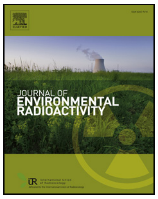
Journal of Environmental Radioactivity 192 (2018) 417–425

Contents lists available at ScienceDirect

Journal of Environmental Radioactivity

journal homepage: www.elsevier.com/locate/jenvrad



Evaluation of ecological half-life of dose rate based on airborne radiation monitoring following the Fukushima Dai-ichi nuclear power plant accident

Yukihisa Sanada[a,*], Yoshimi Urabe[b], Miyuki Sasaki[a], Kotaro Ochi[a], Tatsuo Torii[c]

[a] *Fukushima Remote Monitoring Group, Fukushima Environmental Safety Center, Japan Atomic Energy Agency, 45-169 Sukakeba, Kaihama-aza, Haramachi-ku, Minamisoma, 975-0036, Japan*

[b] *NESI Inc., 38 Shinko-cho, Hitachinaka, Ibaraki, 312-0005, Japan*

[c] *Collaborative Laboratories for Advanced Decommissioning Science, Japan Atomic Energy Agency, 790-1 Motooka Ohtsuka, Tomioka Town, Futaba County, Fukushima, 979-1151, Japan*

ARTICLE INFO

Keywords:
Fukushima Daiichi nuclear power plant accident
Radiocesium
Airborne radiation monitoring
Unmanned aerial vehicle

ABSTRACT

Airborne radiation monitoring was conducted in order to evaluate the influence of radionuclides emitted by the Fukushima Daiichi Nuclear Power Plant (FDNPP) accident throughout Japan. Carrying out airborne radiation monitoring using manned and unmanned helicopters, the we have developed and established an analysis method concurrently with the development of this monitoring method. In particular, because the background radiation level differs greatly between East and West regions of Japan, we have developed a discrimination method for natural radionuclide and cosmic rays using the gamma energy spectra. The reliability of the airborne radiation monitoring data was validated through comparison with large amounts of ground measurement data. The ecological half-lives of short and long components for decline of the ambient dose equivalent (air dose rate) were 0.61 years and 57 years, respectively, based on the results of air dose rate of airborne radiation monitoring using manned helicopter. These results indicate the importance of airborne monitoring to evaluate and predict the radiation exposure of residents.

1. Introduction

To evaluate the influence of radionuclides emitted by the accident at the Fukushima Dai-ichi Nuclear Power Plant (FDNPP) of the Tokyo Electric Power Company Holdings, Inc. Caused by the Great East Japan Earthquake, various types of environmental radiation monitoring data have been acquired by many governmental institutes and universities. An airborne radiation monitoring technique is suitable to grasp the overall distribution of the ambient dose equivalent (referred to hereinafter as the air dose rate) and the deposition of radionuclides because such a technique can be used to (1) measure widely distributed radionuclides with less manpower and within short periods, (2) display maps that are easy to understand visually, and (3) obtain measurement results at locations (e.g., forests and mountains) that are not easily accessible to humans. Analysis of the temporal and spatial changes in the air dose rate based on multiple airborne radiation monitoring datasets is useful for predicting and evaluating the radiation exposure to inhabitants.

The current airborne radiation monitoring technique was established in the early 2000s. Specifically, European scientists conducted pioneering studies of airborne radiation monitoring after the accident at the Chernobyl nuclear power plant. The method of data acquisition, calibration, and mapping developed by Aage et al. (1999) is the basic technique at present. Allyson and Sanderson. (1998) proposed a calibration technique by using Monte Carlo simulation. Tyler et al. (1996) proposed field-of-view airborne radiation monitoring by comparing airborne data with ground data. Through the European comparison project (Eccomags project), the data acquisition method and methods for analysis of airborne radiation monitoring data developed by each European country were unified (Sanderson et al., 2004).

In Japan, triggered by the Three Mile Island nuclear power plant accident in 1979, research and development of an airborne radiation monitoring system using a manned helicopter (MRM: Manned helicopter Radiation Monitoring) were initiated primarily by researchers from Japan Atomic Energy Research Institute (reorganized as the Japan Atomic Energy Agency: JAEA) (Saito et al., 1988; Nagaoka and Moriuchi, 1990). However, methods of data acquisition, data analysis, and the MRM mapping, which correspond to measurement of wide areas in this case, had not been established.

After the FDNPP accident, the MRM national project was started by

---

[*] Corresponding author.
E-mail address: sanada.yukihisa@jaea.go.jp (Y. Sanada).

https://doi.org/10.1016/j.jenvrad.2018.07.016
Received 25 September 2017; Received in revised form 11 April 2018; Accepted 16 July 2018

the Ministry of Education, Culture, Sports, Science and Technology of Japan and the Department of Energy in the USA (Lyons and Colton, 2012; Blumenthal, 2012). Even though MRM initially monitored only the area around the FDNPP, the areas surveyed were gradually expanded, and eventually, airborne radiation monitoring was performed in eastern Japan, excluding Hokkaido, after October 2011 and in western Japan and Hokkaido, after May 2012 (Sanada et al., 2014a). The distributions of air dose rate at a height of 1 m above ground level (agl.) and of the concentration of radioactive cesium (^{134}Cs and ^{137}Cs) on the ground surface were monitored in all areas in Japan under this MRM project. This monitoring project is ongoing with periodic surveys conducted by the Nuclear Regulatory Authority of Japan (NRA) and JAEA (NRA, 2017). While conducting the MRM project, we developed and established data processing and calibration methods concurrently with the development of a monitoring method. Especially, because the background radiation level differs greatly between the eastern and western regions of Japan, we developed a discrimination method for natural radionuclides as the dominant background, a method for setting the parameters for conversion to the air dose rate near the ground level, and a mapping method (Sanada et al., 2017).

A radiation measurement technique that is more detailed than the method using a manned helicopter is required to formulate a decontamination plan and evaluate the effect of decontamination. Radiation measurement using an unmanned helicopter (URM: Unmanned helicopter Radiation Monitoring) is one solution because an unmanned helicopter can be used to generate detailed air dose rate maps by flying below 150 m, in accordance with Japanese aviation law. URM was developed for monitoring high air dose-rate areas and riverbed areas (Sanada et al., 2014b, 2015). Analytical methods for converting airborne detector count rates to air dose rates at 1 m agl. have been established based on the MRM method, and the validity of the MRM method has been demonstrated thorough comparisons with large amounts of ground measurement data (Sanada et al., 2016).

Several years after the FDNPP accident, evaluation of temporal changes in the air dose rate is required for the evaluation of radiation exposure to inhabitants and for post-accident response. In previous studies, temporal changes in the air dose rate at approximately 5 km from the FDNPP were evaluated regionally based on detailed monitoring results using URM (Sanada et al., 2016). However, temporal changes in the air dose rate over an entire contamination area (approximately 80 km from the FDNPP) based on a comparison of the results of MRM and URM were not evaluated. Knowledge of not only the changes in the air dose rate but also of the regional characteristics of the changes in the air dose rate can be obtained through an analysis of sequential MRM and URM data. In this article, we present the methods and results of the MRM and URM missions performed around FDNPP. In addition, we attempt to calculate the effective and ecological half-lives considering the tendency of the temporal change and discuss the characteristics of the changes in the air dose based on these results.

2. Materials and methods

2.1. Airborne radiation monitoring system and data collection

The dedicated MRM radiation detection system (RSX-3, Radiation Solution, Inc., Mississauga, Canada), which was installed on a manned helicopter, is shown in Fig. 1(a) and (b). This system consists of six large NaI detectors (dimensions: 2″ × 4″ × 1″, total NaI crystal volume: 12.6 L), a data processing unit (RS501 and RS701), and a Global Positioning System (GPS) receiver, as shown in Fig. 1(c). The system acquires a once-per-second readout of the spectrometers to produce a 1024-channel energy spectrum rated at 3 keV per channel. The readings are synchronized with time via the GPS receiver. The spectrum and the GPS data (date, time, latitude, longitude, and height above ellipsoid) are recorded every second.

After the FDNPP accident, unmanned helicopters, R-MAX G1 (manufactured by YAMAHA Co., Ltd., Iwata, Japan), originally developed for spraying pesticides, were used for radiation measurements, as shown in Fig. 1(d). These helicopters are operated manually for takeoff and landing, and they have a program operator for autonomous flight and an operator for the radiation detector. An unmanned helicopter can conduct a programmed flight with the help of detailed self-localization by using a Real-time Kinematic Global Positioning System (RTK-GPS), and its flight waypoints and altitude can be set. Detailed specifications of the unmanned helicopter are given in Sanada et al. (2016). Three $LaBr_3$:Ce scintillation detectors (dimensions, 1.5″ϕ × 1.5″H; total $LaBr_3$:Ce crystal volume, 0.13 L) are used in the URM radiation monitoring system, which was designed by the authors of the present study and constructed by the Japan Radiation Engineering Co., Ltd., (JREC, Hitachi, Japan). These detectors are arranged in a housing with the data processing substrate, as shown in Fig. 1(e) and (f). The detectors record the once-per-second readout of the spectrometers to produce a 1024-channel energy spectrum rated at 3 keV per channel. The data from these detectors are sent to a ground station via a radio channel independent of the helicopter control signal channels. The position of the helicopter and the total count rate information of the detectors are displayed on a map at the ground station in real time.

The airborne radiation monitoring program was conducted regularly by using these monitoring systems as a national project. In the present study, several data sets of MRM and URM were used, as summarized in Table 1. The flight paths of each monitoring session are shown in Fig. 2. Basically, the flight line space of the MRM was 1.8 km (= 1 nautical mile). From MRM-2011-01 to MRM-2011-03, the flight plan was devised considering the climatic conditions and the topography from the viewpoint of flight security. After MRM-2013-01, the flight path was unified to evaluate detailed changes in the air dose rate. The flight line space of the URM was 0.08 km, and the flight line was set to be the same every year. The measurement area of URM-2012-01, which was approximately 5 km from FDNPP, was smaller than those of other monitoring sessions.

2.2. Data processing

This section describes the method used to analyze the measurement data. The detailed methods of MRM and URM are described in our previous articles (Sanada et al., 2016 and Sanada et al., 2017, respectively). Other techniques for analyzing radiation measurements from aircraft are described elsewhere, for example, in International Atomic Energy Agency (IAEA) reports (IAEA, 2003). To convert MRM and URM data at the flight altitude to the air dose rate at a height of 1 m agl., a straight topographically flat road with a relatively flat distribution of the air dose rate was set as the test line. A conversion factor (CD: μSv h^{-1} cps^{-1}) was used to convert the count rate at the flight altitude in air to the air dose rate at 1 m agl. Actually, calculation can be performed by comparing the count rate at the flight altitude to the air dose rate measured at 30 survey points around the test line by using a NaI survey meter. Furthermore, flights at various altitudes from 150 m to 1000 m (URM: from 10 m to 150 m) were conducted over the test line and the effective attenuation factor in air (AF) was obtained from the relationship between the count rate and the flight altitude.

Radiation measurement using the airborne radiation monitoring methods is influenced by the following four sources of background radiation: 1) cosmic rays, 2) radiation contamination by the body of the aircraft, 3) natural nuclides in the detector crystal, and 4) radiation from radon decay products in air. To eliminate the contributions of these background radiation sources from the gamma ray spectra obtained, background count rate data ($C_{BG:}$ cps) acquired above the sea were used. Using the air dose rate conversion factor obtained over the test line, the count rate (C_{all}: cps) obtained at the flight altitude was converted into the air dose rate 1 m agl. (D_{1m}: μSv h^{-1}). To correct the flight altitude, the absolute altitude with respect to the ground level was first obtained by subtracting the 10-m cell elevation data obtained