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Combined Compton and Pinhole Imaging of Distributed Plutonium-238 Holdup

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***Abstract*—Between 1978 and 1983, the Plutonium Fuel Form Facility at the Savannah River Site was used to produce approximately 165 kilograms of iridium-encapsulated ^{238}Pu for use as radioisotope thermal generators, primarily for the space program. After the facility was placed in standby, the remaining ^{238}Pu rendered the facility's nine shielded cells inoperable and inaccessible. Accurate knowledge of the amount and extent of this material is required before decontamination can begin.**

The Germanium Gamma-Ray Imager (GeGI), developed by PHDS Co., was used to perform both pinhole imaging and Compton imaging of the cells in order to visualize and quantify the distribution of holdup. These images were then used to simulate the response of a high-efficiency germanium detector to obtain plutonium masses with a minimum detectable activity (MDA) of 0.26 mCi (<0.1 mg). The resulting data incorporates Compton imaging, pinhole imaging, visual camera images, and MCNP modelling to fully characterize material in the cell. Characterization of cells 6–9 will be presented, with plans to utilize the same approach for future measurements of cells 1–5.

I. Introduction

Between 1978 and 1983, the Plutonium Fuel Form (PuFF) Facility at the Savannah River Site was used to produce approximately 165 kilograms of iridium-encapsulated ^{238}Pu spheres and pellets for use as radioisotope thermal generators, primarily for the space program. The facility consists of two lines of shielded cells, the east cell line used to process Pu-238 oxide into spheres or pellets, and the west cell line used to encapsulate the fuel forms in iridium. In 1984, the facility was placed in standby, and the highly-corrosive ^{238}Pu rendered much of the facility inoperable and inaccessible [1]. In order to begin decontamination and decommissioning of the facility, an accurate inventory and knowledge of the plutonium holdup inside the cells is required.

Over the past decade, various measurements have been made to attempt to quantify the holdup present in these cells [2]. Precise quantification, however, is difficult without a complete understanding of the distribution of the source material. The availability of portable, high-resolution gamma-ray imagers such as the Germanium Gamma-Ray Imager (GeGI) [3] enable distributed sources of material such as ^{238}Pu to be located precisely. This knowledge of the source distribution is critical to inform decontamination efforts, for example, how much material is on the floor, walls, filters, or various machinery. In addition, these source distributions can be used to quantify the total activity by coupling the image with Monte Carlo models.

II. Measurements

Two high-purity germanium detectors were used to perform these measurements. The first is the GeGI, a double-sided strip detector which can perform Compton imaging (at energies above 140 keV) and pinhole imaging (at and below 662 keV). The imager includes a visible light camera which is well calibrated in position to provide accurate image overlays onto the scene. The second is a high efficiency coaxial detector (>120% relative efficiency), with a Monte Carlo model which has been benchmarked to point sources in the laboratory. This high efficiency detector is used to obtain total gram quantities of plutonium once the distribution has been imaged.

Measurements began on cells 6–9, which contained the least amount of material, with plans to characterize cells 1–5 in the future. The typical strategy is to first take a bulk assay using the high efficiency detector, in order to determine if the cell has enough activity to be imaged. For cell 9, which did not have any measurable contamination, this result also determines the minimum detectable activity (MDA). Next, a Compton image is acquired using the imaging detector to determine the overall extent of contamination. Based on this information, multiple pinhole images are then acquired at different orientations. Figure 1 shows the imager behind the pinhole aperture before being moved into position.

Fig. 1. The GeGI detector placed behind the pinhole aperture, ready to be moved into position in front of a shielded cell.

^{238}Pu emits gamma rays at a wide range of energies as seen from figure 2, the most prominent at 99, 152, and 766 keV. In addition, the material contains multiple impurities, such as ^{241}Am and ^{208}Tl, which emit photons at 59 and 2615 keV,

respectively. This provides multiple energies to image in both the Compton and pinhole modalities. In particular, the 59 and 99 keV photons perform well for the pinhole imaging, while 766 and 2615 keV provide good Compton imaging results.

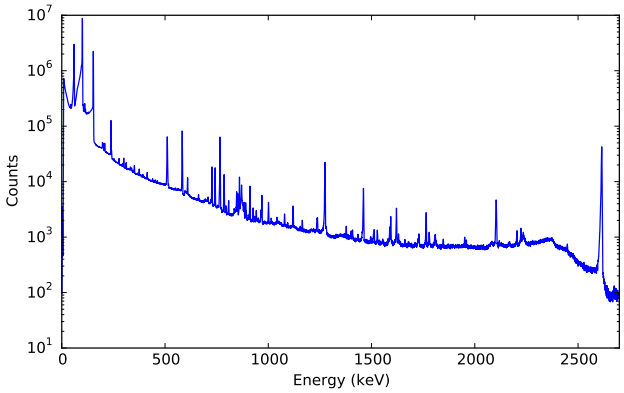

Fig. 2. Typical spectrum of the ^{238}Pu source term measured by the high-efficiency detector. Acquisition was 23 hours live time.

III. Results

The results presented here are for cell 6, as it was the only cell with sufficient activity to obtain a pinhole image. Figure 3 shows the Compton image for the 766 keV gamma ray in the GeGI detector. Acquisition was taken for 48 hours, accumulating a total of 1388 Compton events for this photon energy. The resulting image indicates that the material is primarily on the floor of the cell, and is not uniformly distributed. At this point, the known cell geometry can be used to assist in properly aligning the Compton and visual images, which indicates that the uppermost extent of the distribution is not on the floor, but is associated with the transfer tube on the back wall.

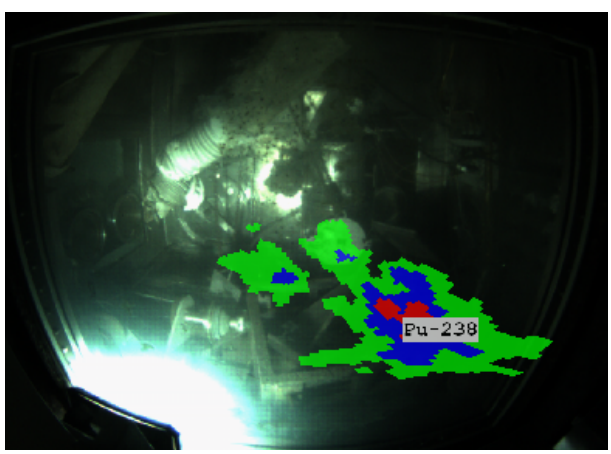

Fig. 3. Compton image of ^{238}Pu 766 keV source distribution in cell 6, overlaid on the camera image. Red corresponds to 90th percentile in the raw Compton image, blue to 70th, and green to 50th (FWHM).

Next, the pinhole imager is used to obtain better resolution. With the pinhole in place, the acquisition time increases to 96 hours per exposure. Two pinhole images were taken, one looking straight ahead to determine the extent of contamination on the wall, and the second pitched down towards the floor at an angle of 45°. Figure 4 shows the two resulting images for the 59 keV gamma ray from ^{241}Am. Due to the low energy, most of the events interact only in the front of the detector. By using the timing difference between strips on the opposite sides of the detector, the imager is able to estimate the depth of the interaction. These images include only events that interacted in approximately the first 3 mm of germanium. The combined counts used in this image after the depth cut is about 10^5.

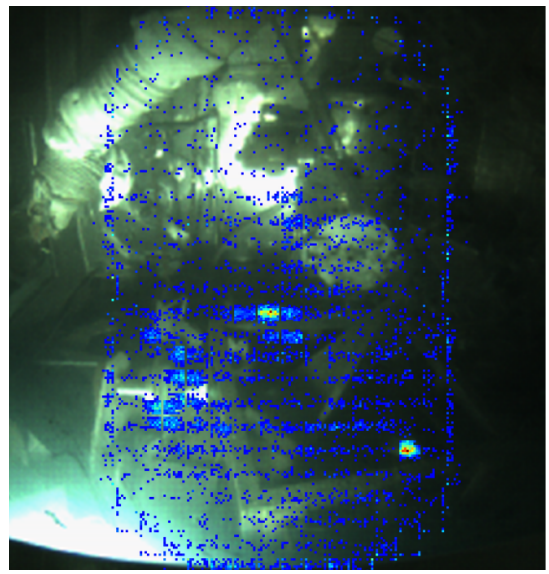

Fig. 4. Two pinhole images, pitched 45° apart, of ^{241}Am 59 keV source distribution in cell 6, overlaid on the camera image. Red corresponds to the maximum intensity, which was 58 counts per subpixel.

The pinhole image shows a source distribution which is consistent with the Compton image, while also providing improved image resolution for a few hot spots. For example, two relatively strong hot spots appear to be localized contamination on the steel frame. By looking at the ratios between the 59 keV and the 99 keV intensities in the image, these hot spots indicate contamination on the surface of the frame with little attenuating material, while the diffuse source across the floor shows more attenuation due to the steel machinery in the cell. At this point, the high-efficiency detector spectrum can also be consulted; peak ratios in the bulk assay spectrum indicate that the majority of the activity is indeed lightly shielded. Now, using the known source distribution, the total activity in the cell was calculated and compared to previous results [2].

IV. Conclusion

Compton and pinhole imaging are two complementary imaging modalities, and with current state-of-the-art technology, both can be obtained in a single device. In addition, the use of a non-imaging detector to provide high-efficiency measurements can use these results to quantify the activity with high precision. With this information, decontamination is now planned for cells 6–9, and the same approach will be used in the future to measure the much higher activities in cells 1–5.

This work also demonstrates how many different data streams can be combined to reinforce and refine the knowledge of a source distribution in an area of interest. In addition to the fusion of the gamma-ray images with visual imagery, additional context can be gained from using a Monte Carlo characterized detector and the geometry of the scene (here, known from blueprints, but also obtainable from range-finding or other scene reconstruction approaches).

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