Chapter 10
Time Trend Change of Air Dose Rate on Paved Areas in Fukushima City After the Fukushima Daiichi NPP Accident

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Abstract The Kinki University Atomic Energy Research Institute investigated radioactive contamination resulting from the Fukushima Daiichi Nuclear Power Plant accident in urban areas of Fukushima City, Fukushima Prefecture, Japan. Activity measurement of the surface soil and a survey of the dose rate distribution in urban areas were performed. From the results of this research, dose rate changes in paved areas became clear, and gradients of the dose rate decrease for different paving materials were measured and analyzed.

Keywords Activities • Distribution • Dose rate

10.1 Introduction

On March 11, 2011, the Tohoku Region Pacific Coast Earthquake and the subsequent tsunami occurred, causing the Fukushima Daiichi Nuclear Power Plant (Fukushima Daiichi NPP) accident. As a result of the failure of the NPP's coolant systems, hydrogen explosions occurred that released radioactive materials to the general environment [1–6].

The released radioactive materials were dispersed as radioactive plumes over wide ranges of the Tohoku and Kanto regions. These radioactive plumes were deposited to grounds, building surfaces, and other substrates through several processes. Several surveys tried to measure the contamination in general environments [1–6].

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The Kinki University Atomic Energy Research Institute (Kinki University AERI) has conducted research in the Fukushima area since the middle April of 2011 [6]. Two types of measurement were conducted: the measurement of the activity of radioactive materials in surface soils and the measurement of dose rate distributions in urban areas. From these measurements, it became clear that the concentration of radioactive materials that had dispersed from the Fukushima Daiichi NPP decreased faster than the physical half-lives of the radioactive materials themselves in the urban parts of the Fukushima Naka-Dori area.

In this chapter, the methods used and some of the results of the measurements are presented.

10.2 Methods

Kinki University AERI researched radioactive materials at Fukushima station (East Japan Railway Company) neighborhoods, which is located at the center of the downtown of Fukushima city. This place is 60 km from the Fukushima Daiichi NPP in a northwestern direction. The dose rate in the downtown area was more than ten times greater than the published environmental background dose rate [6, 9].

Two types of research were undertaken in this work: the first was a dose rate survey, and the other was an activity measurement for surface soils in the urban area. The measurement area of the dose rate survey and the surface soil sampling point for activity measurement are shown in Fig. 10.1. These places are in a 1-km neighborhood, because quantities of fallen radioactive materials in a unit square footage and ratios of radioactive nuclides were thought to be similar in these research locations. Both studies have continued since April 2011.

The methods of the two studies are described in the following sections.

10.2.1 Measurement of the Radioactivity in Surface Soils

Surface soils have been collected since April 2011. Figure 10.2 shows a photograph of the soil sampling location. Soil samples were collected from a 30×30 cm^2 area and a ground depth of 1 cm with a scoop at the center of the ground (Fig. 10.2). The collected soils were mixed and packed in U-8 sample cases at the sampling place. These samples were measured with a high pure germanium detector at Kinki University AERI in Osaka that was calibrated with a standard volume source, and the measured gamma spectrum was analyzed using the nuclide library of ORTEC EG&G. Measurement time was 1,800 s for each sample. The data include a summing effect correction and a self-shielding effect correction.
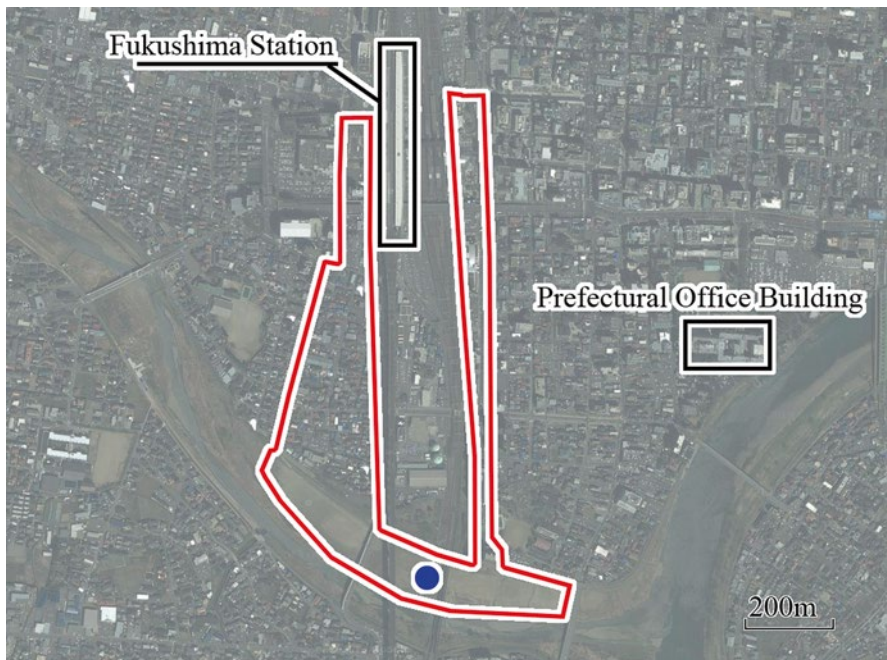
Fig. 10.1 Map of the research area in Fukushima City. *Red line*, research area for a dose rate measurement; *blue point*, sampling point of surface soils for a specific activity measurement

Fig. 10.2 Photograph of soil sampling point taken April 17, 2011. Soil samples were taken at the center of this ground

10.2.2 Dose Rate Distribution Survey

In this measurement, a GPS-linked NaI(Tl) scintillation counter [7] was used to simultaneously record the dose rates and location. The GPS-linked NaI(Tl) scintillation counter includes three components: the first component is the radiation detection unit, which uses a NaI(Tl) survey meter (TCS-171; Hitachi-Aloka Medical) and a microcomputer board (CQ-V850; ESP); the second component is the GPS receiver unit, which uses a USB-linked GPS receiver (UMGPS/MF; IODATA; GPS receiver chip, SiRF StarIII); and the last component is a data acquisition unit, an Ultra-Mobile PC (FM-V BIBLO LOOX U/ C30; Fujitsu). The radiation detection unit and the GPS receiver unit are linked to the data acquisition unit where dose rate and GPS data are saved. The data acquisition software was developed and built using the Visual C#/ .NET Framework (Microsoft).

The whole system was put in a portable bag with the detection head of the radiation detector positioned 50–60 cm above ground, and the measurement was taken while walking at a speed of about 100 m/min. The height of the radiation detector was determined from the limits of the detector equipment.

In the research area, there are some typical areas paved with different materials. Figure 10.3 shows a cushion paving area, Fig. 10.3b is a block paving area, and

Fig. 10.3 Sites for dose rate distribution measurement photographed July 17, 2011: cushion paving area (**a**), block paving area (**b**), and normal asphalt paving area (**c**). Dose rates were measured by walking at the center of the walkway

Fig. 10.3c is a normal asphalt paving area. Dose rates were measured with walking at the center of the walkway in the photographs.

10.3   Results

10.3.1   Measurement of the Radioactivity in Surface Soils

Results of the measurements ranging from April 2011 to July 2012 have already been published [6, 8, 9]. Almost all the radioactive nuclides from the Fukushima Daiichi NPP decayed to approximately background levels by the middle of 2011, except for ^{134}Cs and ^{137}Cs. Figure 10.4 shows a time trend of ^{137}Cs activity in ratios for the April 17, 2011 sample. Figure 10.4 shows a radical decrease between September 2011 and October 2011 as a result of water exposure of the sampling place by a typhoon [No. 15 (2011), named Roke]. It is surmised that the water exposure carried away thickly contaminated surface soils from the place, bringing lightly contaminated muds. After a few months, an increase is seen between April 2012 and May 2012 because of the change of sampling soil type. Until April 2012, I sampled sand-type soil that is similar to the ground surface soil before the water exposure. Since May 2012, I sampled mud-type soil that is presumed to have come with water exposure. With this change, ^{137}Cs activity increased. Furthermore, the ^{137}Cs activity decreased drastically again between January 2013 and February 2013. In this period, decontamination of the sampling point was carried out by Fukushima City, and as a result the ^{137}Cs activity decreased.
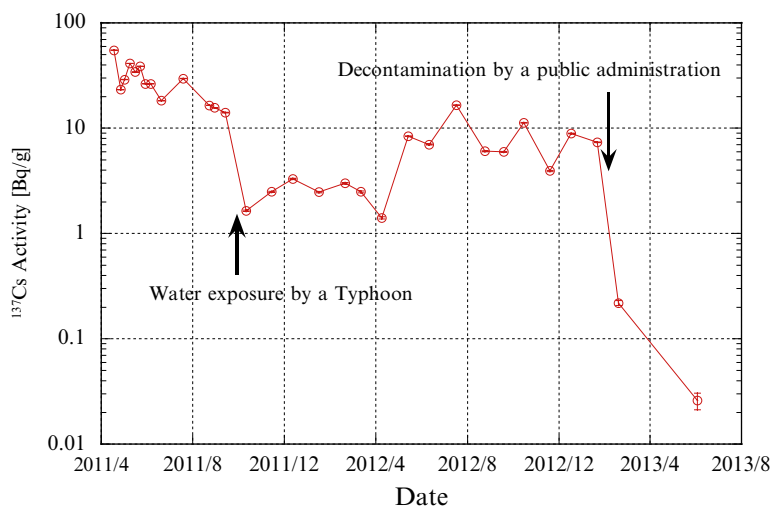

Fig. 10.4   Time trend change of ^{137}Cs activity of surface soil samples. *Horizontal axis*, date; *vertical axis*, specific activity; *circles*, measured activities
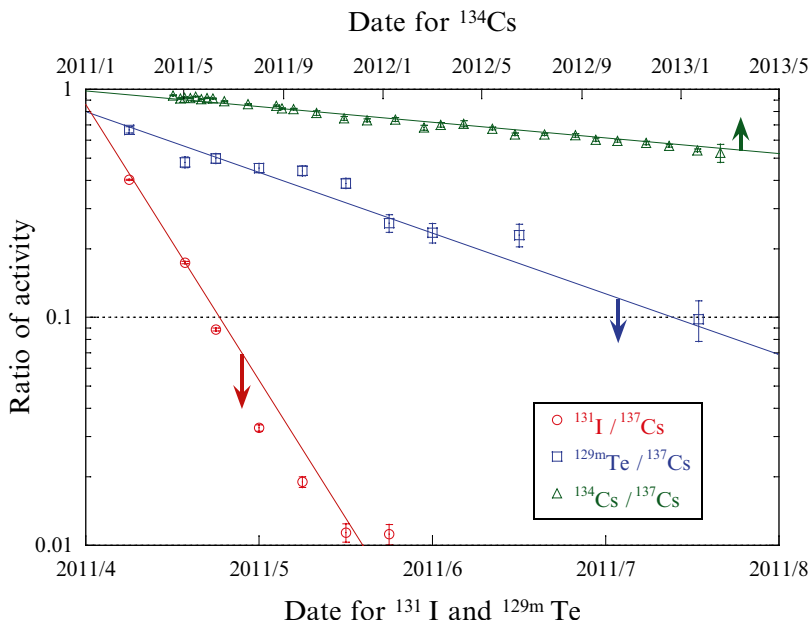
Date for ^{134}Cs

Fig. 10.5 Ratios of activity. *Vertical axis*, ratio in activity for ^{137}Cs; *upper horizontal axis*, date for ^{134}Cs/^{137}Cs ratio; *lower horizontal axis*, date for ^{131}I/^{137}Cs and ^{129m}Te/^{137}Cs ratio. *Circles* show ^{131}I/^{137}Cs activity ratios, *squares* show ^{129m}Te/^{137}Cs activity ratios, and *triangles* show ^{134}Cs/^{137}Cs activity ratios. ^{131}I and ^{129m}Te decreased following their physical half-lives

The data show that activity of ^{137}Cs was in a decreasing trend with time and the gradient of the trend was faster than the physical half-life of ^{137}Cs decay.

For more detailed analysis, activity ratios of other radioactive nuclides for ^{137}Cs activity are shown in Fig. 10.5. From this result, the ratios of radioactive nuclides are following their physical half-lives, which means the radioactive nuclides moved together with ^{137}Cs in the general environment after the fallout.

10.3.2 Dose Rate Distribution Survey

Some of the earlier results of this measurement have been published [6, 8, 9], showing dose rate distributions in the urban part of the Fukushima Naka-Dori area had changed. The change in the dose rate in paved areas (with time) is described in this chapter.

A characteristic dose rate distribution change (Fig. 10.6) is shown by dose rate distributions of the Fukushima station neighborhood close to the soil sampling point. Figure 10.6a shows the dose rate distribution on April 17, 2011, and Fig. 10.6b shows the dose rate distribution on October 13, 2012.
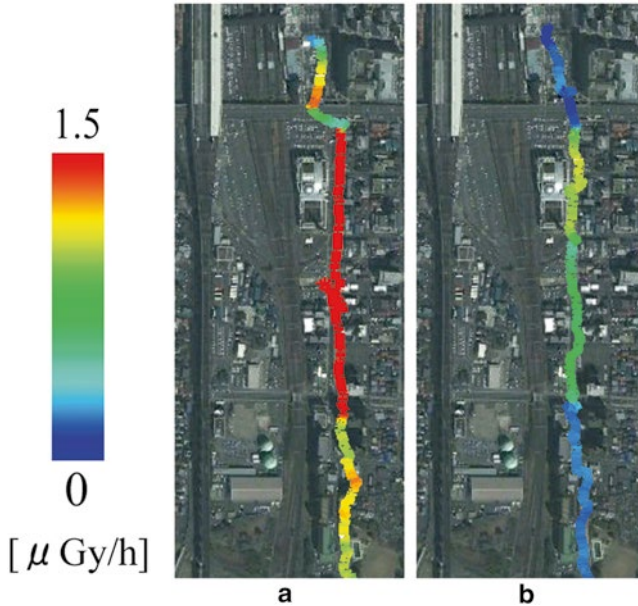
Fig. 10.6 Dose rate distributions in Fukushima City. *Lines* indicate the survey route and their *color* the measured dose rate on April 17, 2011 (**a**) and October 13, 2012 (**b**)

The dose rate on October 13, 2012 was lower than that on April 17, 2011 (Fig. 10.6), and the dose rate distribution became much clearer on October 13, 2012. The higher dose rate areas (Fig. 10.6b) were where the streets were paved with cushion, the average dose rate areas were where the streets were paved with blocks, and the lower dose rate areas were where the streets were paved with normal asphalt (Fig. 10.7). The dose rates of these three points decreased with time (Fig. 10.7). The dose rate decreasing rate appears different among the three points in Fig. 10.7.

For more detailed analysis, I compared measured dose rates with calculated dose rates. The calculated dose rate trends were determined as follows.

The air dose rate at Fukushima city is composed of the environmental background dose rate and the dose rate of radioactive materials from Fukushima Daiichi NPP, as shown in Eq. (10.1), where D_{calc} is the calculated dose rate, D_{BG} is the environmental background, and D_{RM} is the dose rate from the radioactive materials from Fukushima Daiichi NPP.

$$D_{calc} = D_{BG} + D_{RM}. \tag{10.1}$$

Background dose rate at Fukushima City was set at 0.044 (μGy/h), calculated from total background dose rate, 0.075 (μGy/h) [=8.6 (μR/h)] [10], and cosmic muon dose rate, 0.031 (μGy/h). The muon dose rate is calculated from 0.031 (μSv/h) at sea level [11] and a height correction equation [11]. The conversion from Sv to
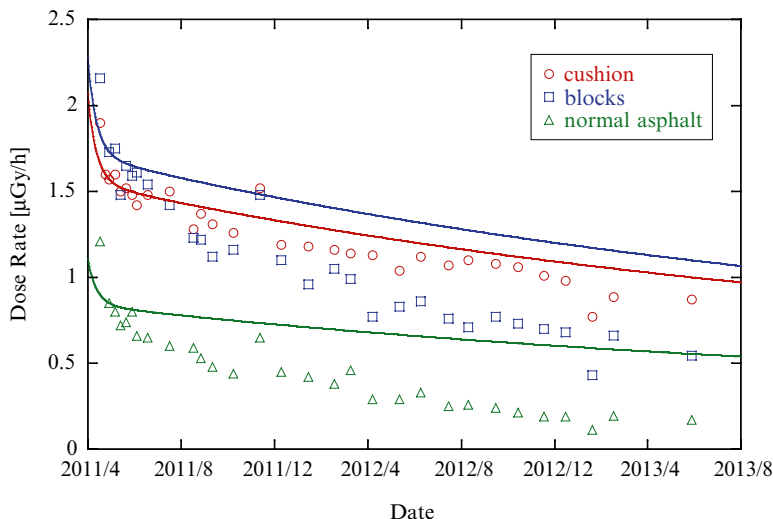
Fig. 10.7 Time dependence of the dose rate for different paving materials. *Horizontal axis* is date and *vertical axis* is dose rate. *Circles* show measured dose rates at the cushion-paved area, *squares* show measured dose rates at the block-paved area, and *triangles* show measured dose rates at the normal asphalt-paved area; *solid lines* show calculated dose rates

Gy was executed with a muon radiation weighting factor, 1.0. Time trend of dose rate from the radioactive materials was calculated from elapsed time from a normalization date, activities of the detected radioactive materials measured in previous studies [6, 8, 9], and the air kerma-rate constant as shown in Eq. (10.2), where A is normalization constant, i is a number of detected radioactive materials measured in the previous work, C_i is air kerma-rate constant [12], SA_i is activity in the surface soil [6], λ_i is a decay constant, and t is elapsed time from the normalization date.

$$D_{RM} = A \cdot \sum_i C_i \cdot SA_i \cdot \exp\left(-\lambda_i \cdot t\right), \tag{10.2}$$

From this formula, the dose rate changes that do not include movement of the radioactive materials can be estimated. A relative decay effect for dose rate change can be estimated from a sum of products of C_i and SA_i. Absolute changes can be set up by the normalization with a measured dose rate. The normalization constant A was determined from the measured dose rate at each point on a normalization date. In this analysis, the normalization date is April 29, 2011, because the consecutive dose rate measurement for the same places shown in Fig. 10.3 started at April 29, 2011. The calculated results are shown as solid lines in Fig. 10.7.

Some differences between calculated and measured dose rates are found in Fig. 10.7. The measured dose rates become smaller than calculated dose rates in all three points with time, and the difference in blocks area looks larger than the
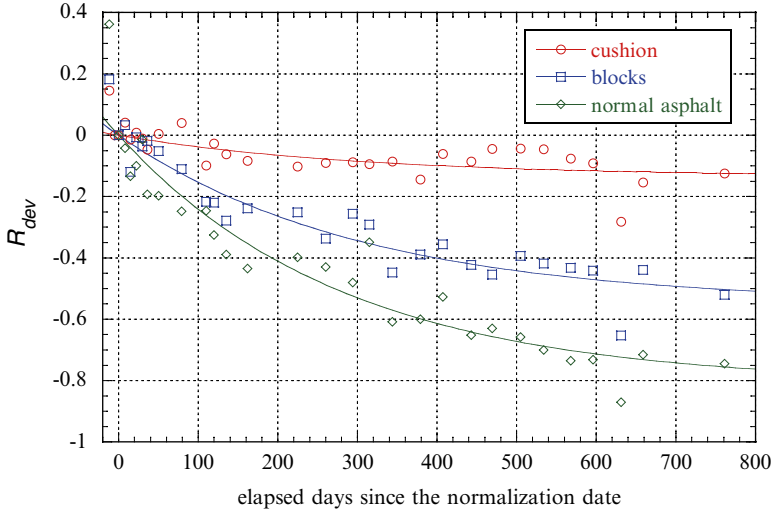
Fig. 10.8 Ratios of the deviations between measured and calculated dose rates for different paving materials. *Horizontal axis* is elapsed dates since the normalization date; *vertical axis* is a ratio of the deviations between measured and calculated dose rates; *circles* show the ratio at the cushion-paved area; *squares* show the ratio at the block-paved area; *triangles* show the normal asphalt-paved area

difference in cushion area. The dose rate differences between calculated and measured were changed to ratios for a calculated net dose rate as shown in Eq. (10.3) to compare decreasing trends.

$$R_{dev} = \left(D_{meas} - D_{calc} \right) / D_{RM}. \tag{10.3}$$

R_{dev} is the ratio for a calculated net dose rate and D_{meas} is a measured dose rate (Fig. 10.8). The decrease in gradient of the cushion-paved area was smallest, and the gradient of the normal asphalt-paved area was largest of the three areas (Fig. 10.8). The ratios for elapsed time were fitted with Eq. (10.4), where k is fixation ratio and r is a decreasing constant to estimate the effect of fixed radioactive materials.

$$R_{dev} = k \cdot \left\{ \exp\left(-r \cdot t \right) - 1 \right\}. \tag{10.4}$$

k describes a ratio of the fixed radioactive materials and r describes a gradient of the decrease. Fitted lines are shown as solid lines in Fig. 10.8, which show different gradients and saturation values. k and r for each point are shown in Table 10.1. The fixation ratio of the cushion area dose rate is highest and that of the normal asphalt area is lowest in the three points.

From these analyses, it became clear that the dose rates on paved areas decrease faster than the physical decay of radioactive nuclides that were speculated to come

Table 10.1 Fixation rate and decreasing constant for different paving materials

Paving material	Cushion	Blocks	Normal asphalt
k	0.13 ± 0.05	0.55 ± 0.06	0.81 ± 0.08
r	0.0033 ± 0.0027	0.0033 ± 0.0008	0.0035 ± 0.0008

from the Fukushima Daiichi NPP, and the decreasing trends are correlated with the paving materials.

This phenomenon is believed to occur by capture activity differences of the paving materials for radioactive materials.

10.4 Conclusion

Kinki University AERI conducted two studies on the radioactive contamination derived from the Fukushima Daiichi NPP in urban areas of Fukushima City since April 2011. One of these measurements was activities of surface soils and the other a survey of dose rate distributions. The results presented herein demonstrate that the dose rate distribution changed with time and that the dose rate distributions in paved areas have different characteristics for different paving materials.

This phenomenon is estimated to occur by capture activity differences of the paving materials for radioactive materials. More detailed studies are needed to acquire evidence of the mechanisms of the phenomenon.

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