Australian Government

Woomera Gamma Imaging

Nuclear Stewardship

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Executive Summary

ANSTO staff visited a CSIRO facility in Woomera, SA from 29/5/2018 until the 31/5/2018 to conduct gamma imaging of a building annex containing ~10 000 drums of waste material. The purpose of the trip was to non-invasively characterise the radiological status of the drums using ANSTO developed gamma ray imaging technology.

Data analysis indicated the presence of ^{214}Bi and ^{214}Pb. Both of these radionuclides are gamma emitting members of the ^{238}U decay series. The ^{238}U decay series radionuclides are often present in naturally occurring radioactive material (NORM) and are found in all rocks and soils. Higher radioactivity levels of ^{238}U decay series radionuclides can be found in NORM such as uranium ore or Technologically Enhanced NORM (TENORM) such as waste streams from ore processing and industrial processes. No other gamma emitting radionuclides were detected above local background from the drums.

Gamma image pairs, for both ^{214}Bi and ^{214}Pb, were generated at five locations which indicated that ^{214}Bi and ^{214}Pb were predominantly co-located in drums. Obtained images indicate that only a select few first layer drums have elevated levels of radioactivity and that the majority contain levels below the detection limits of the gamma ray imaging technology.

Purpose

The objective of this work was to non-invasively characterise the radiological status of drums stored at the Woomera site using ANSTO developed gamma ray imaging technology. Gamma imaging identifies the location of drums with relative higher levels of radioactivity which will inform future detailed characterisation campaigns.

Additional outcomes of this work are demonstration of the non-invasive gamma ray imaging capability and operational insights of gamma imaging deployment at the Woomera site. This includes investigating hardware and algorithmic modifications to the gamma imager for enhanced characterisation, as well as identifying aspects of the broader Woomera project where imaging or detection technology may be beneficial to the characterisation effort.

Method

The ANSTO spectroscopic gamma-ray imaging system ('Cyclops') provides a passive and non-invasive capability to locate and identify sources of gamma emitting radionuclides at distance. The imaging system has a large field of view (360° x 90°), wide energy range (40 keV to 3000 keV) and produces a combined optical/gamma-ray image for the visualisation of the radiation location. The imaging system consists of a 1.5" $CeBr_3$ Scionix scintillation detector located in the centre of dual rotating, mask collimators. Gamma images are then created using any specified energy window of the recorded gamma spectrum using the signal processing theory of compressed sensing (*Compressed sensing, D.L. Donohue, IEEE Trans Inf. Theory 52 (2006), 1289-1306).*

Non-destructive, radiological assessment of waste drums produced by the nuclear industry often employs gamma scanning technology (e.g. segmented or tomographic scanning systems from Canberra or Antech Inc.). However, this technology requires the movement and manual handling of each drum, which potentially poses contamination/spill risks due to age and unknown condition of the drums. Furthermore, a dedicated processing facility in close proximity to the drums would be required which may not be feasible. The use of conventional radiation dose rate surveying equipment to measure each drum also presents its own problem; the closely stacked, stationary configuration of the drums means that dose rate measurements of particular drum will be affected by radiation originating from the surrounding drums.

The use of gamma-ray imaging is valuable as a means of identifying hot spots of gamma-emitting radionuclides within the drums in their current configuration. In contrast to other methods, compressive gamma-ray imaging can be undertaken at a distance which reduces the radiological exposure of workers and measures radiation from its source through a collimator, allowing the location of the source to be determined. As a result, radiation sources from adjacent drums can be resolved individually, based on the spatial resolution of the imaging system being utilised.

Gamma-ray imaging was undertaken at five locations outside the annex, shown in Figure 1. Image location number is ordered chronologically by the time the images were acquired. Bay number is listed with the northernmost bay being labelled as 'Bay 1'. Figure 2 shows the deployed imaging system at two measurement locations. Limited and confined access restricted imaging to the first layer of drums only. It should be noted that neither the annex nor hangar were entered for this activity.

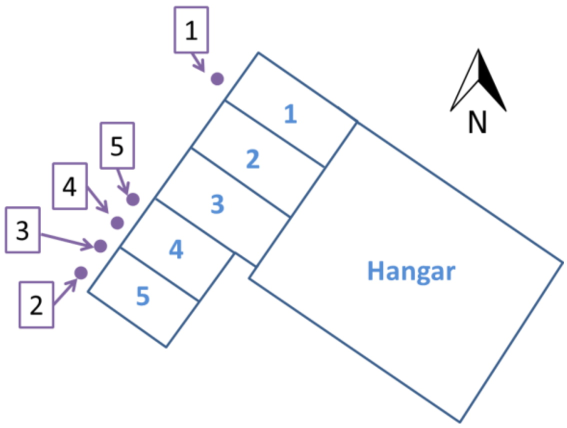

Figure 1: Image locations 1 – 5. Location numbers are shown in purple boxes and annex bay numbers are indicated by the blue text.

The choice of imaging location was informed by previously identified radiation hot spots from *'ANSTO report R180057: Woomera Characterisation: Gamma Survey of Area 1, D. Boardman and S. Hagan (2018)'.* Descriptions of the imaging locations and approximate dose rates at the detector are given in Table 1.

The dose rates at each of the imaging locations (Table 1) are considered low. For reference, the average dose rate from background radiation in Australia is approximately 0.2 μSv/h (*Exposure to background radiation in Australia, S.B. Solomon, Australian Nuclear Association Inc; ANA'97: Second conference on nuclear science and engineering, (1997) 102-106*). Since dose rate is proportional to radioactivity concentration it was anticipated that the gamma-ray images, measured in counts, would need to be acquired for many hours. The mean Woomera temperature at the site varied between ~10.7 °C (9 AM) and 17.1 °C (3 PM) during the days of the imaging activity. Additional heating of the system occurred due to the deployment in the sun. Detector energy calibration during the image acquisition was applied by using two energy calibration measurements at the start and end of each image using a small ^{232}Th mantle source (exempt) over the energy range 240 keV – 2600 keV.

Table 1

Location	Description and Approximate Dose Rate at Detector
Location 1	12.2 m from NE corner, 3 m perpendicular (NW) to drums, ~0.3 μSv/h.
Location 2	4 m from SW corner, 2.1 m perpendicular (NW) to drums, ~0.3 μSv/h.
Location 3	7 m from SW corner, 0.77 m perpendicular (NW) to the drums, ~3 μSv/h.
Location 4	15 m from SW corner, 2.1 m perpendicular (NW) to drums, ~0.6 μSv/h.
Location 5	21.2 m from SW corner, 1.8 m perpendicular (NW) to drums, ~0.5 μSv/h.

Figure 2: Photos of the Cyclops gamma imaging system deployed at Woomera; (Top) Location 2, (Bottom) Location 5, as listed in Table 1.

Gamma Spectroscopy

Figure 3 shows the gamma spectrum recorded at Location 3 (Bay 5, NE side). Only one gamma spectrum is shown here as the spectra at each location are similar and contain identical peak information. For completeness, the gamma spectra from all locations are shown in Appendix A.

The spectra is dominated by the ^{238}U decay series daughters (^{214}Bi and ^{214}Pb), with the ^{232}Th decay series daughter (^{208}Tl) also being present. In contrast, previous background gamma spectroscopy measurements on the eastern side of the hangar and at the Eldo Hotel, two locations not impacted by radioactivity from the drums, (see Figure A6 in Appendix A and *ANSTO report R180057: Woomera Characterisation: Gamma Survey of Area 1, D. Boardman and S. Hagan (2018)*) show that ^{214}Bi (only at 619 keV), ^{40}K and ^{208}Tl are present. The relative count rates and spectral shape of the two background spectra compared with the spectra acquired from locations 1-5 suggest that at imaging locations 1-5:

1) ^{214}Bi is well above background count rates
2) ^{214}Pb is present
3) ^{40}K is not observed

In addition, the gamma spectroscopy results from *Boardman et al.* show that the ^{208}Tl peak at 2614 keV has similar count rates when measured near the drums and during background measurements, suggesting that the ^{208}Tl peak originates from local background radiation.

Therefore, the presence of ^{214}Bi and ^{214}Pb are attributed to drums whilst ^{208}Tl and ^{40}K are attributed to local background radiation originating from the soil.

The presence of ^{214}Bi and ^{214}Pb at locations 1-5 is indicative of some or all members of the ^{238}U decay series in higher activity concentrations than observed in local background measurements. In the ^{238}U decay series, ^{214}Pb decays to ^{214}Bi, and secular equilibrium would be achieved between these radionuclides and higher-order members of the decay series in a matter of hours or days due to their short half-lives. However, direct emissions from other higher-order gamma emitting ^{238}U decay series radionuclides such as ^{234}Th, ^{234m}Pa, ^{230}Th and ^{226}Ra were not observed, nor was ^{210}Pb, a lower-order member of the series. ^{235}U or any gamma emitting members of the ^{235}U decay series were also not observed. This may be due to the low relative abundance, or low emission energies of the gamma rays and attenuation by the steel drums. The presence or absence of other ^{238}U or ^{235}U series radionuclides would need to be established using specialised lab-based gamma spectroscopy equipment.

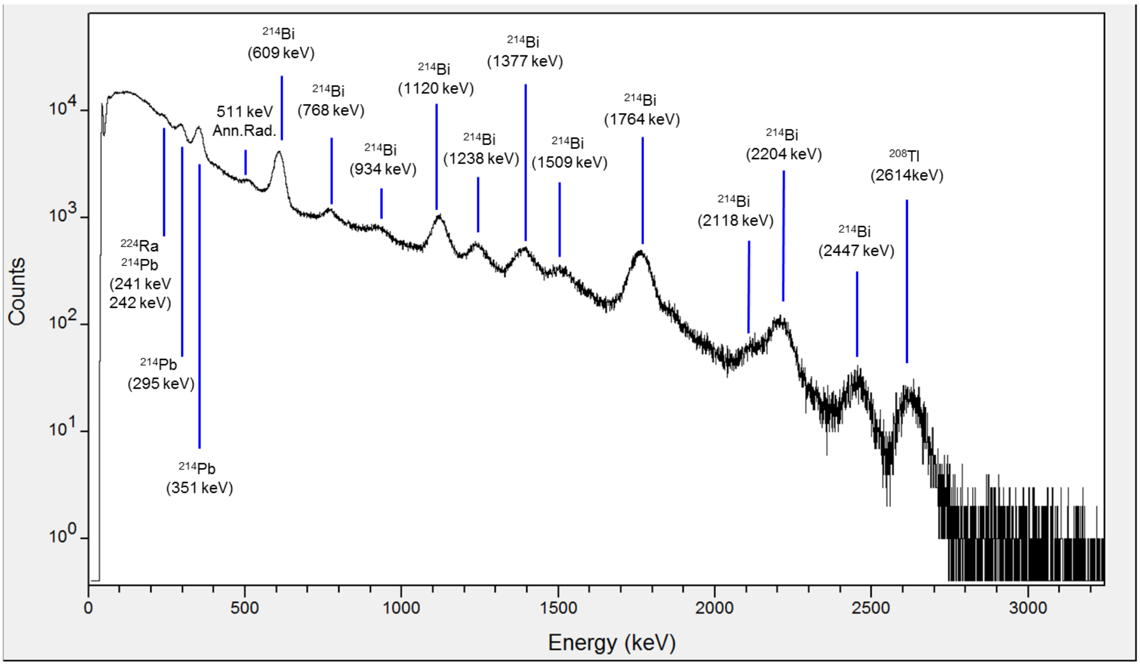

Figure 3: Gamma spectrum recorded at Location 3 (Bay 5, NE side). The spectrum is dominated by peaks originating from the ^{238}U decay series daughters, ^{214}Bi and ^{214}Pb.

Gamma Images

Two radionuclides were identified above background in the gamma spectra for all locations; ^{214}Bi and ^{214}Pb, which are ^{238}U series daughter products. As such, gamma images were produced for both radionuclides at each location using the a) ^{214}Bi 609 keV peak with relative abundance/intensity of 47% and b) the ^{214}Pb 295 keV + ^{214}Pb 351 keV peaks with relative abundances/intensities of 19% and 36% respectively. For all locations, the distribution of ^{214}Bi and ^{214}Pb is similar. This is expected as ^{214}Pb and ^{214}Bi would be in equilibrium with each other and higher-order members of the decay series.

In general, each image shows only a few drums that have elevated levels of radioactivity. The count rates for all images were extremely low (~0.3-20 counts per second at the detector), which required long acquisition times of ~2-4 hours per image. Furthermore, relatively high image noise is attributed to contribution from background radiation and the presence of some radionuclides originating from both the drum contents and the local background. Due to the long image acquisition times required throughout different parts of each day, temperature drift of the detector energy calibration further contributed to increased image noise.

Most drums were observed to have historical labels on the side of the drums, although this labelling is not always visible due to the direction the drums are facing or degradation. Two labelling systems were observed; a set of original identifying numbers marked directly on the drums and a set of updated identifying numbers marked by white stickers. Any other visible markings on the drums were also noted to assist in the identification of listed drums.

Figure 4 shows a gamma image using the ^{214}Pb 295 keV and ^{214}Pb 351 keV peaks, taken at Location 1 (Bay 1), which is an area with a particularly low count rate. Areas with mildly elevated radioactivity were located in the top right and middle areas of Bay 1. The hot spot seen in the bottom right of Bay 1 and near the gazebo is likely image noise; this result can be considered as inconclusive. The extremely low count rates under the ^{214}Bi 609 keV peak meant that a ^{214}Bi 609 keV gamma image was unable to be produced without unacceptably high levels of image noise.

Location 1 (Bay 1)

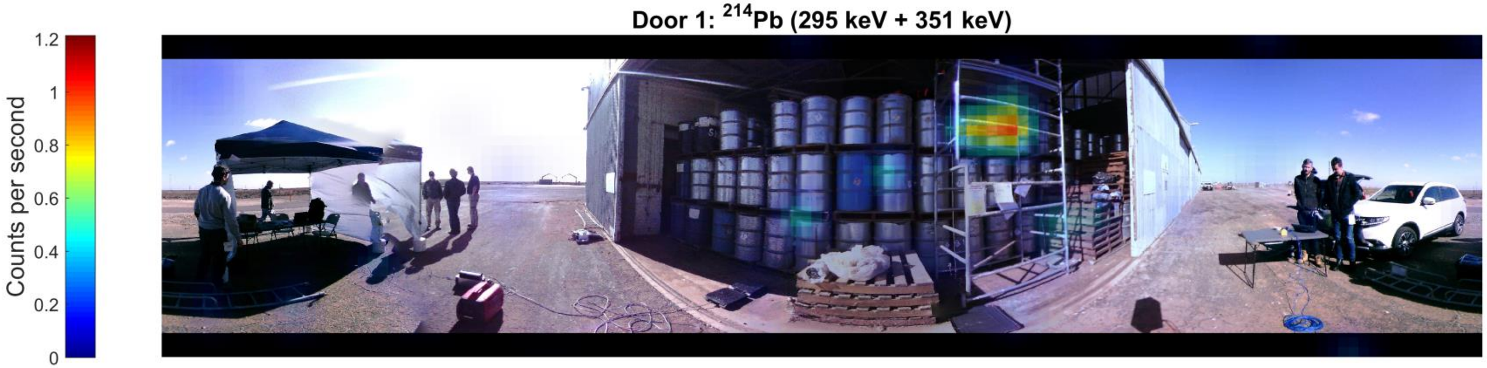

Figure 4: Gamma image from ^{214}Pb (295 keV + 351 keV peaks) at Location 1. The total dose rate at this location was 0.3 µSV/h, which is approximately equivalent to 1.5 × the average background dose rate in Australia, or 10% of the dose rate on an international flight.

Figure 5 shows gamma images from Location 2 (Bay 5) which are in the area identified as having the highest dose rate in *ANSTO report R180057: Woomera Characterisation: Gamma Survey of Area 1, D. Boardman and S. Hagan (2018).* A strong hotspot was identified on the bottom left of Bay 5. The two drums with the elevated dose rate are the drums immediately to the right of the two red drums in the bottom row (the red drums are partially obscured by the left sliding door in Figure 5). The visible identifying marks on these drums are shown in Table 2.

Table 2

Drum	Updated Number	Original Number	Other markings
Left	None	3145	None
Right	05514	3147	FBK204

Location 2 (Bay 5, SW side)

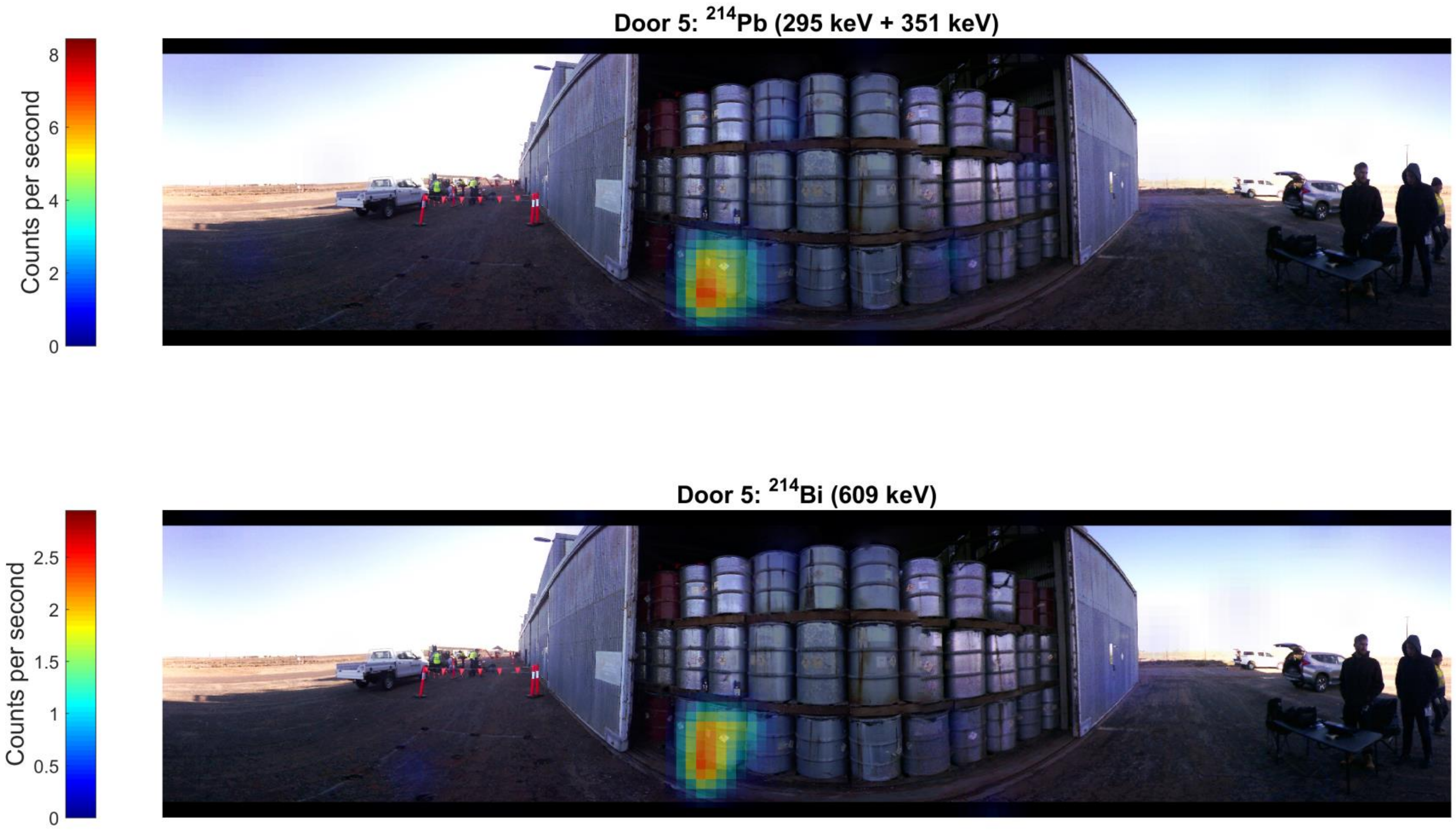

Figure 5: Gamma images from (top) ^{214}Pb (295 keV + 351 keV peaks) and (bottom) ^{214}Bi (609 keV peak) at Location 2. The total dose rate at this location was 0.3 µSV/h, which is approximately equivalent to 1.5 × the average background dose rate in Australia, or 10% of the dose rate on an international flight.

Figure 6 shows a close up, higher resolution gamma image of the two drums identified as hot spots in Figure 5 (Location 2, Bay 5). The bottom two thirds of both drums are identified as the primary regions with radioactivity.

Location 3 (Bay 5, NE side)

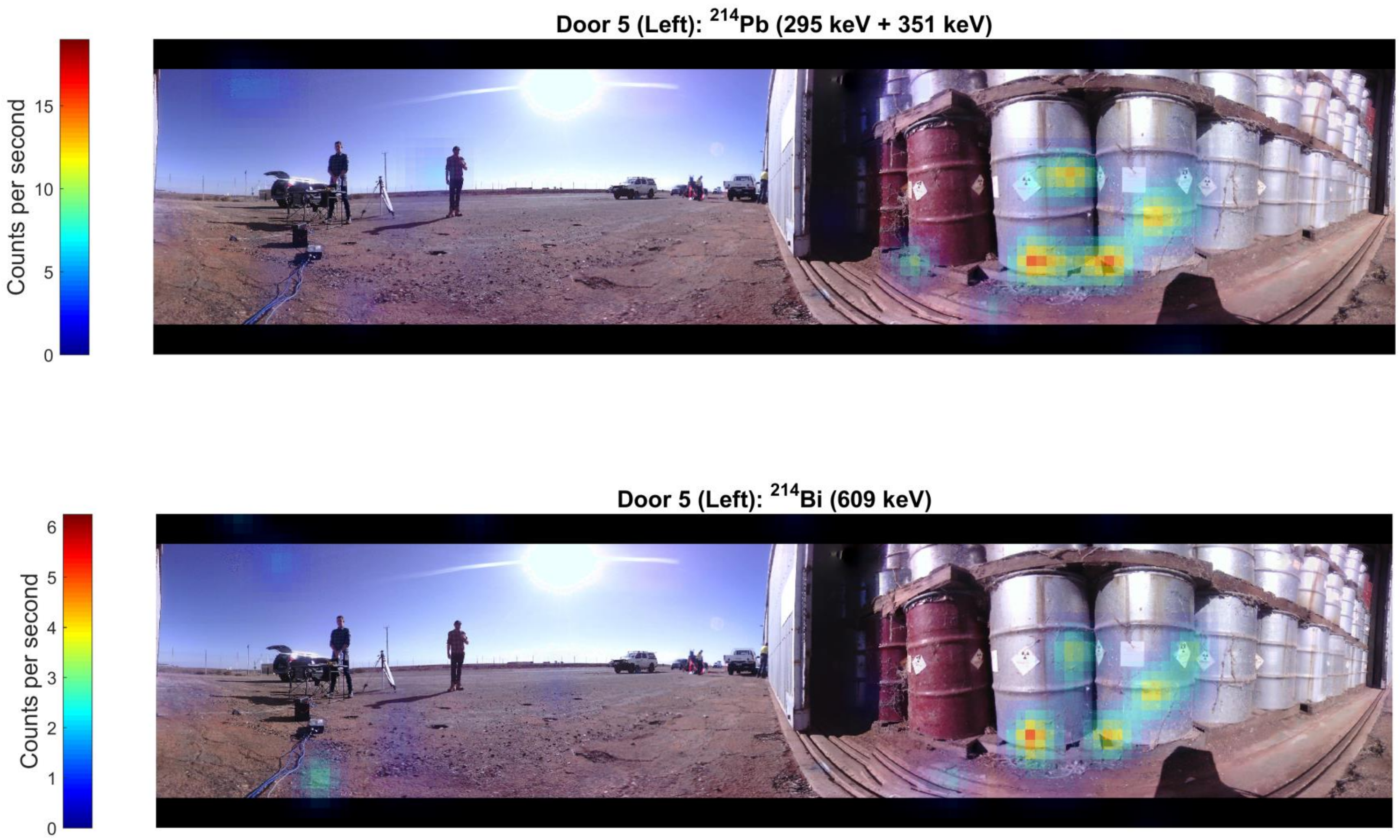

Figure 6: Gamma images from (top) ^{214}Pb (295 keV + 351 keV peaks) and (bottom) ^{214}Bi (609 keV peak) at Location 3. The total dose rate at this location was 3 µSV/h, which is approximately equivalent to the dose rate on an international flight. NB The dose rate at this location is higher as the camera is very close to the drums, ~85 cm, to allow for higher resolution imaging.

Figure 7 shows gamma images from Location 4 (Bay 4). One drum is identified to have a significantly higher count rate compared to the surrounding drums. This drum is located to the immediate right of the two green drums in the bottom right of Bay 4. The updated number identifying this drum is 05925, with no other visible identifying markers.

Location 4 (Bay 4, SW side)

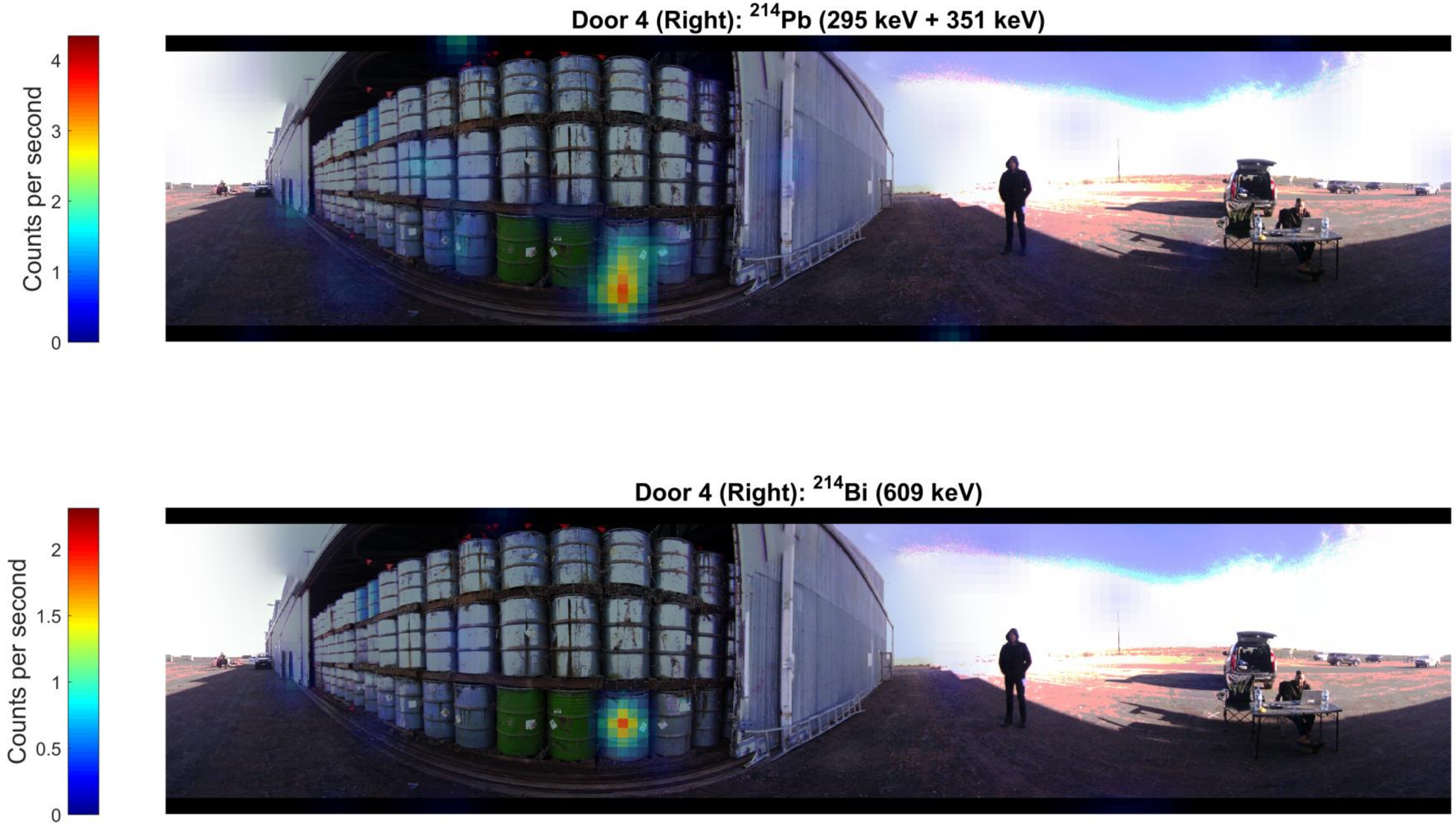

Figure 7: Gamma images from (top) ^{214}Pb (295 keV + 351 keV peaks) and (bottom) ^{214}Bi (609 keV peak) at Location 4. The total dose rate at this location was 0.6 µSV/h, which is approximately equivalent to 3 × the average background dose rate in Australia, or 20% of the dose rate on an international flight.

Figure 8 identifies a region of higher activity drums at Location 5, in the top left of Bay 4. The identifying marks on these drums are shown in Table 3.

Table 3

Drum (as labeled in Figure 8)	Updated Number	Original Number	Other markings
A	06072	None	FBK9
B	06060	None	None
C	06061	None	None
D	None	None	None
E	05606	None	None

Location 5 (Bay 4, NE side)

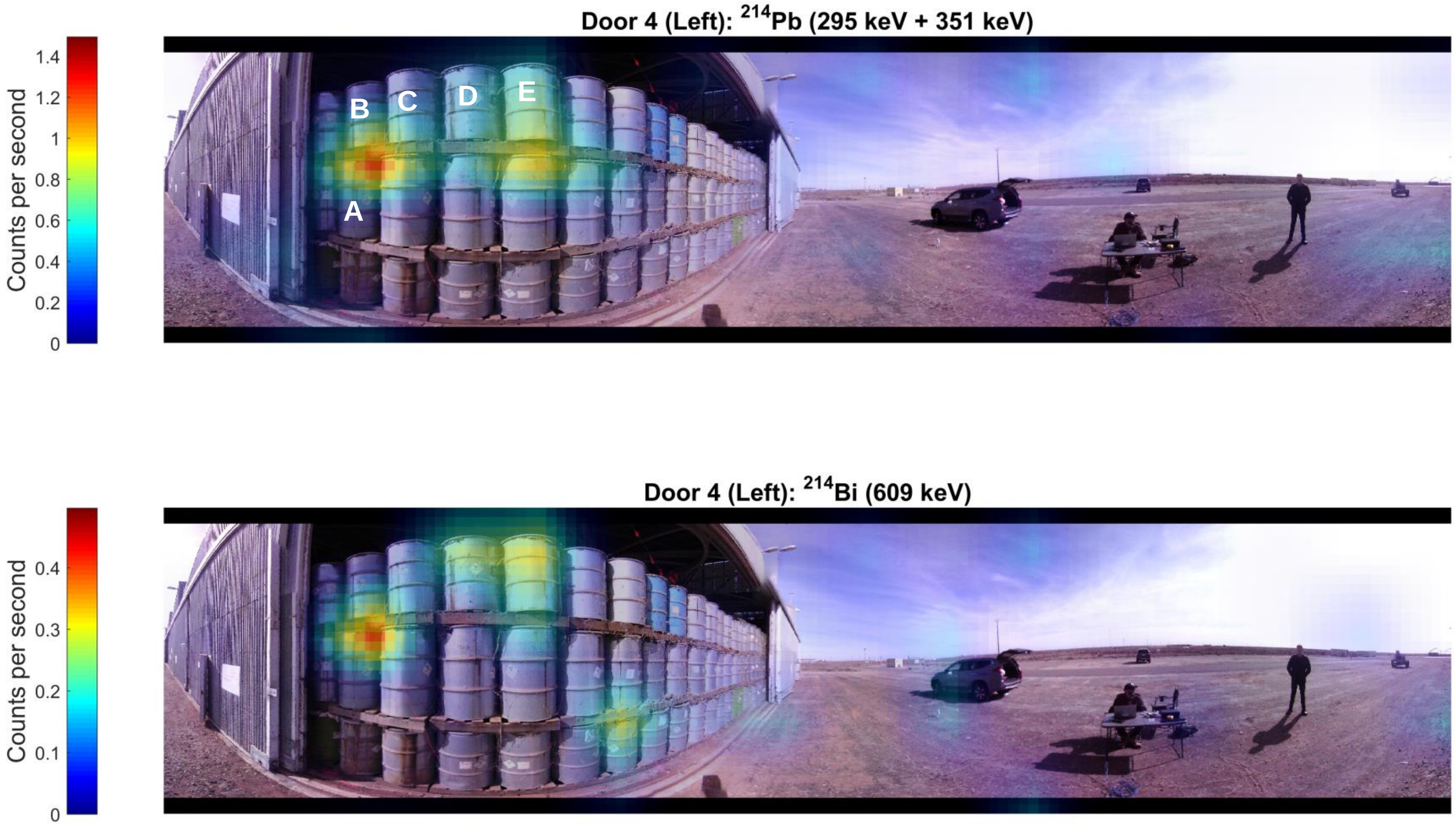

Figure 8: Gamma images from (top) ^{214}Pb (295 keV + 351 keV peaks) and (bottom) ^{214}Bi (609 keV peak) at Location 5. The total dose rate at this location was 0.5 µSV/h, which is approximately equivalent to 2.5 × the average background dose rate in Australia, or 17% of the dose rate on an international flight.

In Figures 4-8, the count rates in the ^{214}Pb gamma images are higher than the ^{214}Bi gamma images. This is due to the wider energy range used for the ^{214}Pb images and the relative counting efficiency of the detector at different energies.

Future Work

Future imaging campaigns would incorporate several improvements from the lessons learnt during this trip. Incorporating detector energy calibration temperature compensation electronics, increased shielding beneath the detector for enhanced background radiation attenuation, and slight adjustments to data acquisition parameters is likely to increase signal-to-noise and overall image quality, as well as reduce total image acquisition time. In addition, the implementation of LIDAR technology to capture 3D distance information of the drums may enable the imager to be used for rapid drum activity estimation.

Not all areas of the annex were accessible for imaging due to scheduled maintenance of the annex roller doors and difficulty opening several of the doors. Future campaigns would provide more comprehensive imaging at a greater range of locations. In future trips, there is also possibility of deploying two imaging systems for simultaneous image acquisitions. Further investigation into deploying a gamma imaging system to measure the top of the drums through the use of a robot or elevated platform will also be undertaken.

Conclusion

Gamma images were generated for the key radionuclides present in several locations along the western edge of the annex building at the Woomera site. The radionuclides detected were ^{238}U decay series daughters (^{214}Bi and ^{214}Pb). Only a very small proportion of drums were identified to have elevated levels of radioactivity. Due to access restrictions and shielding of the drums deep in the building, only the first layer drums could be imaged.

Two drums with elevated levels of radioactivity were located and identified to be in Bay 5. Subsequent higher resolution images of the drums of interest show that the radioactivity is primarily located within the bottom two thirds of these drums. In Bay 4, one drum with elevated activity was located in the bottom, right side as well as a small cluster of five drums in the top, left corner. Two hotspot areas were identified in the middle and top right regions of Bay 1.

Appendix A

Location 1 (Bay 1)

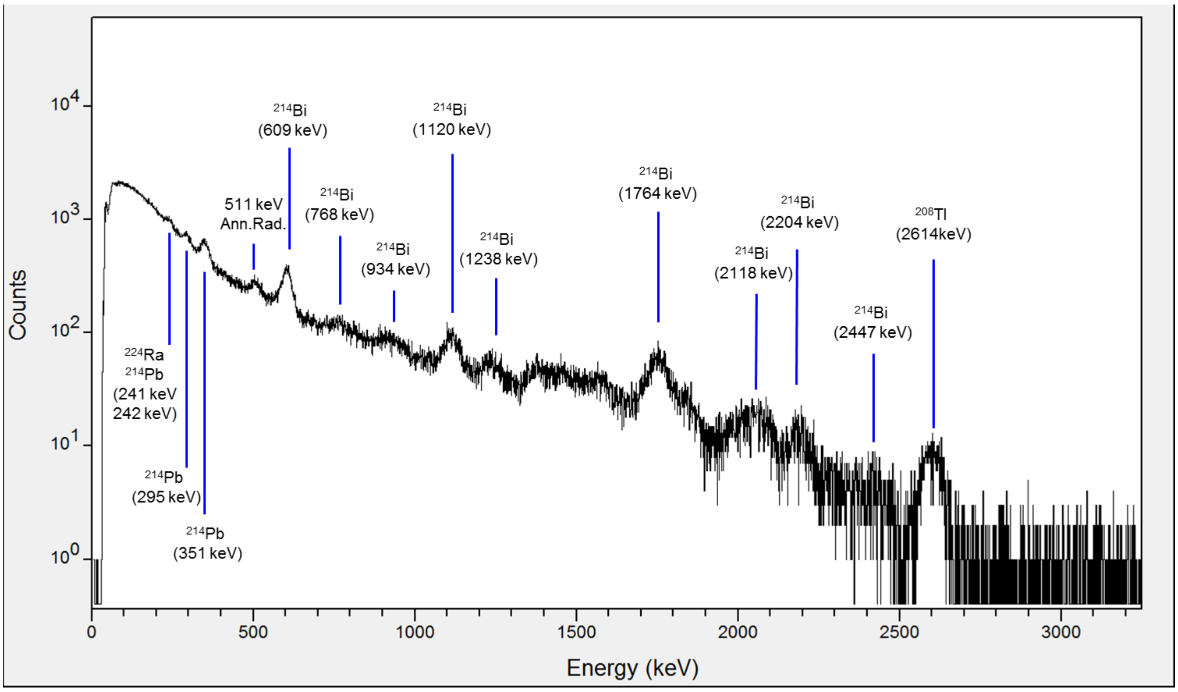

Figure A1: Gamma spectrum from Location 1 (256 minutes total acquisition)

Location 2 (Bay 5, SW side)

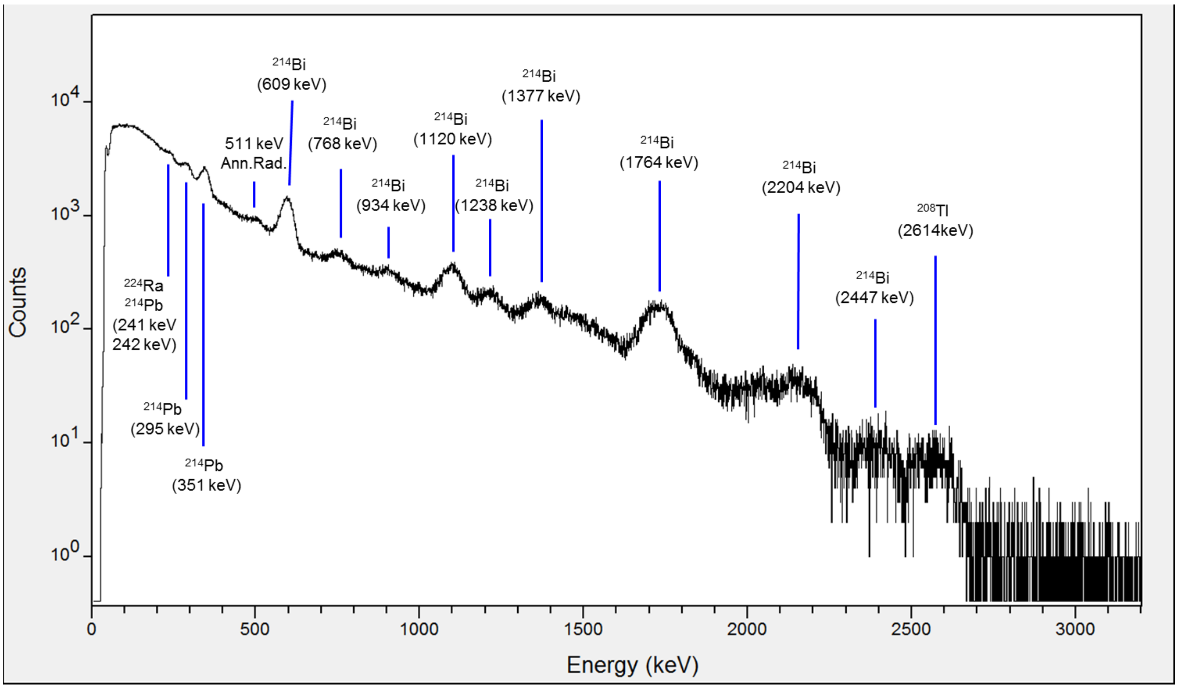

Figure A2: Gamma spectrum from Location 2 (256 minutes total acquisition)

Location 3 (Bay 5, NE side)

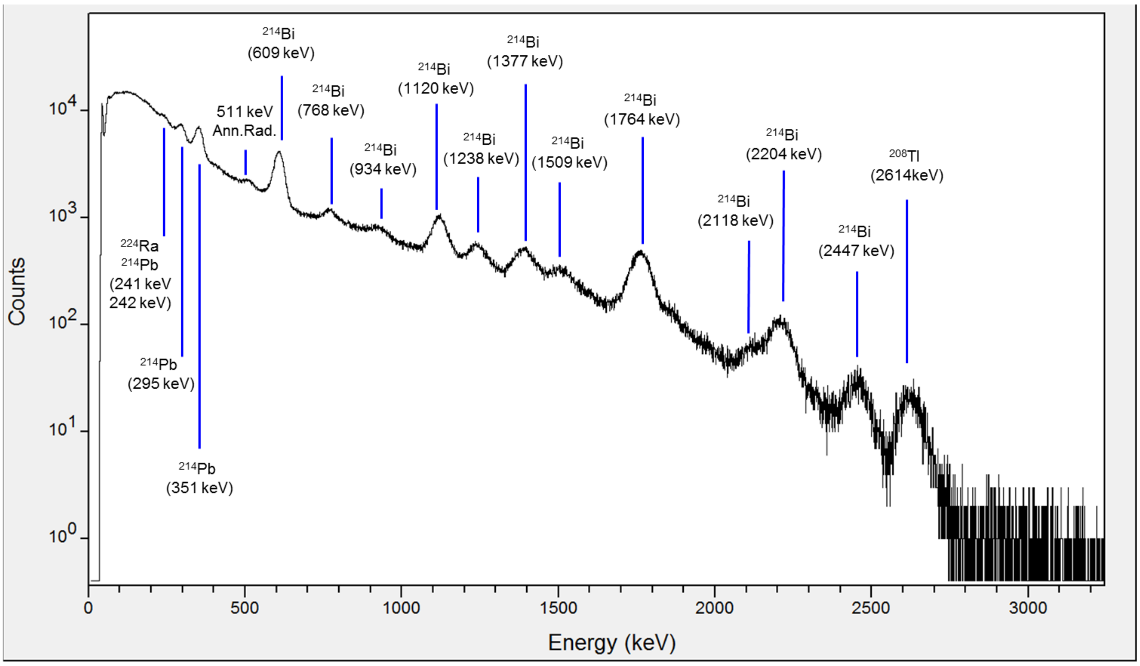

Figure A3: Gamma spectrum from Location 3 (183 minutes total acquisition)

Location 4 (Bay 4, SW side)

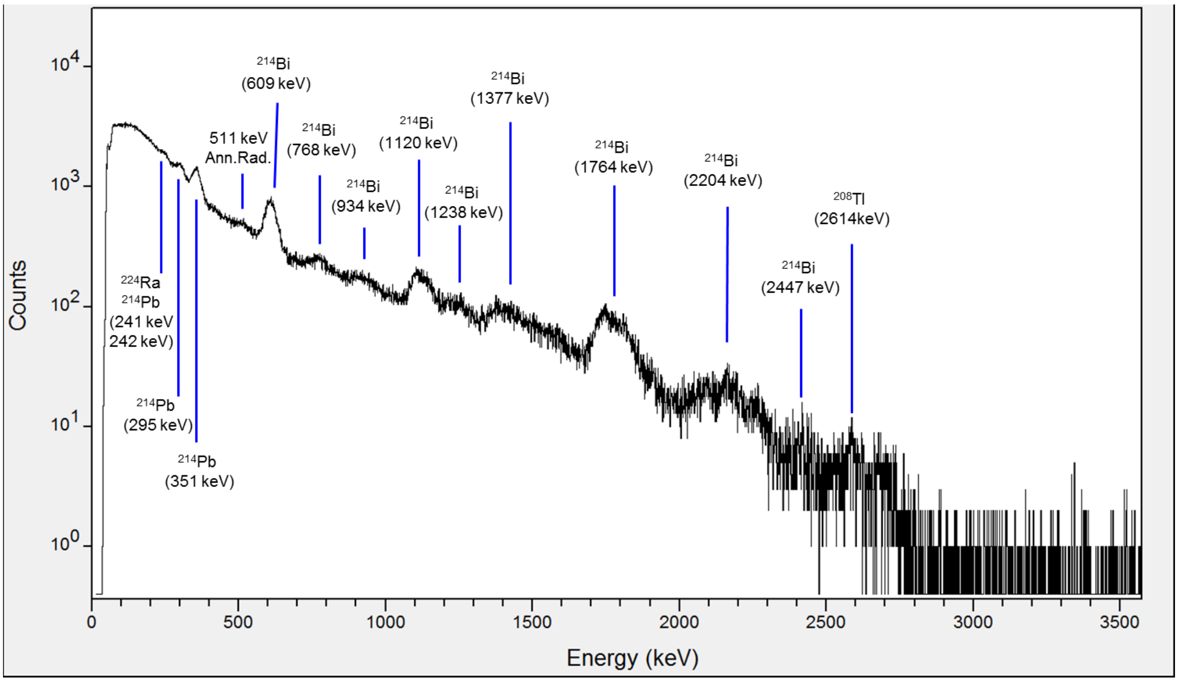

Figure A4: Gamma spectrum from Location 4 (150 minutes total acquisition)

Location 5 (Bay 4, NE Side)

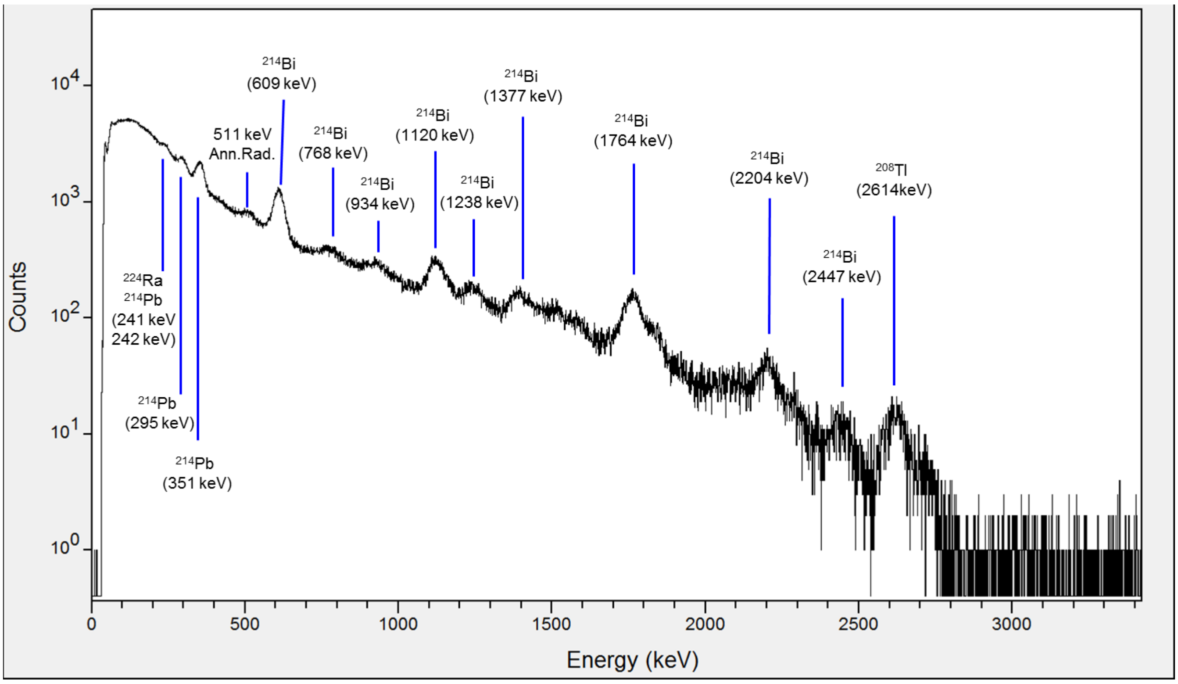

Figure A5: Gamma spectrum from Location 5 (205 minutes total acquisition)

Reference Background Gamma Spectra (NE side of hangar and Eldo Hotel)

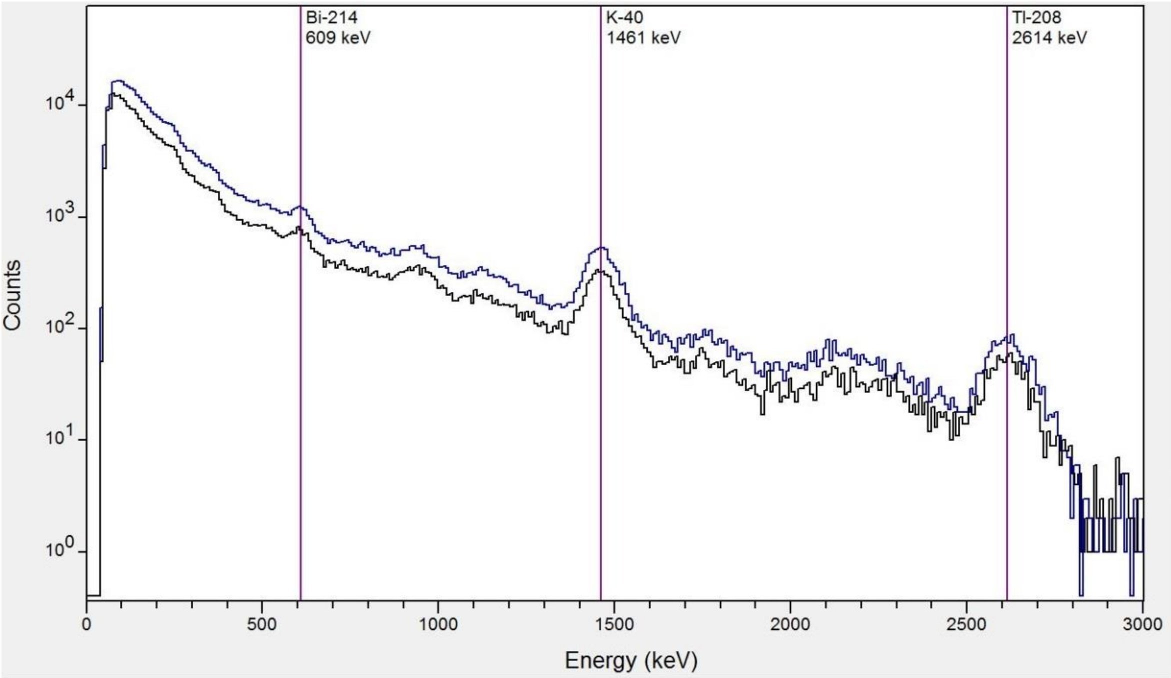

Figure A6. Background gamma ray spectrum acquired on the north east side of the hangar (black line) and the Eldo Hotel carpark (blue line). 1200 s total acquisition per spectra. Note the spectra in this figure were recorded with a different detector than the one used for Figures A1-A5. As such, direct comparison of count rates in not meaningful.