Development of tomographic image-based verification technique for spent fuel assembly with artificial intelligence and Monte Carlo methods

[1] Department of Radiation Convergence Engineering, Yonsei University
[2] Department of information and statistics, Yonsei university

Hyung Joo Choi[1], Hyun Joon Choi[1], Se Hwan Choi[2], Jae Joon Ahn[2], Yong Hyun Chung[1] and Chul Hee Min[1*]

Purpose: Single-photon emission computed tomography (SPECT) is considered by the International Atomic Energy Agency (IAEA) as one of the most attractive techniques for the safeguarding of spent fuel assembly due to its intuitive ability to detect missing fuel pellets or fuel rods. To reduce the verification time, one of the advanced method is to discriminate a noise pattern of fuel rods in a low-quality tomographic image obtained within a short time. Currently, an artificial intelligence method has been actively investigated and showing outstanding performance in image quality improvement. The aim of this study is to develop a fast verification technique of spent fuel assembly using a deep learning-based de-noised image reconstruction and Monte Carlo (MC) methods.

Materials and Methods: A dual-head SPECT system was modeled in GATE (v. 8.1) MC simulation software. A 64-channel detector head is composed of 0.3 × 4 × 4 (front side) and 0.3 (back side) cm^3 trapezoidal bismuth germanate scintillators and 0.2 × 5 × 4 cm^3 slits surrounded by tungsten materials in front of each scintillator, located at 0.4 cm intervals. A 3 × 3 spent fuel assembly consists of nine fuel rods, 0.994 cm in diameter, located at 1.269-cm intervals. The major radionuclide of the spent fuel is Cs-137 because of its long half-life. A total of 511 tomographic images for missing patterns of 3 × 3 fuel rod array were reconstructed by filtered back-projection (FBP) algorithm using 400 projection data obtained during a 360-degree rotation. For these missing patterns, ground truth (GT) images filled with electron densities of fuel assembly materials were generated based on detailed geometrical information. A Convolutional Auto-Encoder (CAE) deep learning model has applied to de-noise the low-quality FBP image. The CAE model was trained using 501 GT-FBP image sets and 10 images sets were used to evaluate the model performance.

Results: As the training parameters of the CAE model, the batch size, number of iterations, and training epochs were determined with 1, 501, and 100 respectively. When the epoch reached 16 times, the loss function reaches almost zero, indicating that the CAE model was successfully trained. With the CAE model, the low-quality FBP images were successfully de-noised, similarly to the GT images. In a comparison of GT, FBP, and CAE images for three sample missing patterns of 3 × 3 fuel rod array, the average differences in pixel values for the region of interest in the subtracted images between the GT and FBP images and the GT and CAE images were 7.7, 28.0, and 44.7% and 0.5, 1.4, and 1.9% for sample 1, 2, and 3, respectively. In the de-noising performance evaluation of the CAE model for four different FBP image qualities (scan time: 0.6, 10, 20, and 60 minutes), the lowest-quality FBP images obtained for 0.6 minutes were not sufficiently clear to discriminate the missing patterns, however, the CAE images could successfully estimate the missing patterns for all image qualities.

Conclusions: In this study, we developed a de-noised image reconstruction technique using a CAE model to reduce the total verification time for spent fuel assembly. The results of this study showed that the CAE model is capable of greatly improving the image quality from the low-quality tomographic images, making them almost identical to the GT images. Furthermore, we confirmed that it is possible to reduce the image acquisition time by approximately 10 times, and we expect that it can be increased through optimizing the CAE model. In the future, we will apply the CAE model to experimentally obtained tomographic images using an unirradiated test fuel assembly installed in the Korea Institute of Nuclear Nonproliferation And Control.

Keywords: single-photon emission computed tomography, spent fuel assembly, Monte Carlo simulation, artificial intelligence, deep learning, convolutional autoencoder, image reconstruction