Performance Characteristics of a Third-generation Spectroscopic Vehicle Portal Monitor based on High Purity Germanium Detectors

T. R. Twomey, J. Long, and F. Sergent
ORTEC
AMETEK Advanced Measurement Technology
801 South Illinois Avenue
Oak Ridge, TN, 37831 USA
Email: Tim.Twomey@ametek.com, Johnny.Long@ametek.com, Frank.Sergent@ametek.com

ABSTRACT

The general need for improved detection performance and reduced decision time for portal monitors, freight container scanners, and mobile search systems is being achieved with systems utilizing High-Purity Germanium (HPGe) detectors. Highly specialized software analyzes the spectroscopic data to produce accurate results in live time. To meet the need, a new generation monitor has been developed using eight integrated gamma-ray spectrometers, video recording of the container, automatic spectroscopic and video data collection, analysis, reporting, alarming, and archiving all raw data and results. Previous work reported on the modeling of the performance of a primary cargo portal based on similar HPGe detection systems with 12 HPGe detectors on each side of the traffic lane. The expected performance of this 24-detector cargo portal was shown to exceed the ANSI N42.38 requirements. In other work, performance data were presented of a secondary freight portal monitor with 4 detectors on each side of the traffic lane. Operational experience from the installed system has been reported. These results were used in a new design of a portal monitor providing primary inspection capabilities to comply with the performance requirements of ANSI N42.38, with 16 HPGe detectors along with improved identification algorithms. This paper will describe the elements of the new primary portal design and present test results on its performance relative to previous systems.

Keywords: radioisotope; integrated systems; germanium detectors; HPGe; illicit trafficking; monitoring

INTRODUCTION

The use of High Purity Germanium (HPGe) detectors in portal monitors for the detection of illicit radioactive materials in freight containers has shown the efficacy of these devices in detecting nuclear materials. Portal monitors based on HPGe detectors are in use several places around the world. Some of these have been described in previous works. Such a monitor was developed using eight integrated gamma-ray spectrometers, video recording of the container, automatic spectroscopic and video data collection, analysis, reporting, alarming, and archiving all raw data and results. Previous work reported on modeling the performance of a primary cargo portal using 12 HPGe detectors on each side of the traffic lane. The expected performance of this 24-detector cargo portal was shown to exceed the ANSI N42.38 requirements. [1, 2] Based on the experience gained from results from these portals, a portal monitor was designed to provide primary inspection capabilities to comply with the performance requirements of ANSI N42.38, with 16 HPGe detectors in the form of fully integrated spectrometers, referred to as IDM-200-P modules. In addition to the new IDM, the identification algorithms, detector mounting, and data processing were improved.

The testing described here was performed at the ORTEC factory test facility and by an independent laboratory. Radiological performance was the main focus of the testing. The tests used neutron sources and several of the gamma-emitting nuclides in ANSI N42.38 (with some differences in activity to those specified in the current standard). Single and combinations of the specified sources were tested and samples of special nuclear materials were tested in the special test facility at the independent laboratory. The test results show the ORTEC HPGe-based portal performs well, especially for identifications and mixtures, and the unambiguous nature of the results means that overall operational costs can be reduced in an operating facility by removing the need for re-test or manual inspection.

EQUIPMENT AND SETUP

<u>HPGe Detectors</u>

The HPGe detectors are IDM-200-Ps, as shown in Fig. 1. The IDM-200-P is a completely self-contained package, comprising a single, large-area, mechanically-cooled, high-purity germanium (HPGe) detector of standardized crystal dimensions and all necessary spectrometry electronics in a rugged, low-power configuration. The detector element is an 85 mm diameter x 30 mm deep HPGe crystal. The electro-mechanical cooler, hardened cryostat, USB connection, advanced signal processing, and multichannel analyzer (MCA) are in the housing. The MCA uses the 1460 keV peak of ^{40}K for gain stabilization. The large diameter detector is optimized for energies from 100 keV to 400 keV with sufficient response up to 3 MeV, which is the ideal energy range for detection of SNM. The IDM is mains powered with an internal battery which is used as backup for up to 2.5 hours if mains power is lost. The unit is shown sitting vertically, but it is mounted horizontally in the cabinets. The handles are to facilitate installation and removal of the IDM in the portal monitor cabinet.

The detectors and electronics are controlled (through USB 2.0) by computers mounted with the IDM-200-Ps within each portal cabinet on

Figure 1. Interchangeable Detector Module (IDM – 200-P)

Figure 2. Installed HPGe Portal at ORTEC Test Facility in Oak Ridge

either side of the traffic lane. These local computers communicate with the control computer, which can be located remotely via an Ethernet connection. Each cabinet includes an HVAC system and controller to maintain the internal temperature at a satisfactory level, as well as a UPS power backup supply. The front of each cabinet has a plastic window to minimize the attenuation of gamma rays to the detector. Figure 2 shows the ORTEC test facility in Oak Ridge. Referring to the far cabinet in the figure, the HPGe detectors are in the left-hand side of the cabinet and the neutron detectors are in the right-hand side of the cabinet.

Table I. Nuclides and activities actually used in independent laboratory testing and given in N42.38-2006 and N42.38 Draft

Radionuclide	Test Activity (μCi) or Mass Unshielded	Test Activity (μCi) Shielded	N42.38-2006 Standard Activity (μCi) Unshielded	N42.38 Draft Standard Activity (μCi) Unshielded
^{241}Am	50.7		47	47 (1.74 MBq)
^{133}Ba(i)	9.76	138.3 in 3 cm steel	9	
^{57}Co(i)	12.4 - 12.9 or 13.1		15	
^{60}Co	7.27	26.1 – 28.3 in 3 cm steel	7	7 (259 kBq)
^{137}Cs	13.2	84.4 in 3 cm steel	16	16 (592 kBq)
^{67}Ga	13.4 or 97.2 – 92.2	92.2 - 97.2 in 7.64 cm PMMA	16	94 (3.48 MBq) Shielded
^{131}I	8.79 - 8.95	20.6 – 28.5 in 7.64 cm PMMA	10	23 (851 kBq) Shielded
^{192}Ir	8.86 - 9.64		6	
^{40}K	128 kg		128	
^{99m}Tc	16 – 19.1	130.1 – 183.5 in 7.64 cm PMMA	16	127 (4.7 MBq) Shielded
^{201}Tl	8.4	96.3 in 7.64 cm PMMA	10	88 (3.26 MBq) Shielded
^{226}Ra	8		8	
^{232}Th	14.3		14	
DU	0.63 kg (100 cm^2)		4.5 kg (46 cm^2)	25 μR/h ± 20% at 40 cm
DU	2.52 kg (400 cm^2)			
HEU	45.35 g sphere		237g (6.5 cm^2)	25 μR/h ± 20% at 40 cm
WGPu	3.5 g disk	3.5 g with 5 mm steel shielding	15 g with 1 cm steel shielding	25 μR/h ± 20% at 40 cm
^{252}Cf	2 x 10^4 n/s ±20%		2 x 10^4 n/s ±20%	2 x 10^4 n/s ±20%

Notes: i. The uncertainty of actual activity value of each source shall be less than ±10% (k = 1).
ii. The actual activity of each source at the time of testing shall be within ±20% from the values listed above.
iii. The tolerance in the thickness of the shielding materials is ±10 %.

Shielding

The IDM-200-P includes some steel shielding (the black ring around the detector endcap in Fig. 1) to reduce radiation from outside the detection zone. The steel shielding extends from just behind the detector crystal forward for a distance of 10 cm. It is 12 mm thick for 4 cm and 25 mm thick for the remaining length. To reduce the general background and radiation from adjacent containers, side shields were added in the cabinet. The horizontal Field of View (FOV) is the area in front of the detectors where a source of gamma rays (NORM or other source) could contribute to the spectrum.

The side shielding limits the horizontal FOV to about 120º for low-energy gamma rays. The vertical FOV is unrestricted.

The truck occupancies are determined by magnetic loop sensors in the ORTEC portal and break beam sensors were used in the laboratory portal.

Mounting

ORTEC Test System:

Sixteen IDM-200-Ps are mounted symmetrically in two vertical pillars formed by 2 environmentally controlled cabinets: one upper, one lower, on either side of the road. Four IDMs are mounted in each cabinet, giving eight on each side of the traffic lane. The cabinets and internal shielding define the detection zone to be from 0.5 m to 4.1 m above the ground, when installed on a curb of 20 cm. This will meet the requirements to scan a shipping container.

The cabinets are positioned with the front faces 4.6 m apart.

Independent laboratory:

The cabinet front faces were also 4.6 m apart because of building height restrictions, rather than the N42.38 separation. Sixteen IDM-200-Ps are mounted symmetrically in two vertical pillars formed by 2 environmentally controlled cabinets, one upper, one lower, on either side of the road at vertical positions starting at 0.25 m above mounting surface level with center-to-center spacing of 0.5 m. The vertical detection zone was lower than 4.1 m, the cabinets were mounted on a curb height smaller than 20 cm.

Sources and attenuators

The sources used were various point sources and volume sources derived from ANSI N42.38. Table I shows the actual sources used in the testing at the independent laboratory and the activities given in N42.38-2006 and N42.38-2013 Draft. Note that for some nuclides and SNM, these quantities are mainly lower, sometimes significantly lower, than the quantities given in N42.38-2006 and the draft N42-38-2013 draft. Other nuclides listed in the standard were not used in the testing. The HEU source used at the independent laboratory was specially constructed as a hollow sphere so the effective mass was 1 to 1.5 kg, that is, the flux of the gamma-ray emissions of the test source nearly duplicate those from a solid sphere of a larger mass of HEU.

The DU sample used for independent laboratory testing had a total weight of 0.63 kg and was in the form of a flat square with an area of about 100 cm^2 with a thickness of 0.3175 cm. The large flat surface of the DU slab faced the detectors. DU measurements were carried out with either one slab or four slabs placed so that the total surface area of 400 cm^2 (2.5 kg) faced the detectors. The orientation of the source relative to the SRPM was the same for all the tests.

The WGPu source was a 3.5 g cylinder or disk without shielding. During the measurements the base of the cylinder was parallel to the floor. Masking measurements using the WGPu cylinder were performed with the source shielded by 5 mm of steel to reduce the gamma-ray flux of ^{241}Am in the detector to less than 10 times the flux of 414 keV gamma ray. For all other measurements the bare WGPu source was used. The emissions from the bare 3.5 g cylinder are equivalent to the emissions of an 11 g sphere in 1 cm of steel shielding. The N42.38 standard specifies a 15 g sphere with 1 cm of steel shielding.

The tests at the ORTEC test station were performed using ^{133}Ba, ^{241}Am, ^{57}Co and ^{60}Co gamma-ray sources and a moderated ^{252}Cf neutron source. The sources were placed in a regular box-body truck. The truck walls were 12.5 mm wood and 1 mm aluminum over the whole sides with thicker horizontal rails spaced on the sides. No other shielding was used. The source activities used were similar to the "bare" activities given in N42.38. Note that except for the middle IDM, the attenuation thickness of the truck sides will be greater than the simple thicknesses.

Efficiency

The measured efficiency of the HPGe detectors is shown in Fig. 3. These measurements were taken at the testing laboratory. The top position was at 4.5 m, which is above the stated detection zone of the tested portal.

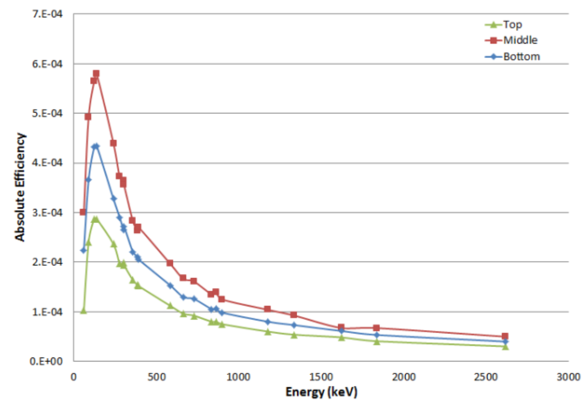

Figure 3. Efficiency vs Energy for the Source at Three Different Heights and Horizontally Centered.

ANALYSIS and METHODS

Peak Quality Factor

The identification of the nuclide is based on the presence in the spectrum of selected intense gamma rays from that nuclide. The gamma rays used for each nuclide are given in a table stored in the analysis software. The gamma rays in the table are given in several references [3, 4, 5, and 6]. The peak is present in the spectrum if a measured parameter of the peak is above a threshold. For this work, the peak parameter used is the peak quality factor (Q) and is defined as the net peak area divided by the uncertainty in the net peak value [2]. The Q value depends on the peak signal and the background under the peak. The threshold is based on the desired false positive rate and false negative rate [7]. There is a threshold specified for each gamma ray in the analysis table. The identification is based on the full energy gamma ray signal and not on gross counting.

Background

The spectrum net peak areas are determined using a background value determined dynamically from the same sample (trial) spectrum, so there is no requirement to use a previously stored background. This entirely avoids the problem of background suppression or enhancement (both gamma ray and neutron) by high density shipments and variations in the background by natural causes, such as the weather. Backgrounds are, however collected during idle times and occupancies with no nuclides detected. These measurements are used to determine the nuclides and gamma rays in the environmental background as well as the neutron background count rate. The background spectrum peaks are used to perform a "peak background subtraction" in order to detect high NORM in the cargo. The neutron count rate is used to determine high neutron flux.

Data streams from single or multiple IDMs can be used to improve the detection ability by aggregating data from 2 to 16 detectors in any combination into a single spectrum and calculating a composite Q value from the result. The detector responses are aligned to minimize spectrum quality reduction. This can result in a Q for the portal of up to 16 times the efficiency of a single IDM depending on the nature and location of the source. In addition, different aggregations of detector responses can be made and those with the best signal-to-noise ratio used for the identification of gamma-emitting radionuclides. Additional improvements on detection are achieved by collecting short time spectra with no dead time between successive time slices as the vehicle passes through the detection zone.

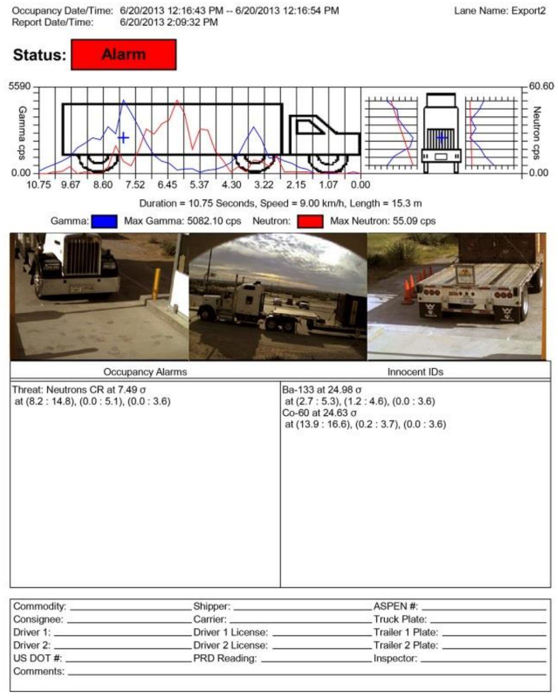

Figure 4. Example Report for High Neutron Count Rate and Non-threat Sources

The software can produce various reports depending on the system setup. Each occupancy will generate a report shown to the operator as in Fig. 4. The report shows the nuclides detected and the position in the container with the highest signal, to help locate the position of the material. The reporting criteria can be set so that only threat nuclides generate an alarm. The entire analysis results, including raw spectra, are saved in a log file. The log file can be read to give the radionuclide results needed for scoring the system and was used in the analysis below.

The analysis methods were the same for both test setups.

The tests at the ORTEC facility were performed with a standard box-body with the sources in the truck body.

The tests at the independent laboratory were the radiological tests described in N42.38 and are static single nuclide gamma ray emitter (shielded and unshielded), static SNM (shielded and unshielded), static mixtures of gamma ray emitters (shielded and unshielded), static neutron source (bare and moderated), transient single nuclide gamma ray emitter (shielded and unshielded), transient SNM (shielded and unshielded), transient mixtures of gamma ray emitters (shielded and unshielded), and transient neutron source (bare and moderated). The transient tests were performed using a source mover capable of positioning the source at the positions in the field of view described in ANSI N42.38. All test parameters were for the Vehicle Monitor as specified in N42.38.

The static tests used a dwell time of 30 s. The transit speed was 8 km/h or 2.22 m/s. For both tests, the sources were approximately centered horizontally in the detection zone and positioned vertically at the middle (2.25 m from floor) and bottom (range from 0.2 to 0.54 m from floor, depending on the source).

RESULTS

ORTEC Tests

The tests at the ORTEC facility used commonly available sources. The activities are according to the current version of ANSI N42.38. The results for tests at ORTEC that were also performed in the independent laboratory tests are shown in Table II. The "Blank" nuclide is the false alarm test. This was done without a vehicle using simulated occupancies overnight.

Table II. Results of ORTEC Testing

Nuclide	Actual Activity (µCi)	Result	Trials	Passes	Correct Result	N42.38-2006 Standard Activity (µCi) Unshielded	N42.38-2013 Draft Standard Activity (µCi) Unshielded
^{241}Am	47	identification	9	7	77.8%	47	47
^{57}Co	15	identification	9	9	100.0%	15	
^{133}Ba(i)	9	identification	19	19	100.0%	9	
^{60}Co	9.5	identification	19	19	100.0%	7	7
Blank	none	no activity	168	168	100.0%		
^{252}Cf	2×10^4 n/s	Neutron count rate	9	9	100.0%	2×10^4 n/s	2×10^4 n/s

All of these tests used the unshielded sources, but the truck sides provided some degree of shielding. The shielding has the most effect at the lower energies as shown by the results.

Laboratory Tests

The tests at the independent laboratory are more comprehensive and are closer to the tests given in ANSI N42.38.

The sensitivity to neutrons was measured with 10 passes through the portal for each source position and both bare and moderated. The neutron background summed for all 4 detectors was measured at 14.5 ± 1.3 cps. The measured neutron count rate for the ^{252}Cf source was 54 to 76 cps and for moderated source was 32 to 59 cps. Figure 5 shows the neutron results. Note that all tests show the detection of neutrons 100% of the time. The "No Threat" was not indicated because any high neutron field is an alarm.

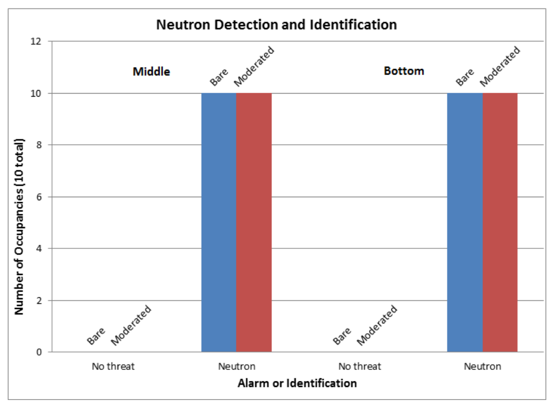

Figure 5. Neutron Detection and Identification

The response to gamma-ray radiation (ANSI N42.38 Section 6.3) results are shown in Fig. 6. The tests were run for ^{133}Ba and ^{60}Co. The test consisted of sixty trials. The "Middle" and "Bottom" refer to the source position in the

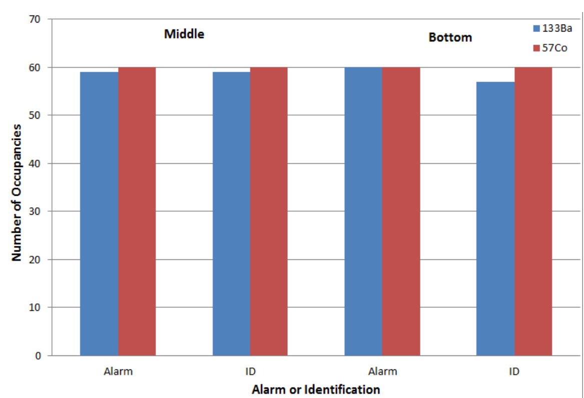

Figure 6. Radiation Detection and Identification

detection zone. This test is for general detection of radiation. In addition to the radiation detection, the analysis also identifies the nuclide. The detection results are very good, being 60/60 in 3 out of 4 tests and 59/60 for the other test. The identification results (not part of this test) are also 60/60 for 2 of the 4 tests and above 57/60 for the other tests.

The identification of single nuclide gamma-ray radiation (ANSI N42.38 Section 6.8) results for the static mode are shown in Fig. 7 for unshielded sources. The tests were run for the nuclides in Table I. Ten trials were run for each source position. In this mode, all nuclides (Table I) were identified in 10 of 10 trials. For WGPu and HEU, there are two entries. One is for the identification of WGPu or HEU exactly and one is for an alarm.

The alarm can be triggered on identifying the sample itself, identifying a nuclide associated with the sample (e.g., ^{241}Am for WGPu), or the detection limit (MDA) for a threat nuclide is above the defined limit (e.g., Pu (MDA)) because of the general increase of counts in the spectrum.

The unshielded single nuclide identification test for the transit (pass through) mode results are shown in Fig. 8. The transit mode collects data for a shorter time than the static mode. The approximate time for the transit is 20% of the static time. The correct result was reported 32/54 trials. Note the high success rate for the threat sources and that some of the source activities used were below the N42.38 specified values.

The results for shielded nuclide identification in both the transient and static mode are shown in Fig. 9. Only 3 nuclides are used in this test. The correct identification was made in 120/120 trials.

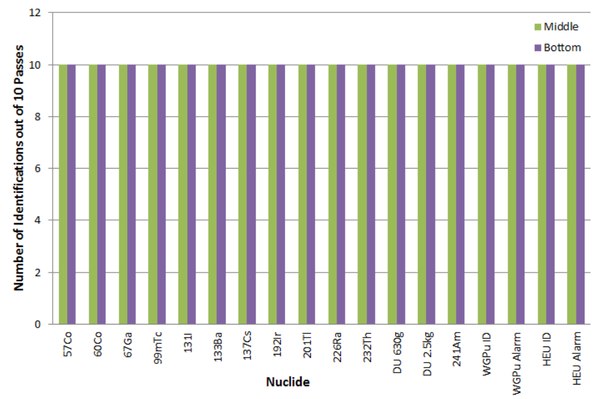

Figure 7. Single Nuclide Identification in Static Mode (Unshielded)

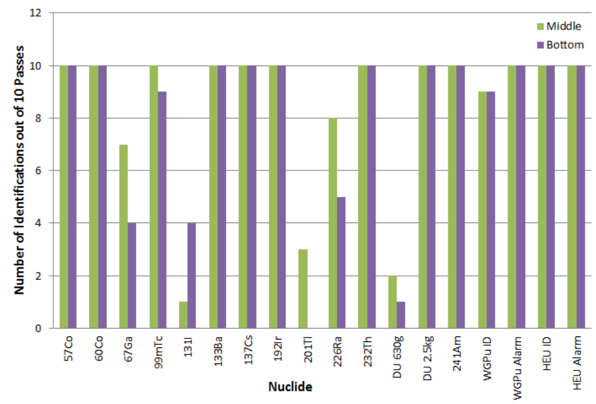

Figure 8. Single Nuclide Identification in Transient Mode (Unshielded)

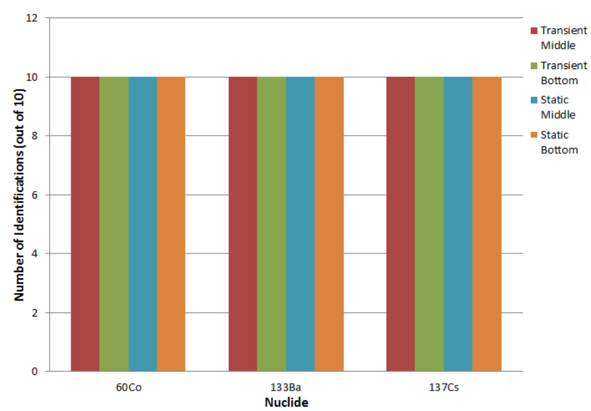

Figure 9. Single Nuclide Identification in Shielded Mode

The results for unshielded medical nuclides in both the transient and static mode are shown in Fig. 10. Only 4 nuclides are used in this test. The correct identification was made in 141/160 trials.

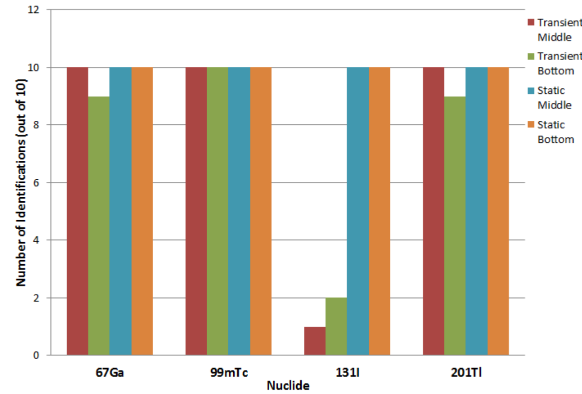

Figure 10. Single Medical Nuclide Identification in Unshielded Mode

The results for unshielded nuclide mixtures in both the transient and static mode are shown in Fig. 11. Only 2 combinations of nuclides are used in this test. The important identification in this case is the HEU or WGPu. These were identified in 70/80 trials. If ^{241}Am is detected above a threshold, it is used as an indicator of plutonium and is an alarm. Alarms were given in 80/80 trials. The non-SNM nuclide was identified in 70/80 trials.

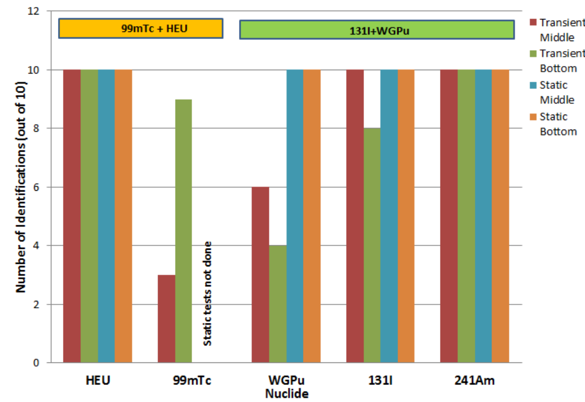

Figure 11. Nuclide Mixture Identification in Unshielded Mode

The results for unshielded nuclide masking test in both the transient and static mode are shown in Fig. 12. Four combinations of nuclides and mask are used in this test. The NORM is 128 kg of KCl. Note that HEU and WGPu quantities are lower than the amounts specified in N42.38. WGPu is only 73% of the specified activity. The important identification in this case is the HEU or WGPu. These were identified in 120/160 trials. If ^{241}Am is detected above a threshold, it is used as an indicator of plutonium and is an alarm. Alarms were given in 148/160 trials. Thus, while WGPu was detected in 2/20 trials of NORM + WGPu, an alarm of suspect material was given in 16/20 times.

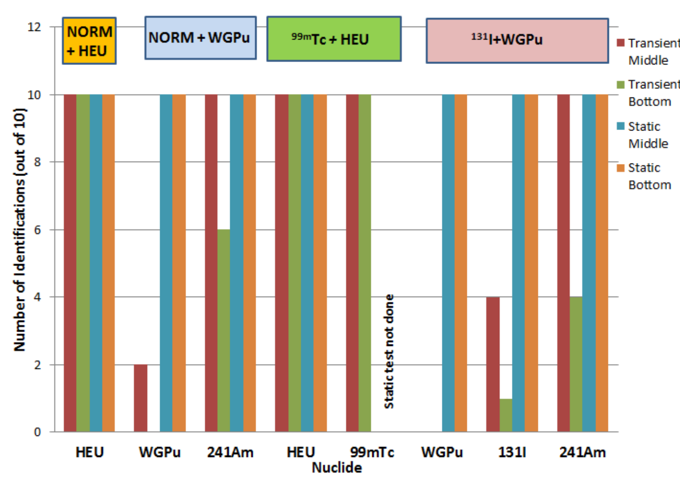

Figure 12. Nuclide Masking Identification in Unshielded Mode

The alarm could cause a static measurement. WGPu was identified in 20/20 static tests. Similarly, while WGPu was not detected in 20 trials of ^{131}I + WGPu, an alarm of suspect material was given in 14/20 times. WGPu was identified in 20/20 static tests.

CONCLUSION

The radiological testing of the ORTEC portal in ways similar to those prescribed in the current ANSI N42.38 spectroscopic portal standard has shown this instrument which is based on HPGe gamma ray detectors and ^{6}Li-based neutron detectors, and which uses the latest ORTEC identification algorithms, can substantially meet the requirements for identification of radionuclides being transported in cargo containers, with and without shielding or masking, in the transit or pass-through mode at the vehicle speeds specified (8 kph).

Compared to previous work, detector and algorithm improvements have enabled the standard requirements to typically be met with the reduced number of 8 detectors (IDMs), on each side of a traffic lane, and the results show best performance in the case of the threat SNM nuclides. The configuration shows adequate spatial uniformity.

Clearly, the superior energy resolution of HPGe detectors can give superior performance by increasing the signal-to-noise ratio in the spectrum. Analysis methods have been improved based on the results of the currently-installed portal systems to include the peak-in-background subtraction, neutron background adjustment, and unidentified peak detection (unexpected nuclides). In previous work it was shown that unlike low-resolutions systems, as detection limits are reached, the HPGe system does not enter a state where false positive results appear with high frequency, leading to indeterminate results [8].

By real-time processing of time-sliced data from individual detectors, the highest reliability for detection and identification is obtained. These two new portals have demonstrated operational reliability for more than 10 months in outside operation in all weather conditions. This, coupled with the ability to configure a standard-compliant primary portal based on 16 reliable detector modules to make a portal that is resistant to both false positives and false negatives, means that the cost-effectiveness of this approach has now been demonstrated. The modularity of the design allows the portal to be easily adapted to any concept of operations (CONOPS). This flexibility and reliability, both operational and radiological, will dramatically reduce the over-all cost of ownership. The cost of ownership is lowered by higher throughput at border crossings (reduced delay of commerce), reduction of the need for human intervention (lower staffing costs), and low downtime (reduced maintenance costs).

REFERENCES

[1] American National Standard Performance Criteria for Spectroscopy- Based Portal Monitors Used for Homeland Security, ANSI N42.38-2006, IEEE, 3 Park Avenue, New York, NY 10016-5997, USA January 2007

[2] Keyser, R.M., Sergent, F. Twomey T.R and Upp, D.L., "Minimum Detectable Activity Estimates for a Germanium-Detector Based Spectroscopic Portal Monitor," Proceedings of the 2006 INMM Annual Meeting, July, 2006

[3] American National Standard for Evaluation and Performance of Radiation Detection Portal Monitors for Use in Homeland Security, ANSI N42.35, IEEE, 3 Park Avenue, New York, NY 10016-5997, USA January 2004

[4] IEC 62484 "Radiation protection instrumentation – Spectroscopy portal monitors used for the detection and identification of illicit trafficking of radioactive material", International Electrotechnical Commission, Geneva, 2008

[5] "Technical and Functional Specifications for Border Monitoring Equipment", IAEA Nuclear Security Series No. 1, IAEA, Vienna, 2006, and "Detection of Radioactive Materials at Borders," IAEA-TECDOC-1312, IAEA, Vienna, 2002

[6] American National Standard, "Performance Criteria for Hand-held Instruments for the Detection and Identification of Radionuclides," ANSI N42.35, IEEE, 3 Park Avenue, New York, NY 10016-5997, USA January 2004

[7] Ronald M. Keyser and Timothy R. Twomey, "False Positive Probability as a Function of Background for Short Data Collection Times in a Germanium Detector Portal Monitor," Proceedings of the 2008 INNM Annual Meeting, July, 2008

[8] Ronald M. Keyser, Neil A. Webster, Michael D. Belbot, and Timothy R. Twomey, "Figure of Merit for Evaluating the Performance of Radionuclide Identification in Portal Monitors and Handheld Devices," 33th ESARDA Annual Meeting, Budapest, Hungary, May, 2011.