Next Generation Germanium Systems for Safeguards Applications

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Abstract. We are developing the latest generation of highly portable, mechanically cooled germanium systems for safeguard applications. In collaboration with our industrial partner, PHDs Co, we have developed the Germanium Gamma Ray Imager (GeGI), an imager with a 4π field of view. This instrument has been thoroughly field tested in a wide range of environments and has performed reliably even in the harshest conditions. The imaging capability of GeGI complements existing safeguards techniques by allowing for the spatial detection, identification, and characterization of nuclear material. Additionally, imaging can be used in design information verification activities to address potential material diversions. Measurements conducted at the Paducah Gaseous Diffusion Plant highlight the advantages this instrument offers in the identification and localization of LEU, HEU and Pu. GeGI has also been deployed to the Savannah River Site for the measurement of radioactive waste canisters, providing information valuable for waste characterization and inventory accountancy. Measuring 30×15×23 cm and weighing approximately 15 kg, this instrument is the first portable germanium-based imager. GeGI offers high reliability with the convenience of mechanical cooling, making this instrument ideal for the next generation of safeguards instrumentation.

1. Introduction

Gamma-ray spectroscopy is the most commonly used method for the non-destructive assay of nuclear materials. Spectroscopic instruments based on NaI, CdZnTe, and liquid nitrogen cooled HPGe are often adequate for this analysis; however, in complex radiation environments these instruments are inadequate and provide inconclusive results. For these cases passive imaging provides spatial information that can be used to supplement traditional safeguard techniques. One such instrument is the Germanium Gamma-Ray Imager (GeGI), a portable, mechanically-cooled detector offering high-resolution spectroscopy and imaging in a single package. The ability to provide spectroscopy and imaging information simultaneously is advantageous as it allows for spectral analysis (using MGA or FRAM) on localized sources. GeGI leverages years of effort in developing segmented germanium into gamma ray imaging systems [1-4]. The addition of such an imaging system will help strengthen existing safeguards techniques and provide additional assurance when verifying nuclear activities.

2. Instrument Specifications

The Germanium Gamma-Ray Imager (GeGI), shown in Figure 1, is a germanium based imaging system, commercially available from PHDS Co. The operational characteristics are summarized in Table 1. This instrument offers the benefits of high resolution and efficiency while the mechanical cooling eliminates the need for liquid cryogen. After the initial five hour cool down GeGI can be operated for extended periods using hot-swappable lithium polymer batteries, eliminating the need for AC power. These features make the system highly portable and easily deployed in a wide-range of environments.

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Figure 1 The Germanium Gamma-Ray Imager (GeGI) with attached PC for instrument control and data storage. The 180° panoramic camera provides an optical photograph to overlap on the Compton and Pinhole images.

Table 1 Operational characteristics of GeGI.

Mass	15 kg
Dimensions (L×W×H)	30×15×23cm
Cool down	5 hours
User Interface	Windows OS
Optical	180° Panoramic camera
Removable Storage	USB storage
Battery	
Internal	1 hour
External (Lithium polymer)	~2-3 hours
External Weight	1kg

GeGI is designed around a 16x16 strip detector with 5-mm pitch strips on an 8cm diameter, 1cm thick germanium crystal (performance summarized in Table 2). As a spectrometer the instrument has a useable energy range from 30keV to several MeV. Two imaging modalities are available, the choice of which depends on the energy of interest. For gamma-ray energies ranging from 40–500 keV, a collimator can be placed in front of the detector for pinhole imaging. This modality offers high contrast and spatial resolution; however, is limited to a 60° forward field of view. Compton imaging can be used for higher energy radiation from ~150 keV to < 1 MeV, and provides a 4π field of view with a spatial resolution of ~6°.

Table 2 Spectroscopic and imaging performance of GeGI.

Detector Type	Planar HPGe 1 cm thick x 8 cm diameter
Spectroscopic	
Resolution	2.1 keV at 662 keV
Energy Range	0.04 - 3 MeV
Imaging - Compton	
Spatial Resolution	~6°
Energy Range	0.15 - <3 MeV
Imaging - Pinhole	
Energy Range	40-500 keV

3. Measurements

The following discusses three safeguard scenarios where the combined spectroscopic and imaging functionality of GeGI provides enhanced capabilities: facility monitoring, radiation environment mapping, and the assay of waste storage.

3.1. Holdup and Facility Monitoring

An early prototype of GeGI was taken to the Paducah Uranium Gaseous Diffusion Plant in Paducah, Kentucky (U.S.). Until its recent shutdown, Paducah had been enriching uranium for use in commercial nuclear power plants. This very large facility has over 400 miles of processing pipes carrying uranium hexafluoride gas (UF_6). One concern is that uranium deposits, or other contamination, can build up over time (holdup) with a significant amount of material accumulating in one or more regions of the facility. As a result the operators have to continually scan the 400 miles of piping with hand-held radiation detectors. This is a costly and time-consuming process. LLNL, ORNL and LBNL collaborated with the Paducah plant to test imaging instruments to try and help with this and other issues at the facility. The idea is that an imager can measure a large area at a time and provide more information than a hand-held detector, such as precise location and distribution of holdup.

In one test the instruments were set up in a large open room of the facility. The prototype GeGI was used to make a 4π Compton image of the area. Figure 2 shows the resulting energy spectrum. The 186 keV and 1001 keV lines from the UF_6 were seen as expected. However, unexpected gamma-ray lines were seen as well. These are easily identified as the characteristic lines from ^{237}Np. An image was then made to show the location of the neptunium source (Figure 3). This image revealed important information. First it precisely located the source of the buildup as coming from a pipe in the ceiling. This would have been difficult to locate with a hand-held instrument because the piping was hidden behind heat baffling in the ceiling. Second it confirmed that the holdup material was localized to a spot, rather than being distributed across the length of a pipe. This information can then be used to assist the cleanup process. It can also aid in quantifying the amount of material.

Imaging was used in other places in the facility as well, such as imaging contaminated equipment prior to disposal and finding previously unknown contamination at the transfer station.

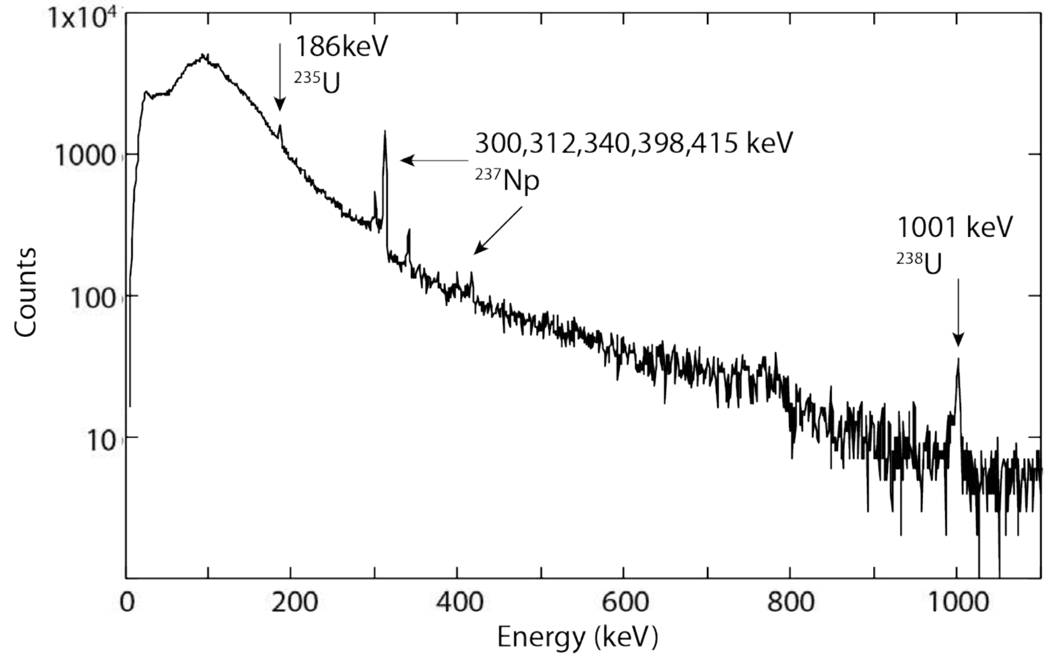

Figure 2 Spectrum taken at the Paducah Uranium Gaseous Diffusion Plant indicating the presence of ^{237}Np contamination of uranium gaseous-diffusion lines.

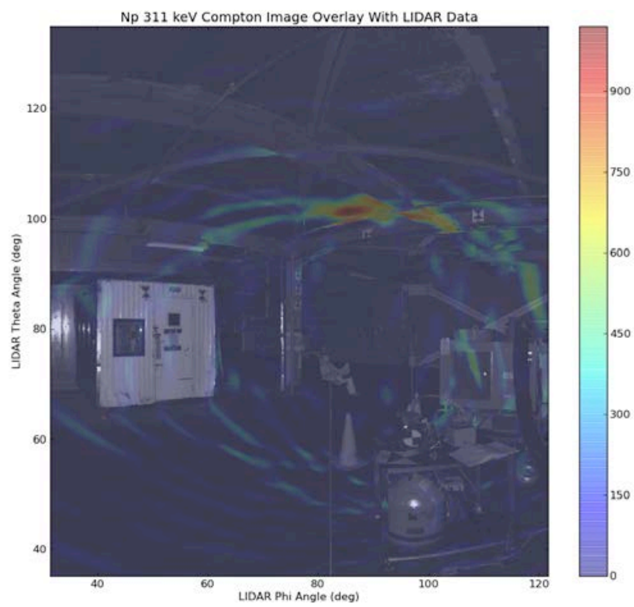

Figure 3 Compton image localizing the pipe with ^{237}Np contamination. This information can be used to quantify the amount of material and for cleanup efforts.

3.2. Radiation Environment Mapping

This instrument can also be used to provide spatial mapping of the radiation environment during on-site inspections to confirm the absence of undeclared nuclear material and activities at declared nuclear sites or to assure the non-nuclear nature of a facility. In such scenarios the ability to localize sources is advantageous as it can determine areas within a site or facility requiring more extensive analysis. Imaging can indicate areas of uncharacteristically high levels of radiation or radioactive isotopes that should not be present given the sites declared activities. In the case of a facility with a declared non-nuclear purpose, GeGI can be used for background radiation measurements and locate anomalous sources. In the example shown in Figure 4 GeGI was deployed in an abandoned building and located a ^{137}Cs source in an adjacent room. Such a measurement can be used to provide assurances as to a facility's non-nuclear function. GeGI can also be used to conduct on-site inspections at declared nuclear sites to confirm past and present activities. For these measurements GeGI can locate sources of ^{235}U from the 186keV gamma ray. Despite the low imaging efficiency at this energy and the presence of background radiation, this has been demonstrated distances of ~28 m (Figure 5). The ability to locate uranium and plutonium can be used to determine areas that should be subjected to more stringent sample collection, thereby creating a more efficient and robust environmental sampling process.

Figure 4 A Compton image of a ^{137}Cs source located in an adjacent room. The imaging capability of GeGI can be used to verify the non-nuclear nature of a facility.

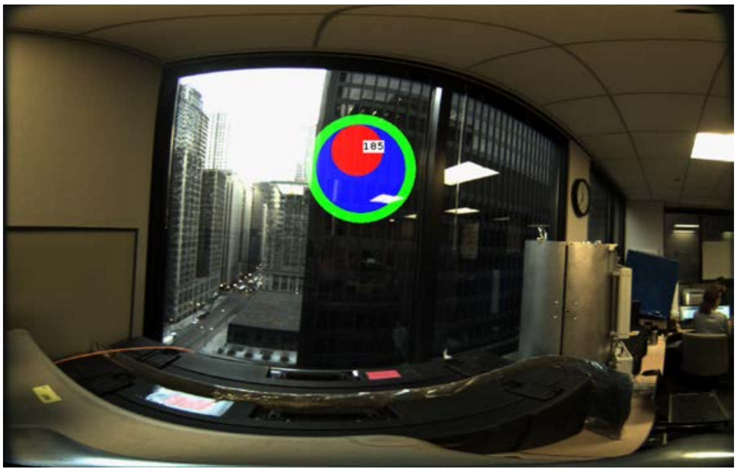

Figure 5 Compton image of highly enrichment uranium (~100 grams of material) located in a building approximately 28 m away. The 186 keV gamma ray from ^{235}U was detected spectrally in 15 minutes and localized within 40 minutes.

3.3.Assay of Waste Storage

The Savannah River Site (SRS) in South Carolina has facilities for assay and storage of nuclear waste. GeGI was demonstrated at an outdoor facility and used to measure the contents of several waste canisters. Although temperatures within the facility exceeded 38°C at 85% relative humidity, the mechanical cooling of GeGI was able to maintain the detector well below the required operating temperature. For these measurements GeGI was positioned in front of a large bin (Figure 6) to measure the radioactivity of the contained waste. The spectrum taken for 650 sec is shown in Figure 7 (left), with the 311, 511, and 662 keV gamma-ray lines clearly visible. From these peaks the instrument was able to localize the sources, Figure 7 (right). As the 59.5 keV peak visible in the spectrum is too low in energy for

Compton imaging a collimator was used to generate a pinhole image. The result (Figure 8) indicated that the source of 59.5 keV gamma rays was a waste drum located behind the bin. With this information GeGI was repositioned to measure these waste drums (Figure 9) and a pinhole image shows three separate bins contributing to the peak at 59.5 keV. A Compton image of the containers behind the bin (Figure 10) revealed that the source of the 311 and 662 keV radiation (Figure 7) were in fact not from the bin but rather several waste drums. Complex radiation environments, such as those at SRS, pose a serious challenge to spectroscopic instruments as the radiation signature from an object being measured can be obfuscated by adjacent sources of radiation. The imaging modalities of GeGI were essential to localize and determine the source of the radiation being measured.

Figure 6 GeGI with PC interface (lower left) was positioned to measure a waste bin at the SRS storage facility.

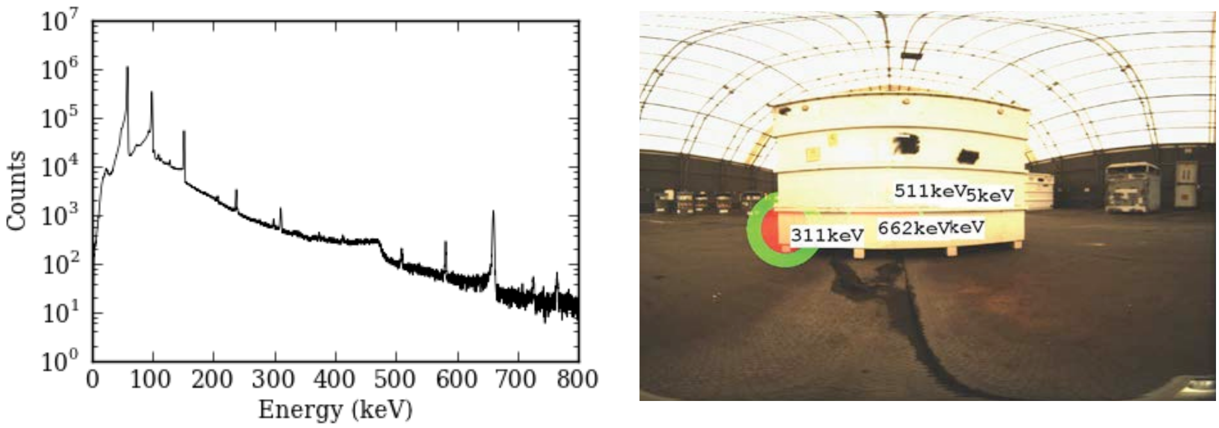

Figure 7 The spectrum taken for 650 sec (left) and Compton image (right) generated from a waste bin shown in Figure 6. The peaks at 311, 511, and 662 keV were used to generate the Compton image and displayed over the optical photograph taken with the 180° panoramic camera. The large peak at 59.5 keV in the spectrum is not suitable for Compton imaging; however, can be imaged using the pinhole imaging mode. Additional measurements revealed the 311 and 662 keV in the lower left corner of the waste bin to be from drums obstructed from view (See Figure 10).

Figure 8 Pinhole image taken of the waste bin shown in Figure 7 at 59.5 keV. This gamma-ray line is visible in the spectrum (Figure 7, left) but was found to be from a waste drum located behind the bin, not the bin itself.

Figure 9 Pinhole image at 59.9 keV, clearly showing the 59.5 keV peak in Figure 7 results from the contribution of three individual waste drums.

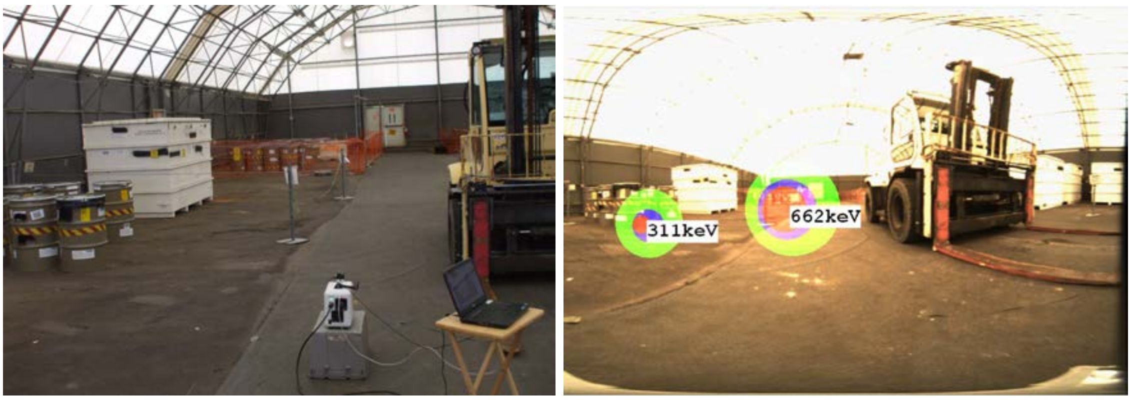

Figure 10 Compton image of the waste drums contributing to the 311 and 662 keV gamma-ray lines in the spectrum shown in Figure 7. Passive imaging allows for the accurate characterization of waste containers, reducing possible interference from adjacent source of radioactivity.

4. Conclusion

Gamma ray imaging systems such as GeGI augment existing spectroscopic safeguard techniques by providing valuable spatial information for the assay of nuclear material. This has been demonstrated in the monitoring of enrichment facilities, for radiation environment mapping of nuclear sites, as well as for the assay of waste storage. Imaging can provide additional assurances in the verification process and contributes to the overall effectiveness of safeguards. As the nuclear activities throughout the world continue to evolve and grow, this tool offers a unique capability to meet emerging challenges to safeguards.

5. Acknowledgements

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6. References

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