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ARTICLE

Development of a gamma camera to image radiation fields

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Measurement of radioactive contamination and confirmation of the decontamination effects are important for the recovery from the nuclear accident at the Fukushima Dai-ichi Nuclear Power Plant. We have developed a gamma camera which can visualize the gamma-ray intensity distribution in real time. Experiments were conducted to investigate its performance. An energy resolution of 2.3 % and spatial resolution of 0.68 m at a distance of 5 m were confirmed. In addition, field tests were conducted in the Fukushima Dai-ichi Nuclear Power Plant. The gamma-ray intensity distribution was successfully visualized within as short a time as 10 seconds in an environment with an air dose rate of 1 – 10 mSv/h. Prominent gamma-ray radiation was found from the penetration holes, which connect the inside and outside of the primary containment vessel. From this result, it was found that shielding the penetration holes will improve the work environment during decontamination and cleanup activities. These results indicate the gamma camera will contribute to decontamination work and radiation exposure reduction for workers.

Keywords: CdTe semiconductor; gamma camera; radiation intensity distribution; real-time visualization; decontamination; radiation exposure reduction

1. Introduction

A number of radioactive materials were released as a result of the nuclear accident at the Fukushima Dai-ichi Nuclear Power Plant. Today, most of them still remain there. There are several devices to measure radiation environment. One popular device is a survey meter which can measure the air dose rate. However, it cannot identify the locations of the radiation sources. It is necessary to find the locations to assist the recovery from the nuclear accident.

One method to find radiation sources is visualization of the radiation intensity distribution. Visualization in real time contributes to a reduction of working time because it makes the work of investigating the air dose rate and decontamination more efficient. Some devices which visualize radiation intensity distribution have already been developed [1-3].

These visualization devices are required to perform many functions, including radionuclide analysis and real time imaging. They are also required to be lightweight and have high spatial resolution. It is not easy to make a single device that fulfills all these requirements. Thus, we have developed a gamma camera with many functions serving to contribute to the recovery from the nuclear accident.

2. Gamma camera specifications

2.1. Device configuration

Figure 1 shows an overview of the gamma camera. Its size is 24 cm (W) x 34 cm (D) x 34.5 cm (H). The gamma camera should have shielding to reduce exposure to background gamma-rays and should also be lightweight for portability. A small detecting module is embedded inside a radiation shield made of lead. The gamma camera, which weighs 15.9 kg, is used as a portable device on the conditions that the environmental dose rate is low and there are prominent hotspots. The gamma camera has an option for additional internal shields. With such additional shielding, the weight of the gamma camera is about 40 kg. This type is used for high accuracy measurements or in areas with a high environmental dose rate. A laser distance meter is embedded inside the housing which covers the whole gamma camera in order to calculate the surface dose rate of objects. An optical camera is also embedded inside the housing to display the gamma-ray intensity distribution on an optical image. These two parts are set outside the shield.

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The gamma camera provides a 43-degree field of view to display the gamma-ray intensity distribution. This provides a field of view of 8 m square at a distance of 10 m from the gamma camera. The optical imaging area is larger than the imaging area of the gamma-ray intensity distribution.

The distribution is displayed basically in real time. It is also possible to display the distribution off-line after the measurement. For the off-line treatments, the gamma-ray intensity distribution is stored as list data and the optical image is stored as JPEG. The image is automatically recorded every 1 second.

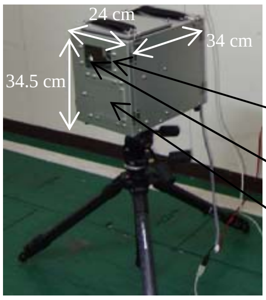

Figure 1. Overview of the gamma camera. A laser distance meter, an optical camera and a small detecting module are embedded inside the gamma camera.

2.2. Detecting module

Figure 2 shows the small detecting module. The module was originally developed for a medical gamma camera [4]. It consists of a CdTe semiconductor detector and ASICs containing the measurement circuit. The CdTe detector consists of a 16 x 16 detection cells array, with a detection area of 4 cm square. Thickness of the CdTe detector is 5 mm. A CdTe semiconductor detector generally has a high energy resolution and high stopping power, and can be used at room temperature. With the ASIC measuring the number of pulses and pulse height, the module can obtain energy spectra with high energy resolution without any cooling system. The energy spectra are measured in each cell. The detecting energy range is 350 keV to 1500 keV.

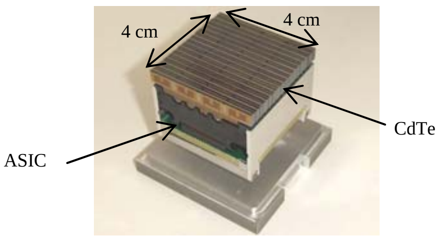

Figure 2. Overview of the small detecting module. The module uses a CdTe semiconductor detector consisting of a 16 x 16 grid of pixels.

2.3. Mapping and controls

By combining the module with a pinhole collimator made of tungsten, the gamma-ray intensity distribution can be measured as a count-rate distribution. **Figure 3** shows the concept used to obtain the distribution. The pinhole collimator limits an area observed by the detection cells. Gamma-rays emitted by a radiation source are detected in a detection cell on the extended line connecting the radiation source to the pinhole. Thus, identifying the cell detecting a gamma-ray become synonymous with identifying the direction from which the gamma-ray comes. The gamma-ray intensity distribution is shown by a colored map overlaid on the image of the same field obtained with the optical camera. The color gradation is shown by linear scale corresponding to radiation intensity. It is not the intensity ratio of radioactivity but that of the gamma-rays detected with the module.

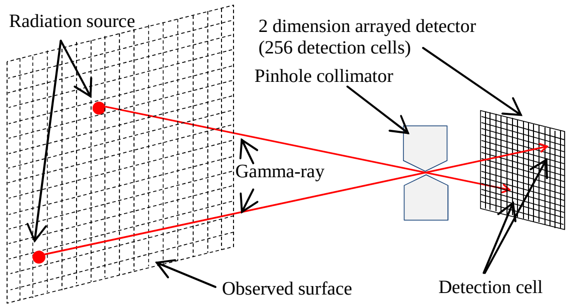

Figure 3. Concept to obtain gamma-ray intensity distribution. A pinhole collimator limits an area observed by the detection cells. By identifying a cell detecting a gamma-ray, the direction from which the gamma-ray comes is identified.

The dose rate distribution at 50 cm above the surface of the observed object, which is defined as the surface dose rate hereafter, can also be displayed on an optical image. The distance between an observed object and the gamma camera is necessary to estimate the surface dose rate. The distance to an object at the center of the observed surface can be measured with the laser distance meter. Distances from other pixels are corrected by trigonometry. Then, the distances are calculated on an assumption that all the objects are on the same plane which is perpendicular to a line connecting the center of the detection module to the pinhole. Needless to say, because the distances estimated with this method are not strict, a better way to measure the distance to each pixel is an objective in the future. The gamma-ray intensity is converted into a surface dose rate using the calculated distance.

Count rates of Compton scattering region and photopeak region in an energy spectrum measured with the detecting module are used for estimation of the dose rate. The dose rate was calibrated with survey meter by using Cs-137 of 2.2 MBq. **Figure 4** shows deviations of the dose rate with the gamma camera from that with survey meter. The distances from the source were about 0.5 m, 1.5 m and 5 m in the figure. This result indicates that the deviation is less than 10 %.

Gamma-rays with energies above 350 keV were typically used to obtain the gamma-ray intensity and dose rate distribution. The upper and lower limits can be changed to any energy. This can allow one to look for specific photopeak to determine what radionuclides contaminate specific location.

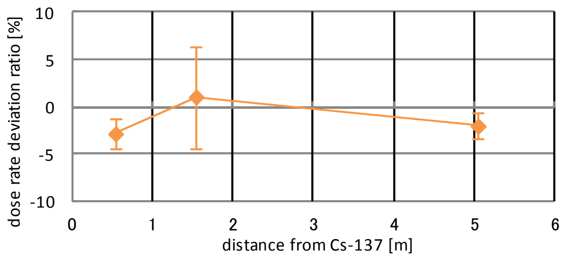

Figure 4. Dose rate deviations between the gamma camera and survey meter. The deviation is less than 10 %.

3. Performance evaluation

3.1. Energy resolution

The most common contaminating radionuclides are Cs-137 and Cs-134, and it is necessary to detect these separately. The nuclide Cs-137 emits the monochromatic gamma-ray with an energy of 662 keV, while Cs-134 emits gamma-rays of various energies, and among them, 605 keV and 795 keV are the most dominant. Thus, the module must have the energy resolution (FWHM : Full Width at Half Maximum) of 4.5 % which can separate 662 keV from 605 keV.

Some experiments were conducted to verify the energy resolution using Cs-137 of 2.2 MBq and Co-60 of 0.13 MBq. The Co-60 source was put on the surface of the detecting module and the Cs-137 source was put at 50 mm from the surface of the detecting module. **Figure 5** shows the measured energy spectra. The energy resolution of the 662 keV photopeak was 2.3 %. This result indicates that the module can separate Cs-137 from Cs-134 spectroscopically. The energy resolution of the 1333 keV photopeak originating from Co-60 was 1.5 %. It is found that the module can detect high-energy gamma-rays with a high energy resolution.

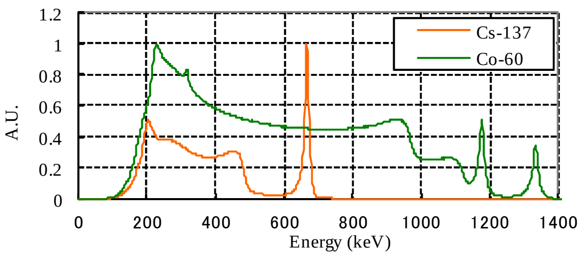

Figure 5. Energy spectra of gamma-rays emitted by Cs-137 and Co-60. The energy resolution of a 662 keV photopeak was 2.3 %. That of a 1333 keV photopeak was 1.5 %.

3.2. Spatial resolution

Two kinds of pinhole collimators were prepared to match the conditions of the dose rate environment. One is for high detection efficiency, and the other is for high spatial resolution. These two pinhole collimators can be interchanged easily.

To verify the spatial resolution, we obtained the image of the field where a point source of Cs-137 was set at the center. **Figure 6** shows the result of the measurements with the source position of 5 m from the gamma camera. In the figure, the horizontal axis represents the pixel number from the left end in the center row of the detecting area. For example, the pixel located at the left end of the detection area is pixel number 1 and that at the right end is pixel number 16. The spatial resolution (FWHM) of the collimator with the high detection efficiency was about 2.6 pixels, and that of the high spatial resolution type collimator was about 1.6 pixels. From the results, it is found that the module can separate radiation sources with a resolution of at least 0.68 m at a distance of 5 m.

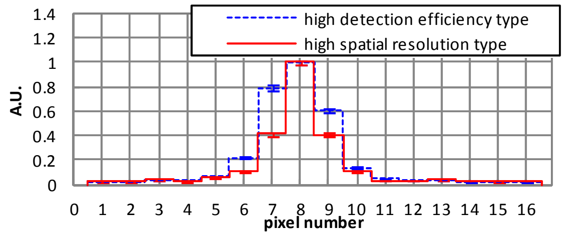

Figure 6. One-dimensional profile of the point source image. The spatial resolution of the high detection efficiency type collimator is 2.6 pixels and that of the high spatial resolution type collimator is 1.6 pixels.

4. Field tests

Some field tests were conducted in the No. 1 reactor of the Fukushima Dai-ichi Nuclear Power Plant. Typical observed objects were penetration holes, which connect the inside and outside of the Primary Containment Vessel (PCV). The gamma camera was set outside the PCV in the reactor building. The air dose rate at the area, which was measured with a survey meter, is 1 - 10 mSv/h. **Figure 7** shows the positional relation. There are penetration holes at A and B in the figure. The gamma camera is set at location P1 to observe penetration hole A, and at location P2 to observe penetration holes A and B.

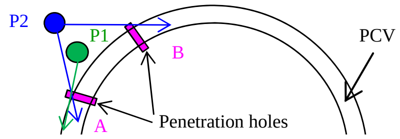

Figure 7. Positional relation for field tests in No.1 reactor of the Fukushima Dai-ichi Nuclear Power Plant. The gamma camera is set at location P1 and P2.

The gamma-ray distribution was successfully visualized within as short a time as 10 seconds. **Figure 8** shows the typical results. P1-A and P2-A are images of the same penetration holes observed from different locations. Two accumulations are seen in both images, and these can be thought to correspond to the same two penetration holes. Radiation source is on the extension of the line connecting the pinhole and the detecting cell corresponding to the accumulation pixel. Such a line can be drawn for every picture measured with the gamma camera. There is radiation source at intersection of these lines. We also took data of computer aided design system into consideration, and reached a conclusion that

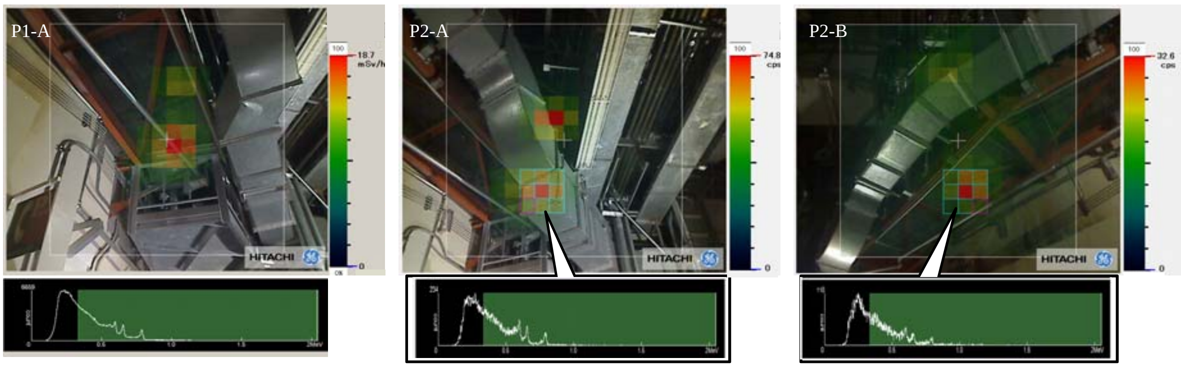

Figure 8. Visualization results in the reactor building of the Fukushima Dai-ichi nuclear power plant. P1-A and P2-A are images of the same penetration holes observed from different locations with the gamma camera. P2-A and P2-B are images of different penetration holes observed from the same location with the gamma camera. The spectrum under the P1-A image is that obtained from all detection cells. The spectra under the P2-A and P2-B images are those obtained from 3 x 3 detection cells corresponding to the accumulation at bottom.

it is high possible that radiation source is in penetration hole. The location releasing the gamma-rays cannot be identified with observation from only one direction. However, by the observations from two or more directions, a releasing location can be guessed. Thus, these two images show that gamma-rays released from penetration holes would be dominant in this area. From this result, it is found that shielding the penetration holes will improve the work environment during decontamination and cleanup activities.

An energy spectrum obtained from all detection cells is shown below the image of P1-A. The spectrum was displayed in real time during measurement. On the other hand, energy spectra obtained from 3 x 3 detection cells corresponding to the accumulation pixels are shown below the images of P2-A and P2-B. These spectra are obtained by off-line processing. Such processing is possible because every detection cell can measure each energy spectrum. There are three photopeaks in each spectrum. The energies of the peaks match those of emitted by Cs-134 and Cs-137; that is, 605 keV, 662 keV, and 796 keV. Thus, it is confirmed that most of the gamma-ray emitting radionuclides outside the PCV were Cs-134 and Cs-137.

The ratio of the photopeak intensities to the whole spectrum in the 3 x 3 pixels differed between P2-A and P2-B. That is thought to be due to a difference whether the gamma-rays entered the detecting module directly or indirectly. In other words, it depended on where the radionuclides were. When photopeak intensities are relatively low as in P2-B, the number of scattered gamma-rays is relatively high. When the gamma-rays are emitted at some locations inside the PCV, they would be scattered by the penetration holes before they entered the module. Thus, the difference indicates that the insides of some penetration holes are highly contaminated, while the others are less contaminated. It is thought that this depends on whether the ends of the penetration holes inside the PCV are blocked or not.

These results of field tests in the Fukushima site indicate that the gamma camera can guess the location of radiation sources and contaminating radionuclides.

5. Conclusion

In order to recover from the nuclear accident at the Fukushima Dai-ichi Nuclear Power Plant, we developed a gamma camera which can visualize the gamma-ray intensity distribution in real time and analyze the emitting radionuclides without any cooling system. Some experiments were conducted to investigate the performance of the gamma camera. The energy resolution of Cs-137 was 2.3 %, which is good enough to separate it from Cs-134 spectroscopically. Spatial resolution was 0.68 m at a distance of 5m. The device found that penetration holes in the PCV are releasing gamma-rays in the Fukushima Dai-ichi Nuclear Power Plant. From the tests, the insides of some penetration holes turned out to be highly contaminated with Cs-137 and Cs-134, and others were less contaminated. These results indicate that the gamma camera will contribute to decontamination work and radiation exposure reduction for workers.

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