Field Tests of a NaI(Tl)-Based Vehicle Portal Monitor at Border Crossings


Abstract— Radiation portal monitors are commonly used at international border crossings to detect illicit transport of radioactive material. Most monitors use plastic scintillators to detect gamma rays, but next-generation monitors may contain NaI(Tl). In order to directly compare the performance of the two types of detectors, a prototype NaI(Tl) monitor was tested at two international border crossings adjacent to a comparable plastic scintillator monitor. The NaI(Tl) monitor housed four large detectors, each 10.2 cm x 10.2 cm x 41 cm. The empirical data set from the two field tests contains approximately 3800 passages with known cargo loads for each vehicle. For a small subset of the vehicles, high purity germanium detector spectra were also collected. During the survey period several vehicles containing commercial products with naturally occurring radioactive material (NORM) passed through the monitor. Typical NORM cargo included pottery, large granite slabs, rock-based floor tiles, construction stone blocks, abrasive material, and fertilizer. Non-NORM sources included a large source of $^{60}$Co (200,000 GBq) and a shipment of uranium oxide, both items being legally transported. The information obtained during the tests provides a good empirical data set to compare the effectiveness of NaI(Tl) and plastic-scintillator portal monitors. The capability to be sensitive to illicit materials, but not alarm on NORM, is a key figure of merit for portal monitors.

I. INTRODUCTION

Conventional radiation portal monitors (RPMs) use plastic scintillators (polyvinyltoluene: PVT) to detect gamma rays emitted by passing vehicles [1-2]. Portal monitors containing PVT detectors are being installed [3] at border crossings by the U.S. Department of Homeland Security’s Customs and Border Protection (CBP). Sodium iodide scintillation detectors may offer improved performance compared to PVT scintillators, by providing spectral information that can be used to discern illicit sources from benign sources [4]. Radiation portal monitors are designed to alarm on nuclear materials that pose a threat to national security. Those using PVT can detect such material by observing an increase in the emitted radiation compared to background. Cargo containing benign sources of radiation also crosses international borders and triggers alarms. Some items of commerce contain naturally occurring radioactive material (NORM) such as $^{40}$K, $^{238}$U, and $^{232}$Th which are naturally present in geologic materials. For example, commercial products such as pottery and cat litter, which are made of clay, are slightly radioactive. Portal monitors that provide enhanced gamma-ray spectra, such as from NaI(Tl) detectors, should be valuable to reduce alarms from NORM. The goal of the tests presented here was to compile a database from which a comparison of the performance of PVT and NaI(Tl) could be performed. Understanding the spectral variation in the radiation signatures of border traffic is necessary for making this comparison. This manuscript discusses the calibration of the equipment and some initial results.

A RPM containing four, large NaI(Tl) detectors was tested at two border crossings in order to monitor commercial vehicles entering the United States. During these tests the NaI(Tl) portal was positioned adjacent to a PVT portal, and data from both types of portals were collected. Figure 1 shows the NaI(Tl) portal adjacent to the PVT portal at one of the border crossings. The prototype NaI(Tl) portal that was tested is a single monitor, located only on one side of the traffic lane. [In normal operation a NaI(Tl)-based portal would contain components on both sides of a lane.]

Pulse height spectra collected during the field test included the following: background, calibration with known sources, vehicle profiles as they traversed the portal monitor and vehicles with cargo stationary in front of the portal. Vehicle profiles include pulse height spectra at 0.1 s time intervals as the vehicles passed through the portals. The type of cargo and its weight were obtained from the vehicle drivers. The test surveyed approximately 3800 trucks, while less than 1% of them emitted a gamma-ray flux sufficient to potentially produce an alarm. Those alarming vehicles primarily

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contained NORM and high-count spectra were collected for those vehicles. A small subset of stationary vehicles was also surveyed using high purity germanium (HPGe) detectors.

**Fig. 1. NaI(Tl) Portal Monitor (right) Located Adjacent to PVT Portal**

**II. EQUIPMENT**

**A. NaI(Tl) Portal**

The prototype RPM contains four individual NaI(Tl) detectors (Figure 2). Each detector is 10 cm x 10 cm x 41 cm (4 in x 4 in x 16 in). The detectors are attached to a 9-cm-diameter photomultiplier tube and are enclosed by 0.5-mm stainless steel. The energy resolution of the individual NaI(Tl) detectors was approximately 8% at 662 keV. Although the raw data contains histograms for individual detectors, all plots displayed and number quoted in this manuscript show the gain-corrected sum of the individual detectors. The composite resolution from the summed signals was about 8.5%.

**Fig. 2. Four NaI(Tl) Detectors inside Portal Monitor**

Two types of material shielded all sides of the cabinet containing the NaI(Tl) detectors except the front and provided collimation in the forward direction. One ancillary goal was to determine the effects of two different background shielding configurations on the measured spectra. For some vehicle passages at the first test site, the shielding was 0.635-cm (0.25-in) lead plus 2.54-cm (1 in) steel on the back and 1.27-cm (0.5 in) steel on sides and bottom. The other shielding configuration used 5-cm (2-in) lead on five sides of the detectors and no steel. The 5-cm lead produced minimal reduction in the background relative to the steel and was not used at the second test site.

Pulse height spectra for the individual NaI(Tl) detectors were obtained using an X-Ray Instrumentation Associates (Newark, CA) DGF-4C multichannel analyzer (MCA), which can process four input signals. Digitized signals from the MCA were obtained as 65,000-channel spectra (no fewer channels being provided by the MCA) that were subsequently consolidated into 512-channel spectra for the analysis of specific energy windows. Signals from the multichannel analyzers were processed in a computer that recorded the individual gamma-ray events in list-mode for subsequent reprocessing. On-line analysis used nine (9) energy windows in the 512-channel spectra parsed into 0.1-second intervals as vehicles passed the portal.

The operator of the RPM is able to view gamma-ray spectra and analysis results in various modes of operation. In one mode, spectra can be accumulated and displayed during acquisition. This mode is useful for setup of the system and obtaining spectra from stationary vehicles. In the “fast mode” operation, the system operates as a RPM, collecting and processing data every 0.1 seconds and calculating radiation alarms based on gross-count and spectral analysis algorithms. The algorithms assess the composite spectra obtained by summing the individual spectra from the four detectors. In the “fast mode” of data collection, background data are automatically collected whenever no vehicle is present. The background spectra for the individual detectors are automatically updated to include only recent data (typically the last 10 minutes).

When monitoring vehicle profiles, operators started and stopped the acquisition when vehicles crossed the entrance and exit points of the portal monitor. For more permanent applications, the system is equipped to interface with presence sensors.

**B. PVT Portal**

The PVT portal contained a single PVT detector of dimension 3.8 cm x 35.6 cm x 173 cm, having two 2.5-cm-diameter photomultiplier tubes on one end. Pulses from the two tubes were summed prior to analysis. At the first test site, the PVT portal contained conventional electronics that separated the energy spectrum into two, broad energy windows. At the second site the PVT portal was operated in a spectral mode using electronics and a MCA identical to that in the NaI(Tl) portal. This provided energy spectra that could later be used for optimal analysis of PVT-based spectral data. The energy resolution of PVT is very poor, with a broad continuum and Compton edges being the main features of the spectra. Location of the Compton edges gives a means for determining the approximate energy calibration.

**C. High Purity Germanium (HPGe) Detectors**

Two HPGe detectors surveyed about 150 vehicles at the second test site after the vehicles had passed the NaI(Tl) and PVT portals. These detectors had 140% and 25% efficiencies relative to a 7.6 cm x 7.6 cm right cylinder of NaI(Tl). Vehicles were stationary for about 300 s during the HPGe measurements. The detectors were mounted on a cart and located about 2 m from the side of the vehicles. The measurements with the HPGe detectors provided high-resolution spectra for comparison with the lower resolution spectra from the NaI(Tl) and PVT detectors. Although the
HPGe data may prove useful for some applications, it is not relevant to the issues addressed in this paper and thus will not be discussed hereafter.

III. CALIBRATION

Calibration of the NaI(Tl) detectors accomplished the dual purpose of establishing an energy-versus-channel correlation and aligning the peaks from the four NaI(Tl) detectors. Energy calibration ensured that the gamma-ray counts were properly parsed into predefined energy windows for data analysis. Five standard sources with activities of approximately 10 µCi provided calibration points: $^{57}$Co, $^{133}$Ba, $^{137}$Cs, $^{60}$Co, and $^{232}$Th. After locating the sources a distance of 2 m in front of the RPM, the 239-keV, 583-keV, and 2614-keV gamma rays in the decay chain of $^{232}$Th provided the primary calibration energies. Using the same source, measurements of the count rates provided a check of consistent detector and electronics operation. Figure 3 (upper part) shows several calibration spectra from the sources, after background has been subtracted. The $^{241}$Am spectrum in the figure was obtained by placing the source directly on the door of the portal, rather than 2 m away, due to its low activity. The $^{241}$Am source helped to define the low-energy cutoff, which was approximately 30 keV. Using this lower level threshold and summing through 3000 keV, the total background count rate in the NaI(Tl) portal monitor averaged 1250 counts per second (cps) at the first site and 1400 cps at the second site.

The same sources allowed calibration of the PVT portal. Figure 3 also shows PVT calibration spectra for sources located at 2 m, after background has been subtracted. The background count rate in the PVT detector averaged 1500 cps at the first site and 1900 cps at the second site. The relatively higher count rate for the PVT background, compared to NaI(Tl) background, at the second site indicates that the lower level threshold was higher at the first site than at the second site (where different electronics were used). Comparing the NaI(Tl) and PVT backgrounds shows that for gross-count equivalency the NaI(Tl) and PVT would have been more closely matched if the NaI(Tl) portal had contained five, rather than four, detectors.

A key figure of merit in characterizing the efficiency of portal monitors is the sensitivity to calibration sources. Table I lists count rates for calibration sources relevant in national security applications. The count rates are shown in the table as counts per second per micro Curie (cps/µCi), after background has been subtracted.

<table>
<thead>
<tr>
<th>Source</th>
<th>Energy Window (keV)</th>
<th>Entire Spectrum (cps/µCi)</th>
<th>NaI(Tl)</th>
<th>PVT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{57}$Co</td>
<td>50 to 160</td>
<td>99</td>
<td>100</td>
<td>109</td>
</tr>
<tr>
<td>$^{133}$Ba</td>
<td>250 to 430</td>
<td>73</td>
<td>147</td>
<td>202</td>
</tr>
<tr>
<td>$^{137}$Cs</td>
<td>590 to 740</td>
<td>46</td>
<td>101</td>
<td>115</td>
</tr>
<tr>
<td>$^{60}$Co</td>
<td>1080 to 1440</td>
<td>77</td>
<td>203</td>
<td>225</td>
</tr>
<tr>
<td>$^{232}$Th</td>
<td>2465 to 2800</td>
<td>8</td>
<td>265</td>
<td>292</td>
</tr>
<tr>
<td>Bkg.</td>
<td>--</td>
<td>--</td>
<td>1400</td>
<td>1900</td>
</tr>
</tbody>
</table>

The spectra of the four individual NaI(Tl) detectors remained well aligned with each other, and maintained their proper energy calibration for many hours (even overnight) despite having no active means for gain stabilization. Gain drifts were less than about ± 2 % during the tests, perhaps because ambient temperatures did not vary widely during the test periods.

IV. DATA AND RESULTS

The conglomerate data set from both ports consists of approximately 3800 vehicle profiles. In addition to gamma-ray signatures, the data set includes vehicle type, cargo type, and cargo weight. During the course of both tests, several vehicles alarmed in the CBP portal monitors. For most of these vehicles, long count runs were subsequently taken with the load stationary in front of the NaI(Tl) portal monitor, as well as the normal drive-through profile.

A. Background Suppression

Figure 4 shows two spatial profiles of gross counts as the vehicles passed the NaI(Tl) portal. The decrease in count rates
is caused by temporary shielding of the detectors from the background radiation by the vehicle. The amount of background suppression (commonly known as “shadow shielding”) depends on the mass and distribution of the vehicle and its cargo. For large, loaded trucks this suppression was about 30% in the gross signal, although the amount of suppression varied significantly from truck-to-truck. As shown in the figure, the amount of background suppression can vary significantly along the length of the vehicle. The cargo of steel wire for one of the profiles in Figure 4 was apparently concentrated near the front and back of the trailer, with a gap in the middle.

![Graph showing background suppression for trucks carrying paper and steel wire](image)

**Fig. 4. Background Suppression for Trucks Carrying Paper and Steel Wire**

### B. On-line Analysis

The on-line analysis algorithm used during these tests analyzed counts in specific windows and examined these counts every 0.1 s as vehicles passed the detector. The NaI(Tl) alarm algorithm compared ratios of counts in various windows to corresponding values for previously collected background data. This particular analysis is primarily intended for highly enriched uranium (HEU) and plutonium, rather than NORM. Table II lists the energy windows used for NaI(Tl).

<table>
<thead>
<tr>
<th>Window Number</th>
<th>Source</th>
<th>Window (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>235U; 226Ra (238U)</td>
<td>155 - 215</td>
</tr>
<tr>
<td>2</td>
<td>235U “background”</td>
<td>250 - 310</td>
</tr>
<tr>
<td>3</td>
<td>239Pu</td>
<td>310 - 375</td>
</tr>
<tr>
<td>4</td>
<td>239Pu</td>
<td>375 - 440</td>
</tr>
<tr>
<td>5</td>
<td>239Pu “background”</td>
<td>500 - 580</td>
</tr>
<tr>
<td>6</td>
<td>208Tl (232Th)</td>
<td>550 - 620</td>
</tr>
<tr>
<td>7</td>
<td>228Ac (232Th)</td>
<td>850 - 1030</td>
</tr>
<tr>
<td>8</td>
<td>208Tl (232Th)</td>
<td>2465 - 2800</td>
</tr>
<tr>
<td>Entire spectrum</td>
<td>-</td>
<td>50 - 3000</td>
</tr>
</tbody>
</table>

**Table II. Energy Windows Used in NaI(Tl) Spectral Analysis**

The PVT detector alarm algorithm relied on excessive count rates or “gross-count alarms” over the entire spectrum. No alarms due to HEU or plutonium were encountered during the field test. All observed alarms exceeded gross-count thresholds. The source of these alarms was NORM, and they had been previously detected at one of the standard CBP portal monitors used for primary screening.

### C. Metadata

Two crucial variables affect the radiation signature of a vehicle: the cargo and the vehicle type. The cargo may contribute to an alarm due to its radioactivity or alter the spectral composition of background. The vehicle type influences how long the vehicle profile extends in time and also alters the spectral composition of background. The observed vehicles ranged in size from personal automobiles up to double tractor trailers. Truck cargo varied from empty up to 20,000 kg. Information from cargo manifests and drivers provided the type of cargo being transported in individual trucks. Paper and wood products, such as rolls of paper, lumber, plywood, veneer, scrap paper, and pallets, were the most common non-radioactive commodities encountered during the test. Other cargo frequently observed included scrap steel and food. Empty fuel tankers were also common. Figure 5 displays a common cargo and vehicle.

![Images of non-radioactive cargo and trucks](image)

**Fig. 5. Examples of Non-Radioactive Cargo and Trucks (wood and fuel truck)**

Cargo with count rates above background was almost exclusively NORM. Pottery (from Vietnam or other far-east countries), large granite slabs (for counter tops), rock-based floor tiles, construction stone blocks, and abrasive material (alumina zirconia) were the most common radioactive cargo. Radioactivity from the alumina zirconia was traced to 234mPa, 226Ra, and 228Th, which are related to 238U and 232Th. Non-NORM cargo observed during the test included one large source of 60Co (516,000 GBq; 5,800 Ci) in an engineered shield and uranium oxide (both shipments being properly manifested).

In addition, several trucks contained low-level radioactive materials. One common example of low-radiation cargo was live trees (in dirt). Data from such cargo will be useful in determining NORM effects on lower alarm thresholds.

### D. Example Spectra

Figure 6 shows spectra from two NORM events (pottery and ceramic tile), along with a background spectra. The data were scaled in the figure to separate the spectra for easier viewing. For all three spectra the dominant sources of gamma rays are the radionuclides 40K, 238U (with its primary gamma-ray signature from the decay product 214Bi) and 232Th (208Tl), which are present in the environment and give rise to both background radiation and NORM radiation. Comparison of the relative magnitudes of the peaks marked by arrows shows the relative abundance of the primary gamma rays. For example, the pottery spectrum contains enhanced 232Th
(2614 keV) and reduced $^{40}$K (1460 keV), compared to the background spectrum. The ceramic tile shows relatively enhanced counts at 609 keV, 1764 keV, 2204 keV, and 2447 keV from $^{214}$Bi, which is a decay product of $^{238}$U.

Figure 7 shows spectra from two non-NORM cargos: $^{60}$Co and UO$_2$. The large, shielded $^{60}$Co irradiation source could not be identified with a hand-held isotope identifier despite its immense activity due to shielding. The characteristic double peaks from $^{60}$Co are distorted by the radiation shield around the source. Uranium oxide (> 4,000 kg) produced a spectrum with high count rates due primarily to 1001-keV and 767-keV gamma rays from $^{234m}$Pa, which is in the decay chain of $^{238}$U. These gamma rays are scattered in the uranium oxide, contributing to the large number of low-energy counts.

![Fig. 6. Background and Alarming Vehicle Spectra](image)

![Fig. 7. Spectra from 60Co and U02Cargo.](image)

IV. V. CONCLUSION

Tests of the prototype NaI(Tl) portal monitor at two international border crossings provided valuable information that can be used to evaluate and compare NaI(Tl) and plastic portal monitors. Of particular importance will be the use of the data to improve the detection and identification of radioactive cargo, including NORM that transits the border. The data are also valuable for testing algorithms based on gamma-ray energies for their capability to interdict the illicit transport of radioactive materials.

Although only a limited number of alarms was encountered during the field tests, the NaI(Tl) detectors did obtain and display spectra that were useful for NORM identification. For example, pottery and ceramic tile cargo showed enhanced amounts of natural uranium and thorium, compared to background. Fertilizer with high potassium content provided a distinct peak in the energy spectrum at 1460 keV, the energy of the gamma ray emitted from $^{40}$K. Experience using the NaI(Tl) detectors showed that gain drifts of the electronics were minimal. However, for proper operation over wider ambient temperatures than encountered during the tests, it will be necessary to stabilize the gain electronically. Such gain stabilization can be readily accomplished using commercial electronics.

Radiation shielding consisting of 0.635 cm (0.25 in) of lead and 1.27 cm to 2.54 cm of steel will be adequate for collimating the detectors in the forward direction. Experiments with thicker lead showed only minimal benefits over this combination of thin lead and steel.

The large number of vehicles surveyed also provides an excellent data set for evaluating the effects of background suppression. Preliminary analysis shows that large, heavy vehicles typically suppress the background by about 30%. The background suppression varies significantly, both with vehicle size and also with cargo distribution along the length of the vehicle. It is very difficult to predict the shape of the background suppression profile, particularly when the cargo is contained within a closed trailer.

V. ACKNOWLEDGMENT

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VI. REFERENCES