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Gamma-ray Imaging Results from The International Partnership For Nuclear Disarmament Verification Belgium Exercise

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ABSTRACT

We describe the performance of a novel gamma-ray imaging system when imaging nuclear fuel as part of an International Partnership for Nuclear Disarmament Verification (IPNDV) exercise hosted by SCK-CEN in Belgium. The single pixel gamma ray imager is designed around the theory of compressed sensing and utilises a CLLBC scintillator detector that can detect both gamma-rays and neutrons. In its current configuration the imager can identify and localise gamma emitting radiation and detect the presence of neutron radiation. The detection, localisation and identification of radiation can provide added confidence for nuclear disarmament verification. In these results, the measured gamma-ray images are overlayed with an optical image, which enables the end user to easily visualise where the radiation is coming from. Traditional gamma-ray imagers (e.g. Compton camera, pinhole camera, coded aperture camera) typically have a limited energy range and/or a limited field of view. However, the described imager is able to identify and localise gamma emitting radiation over a large field of view (360° × 90°) and across a wide energy range (40 keV to 3 MeV).

The imaging results from measuring shielded and unshielded MOX fuel will be presented. The imaging system identified and localised the nuclear material gamma emissions and also detected the presence of neutrons. The effects of shielding the fuel assembly are seen to hide the localisation information for low energy gamma emissions. However, the imaging of higher energy gamma emissions is able to reveal the full localisation information. Two imaging systems were subsequently setup at 90° to each other (relative to the fuel assembly), which enabled the location of the nuclear fuel to be further confined within the facility. As the technology confirms the presence of nuclear material in the fuel assembly location, it is also confirming the absence of nuclear material being contained elsewhere within the facility room.

INTRODUCTION

Nuclear disarmament verification requires the use of radiation detection technologies to help provide confidence in determining the presence or absence of nuclear material. Initiatives, such as the International Partnership for Nuclear Disarmament Verification (IPNDV), are actively reviewing a broad range of technologies that could be used in nuclear disarmament verification activities.

Gamma-ray imaging is an important passive detection capability that is being utilised in a diverse range of areas, including: nuclear security, nuclear industry, medical imaging and

astronomy [1-3]. Gamma-ray imaging is already being used in nuclear security applications for the detection and localisation of special nuclear materials (^{235}U, ^{239}Pu) and could therefore be a useful tool for nuclear disarmament verification applications.
Traditional gamma imaging techniques have been based on mechanical collimation or through using the kinematics of particle scattering [4-8]. Gamma-ray imagers (such as the Compton camera, pinhole camera and coded aperture camera) typically have a limited energy range and/or a limited field of view (FOV). Dual mode imaging systems, based on Compton camera and coded aperture, have been developed to address these limitations, but there is still a capability gap in quickly imaging low gamma energies across a large FOV.

For imaging in general, when considering the generation of an $N \times N$ pixel image, a pixelated detector performs N^2 simultaneous measurements (one for each detector pixel), whilst a simple raster scanned pixel is required to take N^2 sequential measurements. Compressed sensing is a relatively new theory that can exploit the sparsity within an image and allow the reconstruction of an $N \times N$ pixel image with highly undersampled M random measurements (where $M << N^2$) [9,10]. The required number of measurements is related to the information content of the scene being imaged. For sparse scenes, e.g. point sources, a single pixel detector can therefore quickly image in relatively few measurements. Recent work has demonstrated the generation of gamma images through a compressed sensing technique [11].

This paper describes the results of a prototype CORIS360® gamma-ray imaging system, designed around the principles of compressed sensing, used to image MOX fuel pin configurations at the IPNDV Belgium Exercise, in September 2019. The described imager was able to quickly localise gamma emitting radiation over a large FOV (360° × 90°) and across a wide energy range (40 keV to > 3 MeV). The paper will focus on the imaging capability rather than the spectral analysis of different fuel configurations.

METHOD

The prototype CORIS360® system design consists of a central non-position sensitive CLLBC scintillator detector, surrounded by two nested cylindrical tungsten masks. The CLLBC detector is a dual gamma/neutron scintillator, and for neutron interactions the crystal produces an equivalent gamma energy of 3.1 MeV [12]. The imaging system comes with interchangeable CLLBC detectors in the form of a 0.5" cube and a Ø 1.5" cylinder. The energy resolution of the detectors is ~ 3.5 % at 662 keV. For each measurement, the CLLBC detector sees the linear projection of the combined mask pattern on the scene plane. The changing mask pattern effectively encodes the source location information into the detected counts. Gamma images from any part of the measured spectrum can be generated, given there are sufficient counts. Both the spectroscopic and imaging energy range are from 40 keV to >3 MeV. The system has four optical cameras that are used to generate a 360º × 90º optical panorama of the scene. The resulting gamma images are overlaid onto this optical panorama, which aids the end user in visualising the location of the gamma emissions. The system is compact and has an easy-to-use graphical user interface.

During the IPNDV Belgium Exercise, a range of different fuel assembly configurations (with differing shielding, length, isotopic composition and mass) were imaged at the SCK-CEN. The results presented in this paper are for a MOX fuel pin configuration of 61 pins, 62 % ^{239}Pu content, 1 m long and with 1.1 mm Cd shielding.

RESULTS

Figure 1 shows the spectral and imaging results from the MOX fuel pin configuration detailed in the Method section. The spectrum and images were those obtained after 35 measurements, which took ~ 3.5 minutes to acquire. Figure 1(a) gives the full energy spectrum with several spectral peaks highlighted. A region of interest around the 60 keV peak was used to localise ^{241}Am in Figure 1(b). Figure 1(b) shows the system generated optical panorama with the overlaid ^{241}Am hotspot location. For this fuel assembly configuration, the Cd should be shielding the 60 keV ^{241}Am emissions over the full length, but the gamma imager has localised emissions coming from a gap in the shielding at the bottom of the assembly. Figure 1(c) shows the reconstructed gamma-ray image for the 375 keV ^{239}Pu peak. The higher energy gamma emissions (375 keV) can penetrate through the 1.1 mm Cd shielding and the full length of the fuel assembly is now showing as a source of radiation. It should also be noted that the spectral peak at approximately 3.1 MeV is due to the neutron emissions from the fuel assembly and elevated neutron background. The imager was able to identify and localise the ^{241}Am and ^{239}Pu gamma emissions, as well as detect the presence of neutrons. The other gamma peak emissions, above 60 keV, also generated line source gamma images similar to that of the 375 keV peak.

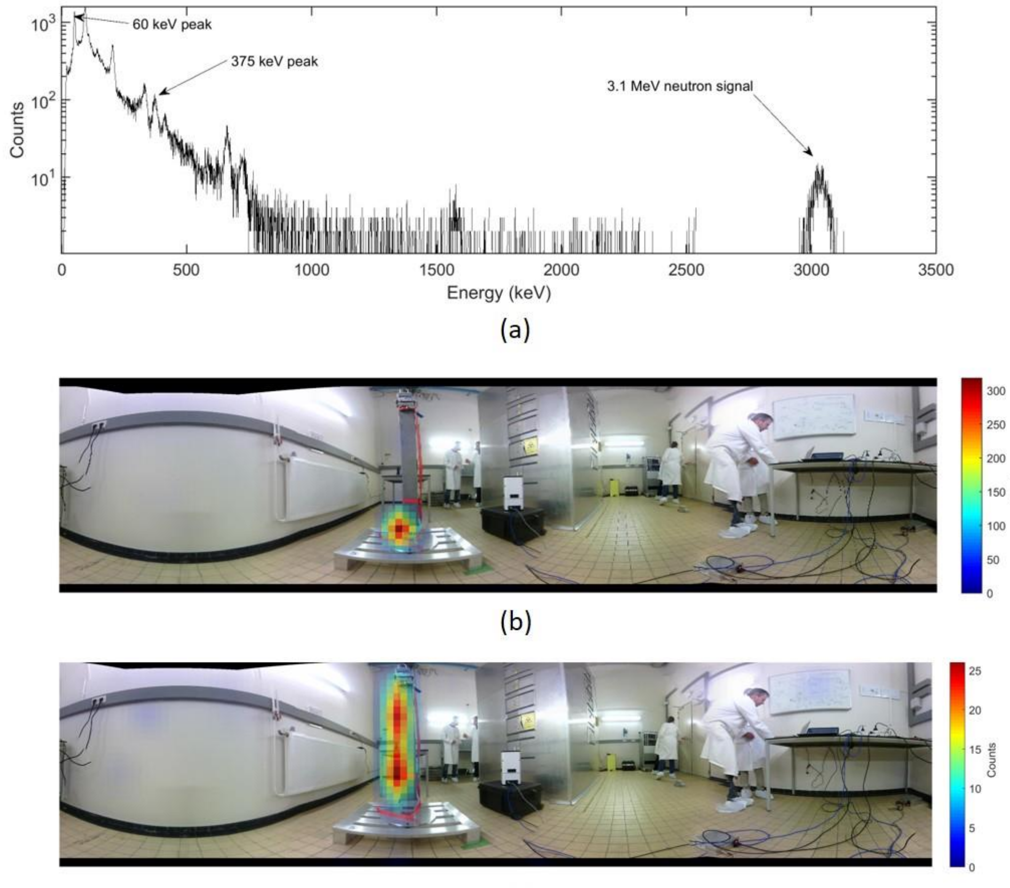

Figure 1. (a) The acquired gamma spectrum, from the prototype CORIS360® imaging system. (b) The resulting ^{241}Am image when reconstructing over the 60 keV ^{241}Am peak labelled in (a). (c) The reconstructed image from the 375 keV ^{239}Pu peak.

The results from two prototype CORIS360® imaging systems, setup at 90° to each other, are given in Figure 2. This is also for the same fuel configuration detailed earlier. Operating two imaging systems in this setup can further confine the location information of the detected gamma emissions. Figure 2 (a) & (c) show the localisation of the ~335 keV ^{239}Pu emissions from the two angles. Figure 2 (b) & (d) show the localisation of the 60 keV ^{241}Am emissions from the two angles. These orthogonal measurements have effectively confined the gamma emissions in 3 dimensions.

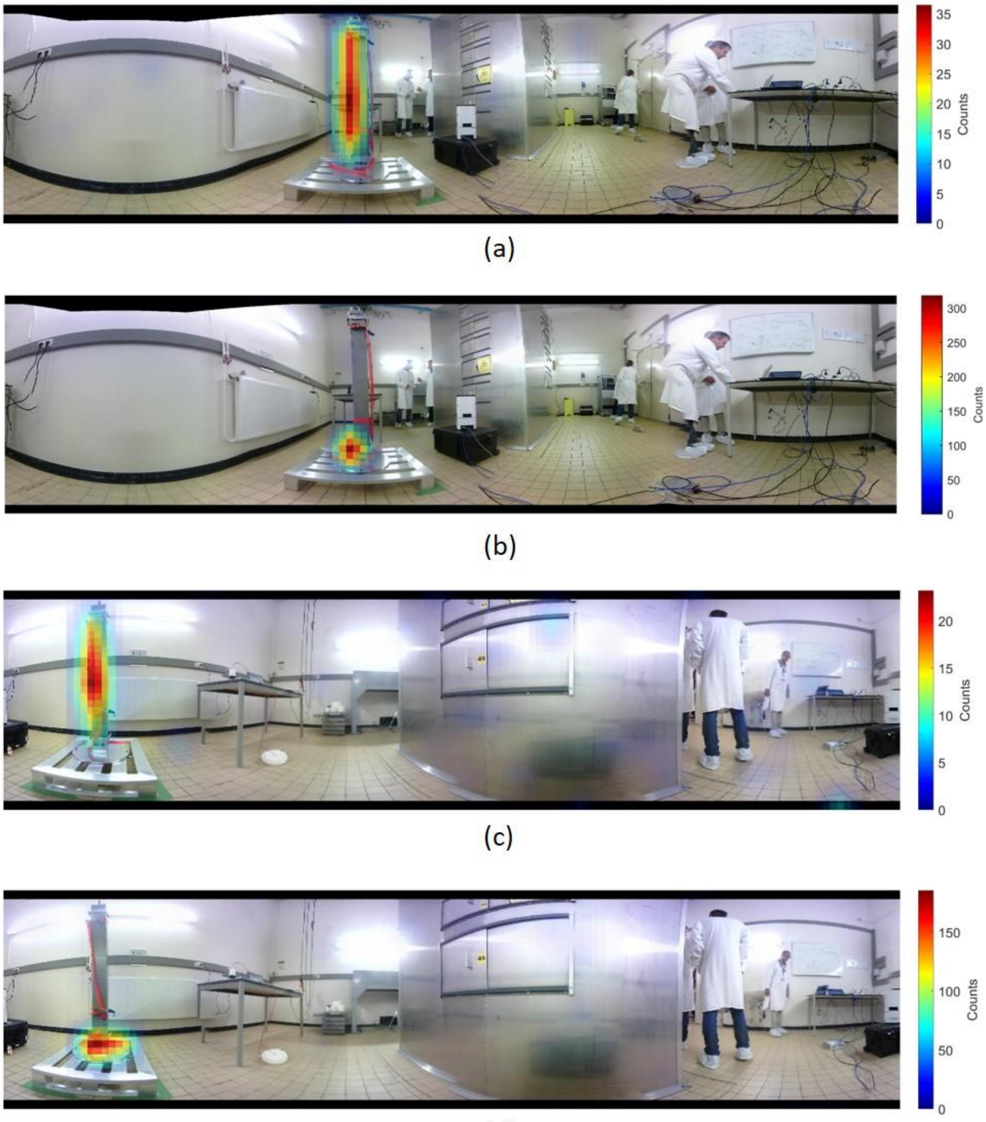

Figure 2. Images of the fuel pins taken by two systems arrange at 90° to each other. Images (a) & (c) show the localisation of the ^{239}Pu peak emissions 335 keV. Images (b) & (d) show the localisation of the 60 keV ^{241}Am emissions.

Discussion

The prototype CORIS360® gamma imaging technology was used to identify and localise gamma emissions (^{239}Pu and ^{241}Am) from MOX fuel pin configurations. The wide field of view (360° × 90°) enables large areas to be scanned when looking for the absence/presence of nuclear material. The effects of shielding on the fuel pins were evident when the Cd shielding hid the

60 keV ^{241}Am emissions for most of the fuel pin length, whereas the higher energy emissions could pass through the shielding. The technology can also detect the presence of neutrons. The use of two imaging systems, setup at 90° to each other, enables the location of the nuclear fuel to be further confined within the facility.

Measurements of the different fuel assembly configurations typically ran for 15-20 minutes, but the imaging technology required just 2-3 minutes to localise the gamma emissions. The image and spectral data were available immediately after the measurement had taken place. Data analysis was completed within a few minutes of completing the data acquisition. An elevated neutron background, within the measurement area, did not create any practical problems with the technology.

The IPNDV have proposed that the monitoring and verification activities, of the nuclear weapon dismantlement process, can occur in 14 key steps [13]. The storage steps would be suitable for measurement techniques that require long measurement times, however, the short measurement times demonstrated in this work means that more steps could potentially utilise gamma-ray imaging.

Information Barriers (IB) must be considered when the use of radiation detection technologies could potentially reveal sensitive information. The energy resolution of the detector and angular resolution of a gamma-ray imager would be key characteristics as to whether an IB would be deemed necessary. For the imaging technology used in this exercise, the system design could be easily modified to degrade the angular resolution and energy resolution properties such that sensitive information would not be revealed.

CONCLUSIONS

The IPNDV Belgium Exercise, hosted by the SCK-CEN, demonstrated that gamma-ray imaging could be a useful tool for nuclear disarmament verification purposes. The gamma imager was able to identify and localise the ^{239}Pu and ^{241}Am gamma emissions from the fuel pins, as well as detect the presence of neutrons. Two imaging systems, setup at 90° to each other, enabled the location of the nuclear fuel to be further confined.

As the technology confirms the presence of nuclear material in the fuel assembly location, it is also confirming the absence of nuclear material being contained elsewhere within the facility room.

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REFERENCES

1. S. R Meikle, P. Kench, M. Kassiou, R. B Banati, Small animal SPECT and its place in the matrix of molecular imaging technologies, Physics in Medicine and Biology 50 (2005) R45–R61
2. F. Carrel et al., GAMPIX: a New Gamma Imaging System for Radiological Safety and Homeland Security Purposes, IEEE Nuclear Science Symposium Conference Record, 4739 (2011)

3. A. Abdo, et al., Fermi Gamma-ray Imaging of a Radio Galaxy, Science 328 (2010), 725-729
4. H. O. Anger, Use of a gamma-ray pinhole camera for in vivo studies, Nature 170 (1952), 200-201
5. R. H. Dicke, Scatterhole cameras for X-rays and gamma-rays, The Astrophysical Journal 153 (1968), L101
6. E. Feniore, T. Cannon, Coded aperture imaging with uniformly redundant arrays, Applied Optics 17 (1978), 337-347
7. T. A. DeVol, D. K. Wehe, G. F. Knoll, Gamma-ray spectral imaging using a single-shutter radiation camera, Nuclear Instruments and Methods in Physics Research A299 (1990), 495-500
8. D. B. Everett, J. S. Fleming, R. W. Todd, J. M. Nightingale, Gamma-radiation imaging system based on the Compton effect, Proc. IEEE 124 (1977), 995-1000
9. D. A. Boardman, A. Sarbutt, A. Flynn and M. C. Guenette, Single pixel compressive gamma-ray imaging with randomly encoded masks, Journal of Instrumentation, Vol. 15, April 2020
10. D.L. Donohue, Compressed sensing, IEEE Trans Inf Theory, 52(4), pp. 1289-1306, 2006
11. E. J. Candes and T. Tao, Decoding by linear programming, IEEE Trans Inf Theory, 51(1), pp. 4203-4215, 2005
12. R. Hawrami et al, $Cs_2LiLa(Br,Cl)_6$ Crystals for Nuclear Security Applications, IEEE Trans. Nuc. Sci. 63 (2016)
13. https://www.ipndv.org/wp-content/uploads/2017/11/IPNDV_14-steps-diagram-Final.pdf