A radioactive contamination monitoring system with a bead-type radiophotoluminescence glass dosimeter

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Abstract

A radiophotoluminescence (RPL) monitoring scope system was constructed to evaluate radioactive cesium contamination. RPL glass sheets were constructed by bonding RPL glass beads to a backing sheet. The RPL scope was constructed using an image intensifier and a CCD camera to detect RPL from the RPL glass sheet. A UV floodlight was also prepared as an excitation light source. The UV floodlight and an image intensifier were pulse-operated for high signal-to-noise RPL detection. In experiments, the RPL of X-ray irradiated glass sheets was measured with this present system. The RPL intensity, which is calculated from the brightness of obtained images, exhibits acceptable linearity to the absorbed dose. Another experiment showed that RPL can be detected at a distance of 10 m between the RPL glass sheets and the RPL detector.

Keywords:

Radiophotoluminescence (RPL)

Bead-type RPL glass dosimeter

Remote monitoring

Radioactive contamination

1. Introduction

The severe earthquake and tsunami that occurred in March 2011 caused a serious accident at the Fukushima Daiichi nuclear power plant. A large amount of radioactive materials including radioactive cesium (^{134}Cs and ^{137}Cs), which remains in the natural environment in the disaster-stricken area due to its long half-life, was emitted from the plant to the atmosphere. According to the Nuclear and Industrial Safety Agency of Japan (NISA), the total atmospheric release of ^{134}Cs and the total atmospheric release of ^{137}Cs was estimated to be 18 PBq and 15 PBq, respectively (NISA, 2015).

Numerous studies of radiative contamination measurement in Fukushima were performed after the accident. The measurement of the distribution of radioactive contamination is essential for efficient decontamination. In a high-contamination area, workers who are engaged in decontamination or radiation measurement must be protected from excessive radiation exposure. Gamma cameras and Compton cameras have been utilized for the detection of radiation hotspots (Kataoka et al., 2013; Woodring et al., 2003). These types of instruments have high sensitivity to gamma rays. In addition to these methods, a simple method for observing radioactivity distribution is necessary for the measurement of a vast scope of locations.

We have proposed a remote monitoring method for radioactive contamination using glass dosimeter materials (Zushi et al., 2014). Few studies have attempted to employ these materials to monitor radioactivity distribution. Silver-activated metaphosphate glass, e.g. FD-7, is a major material for accumulation-type solid-state dosimeters for individual dosimetry. The glass emits orange radiophotoluminescence (RPL); its intensity is proportional to its absorbed dose by the excitation of ultraviolet (UV) light (Yokota et al., 1966; Piesch et al., 1994). This type of glass is frequently referred to as RPL glass. RPL glass exhibits high sensitivity, high accuracy, and superior long-term stability. RPL readout was performed without a loss of dose information. Considering these advantages, this glass is considered to be suitable for the detection of radioactive contamination. For flexible use, sheet-type glass instead of plate-type glass was prepared by bondage of small glass beads to a backing sheet. The RPL glass sheet was placed on the target position once, and two-dimensional RPL imaging was performed after an appropriate time span, depending on the degree of contamination.

In this study, a remote RPL detection system was constructed for radioactivity distribution measurement in a highly contaminated area. Selection of an appropriate distance between the measuring object and the detector can minimize excessive radiation exposure during measurement. RPL glass that was suitable for radioactive contamination monitoring was prepared. A RPL monitoring examination was performed with X-ray

1 irradiated RPL glass sheets to evaluate the characteristics of this system.

2 3 **2. Materials and Methods**

4 RPL glass was constructed from a mixture of reagent-grade NaPO_3 , $\text{Al}(\text{PO}_3)_3$ and
5 AgCl at 1200°C in an electric furnace. The detailed process of fabricating RPL glass was
6 described in our previous paper (Sato et al., 2013). The weight composition of the glass
7 was 31% P, 51% O, 6% Al, 11% Na, and 0.2% Ag. The glass lot was pulverized into
8 particles with diameters that ranged from approximately 0.1 to 1.0 mm. The particles
9 were reheated to melt and then form spherical shape with their surface tension. The beads
10 were uniformly bonded to flexible aluminum foil. The shape of the RPL glass sheets was
11 rectangular with a side length of 40 mm.

12 In personal dosimetry, a UV laser and a photomultiplier were employed for
13 excitation and RPL detection. The two-dimensional detection of feeble RPL due to a
14 decrease in geometrical efficiency was required. Thus, this RPL detection system was
15 composed of a CCD camera and an image intensifier (II).

16 Figure 1 displays a schematic of the detection system. The system consists of a
17 camera lens (CL), two relay lenses (RLs), an II and a CCD camera. Feeble RPL was
18 guided to the II through the CL, and the RL and was subsequently intensified with the II.
19 The intensified RPL image was photographed with the CCD camera through another RL.
20 Each image frame was added for highly sensitive RPL imaging. A personal computer
21 (PC) was prepared for the storage and indication of these images. The II requires three
22 types of voltage supplies: photocathode voltage (V_k), micro-channel plate voltage (V_{MCP}),
23 and phosphor screen voltage (V_s). In this instrument, V_k was pulsed between +50 V (OFF
24 state) to -200 V (ON state) for gate operation of the RPL scope. V_{MCP} was adjusted by a
25 potentiometer to ensure that V_{MCP} enables the adjustment of II gain. V_s , which is
26 employed for conversion from MCP output electrons to photons for indication of the
27 phosphor screen, was fixed to 5.0 kV.

28 Luminescence from RPL glass was divided into two components: RPL and PL. PL
29 has a relatively short decay time of less than $0.3\ \mu\text{s}$, whereas RPL has long decay time of
30 $2\ \mu\text{s}$. To achieve high signal-to-noise ratio measurements, RPL and PL components
31 should be differentiated to ensure that PL intensity has no proportionality to the absorbed
32 dose. Both time-based discrimination and wavelength-based discrimination are required
33 for high signal-to-noise ratios in RPL selection due to the overlap of the decay time and
34 the wavelength of these two components. An optical long-pass filter was prepared for
35 wavelength-based discrimination of the RPL component.

36 As the excitation light of the RPL glass, an LED floodlight that was composed of

1 1000 UV LEDs was employed. LEDs were pulse-operated and synchronized with the II,
2 as shown in Figure 2. The ON time and frequency of the LEDs were set to 50 μ s and 1
3 kHz, respectively. Two II operation time patterns were prepared for the system. Pattern A
4 in Figure 2 was utilized for RPL detection, and Pattern B was utilized for the detection of
5 background light because RPL was almost decayed in this pattern. The RPL intensity was
6 calculated using a comparison of images, which were obtained with these two II patterns,
7 for the reduction of the background light component.

8 A 90kV X-ray source of which target material is tungsten was used for sample
9 irradiation. X-rays were selected for evaluation of the response of RPL glass sheets under
10 simple condition. X-rays used have lower energy than major cesium gamma-rays, but
11 responses of RPL glass sheets to photons can be confirmed. Contribution of beta-rays
12 which are also emitted from radioactive cesium is more dependent on conditions of actual
13 contaminants because of their shorter range.

14 First, in an experiment, the RPL intensity response was examined with X-ray
15 irradiated RPL glass sheets. The distance between the excitation light and the sample or
16 between the sample and the RPL detector was fixed to 1.7 m. Second, a remote RPL
17 detection experiment was performed at a specific distance. In this experiment, an X-ray
18 irradiated sheet and a non-irradiated sheet were arranged in a square lattice-like form on
19 a wall. The distance between the excitation light and the sample was fixed to 10 m, and
20 the distance between the sample and the detector was fixed to 1.5 m. In actual use, the
21 excitation light was visible near the contaminated target by a mobile carriage, for example.
22 However, the detector has to be manually operated for accurate RPL measurement; thus,
23 a specific distance was required to decrease the radiation exposure to users. Remote RPL
24 measurements were examined in this condition.

27 3. Results and Discussions

28 Figure 3 shows an RPL image that was obtained with this system. An X-ray was
29 irradiated on the RPL glass sheet with a collimator with a diameter of 9.0 mm. A RPL
30 spot was detected with this system. The brightness profile in the cross-sectional direction
31 on the RPL spot was shown in Figure 4. The graph indicates that the FWHM of the RPL
32 spot was 10.4 mm and the spot size was broader than the diameter of the collimator, which
33 indicates that the spatial resolution of this system was several millimeters. The results
34 also indicate that the present remote RPL detection system, which was composed of a
35 CCD camera and an image intensifier, can be used for RPL photographing.

36 The relation between the absorbed dose of the glass sheets and the RPL intensity

1 was shown in Figure 5. The absorbed dose of the glass sheets was controlled with X-ray
2 irradiation time. Error bars in Figure 5 indicate the standard deviation of brightness in
3 each RPL spot. The deviation is considered to be due to nonuniformity of beads size,
4 reflection or scattering of RPL photons on the glass surface, and background noise of RPL
5 detection system. The RPL intensity exhibits acceptable linearity in the range from 0.1
6 Gy to 25 Gy for this measurement condition, but in high dose range it can be presumed
7 that the curve should give better fitting with some other non-linear function. In a
8 preliminary experiment it was confirmed that present RPL detection system has linear
9 response to the orange light which is near RPL emission wavelength. The RPL glass have
10 linear response to the absorbed dose, but in high dose range RPL saturation needs to be
11 taken into consideration. As a future issue the response of single glass bead in high (and
12 low) dose range should be evaluated by another measurement method. The minimum
13 detection limit of a RPL imaging system is dependent on the measurement conditions,
14 e.g., distance, excitation light intensity, and background light conditions. The deviation
15 of the RPL intensity was caused by an unevenness of the glass beads in the RPL glass
16 sheets.

17 Figure 6 shows an RPL image and the arrangement of the RPL sheets for the RPL
18 imaging experiment that was performed at a distance of 10 m. Two RPL spots were
19 observed in Figure 6 (a), which correspond with the X-ray irradiated glass sheets shown
20 in Figure 6 (b). The average brightness of each spot exhibited reasonable linearity to the
21 absorbed dose. These results confirmed that the RPL glass sheets and the RPL remote
22 monitoring system were applicable to the detection of radioactive cesium contamination.
23 The transparency of the glass sheets was important for the quantitative measurement of
24 the absorbed dose to ensure that long-term exposure examination in severe conditions is
25 required for the precise evaluation of radioactive contamination.

26 The evaluation of the response to beta-rays of radioactive cesium should be studied
27 further. The contribution of beta-rays is higher than that of gamma-rays when the RPL
28 glass sheet was directly put on the contaminant. However, effect of beta-rays is considered
29 to be more complicated than that of gamma-rays, because beta-rays mainly deposit their
30 energy to the glass surface and the response of RPL glass sheet depends heavily on the
31 beads size and its variation. It may be also necessary to optimize the characteristics of the
32 RPL glass sheet, e.g. diameter of the glass beads and a material of the backing sheet, for
33 the beta-ray measurement.

35 4. Conclusions

36 The RPL measurement system was constructed with RPL glass for radioactive

cesium contamination measurement. Bead-type RPL glass was constructed from glass material powder and was bonded to a flexible backing sheet. The image intensifier in the RPL scope and the UV excitation light was pulse-operated to discriminate RPL and PL components that were emitted from the RPL glass with the difference in the decay time constant. As a basic experiment, the RPL detection experiment was performed with X-ray irradiated RPL glass sheets. A RPL spot was detected from an RPL image that was obtained with this system. The RPL intensity was successfully obtained from the RPL images, and the RPL intensity of this system exhibited reasonable linearity of the response to the absorbed dose. The remote detection experiment confirmed that RPL can be detected at a distance of 10 m between the RPL glass sheets and the RPL detector. These results showed that this system may be applicable for the remote evaluation of radioactive contamination.

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Figure captions

Fig. 1 Schematic of remote RPL monitoring system.

Fig. 2 Timing chart of UV LED floodlight and image intensifier.

Fig. 3 RPL image obtained with the RPL detection system.

Fig. 4 Brightness profile of the RPL spot shown in Figure 3.

Fig. 5 Relation between the dose of the RPL sheet and the RPL intensity.

Fig. 6 Result of remote RPL detection experiment: (a) RPL image obtained with this system and (b) arrangement of RPL glass sheet

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6 (a)

Figure 6 (b)