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A Simulation Study on a Radioactive Nuclide's Distribution within a Fuel rod by a Tomographic Gamma Scanning

Lee Hong-Ki, Hong Kwon-Pyo, Zhang Quanhu
Korea Atomic Energy Research Institute, 150 Duck-Jin Dong, Yuseong-gu, Daejeon

Kim Yong-Uhn
Chungbuk National University, Chongju

hongki74@empal.com

1. Introduction

Gamma scanning measurements are used to determine the radioactive nuclides from an irradiated fuel rod in a hot cell which is a routine task in the Irradiated Materials Examination Facility (IMEF) of the Korea Atomic Energy Research Institute (KAERI), Total gamma spectra of radioactive nuclides and the atomic ratio of ^{134}Cs to ^{137}Cs in a few segments of a single fuel rod are measured by the present gamma scanning system.

For the purpose of determining the radioactive nuclide's distribution in detail within a fuel rod quantitatively, we attempt to upgrade the present gamma scanning system in this paper, therefore, an investigation of the feasibility of the tomographic gamma scanning (TGS) technique, which is one of the promising nondestructive assay (NDA) methods is proposed. The TGS technique is an efficient method and it has an accurate precision for the characterization of several fuel parameters.

In this paper, a principle and an emission TGS and an iterative image reconstruction algorithm are presented first. Secondly, a simulation study is carried out for a fuel rod model derived from the present gamma scanning experimental conditions by considering the configurations of the experimental assembly in a hot cell of the IMEF comprehensively. Several computation schemes have been implemented. Simulation and reconstruction codes have been developed in Matlab language on a personal computer, in these simulations many cases are given to verify the codes. In the absence of actual experiments, simulation experiments with these codes by using a simulated model can be implemented.

2. Emission TGS equation and Simulation methodology

The reconstructed cross section of the measured object is divided into picture elements, voxels. The fraction of the emitted quanta from a certain voxel reaching the detector in a certain position can be calculated theoretically. Summation over all voxels, gives the gamma-ray intensity in the detector in a certain position. The basic expression for the emission TGS may be written as follows:

$$\sum_{j=1}^{J} W_{ij} \bullet f_j = I_i \quad (i = 1,2,\cdots,I \quad j = 1,2,\cdots,J) \qquad (1)$$

where :

W_{ij} is the contribution coefficient from voxel j to the detector a position i

f_j is the gamma-source intensity in voxel j (sought activity in voxel j)

I_i is the measurement (the count rate) data at a position i.

To obtain accurate reconstructions, the W matrix must be accurately modeled. Each W_{ij} is proportional to the probability that a photon emitted from voxel j will be detected by the detector at position i. W_{ij} can be expressed by the following formula [9]:

$$W_{ij} = g_{ij} \bullet A_{ij} \quad (i = 1,2,\cdots,I \quad j = 1,2,\cdots,J) \qquad (2)$$

Where:

$g_{ij} = \frac{S_{\det ector,ij}}{4\pi r_{ij}^2}$, $S_{\det ector,ij}$ is the exposed detector area as seen from voxel j when the detector is at position i; r_{ij} is the distance between voxel j and the detector at position i.

$A_{ij} = \exp(-\sum_k \mu_k d_{k,ij})$, μ_k is the linear attenuation coefficient of the material in voxel k; $d_{k,ij}$ is the ray path length in voxel k for a ray from voxel j to the detector at position i.

3. Simulation

The simulation procedures can be divided into four parts: (1) calculation of the contribution efficient matrix W; (2) simulation of measurements I for pre-set A; (3) reconstruct the intensities A by ART algorithm; (4) verify the tomographic reconstruction algorithm ART.

3.1 Procedures of the Simulation

In order to obtain intensity distribution of radioactive nuclide within simulated samples in the absence of performing time-consuming and expensive measurements, a number of simulations were done. The simulations have been made for 10 by 10 simulated models.

The feasibility of the tomographic method for determination of radioactive nuclide within simulated samples has been studied using simulated intensities. The ability of reconstruction algorithm was investigated.

3.2 Procedures of the reconstructions

The reconstructions have been made by applying the tomographic reconstruction algorithm -- ART algorithm to measurements simulated in a large number of detector positions.

3.3 Simulation results

In order to study the feasibility of tomographic method, reconstructions have been made using simulated measurements from 10 by 10 types of simulated models. Schematic of the simulated equipment is shown in Figure 1 and Parameters in the simulation studies are shown in Table 1. One of the reconstruction simulation results and the corresponding relative error are shown in Figure 2., 3. respectively.

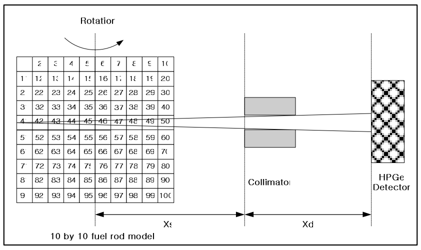

Figure 1. Schematic of the simulated equipment.

Table 1. TGS scanning parameters

Fuel rod model	Voxel number	Voxel size (mm × mm × mm)	Horizontal translation number	Rotation angle number	Rotation angles
10 by 10	10 × 10	1 × 1 × 1	10	15	0, π/15, …, (π – π/15)

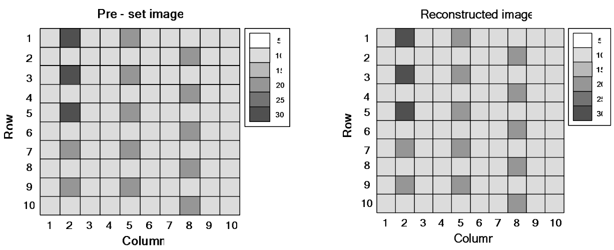

Figure 2. Gray intensity of reconstructed image from 10 by 10 simulated sample.

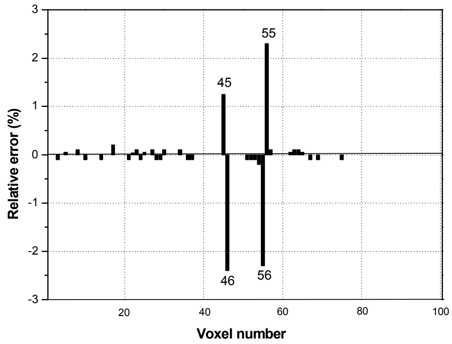

Figure 3. The relative error of the intensity distribution between "reference" value and "reconstructed" value in each voxel for simulated sample (10 by 10).

4. Conclusion

In this work, the potential of the emission TGS method for determining a radioactive nuclide's distribution in a fuel rod quantitatively has been investigated. Tomographic simulations and reconstructions have been performed by a mathematical method for the simulation models and by the ART algorithm by using the projections from the simulation measurements data respectively.

Many cases of a radioactive nuclide's distribution in uniform and non-uniform intensity distributions have been demonstrated, and the results from the reconstruction algorithm, and the ART algorithm, by using the TGS simulation projections have expected errors which are less than 10 % when compared with the reference values. The simulation studies show that the TGS technique is suitable for determining a radioactive nuclide's distribution in a fuel rod.

The research presented here suggests that the TGS technique has the potential of becoming a powerful method for quantitatively determining a radioactive nuclide's distribution in a fuel rod in a hot cell.

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