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US-ROK Action Sheet 34: Safeguards Application of a Hand-held Mechanically Cooled Germanium Spectrometer

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Action Sheet 34:

Safeguards Application of a Hand-held Mechanically Cooled Germanium Spectrometer

Final Report

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Contents

Summary of Results

This report summarizes results of Action Sheet 34 - for the cooperative efforts on the field-testing and evaluation of a high resolution, hand-held, gamma-ray spectrometer, known as SPG (Spectroscopic Planar Germanium), for safeguards application such as short notice inspections, UF6 analysis, enrichment determination, and other potential applications. The Spectroscopic Planar Germanium (SPG) has been demonstrated IAEA Physical Inventory Verification (PIV) in South Korea. This field test was a success and the feedback provided by KINAC, IAEA, and national laboratory staff was used to direct efforts to improve the instrument this year. Key points in this report include:

- Measurement results from PIV
- Analysis of spectra with commercially available Ortec U235 and PC-FRAM
- Completion of tripod and tungsten collimator and integration of user feedback

1 Introduction

The current IAEA high-resolution gamma-ray spectrometer is a germanium-based system that must be cryogenically cooled, typically with liquid nitrogen, for operation. The need for cryogenic liquids makes it impractical for many field applications with limited resources. Also, the cooling requires several hours to complete and is impractical for short notice or no notice inspection. The Spectroscopic Planar Germanium (SPG) is a versatile tool that can significantly enhance current practice of routine and short or no-notice random inspections. This instrument can be deployed in all cases where the traditional high purity germanium (HPGe) detector is currently being used.

SPG is a portable, mechanically-cooled, high purity germanium spectrometer designed for safeguards applications, shown in **Figure 1**. The system weighs less than 6.5lbs (3kg) and can be cooled to operating temperatures in less than 30 minutes. Once cooled, it can operate for 8 hours on battery power. Designed for use in the 30keV to 450keV region and with an energy resolution of 850eV, it well suited for use with MGA and FRAM. These spectral analysis programs can be installed directly on the Windows XP based ultra-mobile PC used for instrumentation control.

Table 1 SPG operating specifications

Dimensions	9×7×9inches (23×18×23cm)
Weight	6.5 lbs. (3 kg)
Battery Runtime	8 Hours
Cool down time	30mins
Resolution	~850 eV at 122 keV

Table 2 Additional component specifications

Tripod with mounting plate		
	Weight	3.6 lbs. (1.6 kg)
	Height	4 - 63 inches (10 -160 cm)
Tungsten/Copper Collimator		

Weight	7.4 lbs. (3.4 kg)

Figure 1 Picture of Spectroscopic Planar Germanium (SPG) with Windows based ultra mobile PC controller.

2 IAEA Physical Inventory Verification at the KHNP Nuclear Fuel Fabrication Facility

SPG was used during the IAEA Physical Inventory Verification (PIV) at the KHNP Nuclear Fuel (KNF) Fabrication facility. This field test campaign provided an opportunity to measure the wide range of materials produced at various steps throughout the nuclear fuel fabrication process. Measurements of natural uranium powders, scrap metals, and fuel pellets of various enrichments were measured. The spectra were then analyzed using MGA to determine the isotopic composition and compared with those declared by the facility. Results from these measurements are summarized in Table 3. The measurements were taken over several days at three locations within the KNF site: UF_6 storage facility, fuel pellet storage, and the fuel fabrication plant.

Table 3 Summary of enrichment measurements conducted at KHNP. Enrichment calculations made using Ortec U235.

Sample Description	Declared Enrichment (%)	Calculated Enrichment (%)	
		U235	FRAM
Canister- Scrap Metal	4	3.938±0.144	3.956±0.318
Canister- Scrap Metal	3.8	3.979±0.294	3.161±0.872
Barrel- UO_2 Powder	3.42	3.443±0.053	2.416±0.493
Pellet- CANDU Fuel	0.52	0.434±0.229	0.919±0.364
Barrel – U powder	0.7	0.569±0.161	8.303±15.813
Hopper - UO_2 Powder	4.65	6.643±0.033	6.749±0.576

2.1 UF_6 Storage Facility

The UF_6 cylinders are stored in an open-air facility onsite. Current IAEA evaluation techniques use liquid nitrogen cooled planar germanium detectors for spectroscopic analysis (see Figure 2) and custom calibrations for determining UF_6 enrichment. SPG was precooled prior to arrival and was immediately able to start measurements on the UF_6 canisters (see Figure 3). The thickness (~2cm) of the UF6 cylinders greatly reduces the intensity of the low-energy gamma rays from ^{235}U with the strongest measureable gamma-ray signature at 186keV. To determine UF_6 enrichment the spectra are analyzed with custom calibrations. These routines were not available process the SPG spectra; however, a comparison of the spectra shown in Figure 5 are in good agreement with those taken by KINAC staff using a planar LN germanium detector. The larger detector volume of the HPGe provides higher detection efficiency and consequently is able to resolve several additional weak lines. SPG was placed on a handcart, shown in Figure 2, and measurements were made with and without a lead-copper collimator, a comparison of the spectra is shown in Figure 4. The background suppression from the collimator was not sufficient to improve the quality of spectra.

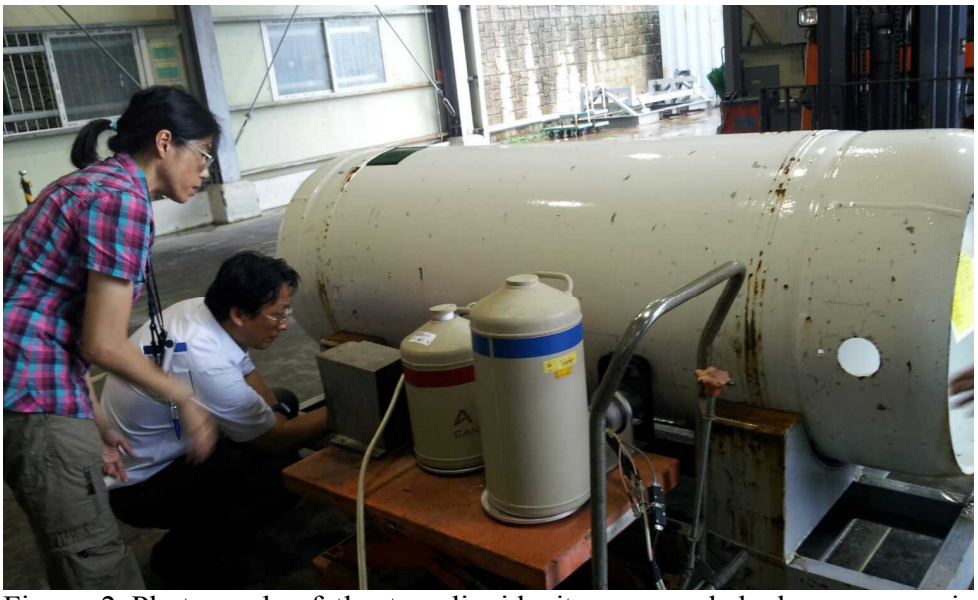

Figure 2 Photograph of the two liquid nitrogen cooled planar germanium detectors used by KINAC and IAEA for the measurement of UF_6 cylinders.

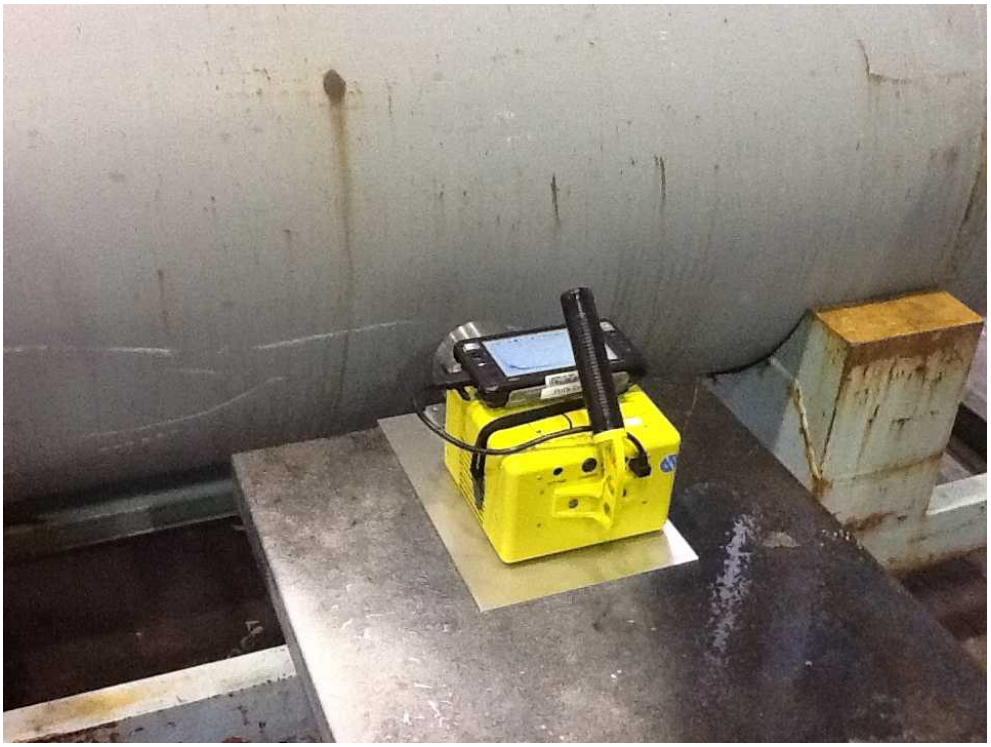

Figure 3 Photograph of SPG with collimator measuring a UF_6 canister.

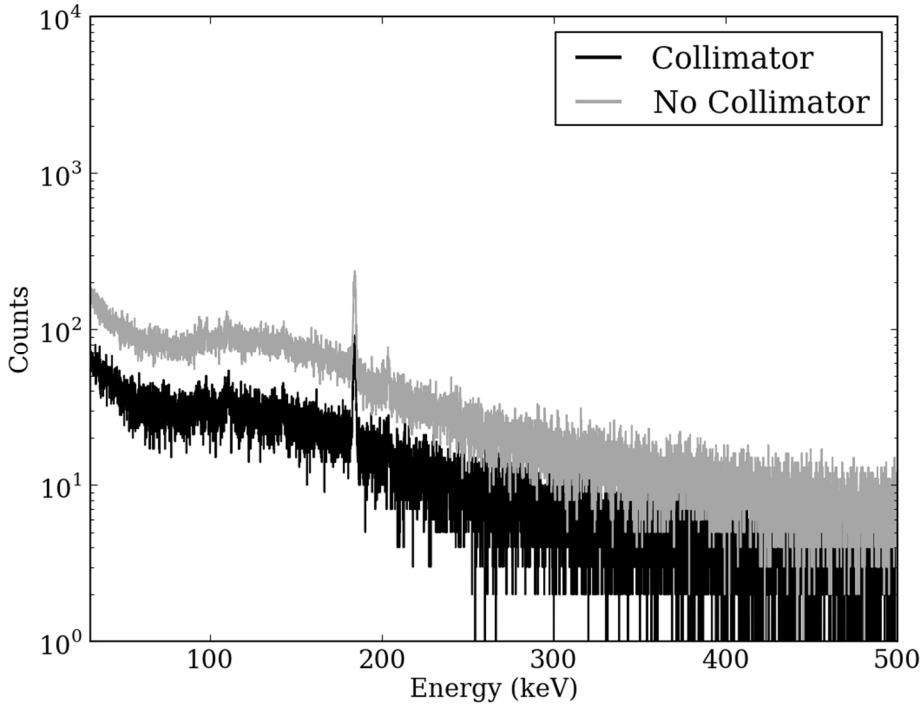

Figure 4 Comparison of two 600sec measurements with and without collimator of a UF_6 canister containing 4.1% enriched uranium.

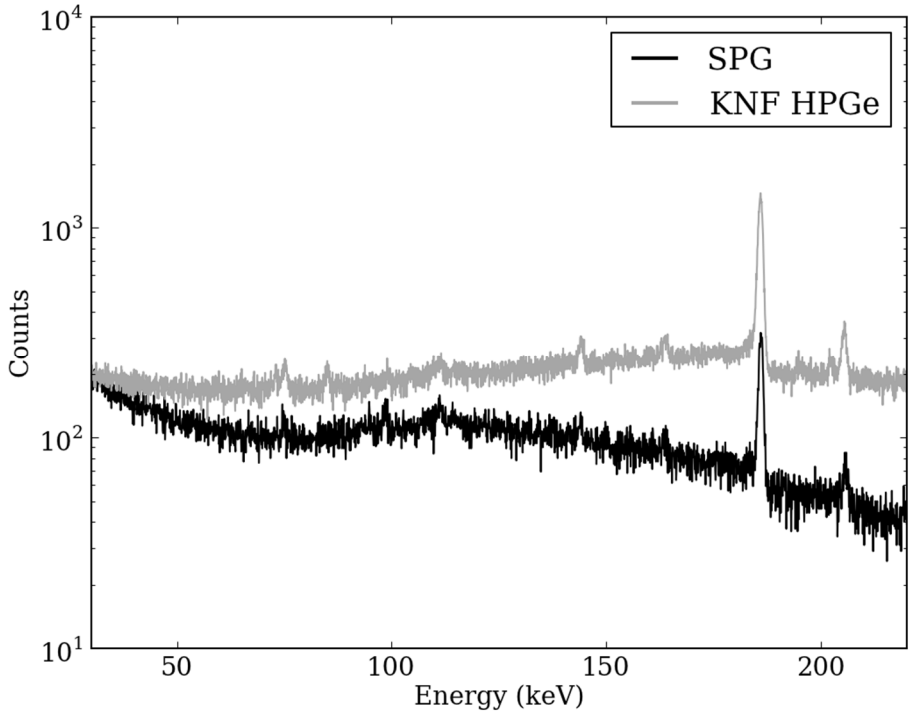

Figure 5 Spectra taken using SPG compared with the KNF liquid cryogen system. Measurement times for the SPG and the HPGe were 400sec and 300sec, respectively.

2.2 Fuel Pellet Storage

Measurements of nuclear fuel pellets were conducted in an air-conditioned storage facility. While SPG was immediately ready to begin measurements (the 30 minute precooling cycle was performed prior to arrival), the lanthanum bromide ($LaBr_3$) detector used by the IAEA required almost an hour to setup (see Figure 7). Enrichment analyses of the fuel pellets were made by measuring six pellets of nominally similar enrichment in a polyethylene holder placed above the LaBr3 detector for 300sec. While SPG provides a higher energy resolution than $LaBr_3$, the small size of the SPG detector required longer measurement times to acquire adequate statistics for spectral analysis programs. The spectra taken using SPG indicated enrichments approximately twice the values measured by the IAEA and KINAC. This discrepancy is most likely the result of poor measurement geometry or possible floor contamination. Future improvements will allow for the use of a polyethylene holder for fuel pellet analysis. Canisters of scrap material available in the storage facility were also measured. These contained larger quantities of material and required less measurement time than the fuel pellets. The spectrum of a canister containing 3.8% enriched scrap powder is shown in Figure 8. Results of the spectra analysis using MGA are shown in Table 4 and are in agreement with the declared material enrichment.

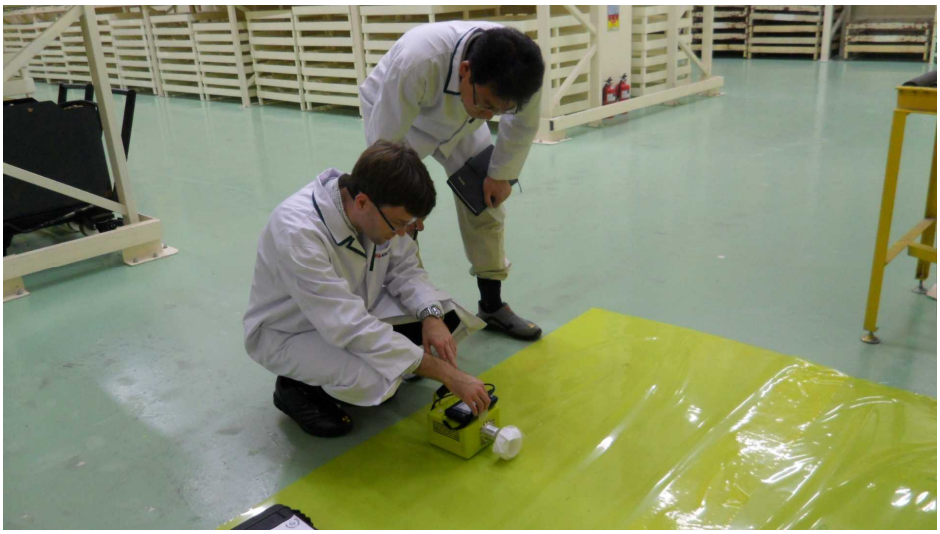

Figure 6 Photograph of the LLNL and KINAC participants measuring fuel pellets.

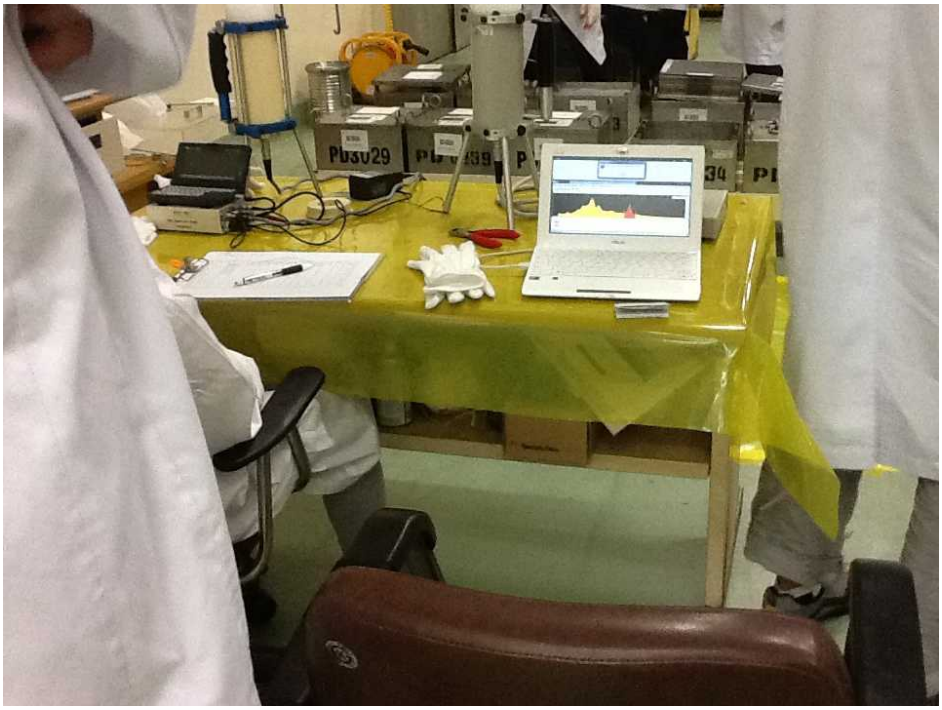

Figure 7 Photograph of the KINAC and IAEA lanthanum bromide detectors for measuring fuel pellets

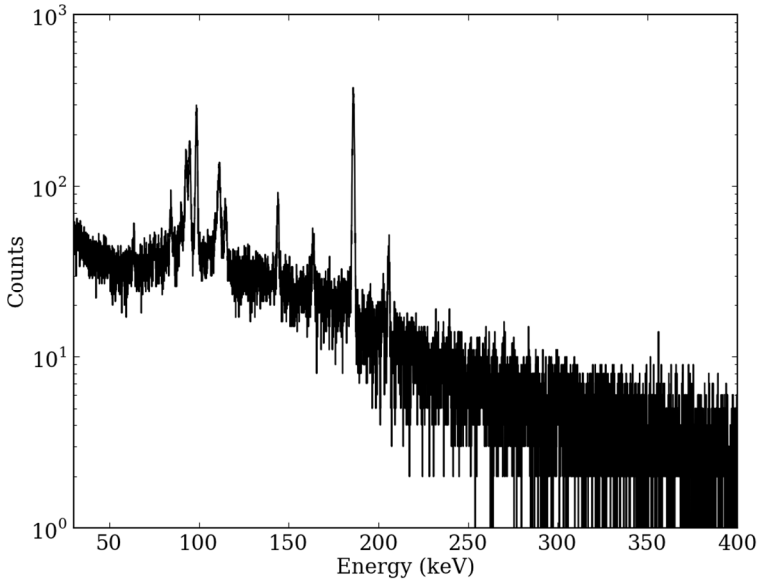

Figure 8 A 300sec measurement of a canister with 3.8% enriched scrap powder.

Table 4 Comparison of declared and calculated enrichment for two scrap metal canisters. Enrichment calculation made using Ortec U235.

Declared Enrichment	Calculated Enrichment
4	3.938±0.144
3.8	3.979±0.294

2.3 Fuel Fabrication Facility

Gross defect and enrichment verification activities were preformed in the fuel fabrication facility. Gross defect measurements were made using a hand held sodium iodide detector, similar in size to the SPG. Each measurement required a 60sec background calibration followed by ~2 sec measurement. Although gross defect measurements address only the presence of uranium, the hand-held NaI provided limited spectroscopic information. This detector is of little use for off-normal measurements that require detailed spectroscopic analysis- as is available with SPG. The spectrum shown in Figure 9 was taken in the same amount of time as was required for the gross defect measurement. Measuring this sample using SPG not only confirmed the presence of uranium but also allowed for isotopic analysis indicating an enrichment of 3.443±0.053, in agreement with the declared value of 3.42%.

SPG was used to measure 0.52% enriched CANDU reactor pellets (see Figure 11). Whereas the measurement environment in the fuel pellet storage facility (discussed in the previous section) introduced large offsets in the calculated enrichment, the laboratory setting here was more controlled and free of contamination. Consequently the analysis with MGA yielded an enrichment of 0.434±0.229, in agreement with the declared value.

The verification of uranium powders and oxides in barrel storage containers is shown in Figure 11. A comparison using the collimator to measure a barrel with natural uranium powder is shown in Figure 12. Although the collimator reduces the background it also suppressed the gamma-ray signatures of interest. MGA analysis for both were in agreement with the expected enrichment of

0.7% (See Table 5); however, the reduced peak intensities in the collimated spectrum resulted in uncertainties ~4 times greater.

Enrichment measurements were made using the same planar germanium system used in the UF_6 storage facility. While the refilling of liquid nitrogen every 4-5 hours was not an issue in the UF_6 facility, the contamination controls in the building prevented the mid-day refilling, forcing the inspectors to closely watch the nitrogen level. Many areas in the building were not air-conditioned and temperatures exceeded those outside and there was concern that the measurements would end early should the nitrogen run out. Again SPG ran without incident throughout the entire day despite these high temperatures.

Enrichment verification measurements were made on storage hoppers containing UO_2 powders. The portability of SPG was very advantageous for measuring partially filled hoppers as positioning the IAEA detector against the sloped sidewalls was very challenging if not impossible (see Figure 13). A hopper containing 459.5kg of 4.65% enriched UO_2 homogenized powder was measured with both SPG and the IAEA planar germanium system and the results compared. The IAEA spectrum was processed using two software packages, MGAU and IMCG, with the primary difference being the IMCG attenuation correction of the hopper wall, which is not included in MGAU. The MGAU calculated a composition of 6.36%, in agreement with the 6.643±0.033 calculated with SPG and Ortec U235 software[1]. Repeating the analysis with IMCG with the ~2mm hopper wall thickens correction the composition was 3.9±0.05.

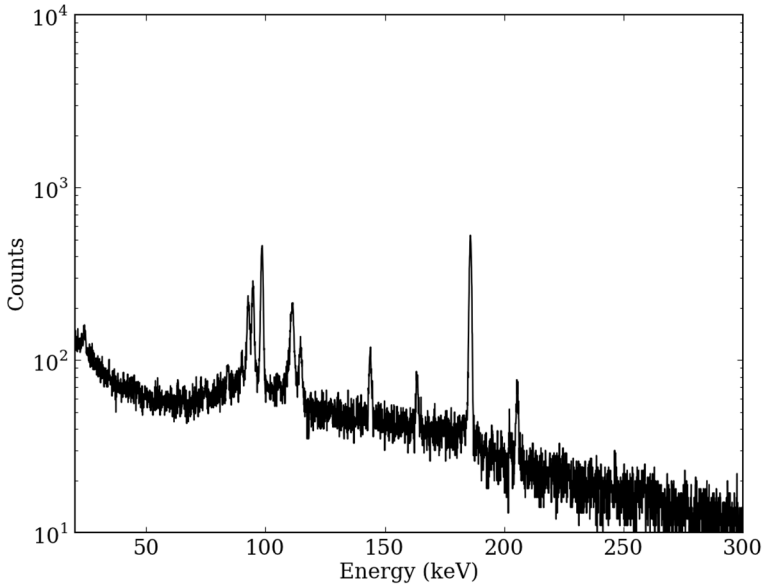

Figure 9 Spectrum taken for 160sec of a hopper containing 450kg of 3.4% enriched UO_2 powder.

[1] Both MGAU and U235 software are based on the same code developed by Lawrence Livermore National Lab. Thus both codes should produce the same results if processed with the same spectrum.

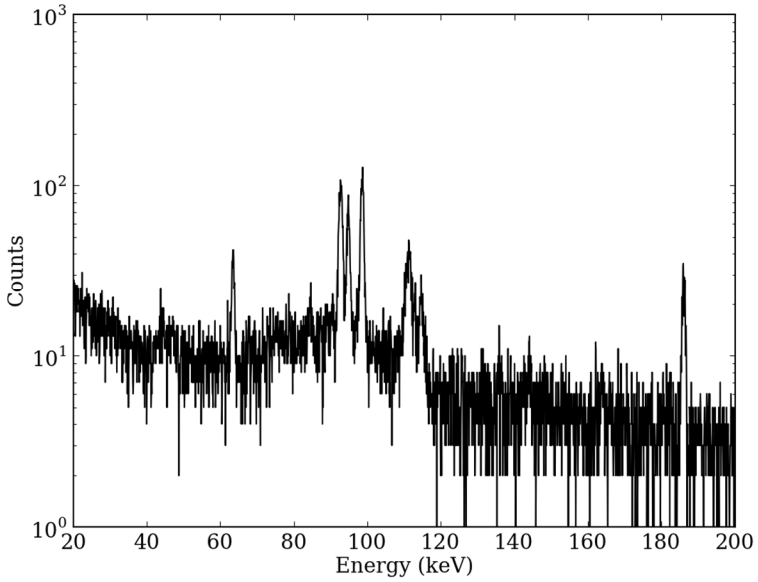

Figure 10 A 200sec measurement of ten 0.52% CANDU reactor pellets.

Figure 11 Photograph of participants from LLNL and KINAC using SPG to measure a barrel containing depleted U_3O_8 powder.

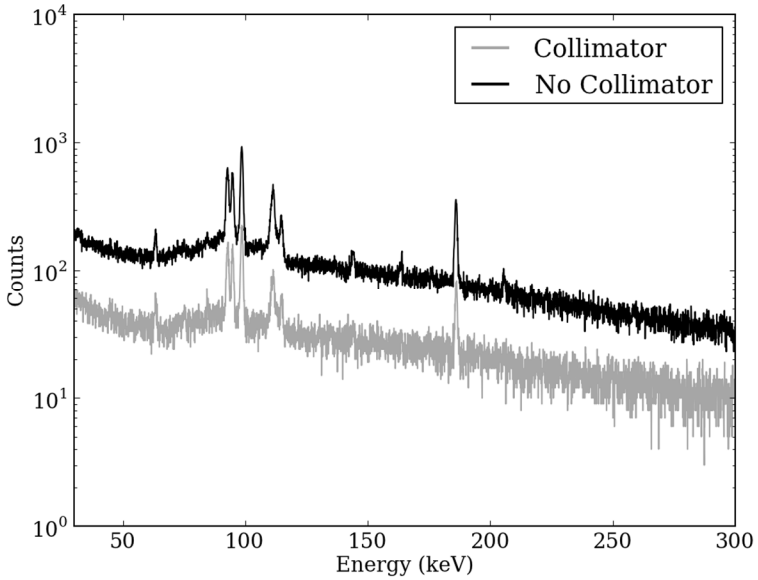

Figure 12 Canister of 337kg of natural uranium powder (0.71%), measured from middle of the barrel for 300sec.

Table 5 Comparison of MGA calculated enrichment from the spectra shown in Figure 12. Enrichment calculation made using Ortec U235.

Configuration	Calculated Enrichment
No Collimator	0.569±0.161
Collimator	0.236±0.606

Figure 13 LLNL, IAEA, and KINAC participates measuring uranium storage hoppers. On the right image note the difficulty of measuring from the sloped sidewalls of the hopper.

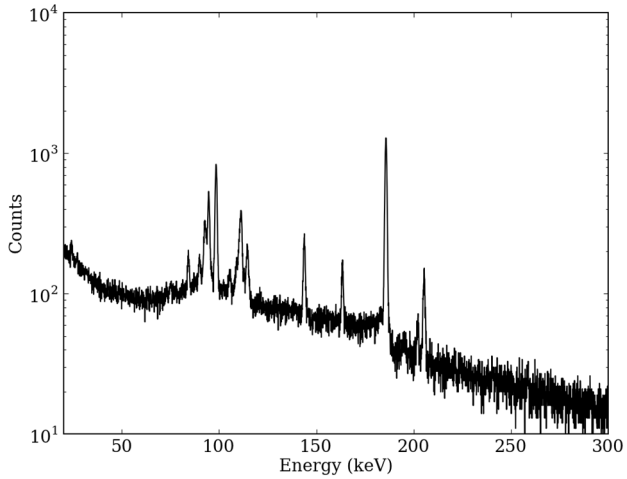

Figure 14 Hopper containing 459.5kg of 4.65% enriched UO_2 homogenized powder. Hopper is shown in the left photograph of Figure 13.

Table 6 Comparison of MGAU, IMCG, and U235 enrichment calculations using the spectra shown in Figure 14.

Software Package	Calculated Enrichment (%)
IAEA-MGAU	6.36*
SPG-U235	6.643±0.033
IAEA-IMCG	3.9±0.05

*Uncertainty not provided.

3 Integration of User Feedback

The field-testing of SPG during the PIV and INL were very productive and an excellent opportunity to demonstrate this technology to a wide range of users. The feedback identified shortcomings of the systems that required attention. In many environments the user was required to hold the device by hand for a measurement. During a campaign such as a PIV this is impractical. The collimator was also shown to be ineffective and needed a redesign with a cadmium window to better shield the detector. Numerous software improvements were also necessary to improve usability and stability during operation. Lastly, analysis software (MGA, PC-FRAM) integrated into the SPG software would provide the user with isotopic information. For measuring sources where count rate is a concern, a collimator was necessary to shield the detector. The collimation also needed to be flexible should a larger field of view be necessary. In following we discuss how the feedback from end user has been used to direct areas of improvement for SPG.

3.1 Spectral Analysis Software

Spectra generated using SPG can now be directly analyzed using both MGA and PC FRAM. These are the standards for determining isotopic composition and streamlining the analysis of SPG spectra is critical for on-site IAEA inspections and other safeguard activities. This modification has increased the usability of the instrument, making it a more viable replacement to existing commercial technology.

3.2 Integration of Tripod and Collimator

Throughout the PIV in South Korea it was recognized that a tripod system and collimator would be advantageous for SPG. During the PIV carts and chairs at the facility were often used position SPG for a measurement. In certain cases these were not available and a user would have to hold the instrument during each 300sec measurement. Measurement of highly radioactive samples required the instrument be shielded to suppress scatter and the field of view be reduced to limit the count rate. The geometry of the system was a challenge to properly shield. To address these issues a tripod was selected that provided a large range of motion and was capable of supporting the instrument and collimator securely. The lead/copper collimator was designed and includes optional 1mm thick cadmium filters that can be added to suppress low energy gamma rays. The aperture of the front tungsten collimator can be switched for a 5°, 15°, or 30° field of view. The collimator can be used separately from the tripod. The tripod and collimator are shown in Figure 16 and Figure 16.

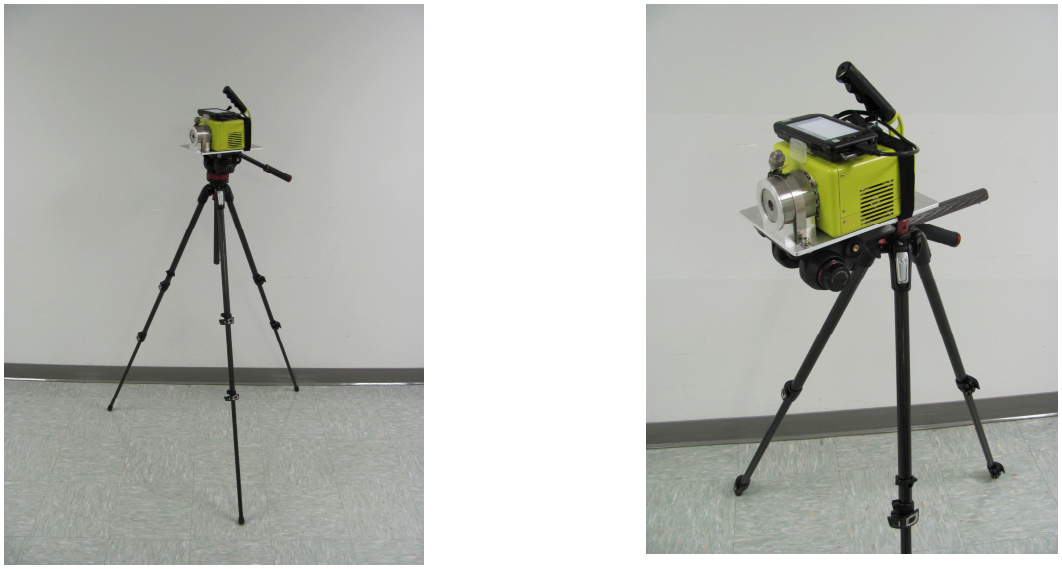

Figure 15 SPG with optional tripod and tungsten/copper collimator. The tripod provides a stable platform for long acquisitions and can be easily detached from SPG for mobility.

Figure 16 The tripod has a wide range of motion that can be used to measure barrels (see Figure 11) and hoppers (see Figure 13) at various heights. This will help significantly in wide range of applications.

4 Conclusion

The field-testing of SPG during the PIV was very productive and an excellent opportunity to demonstrate this technology to a wide range of users including IAEA inspectors. The system was used extensively at three locations in the KNF fuel fabrication facility: UF_6 cylinder storage facility, fuel pellet storage, and fuel fabrication building. The SPG was found to be very portable, robust in harsh environmental conditions and effective in verification of nuclear materials present in the nuclear fuel fabrication plant. The feedback from IAEA inspectors was very positive and encouraging, and indeed the replacement of the liquid nitrogen-filled HPGe with SPG should be seriously considered and explored in the future.

5 Acknowledgement

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