LA-UR-16-29478

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Intended for: Report

Issued: 2017-01-23 (rev.1)

Multiple-Angle Muon Radiography of a Dry Storage Cask

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18 Jan 2017

LA-UR-16-29478

Abstract

A partially loaded dry storage cask was imaged using cosmic ray muons. Since the cask is large relative to the size of the muon tracking detectors, the instruments were placed at nine different positions around the cask to record data covering the entire fuel basket. We show that this technique can detect the removal of a single fuel assembly from the center of the cask.

Introduction

A stand-alone technology to independently verify operator declarations of the number of spent fuel assemblies sealed inside a dry storage cask does not currently exist. The heavy shielding that is inherent to all cask designs, along with the self-shielding between the fuel assemblies themselves, effectively attenuates and scatters the photons and neutrons emitted from spent fuel. This renders measurements of emitted particles unable to give radiographic details of the emission source. Active interrogation techniques with external photon and neutron sources face similar issues. Additionally, all measurements of photons and neutrons must deal with backgrounds produced by the multiple casks that are present at independent spent fuel storage installations.

Cosmic ray muons offer an alternative radiographic probe that is especially well suited to very dense objects. The unique physical properties of these muons limit energy loss to ~ 1MeV per g/cm^2 of material traversed, and the high energies of these particles (from hundreds of MeV up to hundreds of GeV) allow them to penetrate materials that defeat conventional methods. Cosmic ray muons arrive on the surface of the Earth with a mean energy of ~ 4 GeV at a rate of ~10,000/m^2/min.

This report presents data from new muon scattering measurements of a fuel cask, as seen from multiple viewing angles. Previous measurements by the Los Alamos National Laboratory group have shown that muon scattering radiography is sensitive to the fuel content of storage casks, i.e. that the removal of assemblies can be detected without opening the cask [1]. However, the general-purpose instrument used for these first measurements is small relative to the size of the cask, so the first measurements were limited to a relatively small portion of the fuel basket, and the statistical significance was limited. Previous work has shown via simulation that muon scattering measurements covering the complete azimuthal angle can use computed tomography image reconstruction techniques to produce detailed images of the cask and its interior contents [2], however, this requires detectors which give complete angular coverage of the cask. Here we demonstrate limited-angle viewing of the cask fuel basket experimentally. While the data from our limited angle tomography is not as detailed as

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the simulations of full angle tomography, we prove that muon scattering is sensitive to the removal of a single fuel assembly from the center a sealed dry cask.

Measurement

From May – Aug of 2016, two muon 1.2x1.2 m^2 tracking detectors were deployed around the MC-10 cask at Idaho National Lab's INTEC site (see Fig. 1), which is partially loaded with irradiated PWR fuel bundles. The two trackers were each placed in three different positions on either side of the cask, giving a total of 9 viewing positions, in order to provide views of the entire cask. One detector was elevated by 1.2m in order to take advantage of the larger muon flux at smaller zenith angles. More details of the cask and instrument are described in [1]. At each position, data was recorded for ~2 weeks.

When repositioning the detectors, only one was moved at a time. This allows a continuity of the precise positions of the detectors to be maintained throughout the measurement. The detectors can be positioned by hand to accuracies of ±1cm or so, however, the typical scattering angles of muons which pass through the cask are less than 3 degrees. Software which

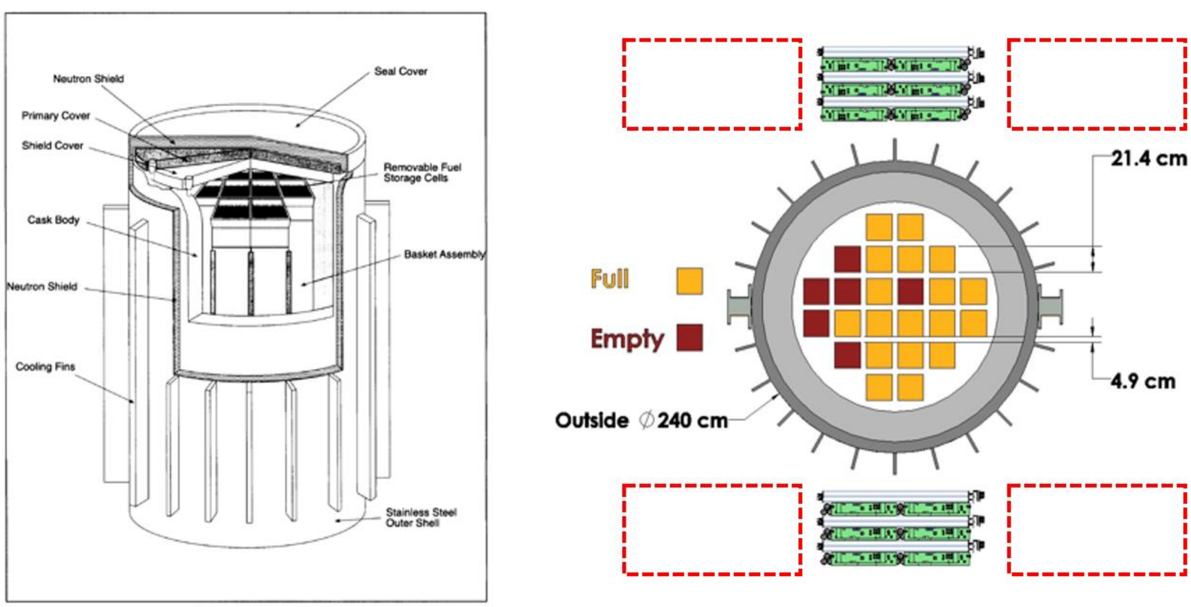

Figure 1, left: The MC-10 cask design [3]. Right: A top-down view showing the loading pattern of the MC-10 cask at INL, with muon trackers shown on either side for comparison [1]. The dashed red boxes indicate the additional detector positions.

uses the muon tracks themselves to align the detectors is used each time the detectors are moved to determine their positions and rotations in a global coordinate system that is common to all measurement angles.

Two unexpected issues arose during the measurement:

-Strong winds at the cask site pushed one of the detectors during the measurement at one point. This was found by our automated alignment software, and the instrument was subsequently secured against the wind.

-The clock distribution to the upper detector suffered from dropouts, which degraded the statistical precision of this measurement by about a factor of 2. Due to safety considerations of working inside a radiation area and at height, this was difficult to fix during the measurement. However, sufficient statistics were recorded to demonstrate this technique can discriminate at the level of single fuel bundles.

Data Analysis and Discussion

The image volume in between the two detectors is divided into 2x4 cm^2 voxels, where the long side is oriented along the line pointing from one detector to the other, and the short side is parallel to the detector faces. Tracks from the top detector are projected to the bottom detector, and for each voxel they pass through, the scattering angle of that track is collected into a corresponding histogram. The histogram bin containing that value of scattering angle is filled with a weight corresponding to the path length of the track through that particular voxel.

For verification purposes the concern is the structure within the fuel basket. To quantitatively examine the basket, we select the area inside the shielding and calculate the scattering angle muons experience averaged over the direction between the two detectors (through the cask). The measured average scattering angles then give a metric that is proportional to the areal density sampled by muons passing from the upper to lower detectors as a function of horizontal position across the cask. This is sensitive to the amount of fuel plus shielding in between the two detectors.

Fig. 2 shows the muon scattering angle averaged through the fuel basket as a function of the horizontal coordinate, compared to a picture of the fuel loading in the cask, and lines denoting the approximate boundaries of the rows in the fuel basket. Moving across the cask, both signal (muon scattering in fuel) and background (scattering in cask shielding) contributions vary. At the edges, where muons traverse the longest path length of shielding material and the least fuel, the background contribution is relatively large (i.e. in rows 1 and 6). In the center of the cask, rows 3 and 4, the background is lowest while the signal from scattering in fuel is highest.

The peaks in the bottom panel of Fig. 2 correspond to the scattering measured across the varying number of fuel assemblies in rows. The two centermost rows, numbered 3 and 4, contain 6 and 5 fuel bundles, respectively. Since the cask body is symmetric about the center, the shielding contributions in these two rows are identical, and therefore the difference in scattering is only due to missing fuel. The measured difference between these two rows demonstrates that muon tomography is sensitive to removal of single bundles of fuel in these locations.

Similarly, we can compare rows 2 and 5, where again the shielding contribution is identical but the fuel content is different. We observe a large difference in muon scattering due to the three missing bundles in row 2 as compared to the completely full row 5.

Finally, in row 1, we observe that despite the absence of fuel, there is still significant scattering due to the relatively long path length muons traverse through the cask shielding material as it curves around the edges. A comparison with row 6, where again the shielding contribution is identical, shows a clear difference due to missing fuel bundles in row 1.

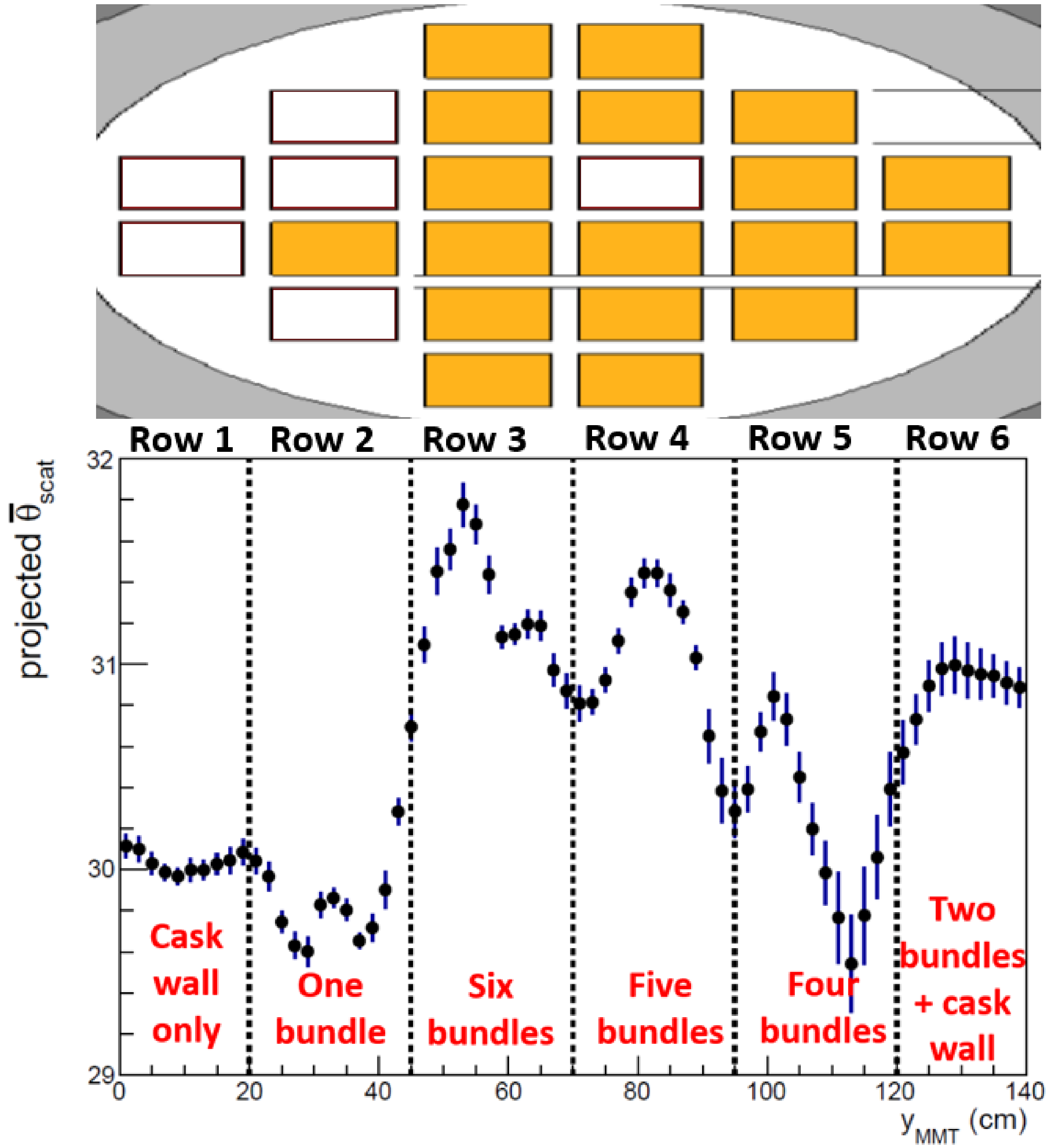

Figure 2: Scattering data from across the fuel basket, projected onto the plane parallel to the detector faces. A drawing of the MC-10 cask fuel basket is shown above for comparison.

Summary/Path Forward

This work shows that muon tomography is sensitive to the removal of a single fuel assembly from the center of a spent fuel cask. While "images" in the form of raw pictures are difficult to obtain with limited angle tomography, the radiographic data that is collected is sufficient to determine whether single fuel bundles have been removed from the center. We are exploring limited angle tomographic reconstruction algorithms and other analysis techniques which will be applied to this dataset as they are developed.

The next steps in developmental experimental work should involve blind tests: imaging casks with unknown content as a test of the discriminatory capability of muon tomography. This should be accomplished with increased detector coverage to more fully coverage the entire cask. Additional muon trackers would each cost ~$200k. Two additional trackers could be placed on either side of the bottom detector (giving 3 lower detectors and one upper detector) to give a broad angular coverage of the cask contents.

Acknowledgements

This work is funded by the National Nuclear Security Agency Office of Defense Nuclear Nonproliferation R&D.

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