Part III
Environmental Radiation and External Exposure

Chapter 10
Development and Operation of a Carborne Survey System, KURAMA

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Abstract A carborne survey system named as KURAMA (Kyoto University RAdiation MApping system) has been developed as a response to the nuclear accident at TEPCO Fukushima Daiichi Nuclear Power Plant. KURAMA is a γ-ray survey system with the global positioning system (GPS) and up-to-date network technologies developed for a primary use of carborne surveys. Based on the success of KURAMA, KURAMA-II, an improved version of KURAMA with better handling and ruggedness, is developed for the autonomous operation in public vehicles to minimize the workload of long-standing radiation monitoring required. Around two hundreds of KURAMA-II now serve for the continuous monitoring in residential areas by local buses as well as the periodical monitoring in Eastern Japan by the Japanese government. The outline and present status of KURAMA and KURAMA-II are introduced.

Keywords Radiometry • Mapping • γ-ray • Carborne survey • Air dose rate • Fukushima Daiichi nuclear power plant

10.1 Introduction

The magnitude-9 earthquake in Eastern Japan on 11 March 2011 and the following massive tsunami caused the serious nuclear disaster of Fukushima Daiichi Nuclear Power Plant, which Japan had never experienced before. Huge amounts of radioactive isotopes were released in Fukushima and surrounding prefectures.

In such nuclear disasters, air dose rate maps are quite important to take measures to deal with the incident, such as assessing the radiological dose to the public, making plans for minimizing exposure to the public, and establishing procedures for environmental reclamation. The carborne γ-ray survey technique is known to be one of the effective methods to make air dose rate maps [2]. In this technique,

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a continuous radiation measurement with location data throughout the subject area is performed by one or more monitoring cars equipped with radiation detectors. Unfortunately, the existing monitoring system didn't work well in the incident. Such monitoring cars tend to be multifunctional, thus too expensive to own multiple monitoring cars in a prefecture. Fukushima was the case, and to their worse, the only monitoring car and the data center were contaminated by radioactive materials released by the hydrogen explosions of the nuclear power plant. The monitoring cars owned by other prefectures were then collected, but such monitoring cars were too heavy to drive on heavily damaged roads in Fukushima. Then daily measurements of the air dose rate in the whole area of Fukushima were eventually performed by humans. The measuring personnel drove around more than 50 fixed points in Fukushima prefecture twice a day, and they measured the air dose rate of each point by portable survey meters. Airborne γ-ray surveys were performed by the Ministry of Education, Culture, Sports, Science and Technology of Japan (MEXT) and the US Department of Energy, but difficulties in the arrangement of aircraft, aviation regulations, and their flight schedules prevented immediate and frequent surveys in the areas of interest.

KURAMA was developed to overcome such difficulties in radiation surveys and to establish air dose-rate maps during the present incident. KURAMA was designed based on consumer products, enabling sufficient numbers of in-vehicle apparatus to be prepared within a short period. KURAMA realized high flexibility in the configuration of data processing hubs or in the arrangement of monitoring cars with the help of cloud technology. Based on the success of KURAMA, KURAMA-II was developed to realize the continuous monitoring in residential areas. An outline of KURAMA and KURAMA-II and their applications are presented.

10.2 KURAMA

KURAMA [10] is a γ-ray survey system with the global positioning system (GPS) and up-to-date network technologies developed for a primary use of carborne surveys. The system outline of KURAMA is shown in Fig. 10.1.

An in-vehicle unit of KURAMA consists of a conventional NaI scintillation survey meter with an appropriate energy compensation, an interface box for the analog voltage output from the detector to a USB port of PC, a GPS unit, a laptop PC, and a mobile Wi-Fi router (Fig. 10.2). Its simple and compact configuration allows users to set up an in-vehicle unit in a common automobile. The software of in-vehicle part is developed with LabVIEW. The radiation data collected every 3 s is tagged by its respective location data obtained by GPS and stored in a csv file. This csv files updated by respective monitoring cars are simultaneously shared with remote servers by Dropbox over a 3G network, unlike other typical carborne survey systems in which special telemetry systems or storage media are used for data

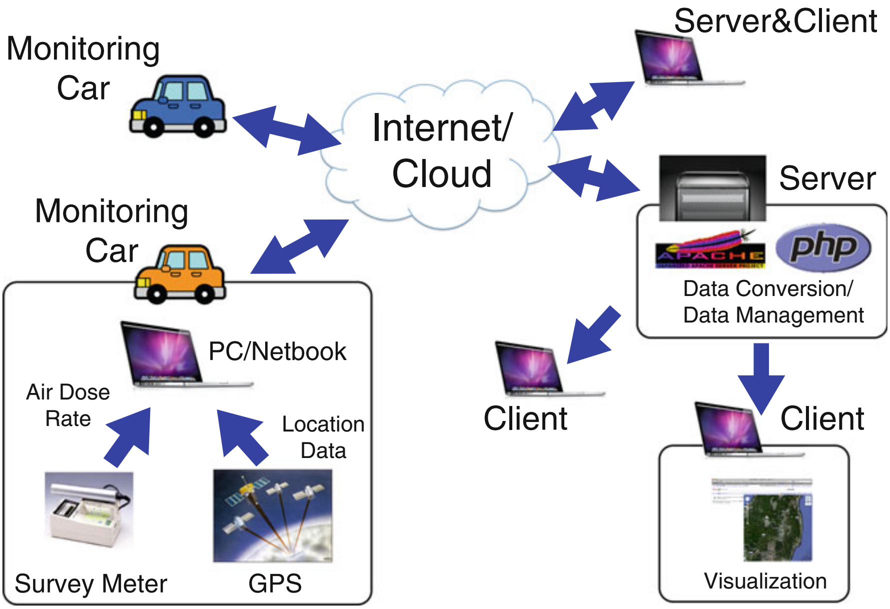

Fig. 10.1 The system outline of KURAMA. Monitoring cars and servers are connected over the Internet by cloud technology

Fig. 10.2 The in-vehicle part is compactly composed of mostly commercial components. (*1*) GPS unit, (*2*) 3G mobile Wi-Fi router, (*3*) MAKUNOUCHI, (*4*) NaI survey meter, and (*5*) PC

Fig. 10.3 The data is simultaneously plotted on Google Earth. The color of each dot represents the air dose rate at respective point

collection. With this feature, anyone can set up their own "data center" anywhere as far as a conventional Internet connection and a PC with Dropbox are available. This kind of flexibility should be required in disasters like the present case because the carborne survey system owned by Fukushima prefecture eventually came to a halt due to the shutdown of the data center by the disaster.

Once the radiation data in csv format is shared with remote servers, the data file is processed by servers in various ways, including the real-time display on Google Earth in client PCs (Fig. 10.3).

10.3 KURAMA-II

Long-term (several tens years) and detailed surveillance of radiations are required in residential areas that are exposed to radioactive materials. Such monitoring can be realized if moving vehicles in residential areas such as buses, delivery vans, or bikes for mail delivery have KURAMA onboard. KURAMA-II [11] is designed for such purpose.

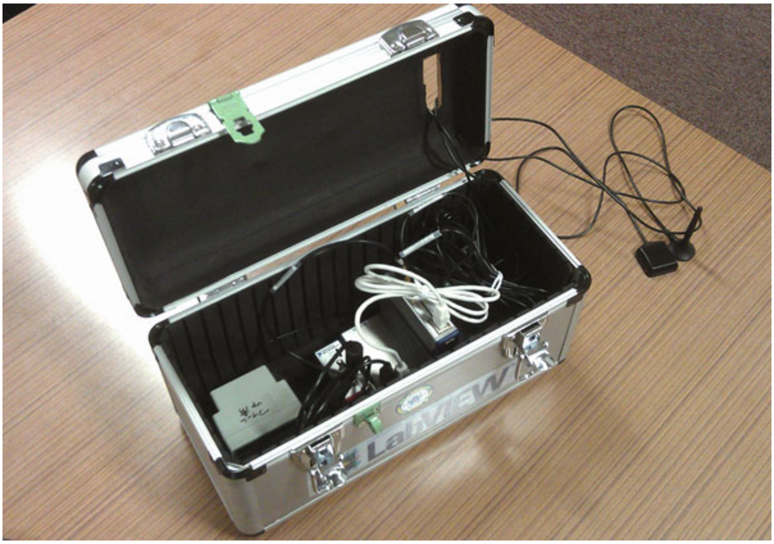

Fig. 10.4 The in-vehicle unit of KURAMA-II. A CsI detector and a CompactRIO are compactly placed in a toolbox with the size of 34.5 × 17.5 × 19.5 cm

KURAMA-II stands on the architecture of KURAMA, but the in-vehicle part is totally redesigned. The platform is based on CompactRIO series by National Instruments to obtain better toughness, stability, and compactness. The radiation detection part is replaced from the conventional NaI survey meter to a Hamamatsu C12137 detector [4], a CsI detector characterized by its compactness, high efficiency, direct ADC output, and USB power operation. The direct ADC output enables to obtain γ-ray energy spectra during operation. The mobile network and GPS functions are handled by a Gxxx 3G series module for CompactRIO by SEA [5]. All of the components for the in-vehicle part are placed in a small toolbox for a better handling (Fig. 10.4).

The software for KURAMA-II is basically the same code as that of original KURAMA, thanks to the good compatibility of LabVIEW over various platforms. Additional developments were performed in several components such as device control software for newly introduced C12137 detector and Gxxx 3G module, the start-up and initialization sequences for autonomous operation, and the file transfer protocol.

CompactRIO is designed for applications in harsh environment and limited space. Therefore, KURAMA-II can be used other than carborne surveys (Fig. 10.5). For example, KURAMA-II is loaded on a motorcycle intending not only the attachment with motorcycles for mail delivery, but also the monitoring in regions where conventional cars cannot be driven, such as small paths between rice fields or those through forests. Also, KURAMA-II with DGPS unit is prepared for the precise mapping by walking in rice fields, orchards, parks, and playgrounds in Fukushima.

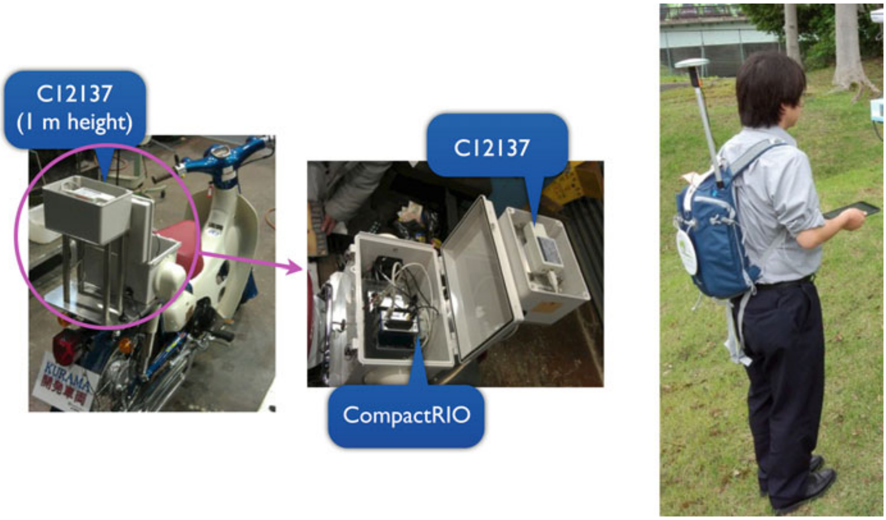

Fig. 10.5 KURAMA-II for bike survey (*left* and *middle*) and walking survey (*right*). All have basically the same hardware and software configuration with different ways of installation. In the case of walking survey, the existing GPS part is replaced with DGPS for the better precision of positioning measurement

10.4 Applications of KURAMA and KURAMA-II

As the developer of KURAMA and KURAMA-II, we have demonstrated possible applications of KURAMA and KURAMA-II through a series of field tests. In the beginning, we demonstrated an efficient γ-ray carborne survey by KURAMA in Fukushima prefecture in collaboration with the Fukushima prefectural government (Fig. 10.6). This result encourages the Ministry of Education, Culture, Sports, Science and Technology in Japan (MEXT) to conduct the first official carborne survey project by KURAMA.

We then carried out a field test of continuous monitoring by KURAMA-II on a local bus in Fukushima city in December 2011 in collaboration with Fukushima Kotsu Co. Ltd., one of the largest bus operators in Fukushima prefecture (Fig. 10.7). Local buses are suitable for continuous monitoring purpose because of their fixed routes in the center of residential areas and routine operations.

Based on the success of the field test on a local bus in Fukushima city, the region of this field test has been extended to other major cities in Fukushima prefecture since January 2013, i.e., Koriyama city, Iwaki city, and Aizuwakamatsu city. Five KURAMA-II in-vehicle units are deployed for this test, and the result is summarized and released to the public from the website [6] on a weekly basis.

The team of the Fukushima prefectural government made precise radiation maps of major cities in Fukushima prefecture mainly for "hot spot" search just after KURAMA was available [3]. Soon, the Fukushima prefectural government sought the possibility to extend the radiation monitoring by local buses over Fukushima

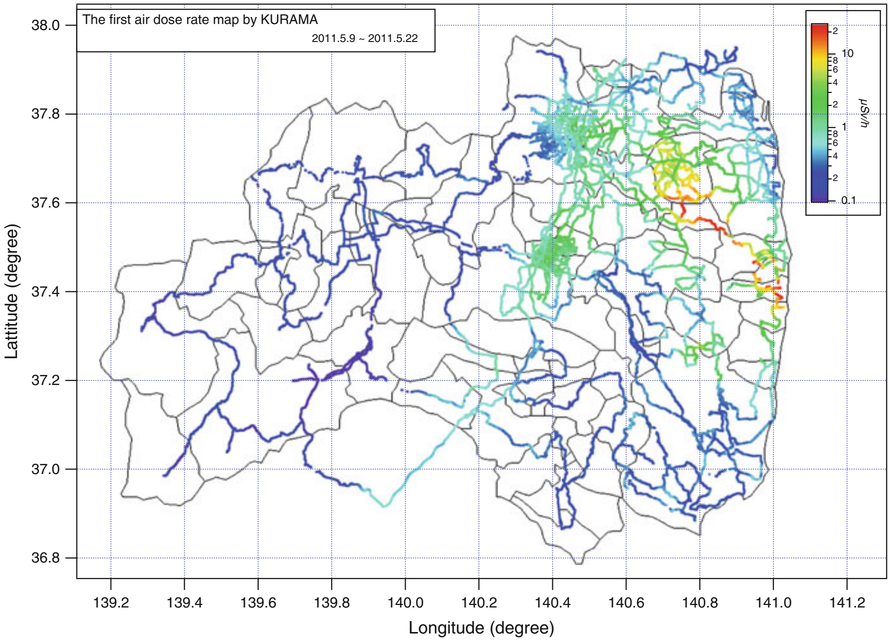

Fig. 10.6 The air dose rate map generated by the first demonstration of KURAMA in May 2011. This was also the first prefecture-wide map of air dose rate in this accident

Fig. 10.7 KURAMA-II under the field test on a local bus

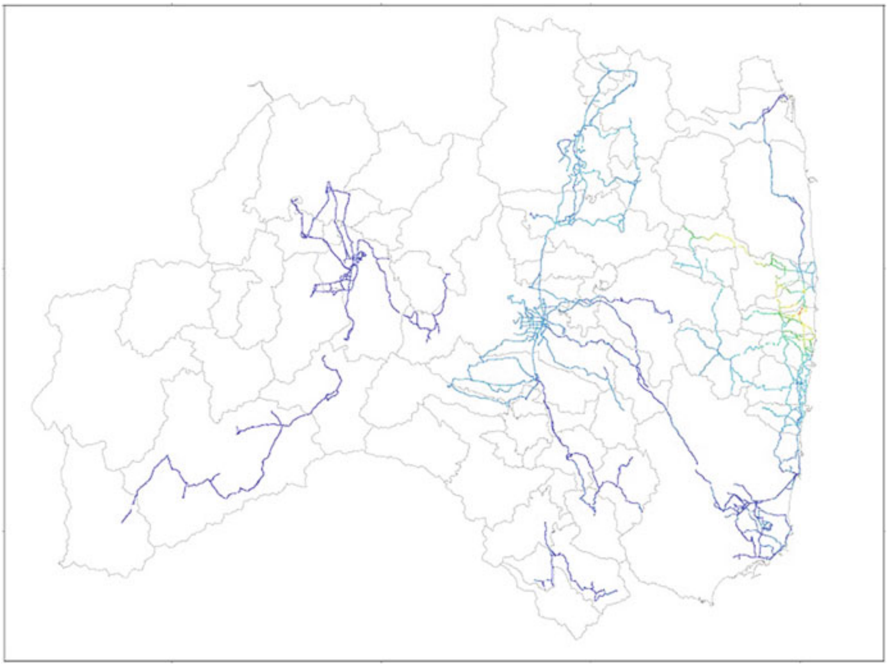

Fig. 10.8 A result of the continuous monitoring by KURAMA-II on local buses conducted by the Fukushima prefectural government [1]

prefecture because they realized the importance of continuous monitoring in residential areas. In August 2015, the monitoring scheme by local buses started as an official operation by the Fukushima prefectural government with the collaboration of Kyoto University and Japan Atomic Energy Agency (JAEA). As of May 2015, 30 local buses owned by bus companies and 20 official cars owned by Fukushima prefecture are continuously operated throughout Fukushima prefecture. Real-time data is released to the public on the display system at the public space of a building in Fukushima city, and the summarized results are available on a weekly basis on the web (Fig. 10.8) [1].

MEXT conducted the very first official carborne survey in Fukushima prefecture and its surrounding area in June 2011. Then they extended carborne surveys in Eastern Japan [8] including Tokyo metropolitan area in December 2011. MEXT started a carborne survey project in March 2012, in which 100 units of KURAMA-II were lent to municipalities in Eastern Japan [7]. KURAMA-II was placed in sedan cars of municipalities, and the cars were driven around by ordinary staff members in respective municipalities, who didn't have any special training on radiation measurement. This survey was successful and proved the performance and scalability of KURAMA-II system. Now, this survey has been conducted periodically by MEXT and the national regulation authority (NRA), which is the successor of the radiation monitoring of the present incident (Fig. 10.9).

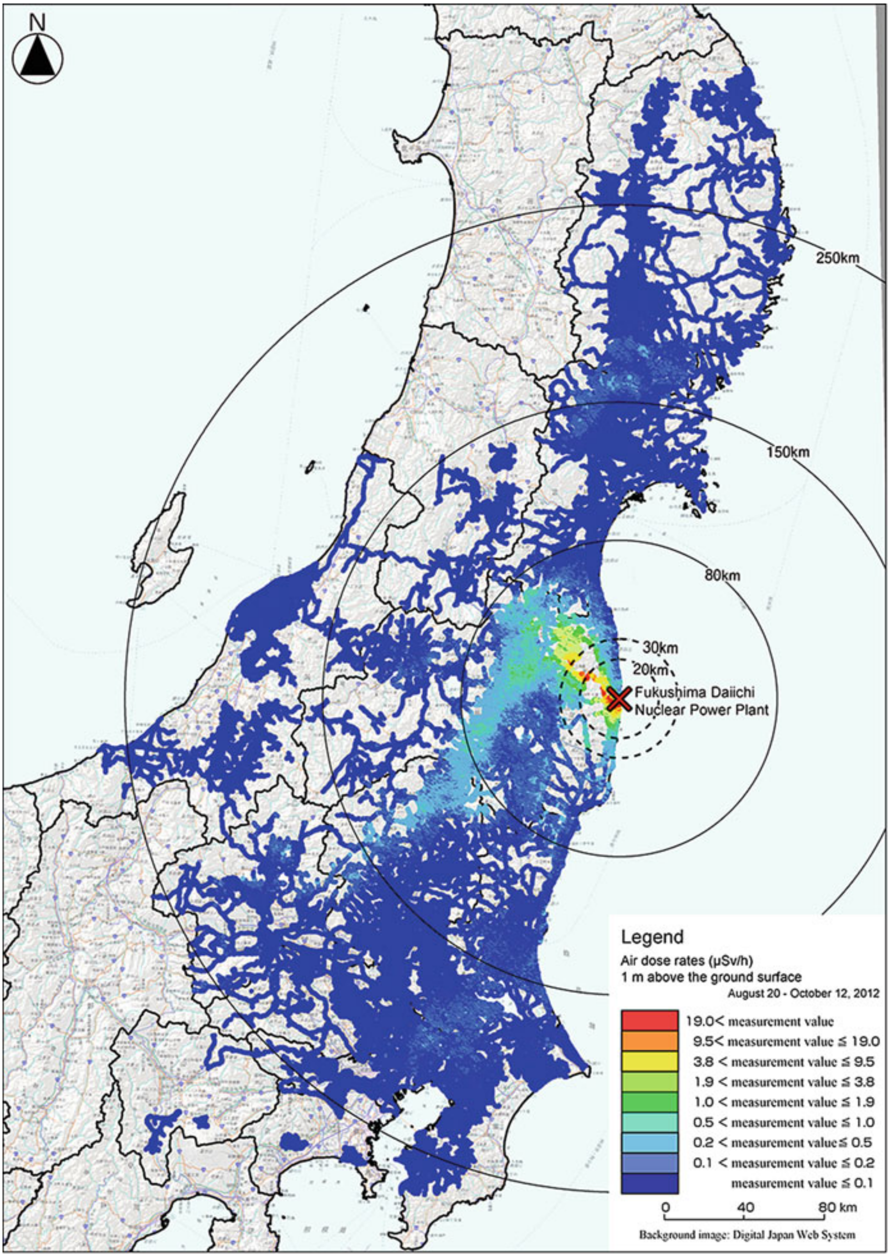

Fig. 10.9 Map of air dose rates on roads measured by KURAMA-II in the periodical survey conducted by NRA between August and October 2012 [9]

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Chapter 11
In Situ Environmental Radioactivity Measurement in High–Dose Rate Areas Using a CdZnTe Semiconductor Detector

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Abstract For the purpose of determining a surface deposition density on soil for radio-cesiums, a CdZnTe (CZT) semiconductor detector whose crystal has dimensions of 1 cm cubic was applied to the in situ environmental radioactivity measurement in deeply contaminated areas in Fukushima region. Even in high–dose rate areas where pulse height spectra weren't able to be properly obtained by the conventional high-purity Ge (Hp-Ge) semiconductor detector, proper pulse height spectra were obtained by the CZT detector with certain accuracy. Results of deposition density on soil for ^{134}Cs and ^{137}Cs derived from net peak areas by the CZT detector seemed consistent, comparing with those measured by the Japanese government. Air kerma rates were estimated by the same pulse height spectra for determining surface deposition density on soil for radio-cesiums. Estimated results showed almost the same values as obtained by the NaI(Tl) scintillation survey meter. The results indicate that the CZT detector can be applied to rapid and simple in situ gamma ray radioactivity measurement in higher–dose rate areas whose dose rates exceed several tenth μSv h^{-1}. The study also strongly supports that the CZT detector is one promising candidate for the detector to be used for checking the effect of decontamination works and for long-term monitoring in heavily contaminated areas.

Keywords CdZnTe detector • In situ gamma ray environmental measurement • Decontamination • Dose rate • Environmental radiation monitoring • Surface deposition density on soil • ^{137}Cs • ^{134}Cs

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11.1 Introduction

After the Fukushima Nuclear Accident, contamination by a vast amount of radioactive materials released due the accident still remains in areas close to the Fukushima Daiichi Nuclear Power Station (FDNPS). Decontamination and remediation works in heavily contaminated areas are recognized a challenging practice. Particularly, methodologies of decontamination and its confirmation of effect in deeply contaminated areas where there are consequently high dose rates have been being intensively developed.

Among methodologies for determining the surface deposition density on soil, in situ environmental gamma ray measurement using high-purity Ge detector [1, 2] is widely recognized effective and reliable and has been playing an important role in the measurement campaign in the whole region of northern part of Japan under the conduction of the government of Japan (http://radioactivity.nsr.go.jp/en/). On the other hand, high dose rates more than tenth μSv h^{-1} impede the precise spectrometry using the Ge detectors caused by their own high sensitivity to gamma rays. In our measurement campaign for investigating the isotropic ratio of radio-cesiums [3, 4], the Ge detector used was not able to show its high energy resolution when measured in higher–dose rate areas. This was caused by broadening each peak in the pulse height spectrum due to overlapping of too many events incoming the detector sensitive region.

Comparing with Ge detectors, a newly developed CdZnTe (CZT) detector has less energy resolution of pulse height spectrum. A CZT detector which has a small detector element is also less sensitive to gamma rays from radio-cesiums. However, a CZT detector has enough energy resolution to distinguish peaks by gamma rays from ^{134}Cs and ^{137}Cs (i.e. its progeny, ^{137m}Ba). The lower sensitivity to gamma rays would enable us to appropriately measure pulse height spectra in the environment whose dose rates reach more than few tenth μSv h^{-1}. In addition, a CZT detector is an easy-to-use, light-weight and coolant-free detector. Considering these characteristics, a CZT detector also would help determine environmental radioactivity even in deeply contaminated areas whose dose rates exceed more than a couple of tenth μSv h^{-1}.

This article describes investigation on the adaptability of a CZT detector to an in situ environmental radioactivity measurement. Before measurements, energy dependence of peak efficiency and angular dependence of peak efficiency for the CZT detector were evaluated. A series of environmental radioactivity measurements were then conducted within the region within several kilometers in radius centering the FDNPS, which is designated as the so-called difficult-to-return zone, which is deeply contaminated areas due to radio-cesiums from the FDNPS. There are still some places whose ambient dose equivalent rates exceed several tenth μSv h^{-1} and require to be remediated. Surface contamination densities on soil due to radio-cesiums were determined from measured pulse height spectra. Air kerma rates at measurement points were also estimated from the same pulse height spectra by means of three methodologies. Measured results were then compared with those obtained by the government of Japan (http://radioactivity.nsr.go.jp/en/). The usability of the CZT was also discussed in this article.

11.2 Materials and Methods

In this study, a CZT detector was used as a detector which applies the rapid and simple in situ environmental gamma ray measurement for determining surface deposition on soil due to radio-cesiums. Considering its characteristics of gamma ray detection described above, a CZT detector is taken as one promising candidate for the purpose. In addition, high-dose areas limit remediation and monitoring activities. As summarized in Table 11.1, a light, easy-to-use, USB-powered and coolant-free CZT detector allows us to expand our remediation and monitoring activities. This strongly will promise rapid, safe and efficient monitoring activities for a limited time. Figure 11.1 shows the appearance and cross-sectional drawing for the CZT detector assembly (Kromek GR1™) used in this study. The sensitive region of the detector is made of CdZnTe semiconductor crystal, and the dimension of the sensitive region is 1 cm^3.

Surface deposition densities of radio-cesiums using the CZT detector were measured from 27 to 28 May 2013 and from 11 to 13 December 2013. The CZT detector was set at the height of 1 m, using a conventional tripod. For obtaining pulse height spectra from the CZT detector and for power supply, a laptop PC was connected to the detector by a USB cable. Open and level fields which have no buildings within at least 10 m from the center of measuring points were selected, as possible. Ambient dose equivalent rates at measurement points were

Table 11.1 Comparison of characteristics of the conventional Ge semiconductor detector and the CZT detector

	High purity Ge semiconductor detector	CdZnTe semiconductor detector
Detector element	Ge	CdZnTe
Typical dimension and shape of detector element	Cylindrical 5.0 cm $\varphi \times 6.0$ cm^L	Cubic $1.0 \times 1.0 \times 1.0$ cm^3
Typical energy resolution for ^{137}Cs: 662 keV (FWHM) (%)	0.2 ∼ 0.3	2.0 ∼ 2.5
Weight (kg)	∼10 (including LN_2)	0.05
Cost (Japanese yen) (initial, including measurement system)	3,000,000 ∼ 10,000,000	600,000 ∼ 1,000,000
(running)	10,000 ∼ per 1 day	0 ∼
Necessary to be cooled	Yes (LN_2 or electric cooling system)	None
External power supply	Required	None

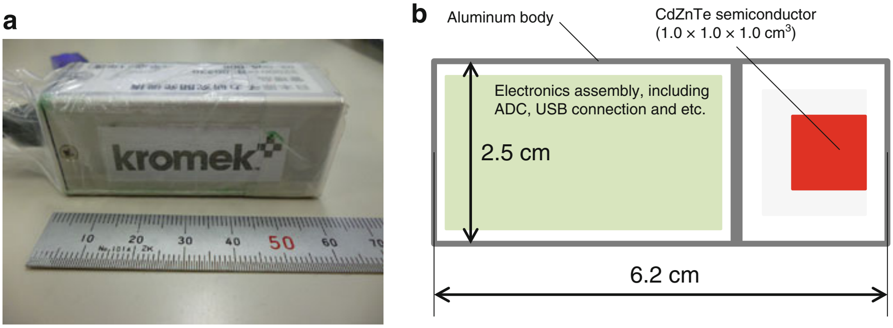

Fig. 11.1 Appearance (**a**) and cross sectional drawing (**b**) for the CZT detector assembly (Kromek GR1™)

also monitored using the NaI(Tl) scintillation survey meter and ranging between 0.2 and 45 μSv h^{-1}. Measurement time for each point changed according to the dose rates and was set to 600 s for high–dose rate areas and 1200 s for lower–dose rate areas, respectively.

Surface deposition densities on soil of each radio-cesium A_a (kBq m^{-2}) were determined by dividing peak areas per second N_f (cps) due to gamma rays from ^{134}Cs and ^{137}Cs by peak efficiencies with energies of gamma rays, P_{eff} (cps (kBq $m^{-2})^{-1}$). Equation (11.1) shows the surface deposition density on soil, $A_{a:}$

$$A_a = \frac{N_f}{\mathrm{P_{eff}}} \tag{11.1}$$

The peak efficiency, P_{eff}, for an incident gamma ray with energy of E (keV) was derived in accordance with Eq. (11.2):

$$\mathrm{P_{eff}} = \frac{N_0}{\phi}\frac{N_f}{N_0}\frac{\phi}{A_a} \tag{11.2}$$

where N_0/φ is a net peak area for full energy absorption of incident gamma ray per unit gamma ray fluence. N_0/φ, was then obtained by measuring pulse height spectra using checking radioactive sources such as ^{152}Eu, ^{60}Co and ^{137}Cs and by calculating using the EGS4 Monte Carlo code. N_f/N_0 is the correction factor for angular dependence of a net peak area for full energy absorption of the CZT detector used. φ/A_a ((cm^{-2} s^{-1}) (kBq $m^{-2})^{-1}$) is a gamma ray fluence rate at 1 m above the ground per unit surface deposition density of each radionuclide of interest, namely, ^{134}Cs and ^{137}Cs. This depends on the migration of soil from the surface of ground, and depth profile of concentration of radionuclides in soil varies as time elapses from the initial deposition. The parameter defined as a relaxation mass per unit area, β (g cm^{-2}), is used to express the vertical distribution of radionuclides deep inside soil [1, 2]. In this study, β was set to 2 and/or 3, in accordance with the recommendation of reference 2. The reference 2 explains the effect of attenuation of gamma rays due to surface soil and migration of radio nuclides on soil according to the time elapsed from initial deposition of radionuclides to the measurement date in detail.

Air kerma rates at measurement points were estimated from measured surface contamination densities on soil by the CZT detector. In addition, using the same spectra obtained by the CZT detector, air kerma rates at measurement places were estimated by the stripping method [5] and the G(E) function method [6]. Evaluating dose rate using the same pulse height spectra would enhance information on measurement points, help shorten staying time in higher–dose rate areas and facilitate a long-term monitoring of heavily contaminated areas. Regarding the stripping method, the response matrix of the CZT detector to mono-energetic gamma rays ranging from 50 keV to 3 MeV was calculated by MCNP-4C code. The pulse height spectrum was decomposed to gamma ray fluence spectrum by applying calculated response matrix. The air kerma rate was then estimated by multiplying fluence-to-air-kerma conversion coefficient taken from ICRP 74 [7] with obtained gamma ray fluence. In contrast, the G(E) function method enables us to directly determine air kerma rates from the accumulated pulse height spectra, by employing the operator defined, "G(E) function." The method has also taken advantage of direct determination of air kerma rates which the effect of scattered gamma ray components is included. The previous literature gives more detailed explanations on the G(E) function method and its application to environmental radiation measurement [6]. The G(E) function for the CZT detector was derived from the calculated responses matrix of the CZT detector to mono-energetic gamma rays ranging from 50 keV to 3 MeV. The EGS4 was used for the calculation. Before determining air kerma rates by pulse height spectra obtained in the field, the calculated response functions were verified by comparing the measured spectra from point sources of ^{137}Cs with the calculated spectra.

11.3 Results and Discussion

As basic characteristics of the detectors for in situ environmental radioactivity measurement, energy and angular dependences of full energy absorption peak efficiency of the CZT detector were evaluated. Figure 11.2 shows measured and calculated peak area per unit gamma ray fluence as a function of gamma ray energy. In the energy region around 100 keV, peak efficiency reaches up to almost 0.9. On the other hand, quite low values with energies more than around 1500 keV suggest that the CZT detector has less sensitivity to energetic gamma ray from ^{40}K and/or ^{208}Tl. Figure 11.3 shows the angular dependence of a relative net peak area for full energy absorption as a function of incident gamma ray energy. In this figure, 0° corresponds to a direction of the detector axis, and 90° is a horizontal direction to the ground. Values in the Fig. 11.3 were normalized by those obtained at 90°. Figure 11.3 indicates that calculated net peak areas for incident gamma rays

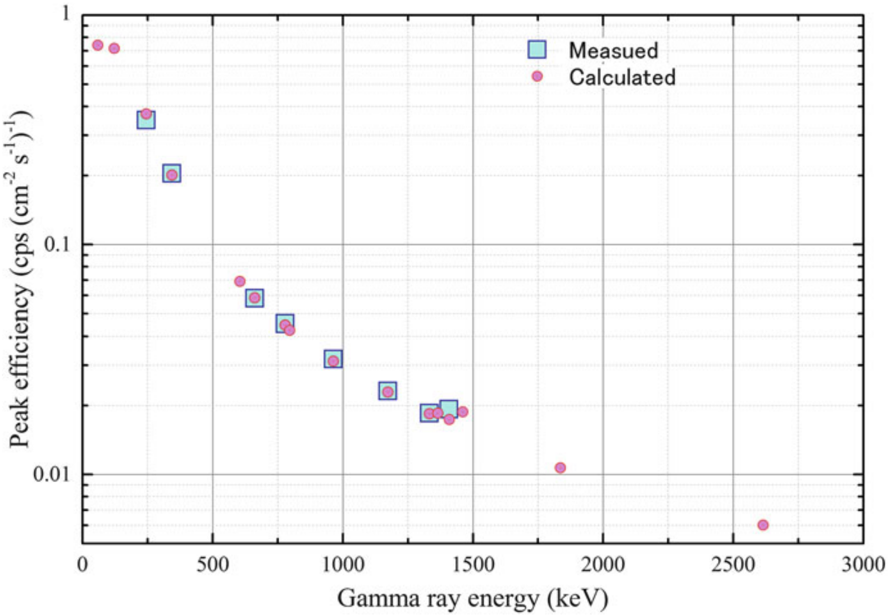

Fig. 11.2 Measured and calculated full energy absorption peak efficiency of the CZT detector

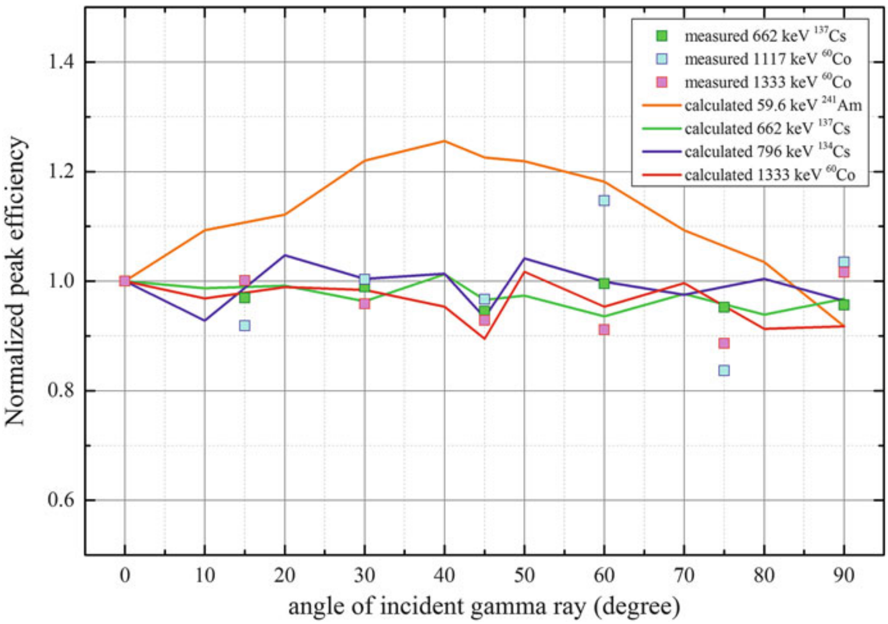

Fig. 11.3 Angular dependence of full energy peak efficiency of the CZT detector as a function of incident gamma ray energy

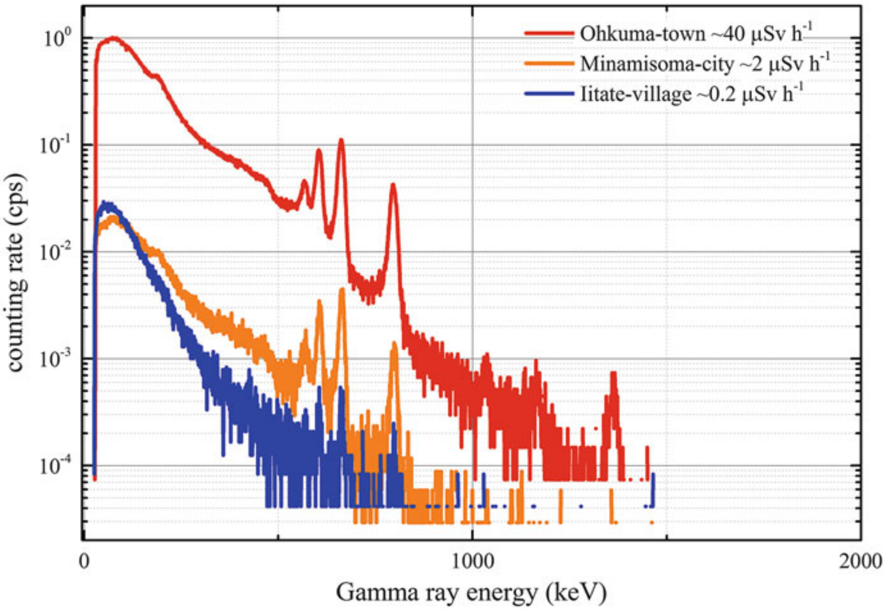

Fig. 11.4 Comparison of pulse height spectra from the CZT detector obtained in areas whose dose rates range between 0.2 and 40 μSv h^{-1}

with energies between 662 and 1333 keV was evaluated to be within 10 % of those obtained at 90° by Monte Carlo calculations using MCNP-4C. Measured results were also found to be within 20 % of those obtained at 90°. This shows that the CZT detector has less angular dependence to gamma rays with energies between 662 and 1333 keV. From measured and calculated results, values of N_f/N_0 for ^{134}Cs and ^{137}Cs gamma rays were both taken as 1.0. Results shown in Figs. 11.1 and 11.2 imply that the CZT detector could allow us to properly measure pulse height spectra in heavily contaminated areas.

In situ environmental radioactivity measurements using the CZT detector were made inside the difficult-to-return zone at several kilometers from the FDNPS and also within 40 km in radius centering the FDNPS. Figure 11.4 shows examples of pulse height spectra obtained in areas whose ambient dose equivalent rates range from 0.2 to 45 μSv h^{-1}. Pulse height spectrum was obtained in 600 s at measurement point whose dose rate was monitored to be 45 μSv h^{-1}. As shown in Fig. 11.4, peaks due to gamma rays from radio-cesiums were clearly identified. The dead time observed in the area whose dose rate was around 40 μSv h^{-1} was around 1 %, and this would lead to the proper measurement for determining on surface deposition density on soil of radio-cesiums. Peaks due to gamma rays from ^{40}K, however, could not be seen in each pulse height spectrum. As shown in Fig. 11.1, the CZT detector has less sensitivity to energetic gamma rays more than around 1500 keV, comparing those from ^{137}Cs. The CZT detector was not able to observe events enough to form the peak due to gamma rays with energy of 1460 keV from ^{40}K.

This might also be rather advantageous, if the detector were to be used for confirming the effect of the decontamination work in higher–dose rate regions. It would be a crucial disadvantage that the CZT detector could not clearly identify peaks due to gamma rays from ^{40}K in the case of general environmental radioactivity measurement. On the other hand, gamma rays emitted from ^{134}Cs and ^{137}Cs have been still contributing to high dose rate in the "difficult-to-return areas." Considering that gamma rays emitted by these contaminants should be well identified, the effect of higher-energy gamma rays from ^{40}K is properly eliminated from pulse height spectra obtained by the CZT detector. From this viewpoint, the CZT detector enables to easily confirm the effect of decontamination work with certain accuracy.

Measured surface deposition densities on soil of ^{134}Cs and ^{137}Cs were summarized in Table 11.2, derived from net peak areas in pulse height spectra and calculated in accordance with Eq. (11.1). All the results in Table 11.2 were corrected to the date of the initial deposition (11 March 2011), by applying half-life of ^{134}Cs (2.0684 y) and ^{137}Cs (30.167 y). In addition to the surface deposition density on soil, air kerma rates due to radio-cesiums at measurement date were estimated from measured results and also listed in the table. Measured results seemed consistent, comparing with those evaluated by the measurement campaign by the government of Japan (http://radioactivity.nsr.go.jp/en/). Results obtained in wider regions are also summarized in our previous report [4].

Table 11.2 Comparison of surface deposition densities on soil within 7 km in radius centering the FDNPS. Measurement was conducted from 27th May 2013 to 28th May 2013

Location	Coordinate of location	Distance from FDNPS (km)	Measured surface deposition density on soil at 11th March, 2011 (kBq m^{-2})		Estimated air kerma rate due to gamma rays from ^{134}Cs and ^{137}Cs at measuring date (μGy h^{-1})
			^{134}Cs	^{137}Cs	
Ohkuma-town, Chuodai	37:25:26 N 141:00:08 E	2.7, W	$(1.10 \pm 0.02) \times 10^4$	$(1.05 \pm 0.03) \times 10^4$	35.8 ± 0.5
Ohkuma-town, Ohno station	37:24:32 N 140:59:07 E	4.4, WSW	$(3.29 \pm 0.24) \times 10^3$	$(3.37 \pm 0.08) \times 10^3$	10.7 ± 0.5
Futaba-town, Kami-hatori	37:27:25 N 140:59:22 E	5.6, NW	$(1.89 \pm 0.13) \times 10^3$	$(1.88 \pm 0.05) \times 10^3$	6.11 ± 0.26

Table 11.3 Comparison of measured dose equivalent rate and estimated air kerma rate in terms of various methods

Location	Coordinate of location	Distance from FDNPS (km)	Ambient dose equivalent rate by the conventional NaI(Tl) scintillation survey meter (μSv h^{-1})	Estimated air kerma rate due to ^{134}Cs and ^{137}Cs at measuring date (μGy h^{-1})	Estimated air kerma rate by the stripping method (μGy h^{-1})	Estimated air kerma rate by the G(E) function method (μGy h^{-1})
Ohkuma-town, Chuodai	37:25:26 N 141:00:08 E	2.7, W	45.3 ± 0.4	35.8 ± 0.5	33.2	37.1
Ohkuma-town, Ohno station	37:24:32 N 140:59:07 E	4.4, WSW	12.9 ± 0.1	10.7 ± 0.5	9.35	14.1
Futaba-town, Kamiha-tori	37:27:25 N 140:59:22 E	5.6, NW	1.63 ± 0.02	6.11 ± 0.26	2.17	3.29

Table 11.3 shows the comparison of air kerma rates, $\dot{K}_{air}$ (μGy h^{-1}), estimated from measured surface contamination densities on soil and in terms of the stripping and G(E) function methods. Measured ambient dose equivalent rates, $\dot{H}^*(10)$ (μSv h^{-1}), at the same measurement points were also listed. All results were corrected at measuring date (28 May 2013). Results obtained in high–dose rate areas were considered to be identical within 6 %. However, results obtained in lower–dose rate region have large discrepancy, particularly between air kerma rate estimated from surface deposition densities on soil and others. This might be caused by improper setting of relaxation mass, β, for determining the surface deposition densities on soil. On the other hand, air kerma rates estimated by the stripping method and the G(E) function method might reproduce actual air kerma rate, comparing with ambient dose equivalent rate obtained by the NaI(Tl) survey meter. Further investigation should be required for more accurate estimation of dose rate at measurement places.

11.4 Summary

A light-weight, easy-to-handle and cooling-free CdZnTe (CZT) semiconductor detector whose crystal has dimensions of 1 cubic cm was applied to the rapid and simple in situ environmental radioactivity measurement in deeply contaminated areas in Fukushima region in 2013. Even in high–dose rate areas more than a couple of tenth μSv h^{-1}, the CZT detector allowed to obtain the proper and fine pulse height spectrum, which is clearly distinguished peaks from gamma rays due to ^{134}Cs and ^{137}Cs. Results of deposition density on soil for ^{134}Cs and ^{137}Cs derived from net peak areas by the CZT detector were evaluated to be between 1.9×10^3 and 1.1×10^4 kBq m^{-2} for each radio-cesium. They were also found to be consistent, comparing with those measured by the Japanese government and obtained in other literature. Air kerma rates were estimated using the same pulse height spectra by the stripping and the G(E) function methods. Estimated results showed almost the same values as obtained by the NaI(Tl) scintillation survey meter, considering the differences of dosimetric quantities.

Throughout performance tests done in this study, the CZT detector has poor energy resolution and less sensitivity to energetic gamma rays with energies above 1500 keV, namely, gamma rays from ^{40}K. However, this means the CZT detector could eliminate interferences, when used in areas whose dose rates are more than a couple of tenth μSv h^{-1} due to contamination by radio-cesiums. The field monitoring test showed the CZT detector is easy to use and helps shorten staying time at measurement points whose dose rates exceed several tenth μSv h^{-1}. The study also clearly indicates that the CZT detector is one promising candidate for the detector to be used for checking the effect of decontamination works and for long-term monitoring in heavily contaminated areas, in order to accelerate implementations of decontamination and remediation works in "difficult-to-return zone."

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Chapter 12
Safety Evaluation of Radiation Dose Rates in Fukushima Nakadori District

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Abstract After the TEPCO Fukushima DAIICHI NPP accident, IAEA and ICRP advised accelerating the decontamination work to clean up the living environment of the areas where additional annual radiation exposure doses are beyond 1 mSv per year (i.e., 1 mSv/y) and to diminish radiation worries. However, the advice was not recognized well because it did not contain clearly understandable numerical data. In the present work, the ambient radiation dose rates in the Nakadori district have been investigated to clarify that the doses are lower than 1 mSv/y in the major part where the decontamination was completed. A part of the district and three municipalities in the special decontamination area have doses of 1.0–2.0 mSv/y. The country-averaged annual doses of natural radiation in the world have been evaluated using the basic data taken from the UNSCEAR 2000 report. The result shows that total annual exposure doses containing cesium and natural radiation contributions in Fukushima are 2–4 mSv/y, which are close to the natural radiation doses in Europe. The risk coefficient of the public exposure limits, 1 mSv/y, has also been evaluated to be 4.5×10^{-7} per year. It is lower than that of traffic accidents by two orders of magnitude. These results will be useful to judge how the safety of the Fukushima prefecture is secured.

Keywords Cesium contamination • Decontamination • Annual exposure dose • 1 mSv/y • Risk coefficient • Natural radiation • Nakadori district • Fukushima

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12.1 Introduction

More than 4 years have passed since the TEPCO Fukushima Daiichi nuclear power plant accident. The accident brought severe contamination by radioactive cesium isotopes in very wide areas of the Fukushima prefecture as well as neighboring prefectures in the Tohoku and Northern Kanto regions. Decontamination work is being done in order to reduce the ambient radiation level in the living space of the areas where the additional annual radiation exposure doses for individuals are beyond 1 mSv per year (i.e., 1 mSv/y). In the area where the work is assigned to the Fukushima prefecture, about 70 % of the decontamination work plan up to FY 2014 (i.e., up to March 2015) has been completed for housing sites [1]. In the special decontamination area where the work is being done by the Japanese government against the regions having a dose below 50 mSv/y, full-scale decontamination has been completed in four municipalities such as Tamura-shi, Kawauchi-mura, Naraha-machi, and Okuma-machi within FY 2014 [2].

As a result, the ambient radiation dose rates were reduced to values less than 0.23 μSv/h in most parts of the decontaminated areas of the Nakadori district and the average radiation dose rate in the former three municipalities was about 0.4 μSv/h in addition to the effect of natural decay of radioactive nuclides and weathering effects by rain and wind within FY. 2014. The local governments of Tamura-shi and Naraha-machi have declared their intent to remove the evacuation order. However, there are in total about 116,000 people who will be forced to evacuate inside the Fukushima prefecture (69,000) and outside (47,000) in March of 2017 [3]. A recent survey about their will to return reports [4] that 37.3 % of the residents moved within the prefecture and 19.8 % outside it and wanted to return to their home town under certain conditions, whereas half of them did not know what they wanted to do or gave no answer. The residents who moved in Fukushima raised the following conditions for returning: completing the decontamination (48.8 %), lifting the evacuation order in addition to decontamination completion (42.7 %), and disappearance of worries regarding radiation exposure (42.4 %). The people who moved outside Fukushima answered as follows: disappearance of worry about radiation exposure (52.2 %), completing the decontamination (45.7 %), as well as insurance of nuclear plant safety in the future (38.9 %). Anyhow, it should be noted that there is a high proportion of strong or vague worry about radiation influence.

Since 2011 international support activities have been energetically performed to accelerate recovery of the eastern region of Japan, especially the Fukushima prefecture by IAEA and ICRP. IAEA has made many technical advisories on the decontamination of the contaminated area, recovery of the town infrastructure, evacuation and return of the residents, as well as safety reinforcement and its examination of nuclear plants, and so on. In the autumn of 2013, the IAEA's international expert Mission Team for Fukushima Remediation Issues issued important advice in order to accelerate the decontamination and people's return that the government should strengthen its efforts to explain to the public that the additional individual dose of 1 mSv/y is a long-term goal [5]. On the other hand, ICRP has given psychological support through the dialogue meeting with the residents of the Fukushima prefecture mainly to discuss radiation problems concerning its influence on health and radiation protection in their daily life. The representative meeting was held on November 3, 2012 in Fukushima-shi. At the meeting, after the residents' presentation on worry about radiation a few members of ICRP answered that the radiation level in Fukushima was close to the natural radiation in their home town [6]. An explanation of "natural radiation" seems to be very instructive and effective for people to become aware of leading a healthy life even under radiation: people are always exposed to radiation from radioactive isotope intake through food, for example, of K40 accumulations to about 4000 Bq in an adult, as well as cosmic rays and gamma rays from soil and radon. However, their suggestions without understandable scientific numerical data have not worked to change the situation of Fukushima as much as IAEA and ICRP expected.

In the present work, the authors have prepared materials to explain the security situation at Fukushima. First they investigated the radiation distributions in the Nakadori district and its neighboring municipalities, and clarified the annual excess exposure doses. They also evaluated the risk of public standard limits of radiation exposure, 1 mSv/y, and country-averaged annual doses of natural radiation in the world. These data should be very useful for residents to recognize that the present status of the Fukushima prefecture is safe and judge how they will live there.

12.2 Radiation Level of Fukushima Nakadori District

The Fukushima Nakadori district is a region comprising the middle third of the Fukushima prefecture. It is sandwiched between the Aizu district to the west and Hamadori to the east. The Nakadori district contains the large cities of Koriyama–shi, local capital Fukushima-shi, and many middle-sized cities such as Date-shi, Nihonmatsu-shi, and Shirakawa-shi, among others. It occupies a major part in the government and economy including industrial activities and agriculture of the Fukushima prefecture. After the accident, many residents moved here from the Hamadori district having the TEPCO Fukushima NPPs. In Fukushima, contamination by radioactive cesium generally becomes lower with moving to the west therefore the problem of radiation in the Nakadori district is lower than in Hamadori.

Decontamination in the "Intensive Contamination Survey Area" where an additional annual exposure dose between 1 mSv and 20 mSv is promoted for living space by the municipalities, initiating from the higher radiation level zone. The present status of the decontamination work (to March 31, 2015) is shown in Table 12.1 [1]. About 70 % of housing and 97 % of farmland of the implementation plan up to FY 2014 has been decontaminated. In the "Special Decontamination Area" containing a total of 11 municipalities, which consists of the "restricted areas" located within a 20 km radius from TEPCO's Fukushima Daiichi NPP, and "Deliberate Evacuation Areas" where the dose was anticipated to exceed 20 mSv/y, the national government performs the decontamination work except where the radiation level area is higher

Table 12.1 Progress of decontamination work in designated municipalities to March 31, 2015

Item	Housing (Household)	Public facilities (Number of facilities)	Roads (km)	Farmland (ha)
Planned to FY 2014	318,392	8,298	8,572	29,720
Implementations	215,126	6,782	3,767	22,412
Progress rate	67.6 %	81.7 %	43.9 %	75.4 %

than 50 mSv/y, where residents will face difficulties in returning for a long time (i.e., "Difficult-to-Return Zone") and has finished the full-scale decontamination for housing, public facilities, roads, and farmland in Tamura-shi, Naraha-machi, Kawauchi-mura, and Okuma-machi within FY 2014 [2]. Lifting the evacuation order for the former two has been declared by the local government, taking account of a radiation level reduction below 0.4 μSv/h on average, as well as that for the special places of Date-shi, Kawauchi-mura, and Minamisoma-shi where the evacuation orders were spotty and issued from the special decontamination area. Housing decontamination has been completed in Katsurao-mura, Kawamata-machi, and Iitate-mura within FY 2014. Full-scale decontamination is continuing, aiming at completion in FY 2017 or FY 2018 for the remaining seven municipalities.

Owing to decontamination as well as the natural decay of radioactive cesium isotopes and weathering effects, present ambient radiation levels have become fairly lower. Figure 12.1 shows the monitoring information of the environmental radiation dose rate estimated at the 1 m height from the surface of the ground which was measured from an airplane [7]. It is found from the figure that the major part of the Nakadori district is colored by radiation dose rates lower than 0.5 μSv/h, whereas a part of Date-shi and Nihonmatsu-shi has a higher radiation level between 0.5 and 1 μSv/h which seems to be assigned to mountainous zones where decontamination has not been done because they lie outside living spaces.

Table 12.2 compares the radiation dose rates recently measured using a survey meter or a portable type radiation detector located at the representative monitoring posts in the important municipalities in the Fukushima prefecture with those on April 29 of 2011 [8]. The recent data become smaller by a factor of 3 through 12 from those of 2011. A small reducing factor means nondecontamination work. All values except for the Fire Center at Yamakiya in Kawamata-machi are lower than 0.23 μSv/h, which is the long -term target for decontamination.

From the figure and table, it can be said that radiation levels in the living space of the Nakadori district are generally below 0.23 μSv/h so that the additional annual dose will be expected to be below 1 mSv/y. Even at a higher radiation level where the ambient dose rate is 0.5 μSv/h, the additional dose would be 2.5 mSv/y.

Soma-shi, Iwaki–shi, and Hirono-machi in the Hamadori district are in the same situation as Fukushima-shi, Koriyama-shi, and Shirakawa-shi. In the special decontamination area, the average radiation dose rates measured in the housing sites of Tamura-shi, Naraha-machi, and Kawauchi-mura after the decontamination were reported [9] to be 0.35 μSv/h (June 2014), 0.38 μSv/h (June 2014), and

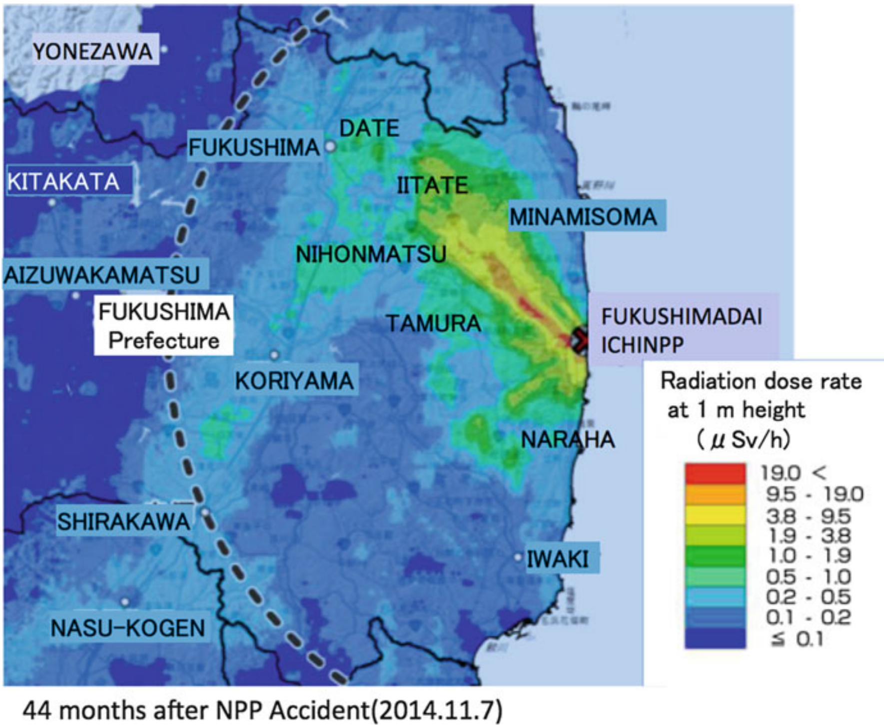

Fig. 12.1 Monitoring information of environmental radiation dose rates in the Nakadori and Hamadori districts measured from an airplane.

0.41 μSv/h (August 2014), respectively. At the places higher than 1 μSv/h before decontamination, the individual average values were reduced from 1.19 to 0.54 μSv/h (7 %), 1.38 to 0.63 μSv/h (19 %,) and 2.02 to 1.03 μSv/h (30 %) arranged in the same order. The value in parentheses expresses a fraction of the number of housing sites over 1 μSv/h.

12.3 International Support Activities

12.3.1 IAEA's International Expert Mission Team for Fukushima Remediation Issues [5]

In the autumn of 2013, the IAEA's international expert Mission Team for Fukushima Remediation Issues came to Japan in response to the request made by the government of Japan, to follow up with the main purpose of evaluating the progress of the on-going remediation work achieved since the previous mission in October 2011. The Team reported [5] that Japan is allocating enormous resources

Table 12.2 Ambient radiation dose rate at the monitoring posts in Fukushima prefecture (unit: μSv/h)

Place		April 29, 2011	Nov. 7, 2014	April 19, 2015
Date-shi	Government office	1.25, 1.23	0.23, 0.21	0.22, 0.19
Fukushima-shi	Kenpoku health office	1.58	0.24	0.22
Kawamata-machi	Government office	0.73, 0.75	0.16, 0.16	(0.14, 0.14)[a]
Kawamata-machi	Yamakiya fire center	3.0 (approx.)	0.68, 0.68	(0.67, 0.67)[a]
Nihonmatsu-shi	Government office	1.39, 1.44	0.25, 0.26	(0.23, 0.23)[a]
Tamura-shi	Local office at Tokiwa	0.26	0.10, 0.09	(0.10, 0.09)[a]
Koriyama-shi	Common building	1.53	0.13	0.13
Shirakawa-shi	Common building	0.64	0.09	0.09
Aizuwakamatsu-shi	Common building	0.18	0.06	0.04
Minamisoma-shi	Common building	0.54	0.11	0.11
Hirono-machi	Shimokitasako meeting place	0.8 (approx.)	0.11, 0.11	(0.08)[a]
Iwaki-shi	Common building	0.27	0.07	0.07

N.B. [a]Value on March 31, 2015

to developing strategies and plans and implementing remediation activities, with the aim of enhancing the living conditions of the people affected by the nuclear accident, including enabling evacuated people to return and that, as result of these efforts, Japan has achieved good progress in the remediation activities and, in general, has well considered the advice provided by the previous mission in 2011.

It also noted that based on the basic principles of the Act of Special Measures, a system has been established to give priority to remediation activities in areas for which decontamination is most urgently required with respect to protection of human health and to implement such measures taking into account the existing levels of radiation. The Ministry of the Environment, as one of the implementing authorities, is coordinating and implementing remediation works giving due consideration to this policy on prioritization. However, the announcement made by the authorities shortly after the accident that “additional radiation dose levels should be reduced to annual exposure doses below 1 mSv in the long run” is often misinterpreted and misunderstood among people, both inside and outside the Fukushima prefecture. People generally expect that current additional radiation exposure doses should be reduced below 1 mSv per year immediately, as they believe that they are only safe when the additional dose they receive is below this value.

Finally, the team gave the following advice: Japanese institutions are encouraged to increase efforts to communicate that in remediation situations, any level of individual radiation exposure dose in the range of 1–20 mSv per year is acceptable and in line with international standards and with the recommendations from the relevant international organizations, such as ICRP, IAEA, UNSCEAR, and WHO. The government should strengthen its efforts to explain to the public that an additional individual exposure dose of 1 mSv per year is a long-term goal, and that it cannot be achieved in a short time, for example, solely by decontamination work.

There remains, however, worry about radiation exposure even after the IAEA advice. The authors think that the nonobjective explanation without understandable data clearly showing a safety of the dose "1 mSv/y" isn't effective in this case. Accordingly, it is worthwhile to publicize a communication to the people to clarify quantitatively the radiological safety of Nakadori district by evaluating the risk of "1 mSv/y" as well as natural radiation.

12.3.2 Community Dialog Forum for Residents of Fukushima Prefecture at Fukushima-shi [6]

This community dialogue forum was held on November 3, 2012 at Fukushima-shi for residents of the Fukushima prefecture to discuss matters such as returning their lives to normal in areas affected with long -term radiation from the TEPCO Fukushima Daiichi NPP accident, concentrating on the effects on health from exposure to radiation, with overseas experts mainly consisting of ICRP members who have expertise and knowledge in this field. After the key note lecture by the forum chair person of ICRP, several speakers from local media, the medical fraternity, and the residents belonging to various fields presented their actions just after the accident and problems they encountered. Almost all the speakers commonly talked about confusion due to lack of knowledge of radiation as well as poor information on the progress of the accident just after its occurrence. They felt strong anxiety regarding radiation. In the discussion, a few ICRP members mentioned that the radiation level of Fukushima was considerably lower in comparison with that of Chernobyl and they recommended comparing it with the natural radiation level. At that time, almost all Japanese had only limited information on natural radiation exposure doses such as the world average and higher values of India and China as well as the values in Japan. The higher values seemed to be not persuasive, because the Japanese knew neither such local high radiation areas in India and China nor the natural radiation levels in the European countries of the ICRP members. The material of Europe Atlas on natural radiation [10] which was informed after the community dialogue forum seemed to be doubtful to the authors, because the values given in the material were several times higher than the well-known world average value of 2.4 mSv/y. Accordingly, it is important to evaluate the country-averaged annual exposure dose by natural radiation for countries familiar to the Japanese. The country -averaged annual exposure dose is described in Sect. 12.5.

12.4 Risk Evaluation of 1 mSv/y for Public Radiation Exposure Limits

The latest recommendation for occupational and public radiation exposure limits have been made by ICRP in 2007 [11], taking account of the result of the long-term cohort study [12] on health effects in Japanese atomic bomb survivors in Hiroshima and Nagasaki, with a focus on not only "stochastic effects," primarily cancer, but also hereditary disorders. The data are given in three categories of exposure situations, namely, planned exposure situations that involve the deliberate introduction and operation of sources; emergency exposure situations that require urgent action in order to avoid or reduce undesirable consequences; and existing exposure situations that include prolonged exposure situations after emergencies. The most important quantities are the recommended dose limits in the planned exposure situations: occupational and public limits given in Table 12.3. The public exposure limit of "1 mSV/y" is taken as the lowest criterion to select the areas to be decontaminated and its risk is one of the most interesting matters to show safety.

The public limits were determined in order to secure excellent safety compared with those of other factors of mortality, on the basis of the concept proposed in 1977 [13]: (1) humans have always been exposed to radiation from the natural environment, the basic sources of natural radiation exposure. Man-made modifications of the environment and human activities can increase the "normal" exposure to natural radiation (2). Radiation risks are a very minor fraction of the total number of environmental hazards to which members of the public are exposed and the acceptable level of risk for stochastic phenomena for members of the general public may be inferred from consideration of risks that an individual can modify to only a small degree and which, like radiation safety, may be regulated by national ordinance. An example of such risks is that of using public transport. On this basis, a risk in the range of 10^{-6} to 10^{-5} per year would be likely to be acceptable to any individual member of the public.

In this chapter, the authors would certify the amount of radiation risk of public limits, "1 mSv/y" by using statistical data on Japanese mortality in 2008. The risk coefficient of the radiation dose of 100 mSv inducing cancer was estimated by using the death increase in a lifetime of 0.5 %, which was given by ICRP, the number of dead, 900,000, and the Japanese population, about 100 million. The results are compared with those of malignant tumors (cancer) and traffic accidents

Table 12.3 Recommended dose limits in planned exposure situations

Type of limit	Occupational, mSv in a year	Public, mSv in a year
Effective dose	20, averaged over 5 years, with no more than 50 mSv in any one year	1 (exceptionally, a higher value of effective dose could be allowed in a year provided that the average over 5 years does not exceed 1 mSv in a year)

Table 12.4 Risk coefficients of natural cancer, traffic accident and radiation exposure

Item	Mortality		Lifetime mortality (%)
	Number of deaths per 100,000 people	A fraction (Risk coefficient)	
Malignant tumors (Cancer)	270.1	2.7×10^{-3}	30.1
Traffic accident	5.9	5.9×10^{-5}	0.66
Radiation exposure of 100 mSv	4.5	4.5×10^{-5}	0.5

in Table 12.4. Because the limits of the occupational and public radiation exposure are one fifth and one hundredth of 100 mSv from the view point of total exposure dose, the risk coefficients were estimated as follows:

Occupational exposure limit 20 mSv/y: risk coefficient $= 9.0 \times 10^{-6}$,
Public exposure limit 1 mSv/y: risk coefficient $= 4.5 \times 10^{-7}$.

Consequently, it is noted that the risk coefficient of “1.0 mSv/y” is satisfactorily lower than 10^{-6} to 10^{-5} per year to be expected by ICRP.

12.5 Country-Averaged Annual Exposure Doses of Natural Radiation in the World

The ICRP members frequently said in the dialogue meetings with the residents of the Fukushima prefecture that the annual exposure doses in Fukushima were as low as those of natural radiation in their countries in Europe. The natural radiation doses in Europe are given in Reference [10] but they seem to be too large compared with the world -average value of 2.4 mSv/y reported in UNSCEAR 2000 [14]. Accordingly, the authors have evaluated the country-averaged annual exposure doses by the natural radiation in the world, on the basis of the fundamental data on indoor radon concentration, external exposure both outdoor and indoor, cosmic rays, and intake of food which were taken from Reference [14].

In the calculation, the authors assumed that a man stayed for 19.2 h (80 %) a day indoors and 4.8 h (20 %) outdoors, and that the concentration of outdoor radon was one third of that of indoor radon, as the conditions had been taken in the estimation of the world -averaged value. The conversion factor from the radon concentration to exposure dose was taken as $Q = 9.0 \times 10^{-6}$ (mSv/Bq m^{-3}) and a decay fraction of radon isotopes to the daughter nuclides contributing to actual radiation exposure as $k = 0.4$ that were ordinarily used in the estimation of the effect of natural radiation. Likewise, the conversion factor of a gamma-ray adsorbed dose to an effective equivalent dose was $C = 0.748$ (mSv/mGy). Annual exposure dose by cosmic rays was assumed to be 0.39 mSv/y for countries near the North Poleand

Table 12.5 Comparison of annual exposure dose due to natural radiation (unit: mSv/y)

Object		Radon	Cosmic rays	Indoor gamma	Outdoor gamma	Intake foods	Total
Japan	Published	0.48	0.30	—	0.33	0.98	2.09
	Present	0.53	0.30	0.07	0.28	0.98	2.16
World average	Published	1.26	0.39	—	0.48	0.29	2.42
	Present	1.17	0.38	0.08	0.44	0.29	2.35

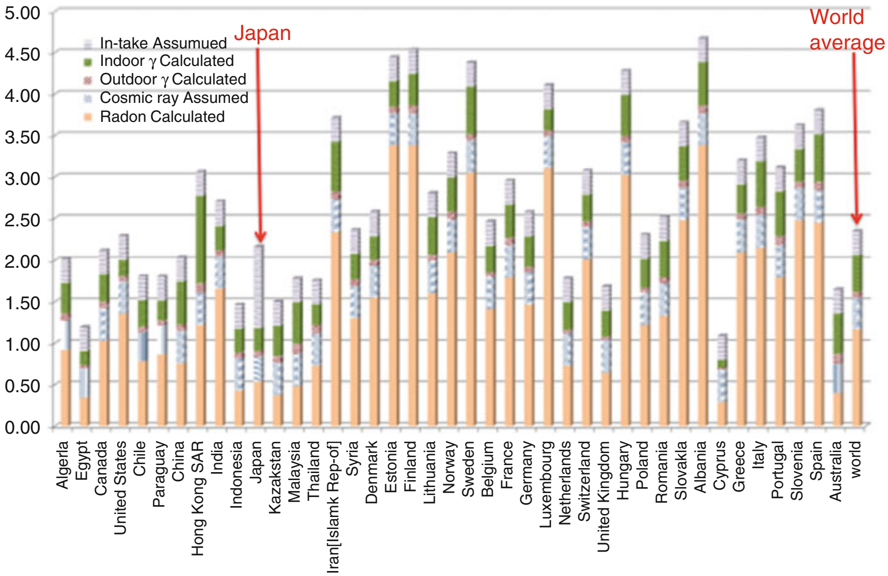

Fig. 12.2 Country averaged annual exposure dose rate due to natural radiation in the world

0.35 mSv/y, otherwise, except for 0.30 mSv/y for Japan. The annual dose due to food intake was also assumed to be the world -averaged value 0.29 mSv/y, except for 0.98 mSv/y for Japan: the Japanese eat many sea products, which contain radioactive isotopes such as polonium-210 and lead-210 and have high dose conversion factors in the human body.

In Table 12.5, the present results for Japan and the world average are compared with the widely published values. Good agreement is observed so that the authors might be convinced that the present method is verified. Figure 12.2 compares the calculated country-averaged annual exposure doses in the world. It is found that the values of northern and eastern European countries such as Finland, Estonia, Sweden, Luxemburg, Hungary, and Albania are quite high, exceeding 4 mSv/h because of high radon concentrations, whereas the values are lower than those of about 7 mSv/y given in Reference [10].

12.6 Discussion

The decontamination of a major part of living spaces of the "Intensive Contamination Survey Area" in the Fukushima prefecture has been done and ambient radiation dose rates have been measured to be below 0.23 μSv/h on average, whereas a higher radiation level is observed in a small part but does not exceed 0.5 μSv/h at the highest. In the special decontamination area of three municipalities such as Tamura-shi, Naraha-machi, and Kawauchi-mura, the average radiation dose rate was 0.38–0.41 μSv/h within FY 2014. At 15–30 % places, slightly high radiation has remained in the amount of 0.54–1.03 μSv/h measured immediately after the decontamination. The additional annual exposure dose for an individual due to radioactive cesium can be roughly estimated by multiplying 5000 h to the ambient radiation dose rate. The additional annual dose thus obtained can be expected to be below 1 mSv/y in most parts of the Nakadori district and 2 mSv/y on average even in the three municipalities.

The total annual dose that the resident will actually receive should be calculated by adding the contributions of natural radiation of about 2 mSv/y to the additional exposure dose due to radioactive cesium isotopes. It can be roughly said that the people in the Nakadori district will be exposed by 3 mSv per year maximum, and 4 mSv on average in the "Special Decontamination Area" of Tamura-shi, Kawauchi-mura, and Naraha-machi. A similar dose will be normally received in Europe, where radon concentration is high, as the ICRP members said.

The present work also clarified that the risk coefficient of 1 mSv/y is quite low, 4.5×10^{-7}, compared with that of traffic accidents of 5.9×10^{-5}. Even in the case of 7 mSv/y where the environmental radiation dose rate is about 1 μSv/h observed in Kawauchi-mura, its risk coefficient is 3.2×10^{-6} and seems to be low enough. Of course, the occupational exposure dose limits are also at a safe level: their risk coefficient 9.0×10^{-6} is one order lower than that of traffic accidents.

Accordingly, the authors hope the present results help people accept the reasonable decontamination work and not aim for instantaneously realizing 1 mSv/y and determine their return back to their hometowns in an environment of a few mSv/y.

Nevertheless, it is considered that the people who moved would be afraid of the influence of low-level radiation on cancer in their children and hesitate to return to their hometown. Low-level radiation brings a stochastic influence on health, essentially increasing death due to cancer with the probability of 0.5 % per 100 mSv in accordance with the linear model with the nonthreshold hypothesis proposed by ICRP [11]. On the other hand, the lifetime mortality of malignant tumors (cancer) is quite high because many stresses in daily life produce much reactive oxygen in a human body. The reactive oxygen damages the DNA of a cell in the human body; a double-strand break is especially a problem likely to produce a cancerous mother cell. Inasmuch as almost all DNA damage is repaired and imperfectly repaired DNA causes cell death (loss of cells) through apoptosis, a person will seldom get the cancer, additively owing to his immunity to guard his body against impermissible different kinds of cells. He may get the cancer by losing immun ability as he ages. Laughter is helpful in strengthening immunity power by increasing killer cells in the human body. Accordingly, spending a daily life without so much stress is important for a person to protect against cancer by reducing reactive oxygen production and keeping immunity power. There is research that shows the stress of daily life produces a double-strand break of the DNA by about 300 times as much as 1 mSv/day radiation exposure does [15]. It might be evidence of the high lifetime mortality of malignant tumors, shown in Table 12.4. Anyhow, it can be said that the influence of low-level radiation below 100 mSv is not so large.

It is a difficult problem how we consider the influence of the total exposure dose of low-level radiation accumulated during a human lifetime. For example, the total dose by natural radiation of 2.1 mSv/y is estimated to be 150 mSv by taking into account agewise sensitivities to radiation. Its risk coefficient can be estimated to be 6.75×10^{-5} according to the LNT hypothesis which was proposed for radiation management in the radiation facilities by the ICRP, and the radiation effect is considered to increase proportionally to the radiation exposure dose. However, there is an idea that the influence of low-level radiation is not transmitted for a long time because its effects are eliminated for a short time by the human body guard system such as the functions of repairing the damaged DNA, immunity against the inimical cells, and so on. Recently, Banto al. [16] discussed human body recovery due to repairing damaged DNA and showed that the radiation effect becomes saturated to certain values. This idea implies that the present risk estimation for the public limits, 1 mSv/y, is always applicable to long-time exposure without integrating the risk per year.

12.7 Conclusion

In the present work, the additional radiation exposure dose in Fukushima is clarified. Newly evaluated country-averaged annual exposure dose by natural radiation and risk coefficient of 1 mSv/y also showed that the Fukushima Nakadori district is safe.

The decontamination work is being carried out throughout the living space of the Fukushima prefecture aiming at a goal in FY 2018. Recent measurements of the environmental radiation dose rates showed that the additional annual exposure dose was generally below 1 mSv/y in the major part of the Nakadori district and about 2.0 mSv/y in the special decontamination area of Tamura-shi, Naraka-machi, and Kawauchi-mura. The total exposure dose taking account of both cesium and natural radiation, 3–4 mSv/y are the same as the dose from natural radiation in Europe. There are no data to show any correlations between such country-averaged exposure doses by natural radiation and the cancer death data which can be taken from Reference [17]. It means that the low-level exposure of natural radiation does not cause any cancers.

The risk of the 1 mSv/y exposure has been certified to be quite low, 4.5×10^{-7} per year, as the ICRP 1977 recommendation expected as a condition of the public exposure limit.

This information should give a light to the residents to live in the Fukushima prefecture in the future. The authors would expect the people outside Fukushima, especially residents of the Tokyo metropolitan area, to correctly understand the risk coefficient of the 1 mSv/y and to recognize that the radiation level of Fukushima becomes lower to the harmless level, and finally to abandon their negative consciousness about Fukushima.

The major cause of cancer is stress in daily life such as an irregular life, unbalanced meals, friction with other people, smoking, and so on rather than radiation. A tranquil life with laughter is very important to protect from cancer rather than worrying about the influence of low-level radiation. Finally, the authors hope that the government and the media will accept the present result and publicize it widely in order to make both Fukushima and the whole of Japan brighter, through acceleration of the decontamination work and the rehabilitation together with the excellent ideas and passionate efforts to recreate a town in the damaged areas.

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Chapter 13
Indoor Deposition of Radiocaesium in an Evacuation Area in Odaka District of Minami-Soma After the Fukushima Nuclear Accident

Hiroko Yoshida-Ohuchi, Takashi Kanagami, Yasushi Satoh, Masahiro Hosoda, Yutaka Naitoh, and Mizuki Kameyama

Abstract The indoor deposition of radiocaesium was investigated for 27 wooden houses in eight areas of Kanaya, Mimigai, Ootawa, Ooi, Kamiyama, Kamiura, Ebizawa, and Yoshina in Odaka district of Minami-Soma, Fukushima Prefecture from November 2013 to January 2015. Odaka district is within a 20 km radius of the Fukushima Daiichi nuclear power plant (FDNPP), which used to be designated as a restricted area and has been designated as an evacuation area. Dry smear test was performed over an area of 100 cm^2 on the surface of materials made of wood, glass, metal, and plastic in the rooms and the surface of wooden structure in the roof-space. Approximately 1000 smear samples were collected in total; 89% of the smear samples obtained in the rooms exceeded the detection limit (0.004 Bq/cm^2) and a maximum value was evaluated to be 1.54 Bq/cm^2; 77% of the smear samples taken from the wooden structure in the roof-space exceeded the detection limit and a maximum value was evaluated to be 1.14 Bq/cm^2. Area differences in surface contamination were observed. Assuming that two horizontal phases of the room have uniform surface contamination with the maximum median

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radioactivity observed in Kamiura (0.1 Bq/cm^2) for 27 houses investigated, the ambient dose equivalent rate for ^{134}Cs and ^{137}Cs in November 2013 was calculated as approximately 0.002 μSv/h.

Keywords Odaka district of Minami-Soma • Evacuation area • Wooden houses • Indoor surface contamination • Fukushima nuclear accident • Smear method

13.1 Introduction

The Great East Japan Earthquake of magnitude 9.0 and the tsunami on March 11, 2011 resulted in major damage to the Fukushima Daiichi nuclear power plant (FDNPP). From March 12 onward, various incidents at multiple units occurred including hydrogen explosions, smoke, and a fire [1] and a large amount of radioactive material was released into the environment and moved as a radioactive plume with the wind [1, 2]. In the evening on March 12, a reading of 20 μSv/h was observed from a measurement made at the joint government building of the city of Minami-Soma, and it is believed that the plume was first blown south by a weak northerly wind and then diffused to the north by a strong southerly wind [1]. In the absence of precipitation, the dispersed pollution caused dry deposition during the radioactive plume pass through the area. In particular, low airtightness in Japanese wooden houses can be the cause of indoor dry deposition [3]. Dry deposition is important as well as wet deposition when assessing the consequences of nuclear accident in the context of risk assessment, as dry deposition is close to where residents live and doses from deposited long-lived contaminants are usually the major long-term hazards. It is necessary for residents to know the level of indoor deposition when they plan temporary access or return home. In this study, the indoor deposition of radiocaesium was investigated for 27 wooden houses in eight areas in Odaka district of Minami-Soma. Then, we assessed the influence of surface contamination on the ambient dose equivalents.

13.2 Methods

13.2.1 Locations of Houses Investigated

From November 2013 to January 2015, the indoor deposition of radiocaesium was investigated for 27 wooden houses in eight areas of Kanaya, Mimigai, Ootawa, Ooi, Kamiyama, Kamiura, Ebizawa, and Yoshina in Odaka district of Minami-Soma, Fukushima Prefecture, as shown in Fig. 13.1. Odaka district, located on the southern end of Minami-Soma, is within a 20 km radius of the FDNPP and all residents were evacuated immediately after the evacuation instruction was issued on March 12, 2011 [1]. On April 22, 2011, Odaka district was shifted to legally

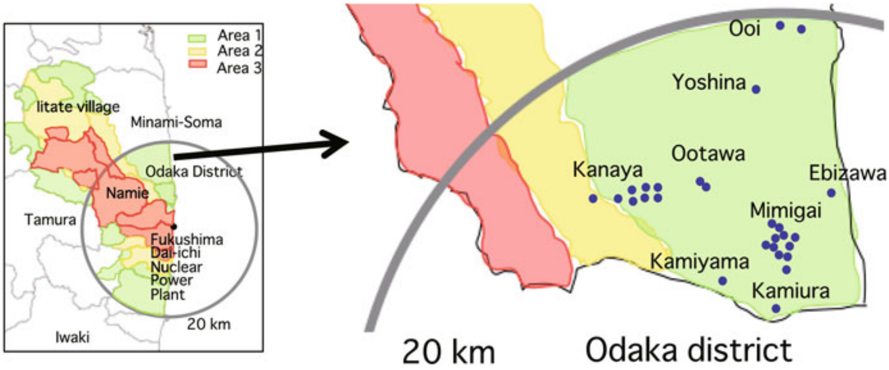

Fig. 13.1 Current status of Odaka district of Minami-Soma, Fukushima Prefecture in April 2015 and the locations of the houses. One *blue*, *closed circle* corresponds to one house at each location

enforceable restricted area [1]. On April 16, 2012, the restricted area was rearranged into three areas responding to the annual cumulative dose [1]. Areas 1, 2, and 3 are those in which the evacuation orders were ready to be lifted; in which the residents are not permitted to live; and where it is expected that the residents will have difficulty returning for a long time, respectively [4]. The Odaka residents were prohibited any access to their homes until April 2012. Decontamination work started from 2014 in Odaka district during the investigation of this study. It did not affect the investigation as it was conducted for the yard, the roof, and the gutter but not for the interior of the house. The current status of Odaka district on April 2015 and the locations of the houses investigated are shown in Fig. 13.1. One blue, closed circle corresponds to one house at each location. All houses are made of wood and are one- and/or two-story structures.

13.2.2 Measurement of Surface Contamination

To estimate surface contamination, dry smear test was performed on the surface of materials in the rooms and in the roof-space. The surfaces over an area of 100 cm^2 of materials were rubbed with moderate pressure using a round smear test paper with a diameter of 2.5 cm. The smear samples were carefully collected from the flat places that were not cleaned or wiped by residents, in every room, and 991 samples were collected in total. The numbers of houses and collected samples for surfaces of wooden, metal, glass, and plastic materials in the rooms, of wooden structure in the roof-space, and of wooden column in the rooms for each area are summarized in Table 13.1.

Radioactivity on smear test paper was measured for 5 min with a plastic scintillator detector JSD-5300 (Hitachi Aloka Medical, Ltd., Japan) and/or a liquid scintillation counter LS-6500 (Beckman Coulter, Inc.) using beta rays emitted from ^{134}Cs and ^{137}Cs, which are dominant nuclides in the investigated period.

Table 13.1 The numbers of houses and collected samples for surfaces of wooden, metal, glass, and plastic materials in the rooms, of wooden structure in the roof-space, and of wooden column in the rooms for each area and the numbers of smear samples exceeded the detection limit (0.004 Bq/cm^2) and below the detection limit for each area

		Wooden, metal, glass, and plastic materials in the rooms			Wooden structure in the roof-space			Wooden column in the rooms		
	Numbers of houses	Numbers of samples	<ND	>ND	Numbers of samples	<ND	>ND	Numbers of samples	<ND	>ND
Kamiura	1	31	2	29	2	0	2	2	2	0
Kamiyama	1	46	0	46	5	0	5	4	2	2
Kanaya	8	231	11	220	45	4	41	16	16	0
Ootawa	2	43	1	42	7	2	5	4	4	0
Yoshina	1	36	0	36	5	0	5	2	2	0
Ebizawa	1	29	4	25	1	0	1	2	1	1
Mimigai	11	334	47	287	52	22	30	18	14	4
Ooi	2	65	21	44	7	1	6	4	4	0
Total	27	815	86	729	124	29	95	52	45	7

In order to estimate the total removable surface contamination, radioactivity on smear test paper (Bq/cm^2) was obtained by the following equation [5, 6]:

$$A_{sr} = \frac{n - n_b}{60 \cdot \varepsilon_i \cdot F \cdot S \cdot \varepsilon_s} \tag{13.1}$$

where n is the gross count rate (min^{-1}), n_b is the background count rate (min^{-1}), ε_i is the instrument efficiency, F is the removal fraction, S is the surface area covered by the smear, for example, 100 cm^2, and ε_s is the source efficiency, that is, the fraction of the decays within the sample that results in a particle of radiation leaving the surface of the source.

The combined efficiency of the instrument and the source for each detector of the plastic scintillator detector and the liquid scintillation counter was determined by measuring a part of samples simultaneously using a high-purity germanium (HPGe) detector ORTEC-GMX-20195-S (AMETEK Inc., USA). The removal fraction was determined by the use of repetitive wipes [5, 6] and the average $\pm\sigma$ of the values was evaluated to be 0.65 ± 0.28. All values of radioactivity were corrected to those in November 2013.

The detection limit, N_d, was defined as 3 standard deviation and calculated by the following equation [7]:

$$N_d = \frac{3}{2}\left[\frac{3}{T_s} + \sqrt{\left(\frac{3}{T_s}\right)^2 + 4N_b\left(\frac{1}{T_s} + \frac{1}{T_b}\right)}\right] \tag{13.2}$$

where N_d is the background count rate (min^{-1}), T_s and T_b are the counting time of the sample and the background (min), respectively, for example, 5 min.

The lower detection limit for surface contamination was obtained when the smear samples were measured using the liquid scintillation counter. The detection limit was evaluated to be 0.004 Bq/cm^2 with Eqs. (13.1) and (13.2).

13.3 Results and Discussion

13.3.1 Indoor Surface Contamination for Odaka Houses

The numbers of smear samples, which were collected from surfaces of wooden, metal, glass, and plastic materials in the rooms, of wooden structure in the roof-space, and of wooden column in the rooms for each area, that exceeded the detection limit and below the detection limit in each area are summarized in Table 13.1. Eighty-nine percent (729/815) of the smear samples obtained in the rooms exceeded the detection limit and a maximum value was evaluated to be 1.54 Bq/cm^2. Seventy-seven percent (95/124) of the smear samples taken from wooden structure in the roof-space exceeded the detection limit and a maximum value was evaluated to be 1.14 Bq/cm^2. This result indicates that the pollution deposited not only in the interior of the house but also in the structure in the roof-space. However, only 13.5 % (7/52) of the smear samples exceeded the detection limit for wooden column in the rooms with a maximum value of 0.07 Bq/cm^2. This difference between former two results and the latter one indicates that radiocaesium deposition on a vertical surface is considerably lower than that on a horizontal surface. The median surface contamination with an interquartile range evaluated from surfaces of wooden, metal, glass, and plastic materials in the rooms for 27 houses in each area is shown in Fig. 13.2a. The interquartile range is expressed by Q1–Q3, which are the middle values in the first half and the second half of the rank-ordered data set, respectively. There seems to be a difference in the median surface contamination depending on areas. In the same manner, the median surface contamination with an interquartile range evaluated from surfaces of wooden structure in the roof-space for houses in each area is shown in Fig. 13.2b. The order of indoor surface contamination was the same between in the rooms and in the roof-space except a value for the house in Yoshina, as shown in Figs. 13.2a, b. Three areas of Ebizawa, Mimigai, and Ooi showing smaller values of the median surface contamination with an interquartile range in Fig. 13.2a, b are located closer to the ocean.

The houses of Kanaya and Mimigai showing a difference in the median surface contamination with an interquartile range in Fig. 13.2a, b are compared. The values of surface contamination in each house Kanaya and Mimigai, in which 8 and 11 houses were investigated, respectively, are shown in Fig. 13.3. The value of median surface contamination with an interquartile range for each house in two areas is exhibited in the left group and the right group, respectively. Generally, it was observed that the values of surface contamination in Kanaya tended to be

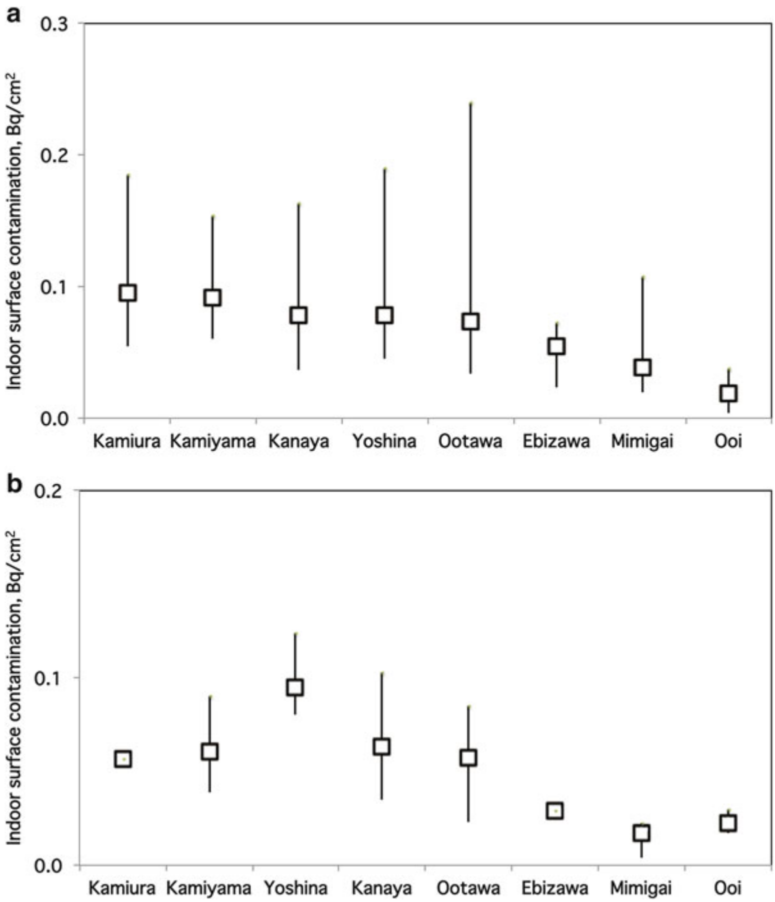

Fig. 13.2 (**a**) Median surface contamination with an interquartile range evaluated from surfaces of wooden, metal, glass, and plastic materials in the rooms for 27 houses in each area. The median and the interquartile range Q1–Q3 are expressed as *squares* and the *bar*, respectively. (**b**) Median surface contamination with an interquartile range evaluated from surfaces of wooden structure in the roof-space for houses in each area. The median and the interquartile range Q1–Q3 are expressed as *squares* and the *bar*, respectively

larger than those in Mimigai; however, a large discrepancy for each individual house was observed in both groups. The difference in characteristics of the houses, which showed the maximum and the minimum median surface contamination, in each group between Kanaya-A and Kanaya-B and between Mimigai-I and Mimigai-S was considered. There was no relationship between the value of surface contamination and the size of the house, the age of the building, the direction of the building (each entrance faces the south or the southeast direction), or area topography around the house. There is no difference in distance from the FDNPP among houses in each group, either. It was noted that residents of both, the houses

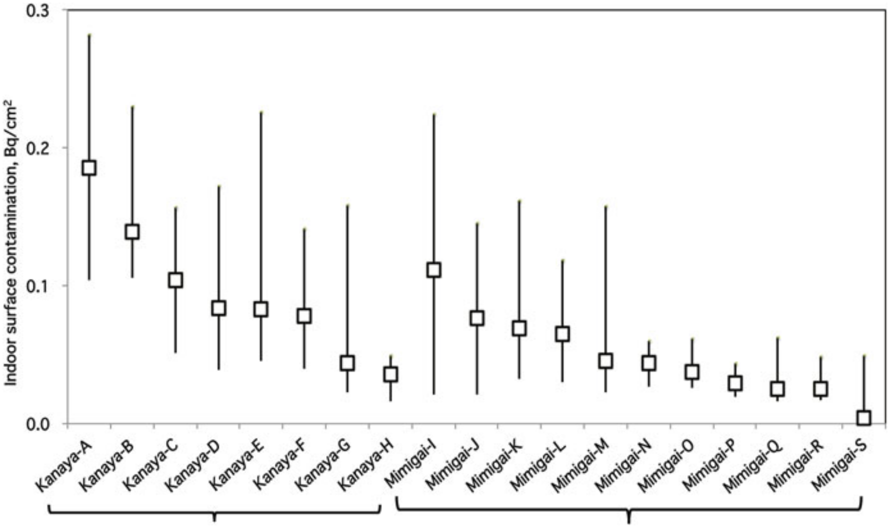

Fig. 13.3 Values of surface contamination in two groups of Kanaya and Mimigai. The value of median surface contamination with an interquartile range for each house in Kanaya and that in Mimigai is exhibited in the *left group* and the *right group*, respectively. The median and the interquartile range Q1–Q3 are expressed as *squares* and the *bar*, respectively

of Kanaya-B and Mimigai-S showing the minimum value of surface contamination in each group, could use running water and they quite often returned home after the restricted area was rearranged on April 2012. Even if the smear samples were carefully collected from places that were not cleaned or wiped, the frequency of residents' entering the house could have an effect on the level of surface contamination.

For houses in Kanaya and Mimigai, the ambient dose equivalents [H*(10)] were measured outdoors using a 1″ φ × 1″ NaI (Tl) scintillation survey meter TCS-172B (Hitachi Aloka Medical, Ltd. Japan). H*(10) was measured outdoors at three or four points for each house and at a height of 1 m above the ground. At each point, measurements were collected by changing the direction of the probe of the survey meter to the four directions of east, west, north, and south, and each measurement was repeated three times. The measurement was conducted before the decontamination work started and all values were corrected to those in November 2013. An average ±σ was obtained for each house, as shown in Fig. 13.4, in the same order as the order of the data in Fig. 13.3. There is a clear discrepancy in the ambient dose equivalents between two groups of Kanaya and Mimigai, showing considerably lower values in the Mimigai group than those in the Kanaya group. A large discrepancy in the values of surface contamination for each house observed, seen in Fig. 13.3, is not seen in Fig. 13.4. It should be noted that Mimigai-I had a relatively low ambient dose equivalent, although the indoor surface contamination was relatively high.

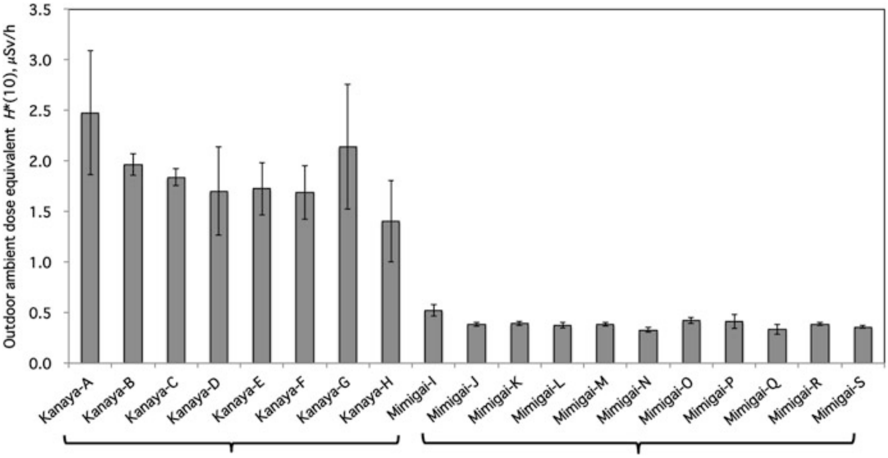

Fig. 13.4 Outdoor ambient dose equivalents [$H^*(10)$] for houses in Kanaya and Mimigai. An average $\pm\sigma$ for each house is shown in Fig. 13.4 in the same order as the order of the data in Fig. 13.3. The average and 1 standard deviation are expressed as *columns* and the *bar*, respectively

13.3.2 Effect of Surface Contamination on the Indoor Ambient Dose Equivalent

The effect of surface contamination on the indoor ambient dose equivalent was evaluated. The photon flux, φ (photons/sec/cm^2) at a point h m distant from the center of a disk-shaped isotropic source with a radius of R m, homogeneously emitting, is obtained by the following equation [8]:

$$\varphi = \frac{Q_s}{4} \ln \frac{R^2 + h^2}{h^2} \tag{13.3}$$

By applying 1 cm dose equivalent rate constant, Γ (μSv · m^2/MBq/h) to Eq. (13.3), the ambient dose equivalent rate, H (μSv/h) at a point h m distant from the center of a disk-shaped isotropic source with a radius of R m is obtained by Eq. (13.4), assuming radioactivity of 1.0 Bq/cm^2 is homogeneously distributed in the source,

$$H = \frac{\pi}{10^2} \Gamma \ln \frac{R^2 + h^2}{h^2} \tag{13.4}$$

Assuming two horizontal phases of the house with dimensions $10 \times 10 \times 3$ m are homogeneously contaminated with the maximum median radioactivity observed in Kamiura (0.1 Bq/cm^2) for 27 houses investigated, the ambient dose equivalent rate for ^{134}Cs and ^{137}Cs in November 2013 was calculated to be approximately 0.002 μSv/h.

The loose and removable surface contamination would cause not only external exposure but also internal exposure from intakes by ingestion and/or inhalation of radioisotopes. We evaluated an example of committed effective dose (μSv) using the radioactivity in dirt in a bag, which was sucked by a vacuum cleaner in the house (Kanaya-E) from the date before the earthquake occurred to November 2013 and effective dose coefficient given by ICRP 72 [9]. The radionuclide concentrations were counted using a high-purity germanium (HPGe) detector ORTEC-GMX-20195-S for 1000 s, revealing that concentrations for ^{134}Cs and ^{137}Cs were $68,600 \pm 0$ and $170,400 \pm 0$ Bq/kg (corrected to November 2013), respectively. In a case that an adult (more than 17 years) once intakes 0.1 g of dust by ingestion, the committed effective dose was calculated to be 0.35 μSv as ingestion dose coefficients are 0.019 and 0.013 μSv/Bq [9] for ^{134}Cs and ^{137}Cs, respectively.

Both, dose of external and internal exposure due to indoor deposition of radiocaesium are evaluated to be relatively low. Surface contamination is loose and easily removable. In our trials of cleaning, surface contamination for wooden materials was reduced to one-tenth after wiping with chemical wiping cloths and further reduced to below the detection limit after wiping with a damp cloth. From a viewpoint of radiation protection, it is strongly recommended to remove surface contamination by cleaning the house before residents return home.

13.4 Conclusion

The indoor deposition of radiocaesium was investigated for 27 wooden houses in eight areas in Odaka district using dry smear test. Comparison of surface contamination between Kanaya and Mimigai houses revealed that the values of surface contamination in Kanaya tended to be were larger than those in Mimigai; however, a large discrepancy for each individual house was observed in both groups. The frequency of residents' entering their house might have an effect on the level of surface contamination. We evaluated external and internal exposure dose due to indoor deposition of radiocaesium and found that these values are relatively low. Surface contamination is loose and easily removable. In our trials, surface contamination for wooden materials was reduced to below the detection limit after wiping with chemical wiping cloths and a damp cloth. From a viewpoint of radiation protection, it is strongly recommended to remove surface contamination by cleaning the house before the residents return home.

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