Nuclear Instruments and Methods in Physics Research A 822 (2016) 48–56

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

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

Spectroscopic gamma camera for use in high dose environments

Yuichiro Ueno [a,*], Isao Takahashi [a], Takafumi Ishitsu [a], Takahiro Tadokoro [a], Koichi Okada [a], Yasushi Nagumo [a], Yasutake Fujishima [b], Yutaka Kometani [b], Yasuhiko Suzuki [c], Kikuo Umegaki [d]

[a] Research and Development Group, Hitachi, Ltd., Hitachi-shi, Ibaraki-ken 319-1221, Japan
[b] Hitachi Works, Hitachi-GE Nuclear Energy, Ltd., Hitachi-shi, Ibaraki-ken, Japan
[c] Measuring Systems Engineering Dept., Hitachi Aloka Medical, Ltd., Ome-shi, Tokyo, Japan
[d] Faculty of Engineering, Hokkaido University, Sapporo-shi, Hokkaido, Japan

ARTICLE INFO

Article history:
Received 23 June 2015
Received in revised form
17 March 2016
Accepted 18 March 2016
Available online 20 March 2016

Keywords:
Gamma camera
Pinhole collimator
CdTe detector

ABSTRACT

We developed a pinhole gamma camera to measure distributions of radioactive material contaminants and to identify radionuclides in extraordinarily high dose regions (1000 mSv/h). The developed gamma camera is characterized by: (1) tolerance for high dose rate environments; (2) high spatial and spectral resolution for identifying unknown contaminating sources; and (3) good usability for being carried on a robot and remotely controlled. These are achieved by using a compact pixelated detector module with CdTe semiconductors, efficient shielding, and a fine resolution pinhole collimator. The gamma camera weighs less than 100 kg, and its field of view is an 8 m square in the case of a distance of 10 m and its image is divided into 256 (16×16) pixels. From the laboratory test, we found the energy resolution at the 662 keV photopeak was 2.3% FWHM, which is enough to identify the radionuclides. We found that the count rate per background dose rate was 220 cps h/mSv and the maximum count rate was 300 kcps, so the maximum dose rate of the environment where the gamma camera can be operated was calculated as 1400 mSv/h. We investigated the reactor building of Unit 1 at the Fukushima Dai-ichi Nuclear Power Plant using the gamma camera and could identify the unknown contaminating source in the dose rate environment that was as high as 659 mSv/h.

1. Introduction

The tsunami following the Great East Japan Earthquake on March 11, 2011 damaged power supply equipment that led to loss of cooling functions and eventually, the severe accident in the Fukushima Dai-ichi Nuclear Power Plant (FDNPP), which resulted in the release of radioactive materials into the environment [1]. Radioactive contamination still remains inside and outside the power plant. To effectively perform decontamination work for restoration from the accident, it is necessary to identify the source positions. Gamma cameras which can visualize a radiation intensity distribution of a wide area in a short time are required, and some gamma cameras have been developed for this purpose. However, it has never been reported that a gamma camera was able to identify the positions of contaminants and radionuclides in the high dose environments where it was surrounded by a lot of radioactive contaminations.

The gamma cameras can be classified into three types: a pinhole type [2–4] and a coded aperture type [5–9], each of which has a collimator, and a Compton type camera [10–14] which does not need the collimator. Each type has different characteristics due to the different imaging principles. Recently, coded aperture cameras and Compton cameras have been developed. These are generally used because high sensitivities are possible and light weight can be realized with an appropriate configuration. It is generally recognized that the pinhole camera has the lowest sensitivity due to the pinhole collimator and is the heaviest due to the shield because scintillators with photomultipliers which are conventionally used in the pinhole camera increase size. However, the pinhole camera is the simplest, most robust and has the best quantitativity by employing enough shielding. If small detectors and circuits are loaded into the pinhole camera instead of scintillators and photomultipliers, the pinhole camera could be used in the high dose environments.

In order to use gamma cameras especially in high dose environments like FDNPP, gamma cameras must not only withstand the high dose rate environments, but also be light and stable enough to allow them to be carried on a robot and remotely controlled in the field. The pinhole camera has the best potential of the three

* Corresponding author.
E-mail address: yuichiro.ueno.bv@hitachi.com (Y. Ueno).

http://dx.doi.org/10.1016/j.nima.2016.03.064
0168-9002/

types in this application because both its principle and structure are the simplest. By using the compact pixelated semiconductor detector module with new modified ASICs (Application-Specific Integrated Circuits) and making a fine resolution pinhole collimator with enough shielding, we have developed a pinhole gamma camera which satisfies the above mentioned requirements especially in the high dose environments.

In this paper, we present the results of performance tests of our original gamma camera.

2. Spectroscopic gamma camera system for high dose environments

2.1. Concept of the system

The developed gamma camera is characterized by: (1) tolerance for high dose rate environments; (2) high spatial and spectral resolution for identifying the unknown contaminating sources; and (3) good usability for being carried on a robot and remotely controlled. To carry out these features we adopted the pinhole camera structure. The key components to determine the performances of the pinhole gamma cameras are a detector module, a pinhole collimator, and shielding structure.

The detector module is the most important component. It must be compact, have a high energy resolution, and withstand a high count rate. Then we adopted the semiconductor detector module we originally developed for nuclear medicine systems [15–17].

The pinhole collimator determines the image specifications (i.e. field of view and spatial resolution) and sensitivity. Roughly speaking, a trade-off needs to be found between spatial resolution and sensitivity. However, there are enough signals in the high dose environments, so we designed the pinhole collimator considering the spatial resolution preferentially.

The shielding structure determines tolerance for the high dose rate environments and the weight of the system. Gamma-rays passing through the shield generate background signals, which should be suppressed to carry out highly quantitative measurement and to keep background signal count rate well below the circuit limit (maximum count rate of the detector module). We determined the necessary shielding thickness by estimating the count rate to keep the system reasonably light in weight.

The performances of the gamma camera are determined compositely by the components as mentioned above. So we set design goals according to the three features, i.e. the gamma camera must: (1) withstand a maximum environmental dose rate of 1000 mSv/h; (2) have a spatial resolution of less than 1.0 m at a distance of 10 m; and (3) weight less than 100 kg so it can be carried by a robot.

2.2. Compact pixelated semiconductor detector module

Our gamma camera has a compact pixelated semiconductor detector module (Fig. 1), which was originally developed for medical applications. With the semiconductor detectors, optical devices such as photomultiplier tubes are not needed, the detectors can be easily pixelated and have a high energy resolution.

The detector module has 256 (16×16) pixels of CdTe and ASICs for signal processing. The thickness of CdTe detectors is 5 mm, and the pixel pitch is 2.5 mm, corresponding to the module size of 40 mm square.

The CdTe detectors have high energy resolution and we had previously developed a low noise ASIC, so the gamma camera can precisely measure the energy of each incident photon. The gamma camera should therefore be able to identify radionuclides and their distribution. Furthermore, the band gap of CdTe is 1.44 eV, and the temperature dependence of the signal gain of CdTe is much less than that of the scintillators [18]. This means that the gamma camera can be used at room temperature inside and outside buildings.

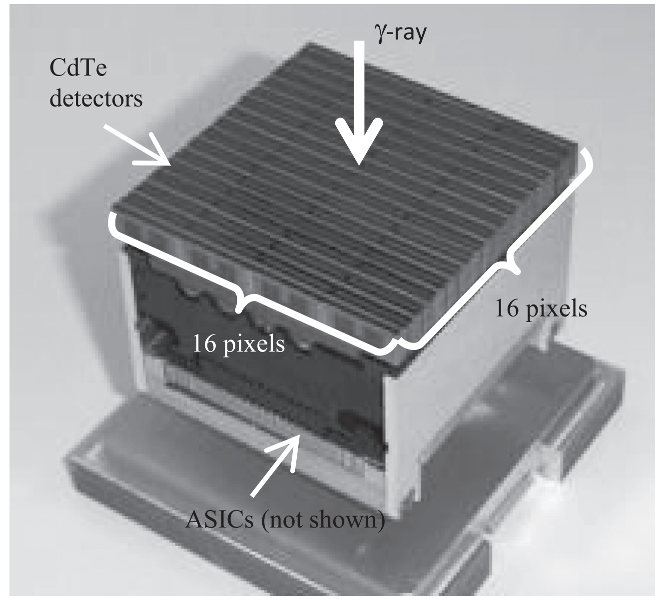

Fig. 1. CdTe semiconductor detector module.

The ASIC was originally developed for nuclear medicine systems, so the count rate performance was not necessarily sufficient for measurements in the high dose environments. The detector module using the ASICs was saturated with the input gamma-rays of 250 kcps. To endure higher count rate, we re-designed the ASIC to have a reduced number of channels bound to one trigger from 16 to 8. By using the new ASICs, the gamma camera is expected to withstand double the count rate and to be used in the high dose environments inside FDNPP without an excessive weight increase.

2.3. Fine resolution pinhole collimator

Pinhole collimator configuration was determined to have the required field of view and spatial resolution. Assuming the gamma camera will be used inside a nuclear plant, we set an 8 m square FOV and a spatial resolution of less than 1 m at a distance of 10 m. With this FOV, the opening angle of the pinhole was calculated to be 59° and the distance r between the pinhole and detectors (see Fig. 2) to be 50 mm.

The diameter of the pinhole was set as 2 mm to achieve the required spatial resolution as derived below. In Fig. 2, b is the diameter of the pinhole, and r and R are the distances between

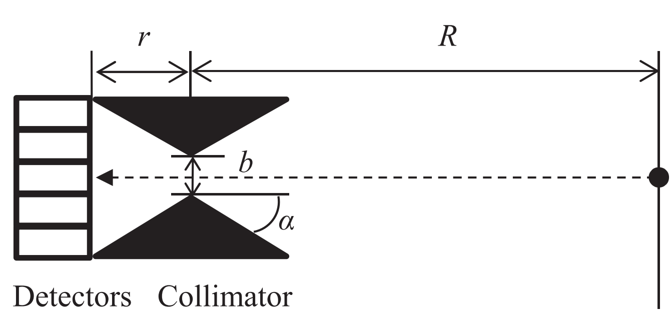

Fig. 2. Schematic of a pinhole collimator.