoretical energy spectra for the dose rate. The results are shown in Fig. 5, representing the peak-to-total ratios in the energy spectrum for dose rates without and with the Al housing materials, respectively.

To calculate the dose rate for detected gamma emitting nuclides using dose rate spectroscopy, the net dose rate, which means the net peak area in the energy spectrum for dose rate, should first be calculated by multiplying the measured net count rate and G-factor. However, the measured net count rate in the carborne survey results reflects real incident photons with diverse angles. In comparison, the simulation process for the G-factor and peak-to-total ratio only reflect the direction vertical to the detector axis. This difference is particularly important since the net count rate obtained from the full energy absorption process of incident photons highly depends on their incident angles to the detector. Therefore, an angular correction needs to be applied to the measured net count rate to represent the same direction used in the G-factor and peak-to-total ratio, as shown in Eq. (2).

This factor was calculated using the Monte Carlo simulation based on two factors, which mean the angular dependence of the detector response and angular distribution of incident photons at the detector position. The angular dependence of a detector response was evaluated by simulating incident photons at several cosine angles and calculating the ratio of peak count rate induced from simulated photons at cosine angles to one at vertical incident to the detector axis. A previously reported result (Ji et al., 2016) was used to obtain the angular distributions of unscattered photons at 1 m above the ground, which were induced from the uniformly distributed photons in the half-space of the ground. Finally, the angular correction factor is shown in Fig. 6, without and with the Al housing materials, respectively.

The dose rate of a nuclide with several gamma-rays consists of the summation of ones induced from all gamma-rays. Therefore, the contribution ratio means the dose rate ratio induced from only one gamma-ray and all gamma-rays emanating from a nuclide. The MCNP code was used to calculate the dose rate in the detector material of a carborne survey system by distributing one gamma-ray and all gamma-rays of a nuclide at a given geometry.

2.3. The carborne survey method

When using diverse survey platforms to assess the ground deposition of nuclides, all survey results should be corrected to represent them in the air 1 m above the ground in order to maintain data consistency from different detectors, loading positions in the carborne survey, and vehicles. In this study, because the developed carborne survey system was loaded on the floor of the trunk, the attenuation correction due to its position in the car was applied to the carborne survey results to represent the condition, that is, 1 m above the ground in the air. A method of attenuation correction to the measured count rate as well as dose rate from the carborne survey was developed by measuring energy spectra inside and outside a car at a fixed position before starting the carborne survey, using a sufficient counting time, as shown in Eqs. (3) and (4).

$$C_{n,att} = \left(\frac{\dot{n_{car}}}{\dot{n_{air}}}\right)_{fixed} \tag{3}$$

$$C_{\dot{X},att} = \left(\frac{\dot{X}_{car}}{\dot{X}_{air}}\right)_{fixed} \tag{4}$$

where, $C_{n,att}$ and $C_{\dot{X},att}$ are the attenuation correction factor of the measured net count rate and dose rate in the carborne survey system, respectively, $\dot{n}$ and $\dot{X}$ are the measured net count rate and dose rate, the indices of the car and air mean the detector position, that is, its loaded position in the carborne survey and 1 m above the ground in the air, and the index of fixed means the fixed position, before the carborne survey, in the car or the air. The net count rate was calculated to evaluate the attenuation correction factor for specific ROIs. Using the same method, the attenuation of dose rate should be calculated with respect to the ambient dose rate as well as dose rate by the nuclide.

Dose rate spectroscopy requires calculating the net count rate in the measured energy spectrum to assess the dose rate for the detected gamma emitting nuclides. However, it is not possible to identify the net count rate in the mobile gamma-ray spectrometry with a short acquisition time. Fig. 7 shows the measured energy spectrum from the carborne survey system during the live time of 2 s at 1m above the ground in the air. The Compton continuum is not clear for the whole energy range or even in the gamma-ray peak of ^{40}K with a relatively high activity level in the ground. To address this, all energy spectra with a short live time, which were measured in the specific site to be assayed, were merged into one energy spectrum to represent the averaged result in the survey site. This merged energy spectrum was then applied to the dose rate

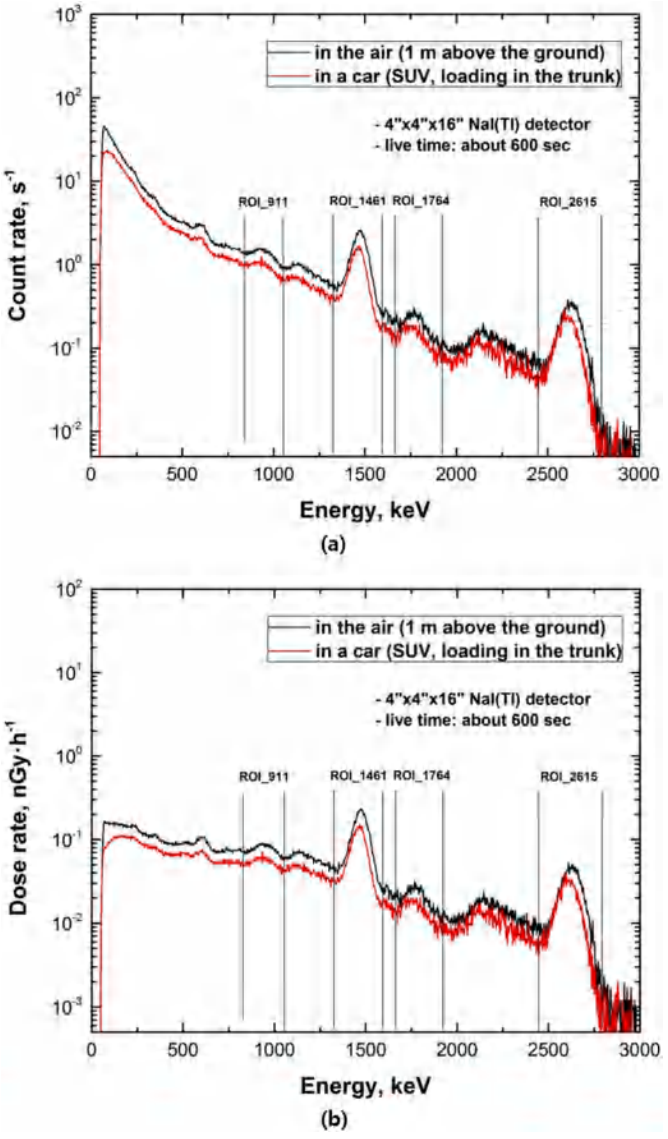

Fig. 8. Examples of the measured energy spectrum for count rate (a) and dose rate (b) taken for 600 s at a fixed position.

spectroscopy to determine the dose rate of detected gamma emitting nuclides using the carborne survey.

Finally, the ambient dose rate at 1 m above the ground can be obtained by applying the attenuation correction factor of dose rate, $C_{\dot{X},att}$, to the dose rate directly measured from the carborne survey, as shown in Eq. (5). The information for dose rates for gamma emitting nuclides detected at 1 m above the ground can also be obtained from the merged energy spectrum during the carborne survey based on a large volume NaI(Tl) detector, according to Eq. (6).

$$\dot{X}_{1m} = \frac{\dot{X}_{car}}{C_{\dot{X},att}} \tag{5}$$

$$\dot{X}_{i,1m} = \frac{n'_{car}(E)}{W(E)} \frac{1}{C_{n,att}(E)} \frac{G(E)}{DP(E)} \frac{1}{CR_i(E)} \tag{6}$$

where, $\dot{X}_{1m}$ and $\dot{X}_{i,\,1m}$ are the ambient dose rate and dose rate by the nuclide at 1 m above the ground in the air, $\dot{X}_{car}$ is the ambient dose rate measured from the carborne survey, and n'_{car} means the net count rate in the ROI from the carborne survey.

Table 2
ROIs around the major gamma-ray peaks of four natural radionuclides in the measured energy spectrum using a large volume NaI(Tl) detector.

ROI	Energy range (keV)
ROI_911	850–1050
ROI_1461	1340–1580
ROI_1764	1680–1850
ROI_2615	2480–2750

Table 3
The attenuation correction factor for the detector's position in a car, for the developed carborne survey system based on a 4″ × 4″ × 16″ NaI(Tl) detector.

ROI	$C_{n,att}$	Dose rate	$C_{\dot{X},att}$
50–3000[a]	0.671 ± 0.013[b]	Ambient	0.686 ± 0.029
ROI_911	0.522 ± 0.089	^{228}Ac	0.521 ± 0.043
ROI_1461	0.580 ± 0.043	^{40}K	0.592 ± 0.035
ROI_1764	0.745 ± 0.071	^{214}Bi	0.777 ± 0.084
ROI_2615	0.690 ± 0.074	^{208}Tl	0.680 ± 0.031

[a] ROI from 50 to 3000 keV.
[b] Gross count rate.

3. Results and discussion

3.1. Attenuation correction factor

To ensure consistency in the survey results when using diverse mobile gamma-ray spectrometry, all measured data from the carborne survey should be converted into dose rate at 1 m above the ground in the air. The attenuation correction for position in the car is an important factor to discuss before undertaking the carborne survey. The energy spectrum using the developed carborne system was then measured at 1 m above the ground in the air, and measured again at the loading position of the survey system, for a period of about 1800 s in the same site. Fig. 8 shows examples of measured energy spectra for count rate (a) and dose rate (b). The count rate was first calculated in the full energy region as well as specific ROIs, such as regions with gamma-rays of 911, 1461, 1764, and 2615 keV from ^{228}Ac, ^{40}K, ^{214}Bi, and ^{208}Tl, respectively. Table 2 shows the dedicated energy range in the ROIs, which was determined from the measured energy spectrum obtained during sufficient counting time. In addition, the ambient dose rate and dose rate of four natural radionuclides were calculated in the energy spectrum for dose rate, using the dose rate spectroscopy. This measurement was repeated at several sites with different ambient dose rate levels and geometries, that is, flat land without any obstacles and a road surrounded with hills.

The averaged values of results from diverse sites with different dose rates and geometries are shown in Table 3, divided into two parts, of count rate and dose rate, according to Eqs. (3) and (4). The attenuation correction factor of the count rate and dose rate is then presented in the range from 0.5 to 0.8 for the developed carborne survey system. The similar attenuation correction factor was shown between the gross count rate from 50 to 3000 keV and ambient dose rate. In particular, the correction factor in the dose rate of four natural radionuclides was also similar to one in the net count rate of four ROIs with major gamma-rays induced from those nuclides, respectively. However, the important thing is the attenuation correction factor does not highly depend on the dose rate level and measurement geometry, as shown by the low standard deviation of the results. This means calculating the attenuation correction factor once is sufficient to correct the survey results into those at 1 m above the ground in the air.

Table 4
The contribution ratio of one gamma-ray to the dose rate of a nuclide at 1 m above the ground.

ROI	Nuclide	Gamma-ray	
		Energy (keV)	$CR_i(E)$
ROI_911	^{228}Ac	911	0.368
		965	0.075
		969	0.238
ROI_1461	^{40}K	1461	1.000
ROI_1764	^{214}Bi	1730	0.039
		1764	0.215
ROI_2615	^{208}Tl	2615	0.809

3.2. Contribution ratio

To calculate the dose rate of detected gamma emitting nuclides during carborne survey using a NaI(Tl) detector, the contribution ratio of one gamma-ray to the dose rate of a nuclide was used as shown in Eq. (6). It was then calculated from the Monte Carlo simulation by uniformly distributing simulated one gamma-ray or all gamma-rays from a nuclide in the ground of infinite half space with a sufficient thickness of about 100 cm. Theoretical dose rates in the detector material were obtained from the MCNP code in the case of two different distributions of gamma-rays of a nuclide. The ratio between two results of one and all gamma-rays distributed in the same geometry was finally used as the contribution ratio of a nuclide.

Table 4 shows the calculation results of the contribution ratio of four natural radionuclides. Because three gamma-rays emanating from ^{228}Ac are contributing in the ROI_911, the summed value of contribution ratios was used to calculate the dose rate of ^{228}Ac from measured net count rate in that ROI, according to Eq. (6). The dose rate of ^{214}Bi was also calculated from the net count rate in the ROI_1764 and two contribution ratios of gamma-rays of 1730 and 1764 keV. In this study, the contribution ratios for four natural radionuclides, such as ^{214}Bi, ^{228}Ac, ^{208}Tl, and ^{40}K, were calculated for the purpose of making baselines for the dose rate of natural radionuclides in a specific site using the carborne survey with a NaI(Tl) detector.

3.3. Carborne survey results

3.3.1. Experimental verification

After preparing the attenuation correction and contribution ratio to directly measure the ambient dose rate and dose rate by the nuclide at 1 m above the ground, the carborne survey was conducted at a reference site with an area of about 50 × 100 m^2. Two survey speeds of 5 and 15 km h^{-1} were employed for the site survey. An acquisition time of 2 s was designated for the carborne survey system, and the energy spectra of incident gamma-rays were periodically collected through a large volume

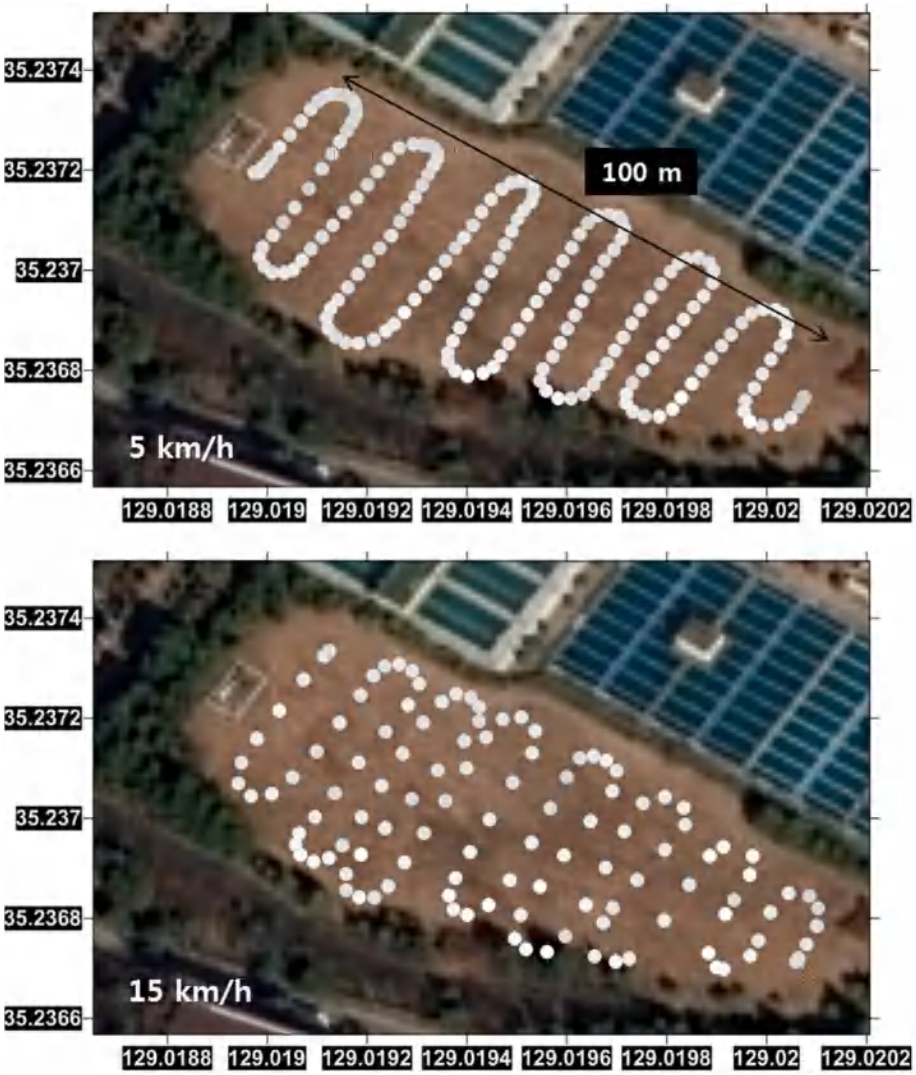

Fig. 9. Tracks of carborne survey for survey speeds of 5 (up) and 15 (down) km·h^{-1}.

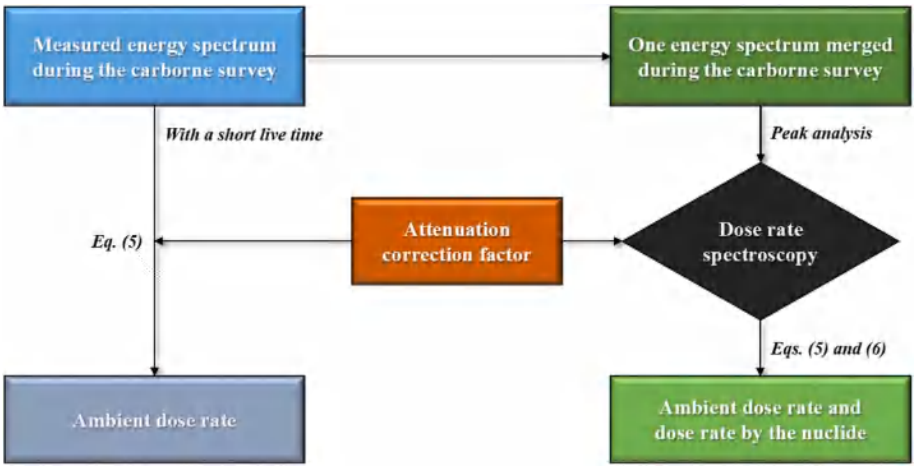

Fig. 10. The procedure of the carborne survey to calculate the ambient dose rate and dose rate of detected gamma emitting nuclides.

Table 5
The results of the carborne survey based on 4″ × 4" × 16″ NaI(Tl) detector according to survey speed at the same site.

Analysis type	Survey speed: 5 km h^{-1}		Survey speed: 15 km h^{-1}	
	Dose rate	$\dot{X}_{1m}$(nGy·h^{-1})	Dose rate	$\dot{X}_{1m}$(nGy·h^{-1})
All energy spectra	Ambient	58.1 ± 2.2	Ambient	58.1 ± 2.6
Merged one energy spectrum	Ambient	58.4 ± 2.2	Ambient	59.1 ± 2.6
	^{214}Bi	6.04 ± 0.53	^{214}Bi	6.72 ± 1.24
	^{228}Ac	4.98 ± 0.58	^{228}Ac	5.97 ± 0.88
	^{208}Tl	12.0 ± 0.3	^{208}Tl	11.6 ± 0.4
	^{40}K	27.8 ± 0.4	^{40}K	27.7 ± 0.5

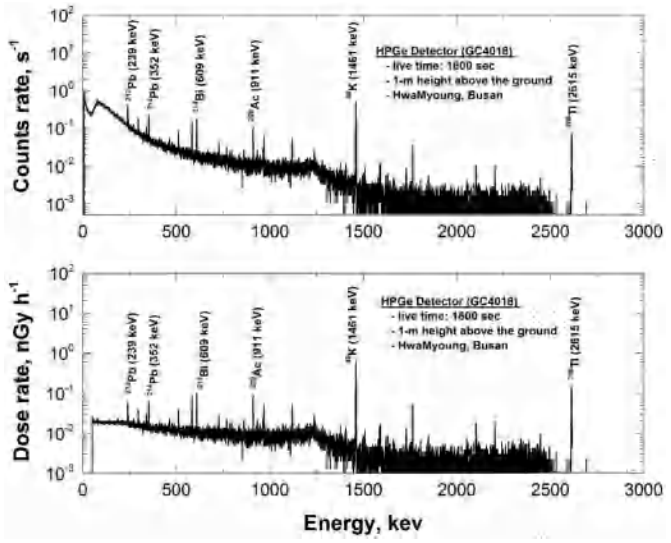

Fig. 11. The measured energy spectrum for count rate (up) and dose rate (down) using a portable HPGe detector.

NaI(Tl) detector during the site survey, linked with the GPS data.

The tracks of the carborne survey are shown in Fig. 9 according to survey speed. Points were marked with GPS data, so denser points indicate lower speeds. For all measured energy spectra with a live time of 2 s, the ambient dose rates were calculated from Eq. (1) to determine the dose rate within the survey vehicle, and then Eq. (5) was used to convert it into one 1 m above the ground in the air. In addition, all measured energy spectra during carborne survey were merged into one

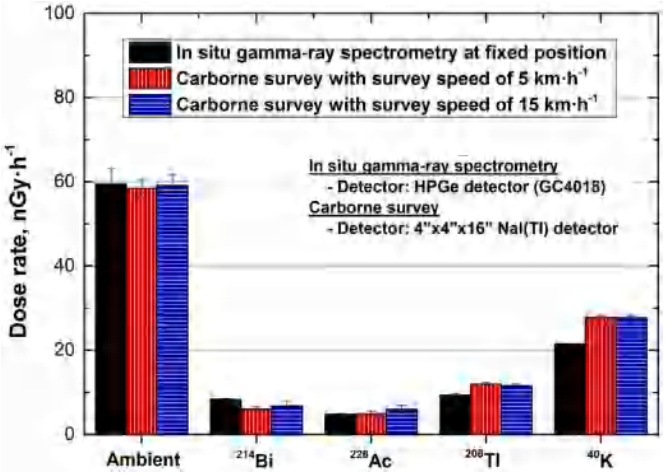

Fig. 12. The comparison of the results from the calculated dose rates from a portable HPGe detector at a fixed position and carborne survey with different survey speeds.

energy spectrum to calculate the averaged dose rates in the whole survey area. The ambient dose rate at 1 m above the ground was re-calculated from the merged energy spectrum with the same method using Eqs. (1) and (5). Using Eq. (6), the dose rates of ^{214}Bi, ^{228}Ac, ^{208}Tl, and ^{40}K were finally determined from the net count rate in the merged energy spectrum during the carborne survey. Fig. 10 shows the procedure of the carborne survey to calculate the ambient dose rate and dose rate of detected gamma emitting nuclides.

Table 5 shows the results of the carborne survey according to the survey speed at the same site. Two results based on survey speed were in good agreement for ambient dose rate as well as dose rate of four natural radionuclides. The summation of dose rates of four radionuclides accounted for about 50.8 ± 0.9 and 52.0 ± 1.6 nGy h^{-1} in the case of the survey speed of 5 and 15 km h^{-1}, respectively. The results were shown to be about 87.5% of the ambient dose rate. It can be estimated that the rest is induced from scattered photons with the surrounding detector material and other natural radionuclides, such as ^{214}Pb, ^{212}Pb, and ^{212}Bi.

To verify the results from the carborne survey, in situ gamma-ray spectrometry based on a portable HPGe (high purity Ge) detector was conducted at a fixed position in the same site. Fig. 11 shows the measured energy spectra for count rate and the converted one for dose rate using the G-factor of the HPGe detector. Following the procedure for dose rate spectroscopy using a HPGe detector (Ji et al., 2016), the ambient dose rate and dose rate of the natural radionuclides were then

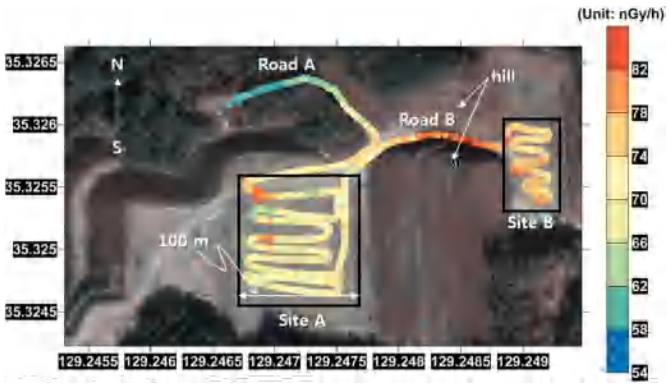

Fig. 13. The track of carborne survey results marked with ambient dose rate and GPS data from the construction site of a research reactor in Busan, Korea.

Table 6
The results of carborne survey based on 4″ × 4" × 16″ NaI(Tl) detector in the construction site of a research reactor in Busan, Korea.

Analysis type	Dose rate	$\dot{X}_{1m}$ (nGy·h^{-1})			
		Road A	Road B	Site A	Site B
All energy spectra	Ambient	59.0 ± 5.6	74.1 ± 3.6	69.3 ± 5.0	73.7 ± 2.2
Merged one energy spectrum	Ambient	56.6 ± 5.4	73.2 ± 3.6	67.8 ± 4.9	72.6 ± 2.2
	^{214}Bi	6.92 ± 0.94 (12.2%)[a]	12.2 ± 2.3 (16.7%)	6.31 ± 0.58 (9.31%)	11.8 ± 1.8 (16.2%)
	^{228}Ac	6.11 ± 0.56 (10.8%)	9.08 ± 2.75 (12.4%)	6.59 ± 0.42 (9.72%)	8.58 ± 1.18 (11.8%)
	^{208}Tl	10.8 ± 0.4 (19.1%)	16.4 ± 0.7 (22.4%)	12.7 ± 0.3 (18.7%)	11.6 ± 0.5 (16.0%)
	^{40}K	27.3 ± 0.5 (48.2%)	37.5 ± 1.0 (51.2%)	33.5 ± 0.3 (49.4%)	37.9 ± 0.6 (52.2%)

[a] ( ): the nuclide contribution to the ambient dose rate.

calculated from an analysis of the energy spectrum for dose rate. The comparison results are shown in Fig. 12. The column without a pattern represents the HPGe detector at the fixed position, and the columns with patterns of vertical and horizontal lines indicate the carborn surveys at 5 and 15 km h^{-1}, respectively. Similar results were achieved in the ambient dose rate using the mobile and ground-based gamma-ray spectrometry. In addition, less than 30% difference in the dose rates of four natural radionuclides was shown between the carborne survey around the site and the results from the portable HPGe detector in the fixed position of the site.

3.3.2. *Application to the site survey*

After verification of the survey results at the characterized site using the HPGe detector, a carborne survey was conducted at a construction site for a research reactor in Busan, Korea to assess the dose rate and build the baselines for natural radionuclides before its construction. Fig. 13 shows the track of the carborne survey with a survey speed of 15 km h^{-1} marked by ambient dose rate and GPS data. Two sites and roads, which were named A and B, respectively, were characterized with respect to the dose rate. Because of the bluff on the north side of road A, the measured dose rate was lower than any other parts. On the other hand, a high dose rate was measured in the road B due to the surrounding hills on both sides. The high dose rate was also more distributed at site B compared with site A, because of the surrounding hills in four directions.

Table 6 shows the survey results divided into four parts, indicating roads A and B and sites A and B. All of the survey results were converted into 1 m above the ground in the air. The values in the parenthesis mean the nuclide contribution to the ambient dose rate, that is, the dose rate of ^{214}Bi accounted for about 12.2% of the ambient dose rate of road A. In general, the nuclide contributions were quite constant per nuclide between road A and site A as well as road B and site B, respectively, in the four survey results. Because of the high contribution of ^{40}K, it could be concluded that the ambient dose rate largely depended on variations in the concentration of ^{40}K in the ground. As a result, these results of carborne survey in the construction site of a research reactor can be used to evaluate the baseline of dose rate induced from background radiations in the site before its operation.

4. Conclusions

A carborne survey system based on a 4″ × 4" × 16″ NaI(Tl) detector was developed to assess the ambient dose rate and dose rate for detected gamma emitting nuclides. A dose conversion algorithm from the measured count rate in the energy bins was equipped in the system from a Monte Carlo simulation. In addition, the dose rate spectroscopy to estimate the dose rate for detected gamma emitting nuclides was applied to the carborne survey by merging all measured energy spectra with a short live time and calculating the net count rate of gamma-rays in the merged spectrum. Using the carborne survey, a procedure was then developed to produce information on all dose rates at 1 m above the ground by applying an attenuation correction and contribution factor. Experimental verification was conducted at a reference site using a portable HPGe detector, to compare the results of dose rates from the carborne survey with those from in situ gamma-ray spectrometry at a fixed position. Good agreement was achieved for the ambient dose rate and dose rate for detected gamma emitting nuclides. This means the procedure developed to calculate the dose rate by nuclide can produce reliable results using carborne surveys.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pnucene.2020.103272.

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