Comparison of NaI(Tl) Scintillators and High Purity Germanium for Vehicle Portal Monitor Applications

James H. Ely, Edward R. Siciliano, and Richard T. Kouzes
Pacific Northwest National Laboratory

Abstract-- **Radiation portal monitors are being deployed at international border crossings to detect illicit transport of radioactive material. Typically, vehicles which have a gamma-ray radiation signature above a certain gross-count threshold proceed through a more thorough inspection to locate and identify the source of radiation. Plastic scintillators (e.g., poly vinyl toluene (PVT)) are the most common gamma-ray detectors for portal monitors, mainly because of their relatively low cost for large-area, high-sensitivity detectors. Plastic scintilators provide gamma-ray detection, but limited spectroscopic information. Sodium iodide [NaI(Tl)] scintillator-based portal monitors can provide isotopic identification and may be useful where isotopic identification is needed. Recently, high purity germanium [HPGe] -based portal monitors have been evaluated since the increased resolution from HPGe can potentially provide isotopic identification more precisely and rapidly if deployed with adequate efficiency.**

I. Introduction

Radiation portal monitors are commonly used at international border crossings to detect illicit transport of radioactive material, including special nuclear material (SNM) suitable for nuclear weapons.

There have been several papers investigating the advantages and challenges of using plastic scintillator and sodium iodide to detect gamma rays in radiation portal monitor applications [1-7]. Until recently, the main applications of radiation portal monitors have been at manufacturing plants and storage facilities for SNM and nuclear weapons as well as screening of scrap metal for recycling. Radiation portal monitors are currently finding increased utilization at international borders and ports of entry. For these border type applications, rapid screening for radiation is needed to minimize impact on commerce while maintaining a high degree of sensitivity to radiation sources in fully loaded vehicles. These requirements necessitate large detector areas positioned as close as possible to the vehicle. The most cost effective solution has been large stationary radiation portal monitors using plastic scintillator material straddling a roadway through which a vehicle passes. Velocity is an important consideration in this screening method since the signal integration time of a radiation source in a moving vehicle is inversely proportional to its speed. In order to screen large numbers of vehicles quickly, a two-step screening approach is most often used. First, the vehicle is screened with a radiation portal monitor to determine if any radiation is present in the vehicle. If radiation is present, a second screening is initiated where the source is located, often with another radiation portal monitor, and identified, typically with a hand-held isotope identifier. This two-step method of screening works well in principle as long as there are not too many innocent radiation sources passing through a port of entry. In fact, there are many items containing naturally occurring radioactive material (NORM) that cross international borders everyday, consisting of material such as fertilizers and earthenware. Another source of innocent alarms is people who have recently received medical treatments with radioactive isotopes. Both the NORM and medical isotopes result in primary alarms, triggering the secondary screening process which increases the time and cost of the overall radiation screening program. Using a detector with isotopic identification capability in the initial screening process can reduce or eliminate many of these innocent alarms while maintaining sensitivity to isotopes of concern. This would thereby reduce the cost and time of radiation screening. Sodium iodide detectors are more expensive than plastic scintillator-based detectors, but provide enhanced energy resolution at ambient temperatures, which enables spectroscopic identification of many specific radionuclides. There have been investigations into the use of NaI(Tl) for radiation portal monitor applications compared to plastic [7]. Use of NaI(Tl) detectors might reduce or eliminate the two step screening process, as the isotope would typically be identified in the first screening step. Although NaI(Tl) has enhanced energy resolution, for unambiguous isotope identification, even better energy resolution is needed. High purity germanium detectors have been the standard for isotopic identification of radionuclides over the last thirty years due to the superior energy resolution compared to NaI(Tl). Typical resolutions of NaI(Tl) detectors are of the order of 5-10% depending on the gamma-ray energy, whereas with HPGe the resolutions are less than 1% (typically a factor of 30 better than NaI(Tl) detectors).

Manuscript received October 2004. This work was supported by the U.S. Department of Homeland Security, Customs and Border Protection, and the U.S. Department of Energy, National Nuclear Security Administration, NA-22. PNNL-SA-42698. PIET-43741-TM-224.

All authors are with the Pacific Northwest National Laboratory (PNNL), Richland, WA 99352 USA. PNNL is operated for the Department of Energy by Battelle under contract DE-AC06-76RLO 1830.

J. H. Ely (509-376-0319, james.ely@pnl.gov)

E. R. Siciliano (509-375-2049, edward.siciliano@pnl.gov)

R. T. Kouzes (509-376-2320, rkouzes@pnl.gov)

0-7803-8701-5/04/$20.00 (C) 2004 IEEE

However, the expense of purchasing and operating HPGe detectors along with the requirement of cooling the detector to liquid nitrogen temperatures and their fragility has tempered the use of HPGe detectors. Recent advances in mechanical coolers may allow HPGe to be utilized in more field-type applications.

Perhaps the most important consideration in a comparison of NaI(Tl) to HPGe for portal monitoring applications is the efficiency of the detectors themselves. There have been many comparisons of the efficiency of NaI(Tl) to HPGe over the years, and in fact, the most common method of specifying a germanium detector is in terms of the relative efficiency compared to a 3 × 3 inch right cylindrical NaI(Tl) crystal. The relative efficiency is measured using a ^{60}Co point source at a distance of 25cm. NaI(Tl) has greater gamma-ray absorption due to the higher effective Z compared to HPGe, and so will have a higher overall efficiency for the same size detector. For isotopic identification, full energy peak efficiency is of considerable importance, and different analytical and semi-analytical functions have been used to describe both HPGe and NaI(Tl) full energy peak efficiencies [8]. For the same size detectors, the HPGe peak efficiency will be less, but because of its superior energy resolution, the isotopic identification capability of HPGe will be superior and the minimum detectable amount (MDA) of source material will be lower. A recent investigation of the efficiencies, resolutions, and MDA of common sized NaI(Tl) and HPGe detector systems has been made with regards to border security applications [9] in which the NaI(Tl) system provided the most efficiency and lowest MDA. However in this comparison the HPGe detector considered was a factor of 6 smaller than the NaI(Tl) detector.

In most applications, there must be a balance between cost and detector efficiency. The cost of HPGe detectors is much more than NaI(Tl) of comparable size, and this factor must be considered for specific applications. The cost comparison of NaI(Tl) to PVT plastic scintillator was investigated and for a typical commercial vehicle portal monitor employing 4 large-area plastic scintillators, the price of NaI(Tl) detector material was ~20 times that of the plastic material [7]. For a 100% relative efficient HPGe detector system with mechanical cooling, the current price is on the order of $75,000. To scale up to the same efficiency of a 4 × 4 × 16 inch NaI(Tl) crystal would require approximately 9 such HPGe detectors. From [7] it was determined 20 of the 4 × 4 × 16 inch NaI(Tl) crystals would be required to match the sensitivity of the plastic scintillator in a cargo type portal monitor; therefore 180 HPGe crystals would be needed to produce the same overall gross sensitivity (gross count rate). This equates to $13.5 million for the cost of a HPGe system with the same gross sensitivity of the commercial vehicle portal monitor using plastic scintillator. This calculation uses simple assumptions but does illustrate the large disparity in price of the HPGe compared to other detector material.

There are other considerations which need to be considered in the comparison of NaI(Tl) to HPGe for vehicle radiation portal monitor applications. HPGe requires cooling, which is more expensive, but removes the problems related to ambient temperature changes which may cause stability problems in NaI(Tl) systems. Rapid temperature changes can crack large NaI(Tl) detectors and the scintillation light output and resulting pulse-height spectra are dependent on temperature. These problems can be overcome in NaI(Tl) systems either by providing constant temperature environments or gain stabilization techniques with thermal insulations, but with added complexity and cost. Cooling for HPGe detectors has traditionally been provided by liquid nitrogen, but for field applications mechanical cooling provides a viable alternative. Investigation into more efficient and robust cooling for HPGe detectors is a current priority for HPGe system manufacturers. Durability is a consideration; NaI(Tl) systems have been designed and used in many field applications, whereas HPGe has been used primarily in laboratory type settings where the thin windows of the detection system can be protected. Since they will typically be used in a fixed location, portal monitors of both NaI(Tl) and HPGe can be engineered to operate in a wide variety of environmental conditions for an extended period of time.

Another factor for consideration is the need for a rapid real-time decision of the presence of any source of radiation above background while the vehicle transits a primary screening portal. For commercial vehicle portal monitors, the vehicle can shield the background as it passes through and lower the background from when no vehicle was present (background depression effect). Because of the very short time for data collection, spectral identification may not be possible, and instead, the baseline for this decision is the background spectrum just prior to vehicle entry. Thus, HPGe systems, with the improved energy resolution, may not have a significant advantage over NaI(Tl) sytems for this real-time decision mode.

II. SCENARIOS

To illustrate the above considerations and help define applications for the use of NaI(Tl) and HPGe in vehicle portal monitor applications, a set of six scenarios are explored below.

1. Screening vehicles in a single step. This application requires isotopic identification in the first screening, with no large-scale secondary screening. This method would be the ideal solution, as there would be very few vehicles that would require additional screening, and the impact on commerce would be minimized. Due to the large cost of either a NaI(Tl) or HPGe system, this option would most likely be feasible only in situations where large numbers of vehicles can be screened at a single point, or where an additional inspection would be time consuming and costly. For example, secondary inspection of a rail car in a train would require the whole train to wait, or the rail car would be pulled from the train, both of which have a significant impact on commerce. Since the HPGe system is anticipated to be an order of magnitude more expensive, sodium iodide based systems would most likely be used in such application.

2. Screening with plastic scintillator based portals in a first step, with single NaI(Tl) or HPGe systems used in secondary screenings. The second screening confirms the radiation signature found in the first pass and identifies the isotope(s). The advantage of this method is that the primary screening uses relatively inexpensive plastic scintillator detectors with a majority of the vehicles screened rapidly and cost-effectively. Vehicles with radiation signatures (primarily NORM or medical isotopes) are then sent to an additional screening area where the radiation is identified. In this way many initial screening areas (lanes of vehicles) can be used and the alarms sent to a central location. For this method the screening time may be increased from seconds (typically) in the first screening to minutes since the traffic volume is significantly lower in a secondary screening process. Increasing the time of screening may allow a reduction in the amount of either NaI(Tl) or HPGe material needed to perform adequate screening compared to the assumptions used earlier based on gross counting efficiency. NaI(Tl) will be more cost-effective in most implementations of this application, but there may be cost-effective solutions for HPGe, especially if the screening time can be increased so that less HPGe material is needed.
3. Masking scenario. This is a situation where there may be an isotope of concern within a load of NORM or masked by a medical isotope. The radiation signature increases the 'noise' in the radiation signal, and therefore masks the isotope of interest. Assuming the same gross efficiency, the HPGe detector would be able to distinguish masked isotopes of lower intensity than NaI(Tl), however, a quantitative comparison is difficult to perform with the number of masking signatures (NORM) which are observed. If one assumes that the masking signature produces high-energy gamma rays, then the masking of isotopes of concern (mostly low-energy emitters) would primarily be from the Compton continuum. In this case, the energy resolution of the HPGe is not as vital as instances where the peak energies are close together and high resolution is needed to distinguish the isotopes. In the masking scenario, HPGe would be the preferred detector, but real-world installations must consider the high cost as well. There are screening situations where masking by NORM would rarely be seen such as in passenger vehicle screening, but masking by medical isotopes, mostly characterized by low energy lines, would be possible. In these circumstances, the energy resolution of the detectors may play an important role in observing SNM in the presence of other low-energy sources.
4. Shielded scenario. Situations where the source of the radiation is located within a load of non-radioactive material may be difficult to identify since the load itself will cause a shielding effect. For those photons not completely absorbed, shielding tends to scatter the gamma-rays to lower energies via the Compton scattering process. The scattered gammas that reach the detector will not contribute to the full-energy peaks, resulting in more challenging identification. HPGe with higher energy resolution will be less affected by the shielding than sodium iodide, assuming the same efficiency for both detector systems. Shielding scenarios will be less probable in passenger vehicle screening, and thus energy resolution is less of a concern. In addition, sources of radioactivity would be more accessible in passenger vehicles, possibly allowing for smaller detector systems.
5. Hybrid systems. A hybrid system may incorporate a plastic scintillator detector with a smaller numbers of either NaI(Tl) or HPGe detectors. These hybrid systems may be more cost-effective, with the plastic scintillator used to confirm the radiation signature and locate the position of highest intensity and the additional detector used for isotopic identification. Such systems would require longer measurement times than standard portal monitors to obtain adequate sensitivity. For NaI(Tl), the added complexity of such a hybrid system may not be warranted, since the cost of sodium iodide is more comparable to the plastic scintillator material. When considering the high cost of HPGe however, the hybrid system becomes more attractive and may provide a cost-effective compromise between efficiency and energy resolution.
6. Portable applications of NaI(Tl) and HPGe. The primary purpose of a NaI(Tl) or HPGe based detector would normally be to identify the isotope producing the radiation signature. Current installations use hand-held detectors to provide this identification. The disadvantages of this approach include small detector size (to remain portable) and more manpower to perform adequate screening. A portal monitor performs a full screening of the vehicle, which is typically accomplished with detectors on both sides of the vehicle dynamically screening while the vehicle traverses the portal. There could be an intermediate solution which would incorporate transportable detectors mounted on a mobile device to provide localized isotopic identification. The detectors could be positioned closer to the source of radiation than a portal monitor and could integrate over a longer period of time. Both of these features would allow for smaller numbers of detectors than needed for a portal monitor system. Having the detectors mounted on a mobile platform would allow for large HPGe detectors with mechanical cooling to be positioned at preferred locations. The challenge of this method would be in the identification of the proper location for the isotopic identification, as the highest radiation signature may not represent the best location if masking is taking place. However, portable detector systems might represent a viable alternative for some installations where a full portal monitor may not be justified. For these applications, where the transportable system's weight is not an issue, the HPGe system might be the optimal choice as isotopic identification would be the primary function of the system.

Comparison of NaI(Tl) and HPGe for portal monitor applications involves some characteristics that have been quantified (e.g., intrinsic detection efficiencies, full-energy peak efficiencies, and cost) and other factors that are more difficult to quantify such as the issue of masking and shielding. Moreover, these factors may be weighted differently, depending on the specific application. As a guide for making these comparisons, the scenarios and anticipated performance of the detectors are summarized in Table 1.

III. CONCLUSIONS

NaI(Tl) and HPGe have been compared for vehicle portal monitor applications. Both NaI(Tl) and HPGe can provide isotopic identification, however HPGe has superior energy resolution, thereby providing a more definite identification. On the other hand, NaI(Tl) is significantly less expensive and more durable than HPGe, so for applications where cost or unattended operations are important factors, NaI(Tl)-based portal monitors may provide the best option.

Primary screening is one application where cost alone can be the determining factor because of the sheer number of portal monitors. The lower cost of NaI(Tl) also allows for larger detectors to be employed than for HPGe. This is an important factor for applications where secondary screening is time consuming and costly and isotopic identification is needed in primary vehicle screening, and the baseline of performance are the total-counts obtained with large-area plastic scintillators. In addition, in applications such as passenger vehicle screening where masking and shielding are less likely, the NaI(Tl) systems may be adequate.

HPGe detectors are more expensive than sodium iodide detectors, but they provide more definite isotopic identification due to their superior energy resolution. HPGe is less affected by masking and shielding effects and is the preferred detector based solely on isotopic identification capability. HPGe however needs cooling, a requirement which makes the system more fragile and costly to operate and maintain. HPGe inherently has less stopping power compared to NaI(Tl) so larger detectors are needed to obtain the same efficiency. For certain portal applications where a small number of HPGe detectors could be used, HPGe may be the option of choice, assuming the cooling and fragility can be addressed.

IV. REFERENCES

[1] W. H. Chambers, H. F. Atwater, P. E., Fehlau, R. D. Hastings, C. N. Henry, W. E. Kunz, T. E. Sampson, T. H. Whittlesey, and G. M. Worth, *Portal Monitor for Diversion Safeguards*, LA-5681, Los Alamos Scientific Laboratory, Los Alamos, NM, 1974.

[2] P. E. Fehlau and G. S Brunson, "Coping with plastic scintillators in nuclear safeguards," *IEEE Trans. Nucl. Sci.*, vol. NS-30, no. 1, pp.158-161, 1983.

[3] P. E Fehlau, C. Garcia, Jr., R. A. Payne, and E. R. Shunk, *Vehicle Monitors for Domestic Perimeter Safeguards*, LA-9633-MS, Los Alamos National Laboratory, Los Alamos, NM, 1983.

[4] P. E Fehlau, *An Applications Guide to Pedestrian SNM Monitors*, LA-10633-MS, Los Alamos National Laboratory, Los Alamos, NM, 1986.

[5] P. E Fehlau, *An Applications Guide to Vehicle SNM Monitors*, LA-10912-MS, Los Alamos National Laboratory, Los Alamos, NM, 1987.

[6] R. L York and P. E. Fehlau, *1997 Update for the Applications Guide to Vehicle SNM Monitors*, LA-13247-MS, Los Alamos National Laboratory, Los Alamos, NM, 1997.

[7] D.C. Stromswold, E.R. Siciliano, J.E. Schweppe, J.H. Ely, B.D. Milbrath, R.T. Kouzes, and B.D. Geelhood, "Comparison of Plastic and NaI(Tl) Scintillators for Vehicle Portal Monitor Applications," IEEE Conference 2003.

[8] M. Sudarshan, J. Joseph, and R. Singh, "Full Energy Peak Efficiency of NaI(Tl) Gamma Detectors and Its Analytical and Semi-Empirical Representations", *J. Phys. D* ***25*** (1992) 1561-1567.

[9] A. Perez-Andujar, L. Pibida, "Performance of CdTe, HPGe and NaI(Tl) Detectors for Radioactivity Measurements", *Applied Radiation and Isotopes 60* (2004) 41-47.

Table 1. Summary Table of Comparison of NaI(Tl) and HPGe.

		NaI(Tl)	**HPGe**
Single Pass Screening		Good	Costly
Second Pass Screening (Commercial Vehicle)	Single System	Good but not ideal for masking and shielding	Costly but preferential if masking or shielding probable
	Hybrid System	Good but may add too much complexity	Preferred for masking and shielding
	Portable	Good	Preferred for masking and shielding
Second Pass Screening (Passenger Vehicle)	Single System	Good	Preferred but costly
	Hybrid System	Good but may add too much complexity	Preferred but costly
	Portable	Good	Preferred