Characteristics of Muon Computed Tomography of Used Fuel Casks Using Algebraic Reconstruction

Zhengzhi Liu, Stylianos Chatzidakis, Can Liao, Haori Yang, and Jason P. Hayward

***Abstract*— Cosmic ray muons passing through matter lose energy from inelastic collisions with electrons and are deflected from nuclei due to multiple Coulomb scattering (MCS). The recent developments in position sensitive muon detectors that can measure incoming and outgoing trajectories of individual muons indicate that MCS could be an excellent candidate for spent nuclear fuel imaging. The main purpose of this paper is to evaluate tomographic scanning of spent nuclear fuel stored within vertical and horizontal dry storage casks. A quantitative analysis of the characteristics of images obtained with filtered back projection (FBP) and algebraic reconstruction techniques (ART) are presented herein, as such a comparison has not been carried out in the past. FBP is a fast tool to determine object boundaries. ART can include muon path models and prior knowledge that can improve resolution and reduce measurement time. The results demonstrate that missing fuel assemblies can be identified with more than 5 projections and that use of muon momentum significantly increases image resolution. It is expected that MCS can be used to successfully reconstruct the dry cask contents and allow identification of all described scenarios in hours. It is also expected that when total variation minimization and a non-local mean filter are applied, ART may yield much better image quality than FBP.**

***Index Terms*— Muon CT, spent nuclear fuel, GEANT4**

I. Introduction

Since the pioneering work of E.P. George [1] and L. Alvarez [2], cosmic ray muons have been investigated for volcano imaging [3], cargo scanning applications [4], nuclear waste imaging [5], and determination of molten nuclear fuel location in nuclear reactors having suffered from the effects of a severe accident similar to the one that happened in Fukushima [6]. The role of cosmic ray muons can also be extended to non-destructive assessment of nuclear materials stored within sealed, dense containers [7].

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Previous efforts of special nuclear material imaging with cosmic ray muons have used either a single view [7, 8] or cylindrically-shaped detectors for reconstruction [9]. In the present work, we consider flat detector geometries with varying spatial resolution, investigating whether an increased number of views could increase image quality for a given acquisition time.

II. Monte Carlo Muon CT Simulations

The Geant4 model used to generate cosmic ray muons is illustrated in Fig. 1, with two pairs of detectors vertically offset by 100 cm and positioned along the sides of a dry storage cask. The separation between each pair of detectors is 10 cm. The zenith angle is ~50° and muon flux is ~20,000 muons/min.

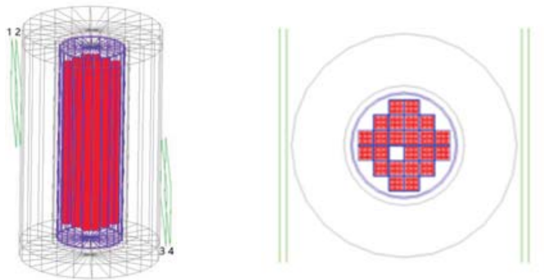

Figure 1. Side (left) and top-down (right) illustrations of the cask and detectors built in Geant4. An assembly has been removed from Row 3.

The detectors, each of dimension 350 cm wide by 150 cm high, are planes with perfect spatial and energy resolution. The muon event generator described in [10] was used to simulate the muon flux at sea level. In our implementation, the cask containing the spent fuel assemblies were fixed in location, while the detectors rotated around the cask. The detectors were rotated at 2° increments to collect data from different views.

III. Muon CT Reconstruction

Due to the small angle scattering, a straight line approximation was use to along to connect the incoming and outgoing trajectories of a muon with the PoCA. The root mean square of the muon scattering angle is taken as the projection information $P_\theta(R,\theta)$ where θ is the azimuthal angle and R is the distance from the center of the cask. Each projection can be analytically expressed as an integration of scattering density along the path [8]:

$$P_\theta(R,\theta) = \iint f(x,y)dxdy$$

where $f(x, y)$ is the scattering density at position (x, y). Filtered back projection (FBP) is often introduced here to reconstruct geometrical information and infer material information. Similarly, this could be expressed numerically if we discretize the reconstruction volume:

$$WX = P$$

where W is the system matrix containing the path length of i^{th} muon in j^{th} pixel, X is scattering density map of the object to be reconstructed and P is projection information. Algebraic reconstruction techniques (ART) can be used to solve the above equation. In this work, we suggest that ART coupled with regularization methods, like total variation minimization and a non-local means filter [11], could significantly improve the quality of the reconstructed image when the dry storage cask is under sampled.

The characteristics of muon CT images were investigated for different numbers of views, pixel sizes and whether or not momentum estimation was included. A quantity of 400,000 muons were used for each view resulting in 20 minutes of measurement time per view.

IV. Results

Fig. 2 shows the reconstruction with and without momentum measurement; position and momentum estimation are ideal here and pixel size is 3.5 cm. Although the location of fuel assemblies can be identified in the case without momentum, the resolution is expected to be significantly improved when there is momentum measurement capability. Fig. 3 shows a comparison between FBP and ART for 5, 9, 45 and 90 views. ART slightly outperforms FBP, especially when limited views are used. Interestingly, a fuel assembly missing can be identified with as few as 5 views.

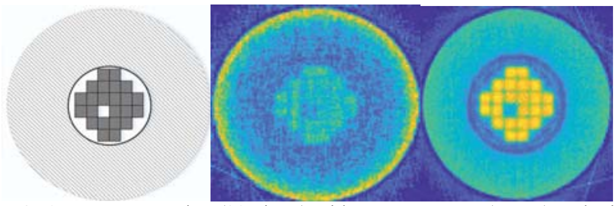

Fig. 2. ART reconstruction (90 views) without momentum (center) and with momentum measurement (right). The phantom is shown at the left.

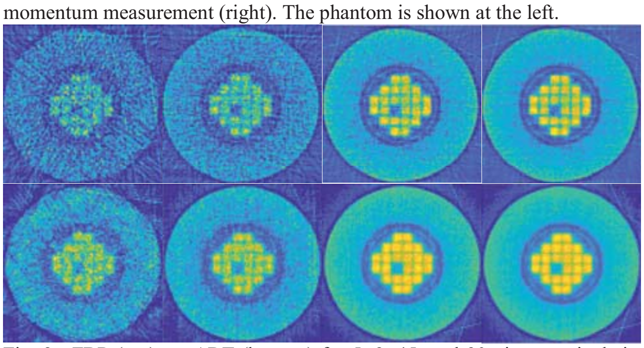

Fig. 3. FBP (top) vs. ART (bottom) for 5, 9, 45, and 90 views – pixel size: 3.5x3.5 cm.

The expected influence of pixel size on the image quality (while momentum is known) varying the pixel sizes from 2 cm to 10 cm were investigated. The image is not clear for 10 cm or larger sizes, but the quality improves significantly when 5 cm pixel size or less is used. Additionally, it is worth noting that a pixel size less than 2 cm exponentially increases the memory and computational requirements. Fig. 4 shows ART results measured along the centerline of a dry cask, comparing the case of a missing assembly with a fully loaded cask. The cask with a missing fuel assembly has a stronger signal than a fully loaded cask; the signal is at least 3 times higher than when the cask is fully loaded.

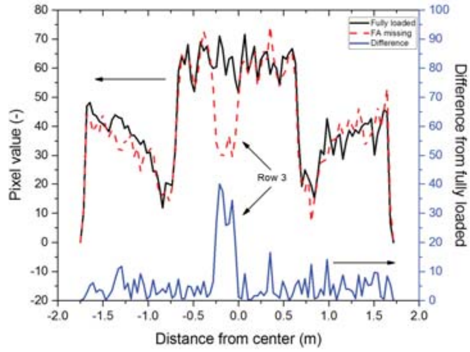

Fig. 4. ART results along the cask centerline for 90 views and 3.5 cm pixel size. Difference from a fully loaded cask is included.

V. Conclusions

The characteristics of muon CT images were investigated for different numbers of views, pixel sizes and whether or not momentum estimation was included. The results demonstrate that missing fuel assemblies can be identified with more than 5 projections which translates to a significant decrease in measurement time compared with a full reconstruction. Further, knowledge of muon momentum significantly improves image resolution. Selection of optimal pixel size is a tradeoff between resolution and computational cost and in our case, it was found to be 5 cm. Finally, it was shown that a missing fuel assembly has a stronger signal than a fully loaded cask.

References

[1] E. P. George, “Cosmic rays measure overburden of tunnel,” *Commonwealth Engineer*, pp. 455-457, 1955.

[2] L. W. Alvarez et al., “Search for hidden chambers in the pyramids,” *Science*, vol. 167, 832-839, 1970.

[3] K. Nagamine, “Geo-tomographic observation of inner-structure of volcano with cosmic-ray muons,” *J. Geogr.*, vol. 104, no. 7, pp. 998–1007, 1995.

[4] G. Blanpied et al. “Material discrimination using scattering and stopping of cosmic ray muons and electrons: Differentiating heavier from lighter metals as well as low-atomic weight materials,” *Nucl. Instr. Meth. Phys. Res. A*, vol. 784, 352-358, 2015.

[5] C. Thomay et al. “Passive 3D imaging of nuclear waste containers with muon scattering tomography,” *J. Instrum.*, vol. 11, p. P03008, Mar. 2016.

[6] H. Miyadera et al. “Imaging Fukushima Daiichi reactors with muons,” AIP Advances 3.5, 052133, 2013.

[7] S. Chatzidakis et al., “Analysis of Spent Nuclear Fuel Imaging Using Multiple Coulomb Scattering of Cosmic Muons,” *IEEE Trans. Nuc. Sci.*, vol. 63, 2866, 2016.

[8] L. J. Schultz et al., “Statistical reconstruction for cosmic ray muon tomography,” *IEEE Trans. Im. Proc.*, vol. 16 (8) 1985-1993, 2007.

[9] D. Poulson et al. “Cosmic ray muon computed tomography of spent nuclear fuel in dry storage casks,” *Nucl. Instr. Meth. Phys. Res. A*, vol. 842, 48-53 2017.

[10] S. Chatzidakis et al. “Developing a cosmic ray muon sampling capability for muon tomography and monitoring applications,” *Nucl. Instr. Meth. Phys. Res. A*, vol. 804, 33-42, 2015.

[11] E. Metin et al. “An iterative tomosynthesis reconstruction using total variation combined with non-local means filtering,” *Biomedical Engineering Online*, 13.1, 65, 2014.