The Use of Muon Tomography in Safeguarding Nuclear Geological Disposal Facilities

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Abstract

Muon attenuation tomography is a powerful tool that employs naturally occurring cosmic ray muons for locating, identifying, and measuring density irregularities in geological overburdens. First applied in the 1950s [3], the technique has very many diverse applications including imaging civil infrastructure such as railway tunnels [4], identifying ore bodies in mines, monitoring magma chambers in volcanoes [5], and identifying voids in pyramids [6, 7]. Muon scattering tomography, which requires the muons to be tracked both entering and leaving the object of interest, can provide valuable information on the atomic number, Z, of objects being imaging in addition to density information. The following reports on a series of simulation studies we have performed to assess the capability of muon radiography to detect a series of potential features that may need to be identified for safeguarding or safety purposes in geological disposal facilities (GDFs) for nuclear waste. Similarly, the application of muon scattering tomography to characterizing the materials encased in nuclear waste drums and to assessing unauthorized diversion scenarios is also presented.

Keywords: muon tomography, nuclear waste, geological disposal facilities
DOI: 10.31526/JAIS.2022.284

1. INTRODUCTION

Muon attenuation tomography (also referred to as "muon radiography" or "muography", henceforth "muography") employs naturally occurring radiation in the form of muons which are created in the Earth's atmosphere. Muons are charged leptons with a mass roughly 200 times that of the electron. High-energy muons, in particular, are highly penetrating and can easily pass through tens and up to hundreds of meters of rock. This enables density variations in an object of interest to be determined via a technique analogous to that of a medical X-ray. Specifically, as is the case with an X-ray, the object needs to be placed between a detector or set of detectors and the flux of cosmic rays which is at a maximum from above and drops off, with a $\cos^2\theta$ dependence towards the horizon (θ being the zenith angle). The generic procedure is to develop an accurate simulation of an overburden of interest which is used to predict an expected muon flux rate in a nominal detection system. The empirical flux observed in a detector system is compared to the predicted flux and any variation attributed to variations in the overburden which can be quantified.

In the case of muon scattering tomography (henceforth "MST"), by placing a detection system on either side of the object of interest, it is possible to track the passage of the muon through the object. Despite the muon's relatively large mass, it can undergo multiple scattering instances as it travels through the material. In principle, the scattering angle of a muon is inversely proportional to (X_o), the radiation length of the material that the muon traverses. Statistically, the distribution of the projected scattering angle of muon through a material with a thickness of X is approximately Gaussian, with a width σ given by [1]

$$\sigma \approx \frac{13.6\,\mathrm{MeV}}{\beta c p}\sqrt{X/X_o}, \tag{1}$$

where βc is the muon velocity, p is the muon momentum, and X_o is determined by [2]

$$X_o = \frac{716.4\,\mathrm{A}}{\rho Z(Z+1)\ln(287/Z)}, \tag{2}$$

where ρ represents the material density, Z is the atomic number of the material, and A is the atomic mass number.

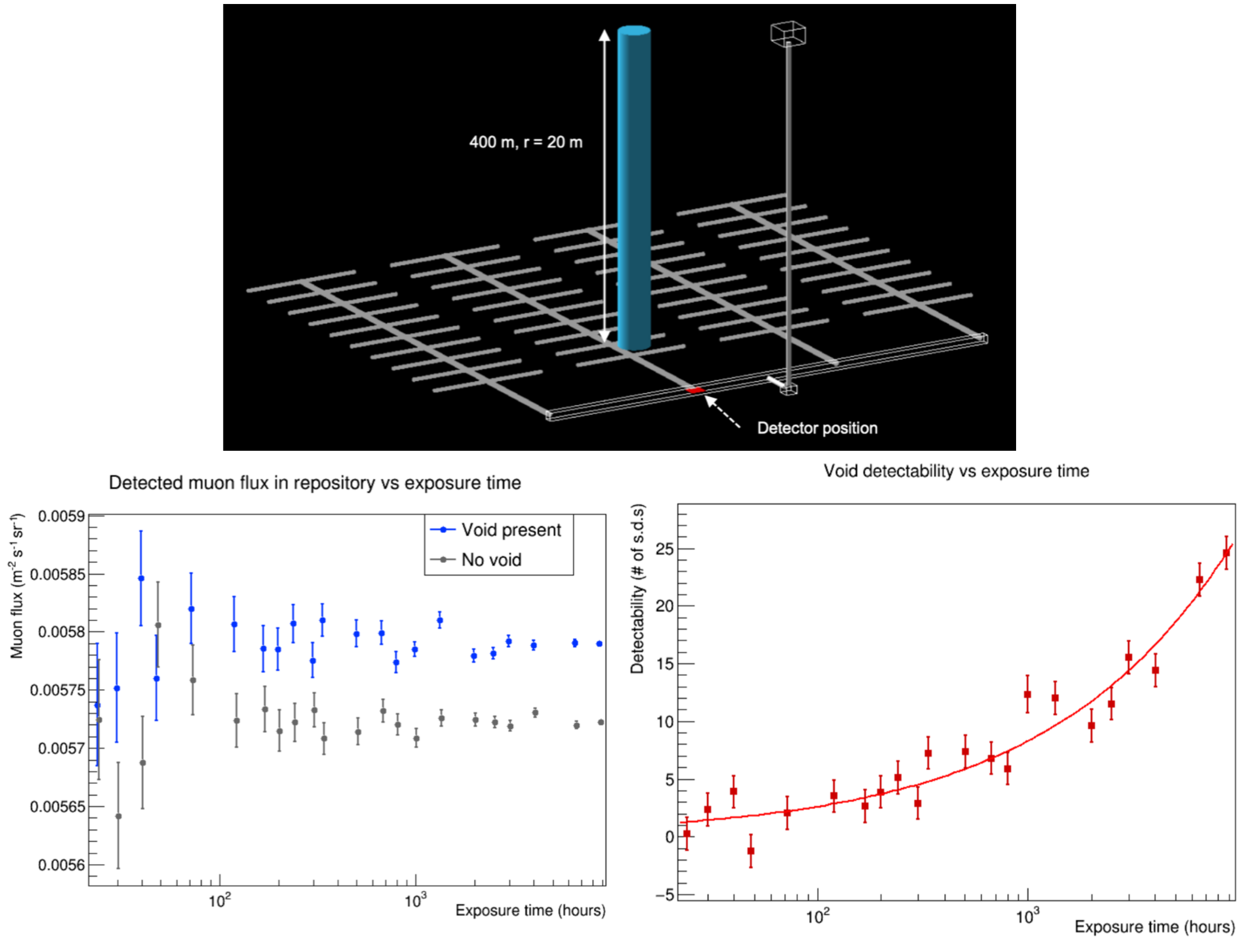

FIGURE 1: (top) Simulated detector and shaft geometry, (bottom left) muon flux as a function of time with and without the shaft present, and (bottom right) void detectability, in the number of standard deviations, as a function of time.

The net result of this is that materials with a higher Z also have a larger X_0. In practice, the object of interest is typically divided into many voxels (3D pixels). Those voxels with a large number of large-angle scatters are likely to comprise higher Z material. Other techniques are subsequently used to combine such pixels into larger volumes of high-, medium- or low-Z materials. Most famously applied to the imaging of the Fukushima reactor [8] MST is an important method to deliver noninvasive imaging alongside materials identification.

2. THE APPLICATION OF MUOGRAPHY TO THE SAFETY AND SAFEGUARDING OF GEOLOGICAL DISPOSAL FACILITIES

A series of “proof of principle” simulation studies have been performed to assess the potential of muon radiography to detect possible features that may need to be identified for safeguarding or safety purposes in geological disposal facilities (GDFs). A nonexhaustive list of potential areas where muography can provide valuable information includes the following:

(i) Safeguarding applications [9]:
   (a) design information verification;
   (b) searching for undocumented voiding;
(ii) Safety applications:
   (a) understanding the condition of the host rock geology;
   (b) sensitivity to water ingress and movement in the overburden;
(iii) Safety and safeguarding applications:
   (a) continuous geological overburden monitoring for overburden change detection;

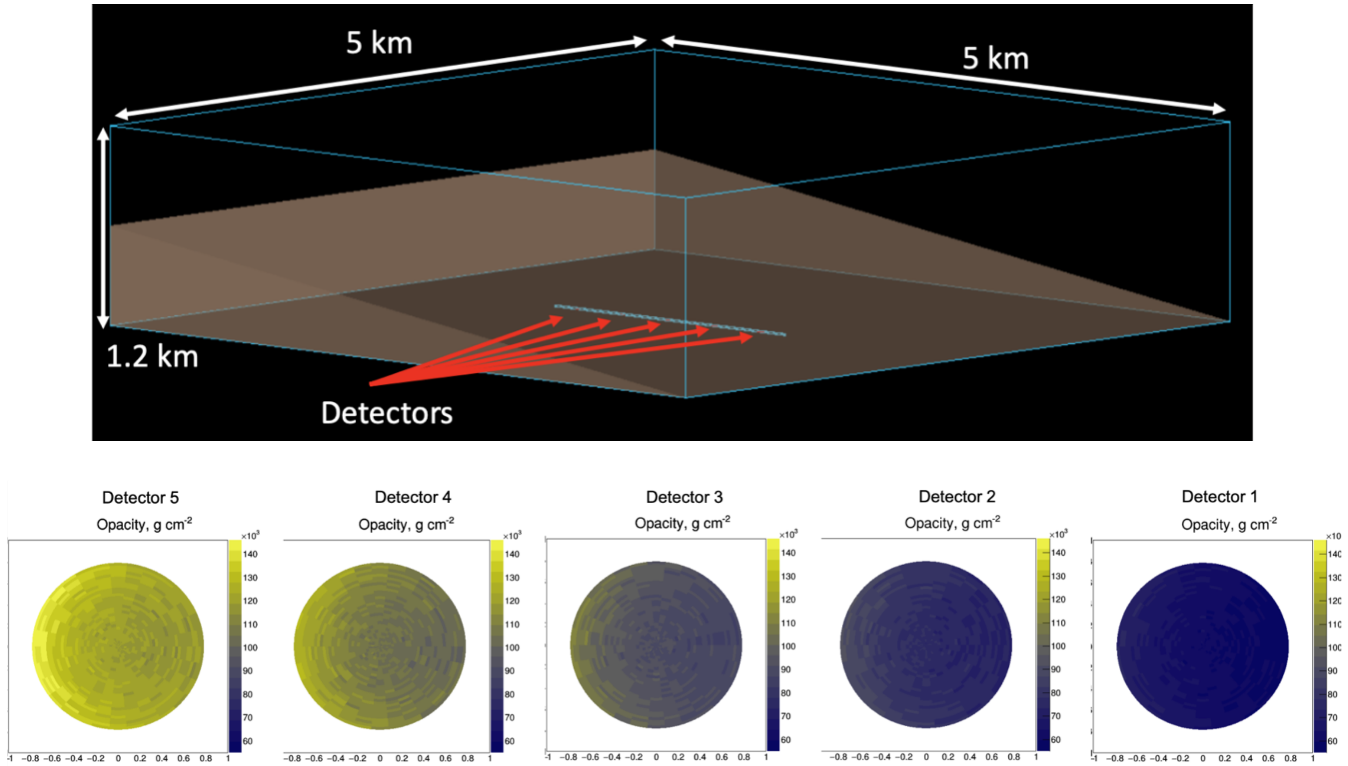

FIGURE 2: (top) Simulated geometry illustrating the granite slope and the 5 detector positions, (bottom) opacity data from the five detectors.

(b) checks of backfill integrity in the vaults;

(c) tunnel lining system checks and monitoring;

(d) monitoring of the GDF.

A number of studies are underway to assess, both qualitatively and quantitatively, the applicability of muography to these different applications. It should be stressed that in the GDF application space we expect that muon tomography will often provide complementary information which can be combined with data from other methods.

An obvious area of interest for a future GDF is being able to confirm that the geological integrity of the overburden is as expected and, e.g., there are no undocumented legacy mine workings since such workings could allow access to areas containing nuclear material under safeguards. When considering imaging at depths of hundreds of meters there is the challenge of working with significantly lower fluxes than at the surface. In order to assess the suitability of muography for such a problem, initial studies have been carried out with nonphysical objects in order to establish an order of magnitude estimates for imaging times.

Figure 1(top) depicts a large (20 m radius) vertical shaft running from a depth of 400 m to the surface in an otherwise uniform overburden of igneous rock.

The response of a single 2 m × 2 m detector placed at an offset of 147.5 m is considered in Figure 1(bottom) which indicates (left) the flux observed as a function of time for an overburden with and without shaft as well as (right) the void detectability as a function of exposure time. Note that the simulated detector is assumed to have 100% efficiency and perfect angular resolution.

The long imaging times can be mitigated via the use of multiple detectors. Further studies to assess the limitations of void size and shape detectability are underway in order to address such questions as "can we categorize sensitivity to a suite of object sizes and shapes?". Initial results from these studies indicate that neither void volume nor subtended angle alone is enough to parametrize the problem and information on, e.g., zenith angle is needed.

A further area of interest is using muography to characterize the geological overburden. Here, a simple granite slope, which is 600 m at its maximum thickness, has been modeled along with a system of five 2 m × 2 m muon detectors. The 5 detectors are assumed to be deployed in a tunnel under the slope (see Figure 2(top)) and are spaced at 400 m intervals. The resulting data, which effectively measures the "opacity" (where 0% opacity means completely transparent), is measured as a function of incident muon angle and is depicted in Figure 2(bottom) which clearly shows the change in opacity with detector position as the granite slope increases in thickness. The granite slope can thus be reconstructed using a suitable regression algorithm such as SART (the Simultaneous Algebraic Reconstruction Technique, see [11] for further detail).

Finally, the application of techniques such as SART, which permit 3D images to be reconstructed from a series of 2D measurements is under investigation to assess the potential of combining images from multiple detection systems to pinpoint features of

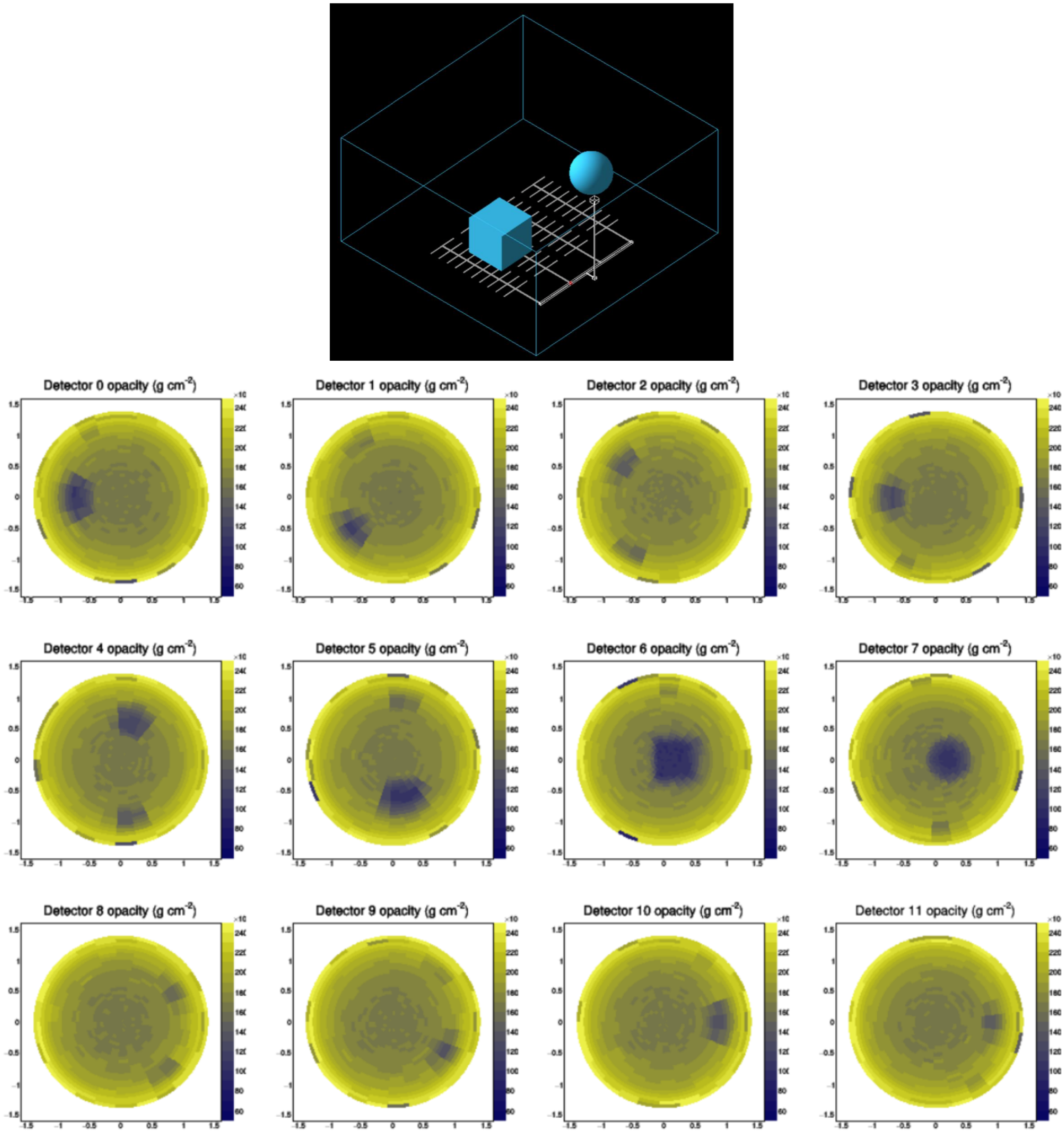

FIGURE 3: (top) Simulated view of the repository geometry depicting two large voids; (bottom) opacity data from 12 different detectors deployed at various positions under the voids.

interest in the overburden. Again, unphysical large features, namely, a cube of side 200 m at (300, 300, -450) m and a sphere of radius 100 m at (300, -300, -450) m, have been employed in these early-stage simulations. Figure 3 indicates the simulated geometry along with opacity data from 12 different detector positions, arranged on a 300 m by 200 m grid 265 m below the objects. This clearly demonstrates that muography is capable of determining both object location and shape information.

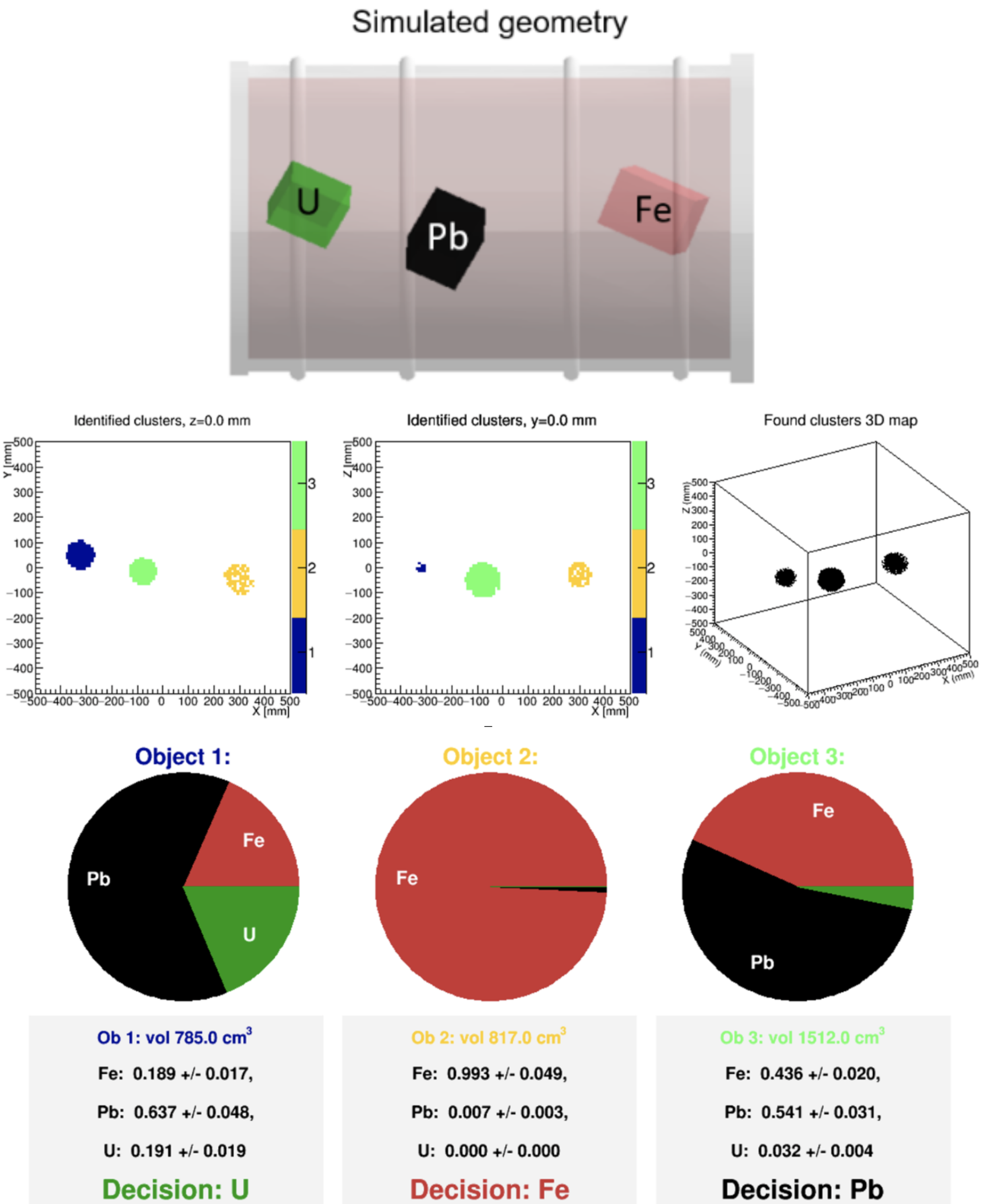

FIGURE 4: (top) Simulated in-drum geometry with 3 cubes of different materials inside the CASTOR/V52 drum, (center) clustering in z, x, and 3D; (bottom) output of the BDT with material identification decision.

3. THE APPLICATION OF MUON SCATTERING TOMOGRAPHY TO SAFEGUARDING GEOLOGICAL DISPOSAL FACILITIES

As discussed above, the muon scattering tomography (MST) technique returns valuable information on the atomic number of the object(s) being imaged as well as density information. In this respect, it is a particularly powerful technique when interrogating nuclear waste containers.

In a study involving the application of machine learning techniques to hidden material identification [10], a two-stage methodology has been developed that first identifies and groups together materials in a concrete matrix and then assigns probabilities to those materials using multivariate analysis techniques. The process is depicted graphically in Figure 4. The geometry under investigation, namely, a drum filled with concrete with 3 objects of different materials and sizes, is illustrated in Figure 4(top). From left to right, the materials and sizes are as follows: Uranium: $10 \times 8 \times 12$ cm, Lead: $12 \times 12 \times 10$ cm, and Iron: $15 \times 11 \times 16$ cm. Figure 4(center) shows the output from the first step whereby material boundaries have been determined and objects with densities different from the host matrix have been clearly identified. Finally, the MST information for the voxels associated with those objects

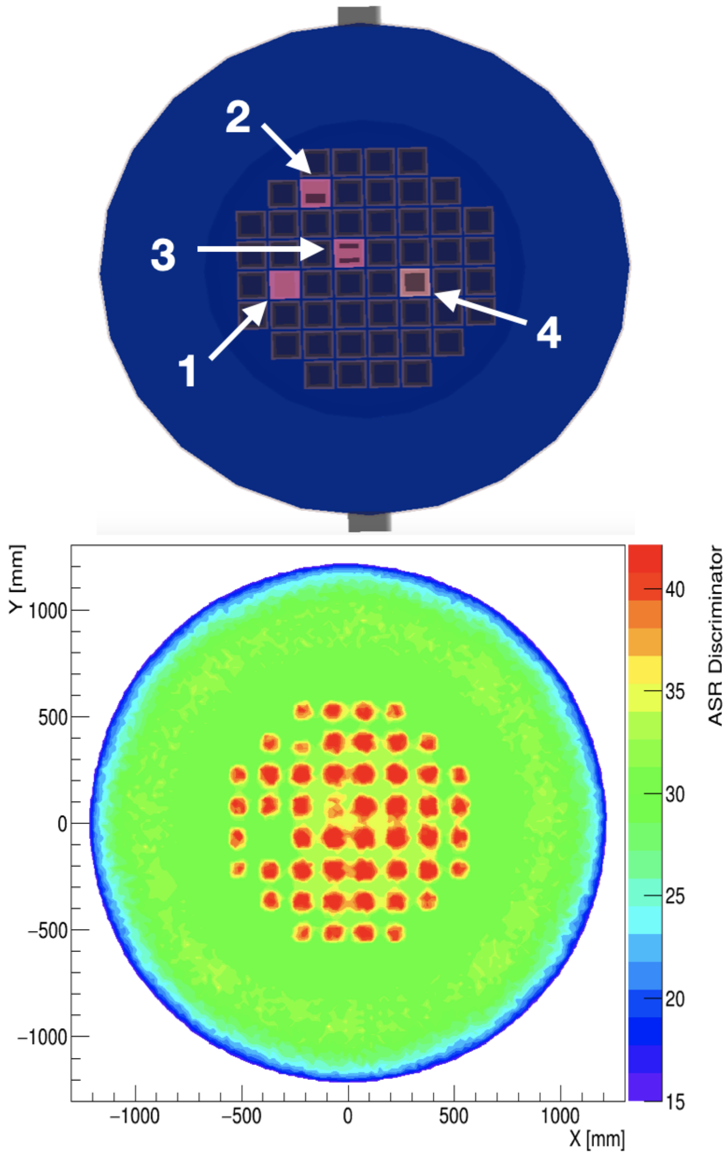

FIGURE 5: (top) Simulated CASTOR V/52 with 4 diversion scenarios considered (see text for detail); (bottom) subsequent image created using muon scattering tomography.

is attributed to a material identification probability using a boosted decision tree (BDT) that has previously been trained on those materials.

A further study using MST has been performed to assess the suitability of the technique to the potential risk of materials diversion. Here, a detailed model of a CASTOR V/52 type storage drum has been developed, and various diversion scenarios have been considered. Figure 5(top) illustrates the package that has been simulated with modifications applied to four of the 52 baskets, specifically: (1) a completely empty basket, (2) a half-loaded basket (side fuel assemblies unloaded), (3) a half-loaded basket (central fuel assemblies unloaded), and (4) a basket where the UO_2 pellets have been replaced with Pb pellets.

Figure 5(bottom) illustrates the resulting image from a study using MST assuming that detectors have been deployed on either side of the drum. Diversion scenarios (1), (2), and (3) are all very clear, while scenario (4), where the UO_2 pellets have been replaced with Pb pellets, is not visible.

Possible applications here include confirmation that a full complement of in-package components is present (i.e., no unauthorized diversion of materials has taken place) and confirmation that any out-going nominally unloaded/empty packages are truly empty.

4. SUMMARY

Muon tomography is a powerful tool that exploits naturally occurring radiation to form images of objects in a noninvasive and nondestructive way. The technique is currently considered globally for a huge range of applications including imaging of civil infrastructure, mines, nuclear safeguards, and material control, and homeland security.

There are a number of areas where muon radiography is a promising technology to address specific problems such as GDF design information verification, integrity assurance, and monitoring. Similarly, muon scattering tomography offers the possibility to identify issues such as material diversion, package voiding, and material identification.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

ACKNOWLEDGMENTS

The muon scattering tomography work discussed here was carried out as part of the CHANCE project which has received funding from the European Union's Horizon 2020 Research and Innovation programme under grant agreement number 755371.

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