A Preliminary Study on Passive Neutron Emission Tomography to Safeguard PWR Spent Fuels in Dry Storage

Wonjong Song, Sungmin Kim, Kyung Taek Lim, and Heejun Chung*

Korea Institute of Nuclear Nonproliferation and Control (KINAC), Daejeon, 34101, Republic of Korea
*Corresponding author's e-mail: hjchung2@kinac.re.kr

Abstract. This work investigates the capability of the new prototype system to detect the removal or substitution of spent fuel assemblies in dry cask storage. Recently, KINAC developed a prototype safeguards system that utilizes passive scanning to obtain the cross-sectional image of spent fuel assemblies in dry casks. The prototype consists of He-4 neutron detectors, collimators, and an integrated control system designed for the detector operation and signal processing. The prototype system was tested a 1/10 scaled-down TN-32 cask fabricated in collaboration with a manufacturing company and Cf-252 neutron sources. Also, a Monte Carlo simulation was performed to evaluate the technical feasibility of the developed prototype for verifying spent nuclear fuels in dry storage.

KEYWORDS: Dry storage, Safeguards, Neutron tomography

1 INTRODUCTION

Establishing the appropriate safeguards approach to resolve the challenges associated with verifying spent fuel assemblies stored in dry casks has been one of the major priorities for the IAEA and the Member States in the past decade. In particular, verifying declared contents in dry casks through a non-intrusive technique is fundamentally challenging due to the physical barriers of a dry cask such as concrete walls, metal walls, and neutron absorbers.

The challenges associated with realizing visual inspection allows considerable leeway in adopting non-destructive approaches. It was shown that there is a notable neutron fluence just outside the dry cask with energies varying from thermal to high-energy fast neutrons due to the sheer amount of fissile materials existing in spent nuclear fuels. Early studies on utilizing non-destructive techniques for dry cask inspection have been focused on gamma-ray tomography [1-3]. In contrast, neutron detection gathered less attention than the other two modalities because of its difficulty measuring neutrons with high spatial resolution. Some studies have exploited neutron detection for inspecting spent nuclear fuels of dry casks, such as neutron fingerprinting, active neutron methods, and neutron spectroscopy [3-5]. Although several techniques have been proposed to satisfy the safeguards requirements, no reliable methods have yet been established for inspecting the integrity of spent fuels in dry casks.

Recently, KINAC developed a prototype system that utilizes passive scanning to obtain the cross-sectional image of spent fuel assemblies in dry casks. The prototype consists of He-4 gas scintillation neutron detectors, collimators, and an integrated control system designed for the detector operation and signal processing. Here, we investigate the ability of a developed prototype to detect the removal or substitution of spent fuel assemblies in dry cask storage. To test the developed prototype, we built a 1/10 scale cask model based on a commercially available dry cask system to mimic a realistic inspection scene expected in South Korea. Also, the obtained experimental results were inter-compared with Monte Carlo simulation results to evaluate its technical feasibility. This study aims to assess the degree to which the fast-neutron counting approach can verify the contents of a dry cask using the designed prototype system.

2 MATERIAL AND METHOD

2.1 Control Unit Design

The designed prototype safeguards system is consists of two main parts: the detector unit and control unit. The detector unit consists of three 670e He-4 detectors manufactured by Arktis Radiation Detectors Ltd [6]. Also, the new 670e model is built based on SiPMs instead of PMTs. Hence, it provides a higher detection efficiency of fast neutrons (600 mm active length at 180 bar) with a lower operating voltage of 12 V [6]. All three detectors were connected in parallel via an RS485 cable connected to the control unit for data acquisition. On the other hand, figure 1 shows the realized control unit that has a dimension of 147 x 140 x 20 mm^2 with four independent layers: 1) windows system board, 2) power supply board, 3) data acquisition board, 4) input extension board.

Figure 1. The four boards of the control unit: (1) Windows system board, (2) power supply board, (3) data acquisition layer, and (4) input extension board

The first layer is the Windows system board that is assembled by implementing a commercially-available H310M-STX board. An intel Core^{TM} i5 was chosen as the main processor to resolve the compatibility issue of embedding the existing Linux platform provided by the manufacturer on Windows OS. Thus, the windows system board is a complete single PC capable of running a customized Linux platform. The second layer is the power supply board. Its primary purpose is to provide all the necessary voltages required to operate the entire control unit and the He-4 detector system. In particular, the board is integrated with two 15W DC-DC regulated single output converters that take the single input of 19 V from the Windows layer and generate the required low voltages for the system on chip (SoC) FPGA and the He-4 detectors. The data acquisition board (DAB) serves as the third layer in charge of processing the TTL pulses generated from the detectors and transferring the acquired information to the Windows system for post-processing. The board is based on SoC FPGA equipped with an 800MHz Dual-core ARM Cortex-A9 processor. From the firmware side, the FPGA device handles the received TTL signals with encoded pulse processing logic that distinguishes different events according to the preset pulse width. The SoC, on the other hand, is responsible for the conversion process and signal post-processing. Furthermore, the DAB is configured to support up to six detectors simultaneously. The last layer is the input extension board equipped with 22 additional TTL ports to exploit more than six detectors with the DAB. It should be mentioned that the current connector type is set to MCX-BNC cable for all connectors; however, they can be easily changed to MCX-MCX configuration if necessary.

2.2 Measurement setup

The experimental setup for performing passive neutron tomography on a dry cask is shown in figure 2. We built a 1/10 scale cask model based on a commercially available dry cask system (in this case, TN-32) to assess the developed prototype safeguards system as a viable technology for passive neutron tomography of dry cask storage. The measurements were taken at the Korea Institute of Nuclear Nonproliferation and Control using 1/10 scale TN-32 cask model, the prototype system, and the Cf-252 source. In particular, the three He-4 detectors were mounted vertically on a customized metal support frame (not shown) and placed near the cask model as close as possible. Also, Cf-252 was hung inside the cask via thread strings attached to the top cover.

The procedures for performing passive neutron tomography are as follows: (1) while having Cf-252 source inside the cask, fast neutrons were measured by three He-4 detectors simultaneously for 5 minutes at each angle, (2) while the detector unit is fixed, the neutron emitting source was moved by rotating the top cover of the cask model at 10°, and the step (1) is repeated from 10° to 360°. Lastly, a MATLAB script was created to implement the acquired projection data and perform an image reconstruction through filtered back projection (FBP).

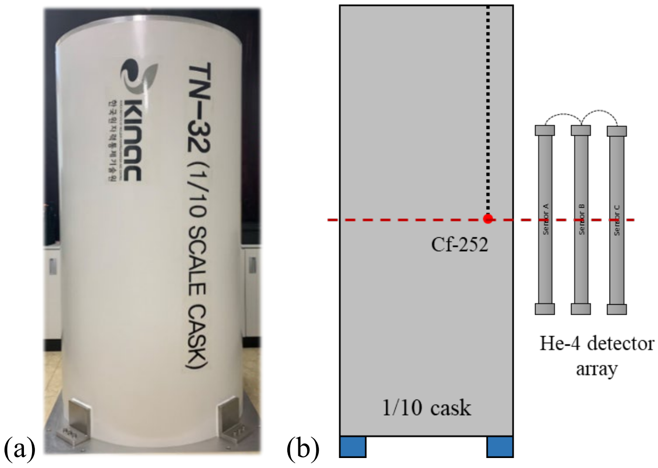


Figure 2. (a) 1/10 scale TN-32 cask model, and (b) experimental setup based on the He-4 detectors

3 PRELIMINARY RESULT

Figure 3 shows the sinograms and reconstructed FBP images of measured fast neutrons. We can see the highest neutron counts are marked in red, whereas the weaker ones are represented in blue. The reconstructed image implies that the designed prototype can detect a neutron-emitting source by acquiring projection of fast neutron counts. On the other hand, the distribution of red pixels seems as if the neutron source is placed in the center of the cask, which is not true compared to the experimental setup described in figure 2. To verify the FBP image based on the measurement data, we performed an MCNP simulation based on the identical experimental setup, and the results are reported in figure 4. Indeed, we can see that the FBP image of the MCNP simulation is similar to that of measurement data. Unfortunately, the simulation result also has the neutron-emitting source in the center of the cask, which is identical to that of figure 4 (b). The main reason for the inaccuracy in the source position of both measured and simulated FBP images is that the number of pixels (i.e., He-4 detectors) available to acquire the projection data is insufficient to identify the source position. In fact, having three He-4 detectors implies that the ideal region-of-interest that the image can have is three at the maximum. Thus, additional He-4 detectors would be required to enhance the image spatial resolution and identify the source position accurately.

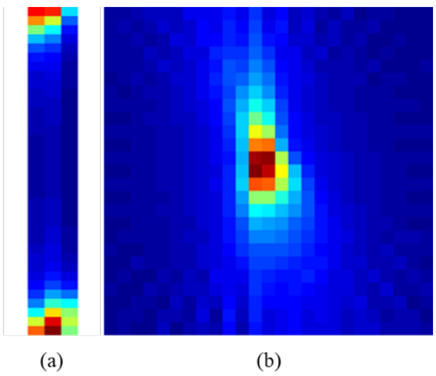
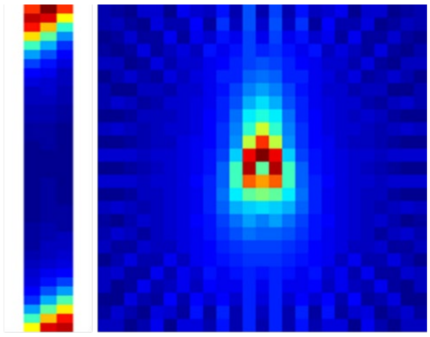


Figure 3. (a) Sinogram (b) FBP of measured projection data from 0 to 360° using the prototype system and 1/10 scale cask model



(a) (b)

Figure 4. (a) Sinogram (b) FBP of simulated projection data from 0 to 360° using the prototype system and 1/10 scale cask model in MCNP.

4 CONCLUSION AND FUTURE WORK

This paper describes the development of a prototype system to safeguard and verify the contents of a dry cask. The prototype was realized by implementing three He-4 neutron detectors with Windows-based hardware and a compact SoC FPGA module. In particular, we demonstrated the validation of the designed system through a test experiment via the prototype on the 1/10 scale cask model and Cf-252 source. Furthermore, the obtained experimental results were compared with the MCNP simulation to verify the prototype's capability for verifying the content of a dry cask through passive neutron tomography. Future work will be focused on improving the developed prototype to enhance the spatial resolution of an acquired image for identifying the source configuration accurately.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

[1] Campbell, L.W., Smith, L.E., and Misner, A.C., 2011. High-Energy Delayed Gamma Spectroscopy for Spent Nuclear Fuel Assays. IEEE Transactions on Nuclear Science, 58(1).

[2] Mozin, V., et al., 2012. Delayed gamma-ray spectroscopy for spent nuclear fuel assay. Journal of Nuclear Materials Management, 40(3), p. 78-87.

[3] Ziock, K.-P., Caffrey, G., Lebrun, A., Forman, L., Vanier, P., Wharton, J., 2005. Radiation imaging of dry storage casks for spent nuclear fuel, in: Conference Record of IEEE Nuclear Science Symposium.

[4] Rauch, E.B., 2016. Signatures of extended storage of used nuclear fuel comprehensive final report. http://dx.doi.org/10.2172/1327981. http://www.osti.gov/scitech/servlets/purl/1327981.

[5] Lewis, J. M., 2014. ACTIVE NEUTRON METHODS FOR NUCLEAR SAFEGUARDS APPLICATIONS USING HELIUM-4 GAS SCINTILLATION DETECTORS. Doctor of Philosophy dissertation, UMI number: 3691345.

[6] Arktis Radiation Detectors Ltd., 2017. "S670e: Combined Fast and Thermal Neutron Detector." Available: www.arktis-detectors.com.