

Overview of Portal Monitoring at Border Crossings

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Abstract -- The Bureau of Customs and Border Protection has the task of interdicting illicit radioactive material at ports of entry. Items of concern include radiation dispersal devices (RDD), nuclear warheads, and special nuclear material (SNM). The preferred survey method screens all vehicles in primary and diverts questionable vehicles to secondary. This requires high detection probability in primary while not overwhelming secondary with alarms, which could include naturally occurring radioactive material (NORM) found in acceptable cargo and radionuclides used in medical procedures. Sensitive alarm algorithms must accommodate the baseline depression observed whenever a vehicle enters the portal. Energy-based algorithms can effectively use the crude energy information available from a plastic scintillator to distinguish NORM from SNM. Whenever NORM cargo limits the alarm threshold, energy-based algorithms produce significantly better detection probabilities for small SNM sources than gross-count algorithms. Algorithms can be best evaluated using a large empirical data set to 1) calculate false alarm probabilities, 2) select sigma-level thresholds for operationally acceptable false alarm rates, and 3) determine detection probabilities for marginally detectable pseudo sources of SNM.

I. INTRODUCTION

The defense philosophy of the US changed after the terrorist attack on September 11, 2001. The threat vectors for delivery of nuclear weapons or radioactive materials expanded from military systems to include transportation modes used by commerce and passenger carriers. Sophisticated military systems such as missiles and bombers allow weapon delivery to specific targets at specific times and are useful for destroying or deterring the use of other nuclear weapons. However, terrorist attempts to create psychological and economic disruption do not require the precision or timing of such sophisticated delivery systems. As a result, defensive measures must include radiation screening of cargo and passenger transportation modes for the SNM used in nuclear weapons and other radionuclides that might be used in RDDs.

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The Bureau of Customs and Border Protection (BCBP) has the task of interdicting illicit radioactive material at ports of entry. Pacific Northwest National Laboratory (PNNL) is deploying passive radiation portal monitor (RPM) systems on their behalf.

II. SOURCES OF CONCERN

The nuclear warhead/bomb is a weapon of mass destruction. If detonated in a major US city or port, there would be a massive direct loss of life and extensive physical damage to the city's infrastructure. Rebuilding on the contaminated site might be problematic. If a warhead were detonated anywhere within the US, the physical damage would be severe.

All nuclear weapons contain SNM as the fissile material, which undergoes a nuclear reaction during detonation to produce blast and a host of fallout fission products that contaminate a large surrounding area with radioactive material. Weapon-grade plutonium (WGPu – ^{239}Pu) and highly enriched uranium (HEU – ^{235}U) are of special concern. WGPu can be readily detected by passive RPMs using either 1) neutron sensors to detect the spontaneous fission of ^{240}Pu present at about 6% in WGPu or 2) gamma rays. The 414-keV gamma ray from ^{239}Pu is a primary indicator of WGPu [1]. Neutron detection is a useful detection method for WGPu, because the neutron background rate is much lower than the gamma background rate, and NORM does not emit neutrons. In contrast, HEU is more difficult to passively detect, because 1) HEU does not emit neutrons at a useful rate, 2) the overall gamma emission rate is much lower, and 3) the 186-keV gamma ray from ^{235}U is less penetrating. Alternate and more penetrating indicators of HEU can be the 1001-keV gamma ray from $^{234\text{m}}\text{Pa}$, which is a daughter of ^{238}U (7% of HEU) and the 2614-keV gamma ray from ^{208}Tl , which is a daughter of ^{232}U (trace levels). The 1001-keV peak also occurs more strongly in natural and depleted uranium spectra, which are of less interest. The 2614-keV peak is also strongly associated with NORM.

The RDD or “dirty bomb” is a weapon of mass disruption rather than mass destruction. The RDD would primarily inflict psychological damage on our citizens and terrorize them. A RDD has the potential for major economic disruption, which could impose a high cost on the economy. If a RDD were detonated, there would be a temporary loss of the immediate area, and some lives could potentially be lost in the initial explosion. The country would have to bear radiation decontamination expenses, which would be minor compared to the cost of a nuclear warhead detonation. A RDD denotation would have many similarities to what occurs when a steel mill accidentally melts a substantial radiation source present within recycled scrap metal (e.g., the immediate area is contaminated, production is lost, cleanup is expensive, but recovery occurs).

A RDD could contain any of a large number of radionuclides. However, in contrast to a nuclear weapon, the entire amount of radioactivity is present during transport and must be substantial (i.e., kiloCurie levels) to effectively contaminate a significant area. Potential radionuclides include fission products found in spent nuclear fuel and commercially used radioisotopes. Such radionuclides emit sufficient gamma ray, neutron, or bremsstrahlung radiation to be rapidly detected by RPMs. Almost any large or intense radiation source should be investigated as a potential RDD.

One of the main limitations for the application of RPMs is the naturally occurring radiation that is present in all materials. The detection of neutrons from cargo is very unique to WGPu and a few man-made sources. Thus, detection of excess neutrons is immediately far more serious than the detection of excess gamma rays. Since NORM and medical radionuclides emit gamma rays, the simple detection of an increased gross gamma-ray count is not necessarily unique to SNM or RDD threats. The energy of the primary gamma ray is crucial to a unique threat signature. An initial screening with a large area plastic scintillator is adequate to rapidly identify potential problematic cargo in the large flow of commerce. Both HEU and WGPu have spectral profiles with lower-energy components than NORM and can be readily distinguished from NORM by energy-based alarm algorithms.

III. SURVEY STRATEGY

It is necessary to survey every vehicle entering the country for radioactive cargo, and one expects only a very few threatening radionuclide cargos. It is extremely important to intercept a radionuclide threat item. This differs from surveys for drugs or other contraband, where one can have effective enforcement while only surveying a statistical sample of vehicles, especially when intelligent targeting can increase detection probabilities. Since a huge volume of cargo enters at some ports of entry, the time available for surveying each vehicle is limited by the desire to facilitate the flow of legal commerce. Since one of the impacts of a RDD detonation is the subsequent economic impact from reduced trade, it is undesirable to cause a similar economic problem in the desire to alleviate RDD smuggling.

BCBP has traditionally relied on a two-tier screening process where all vehicles are rapidly screened in primary followed by a more extensive screening of a few suspect vehicles in secondary. The use of RPMs naturally fits this approach. Every vehicle passes through a RPM just prior to stopping at the booth for primary screening. The detection probability (DP) in primary screening must be very high, because normally any vehicle that does not produce a primary alarm will be released. The false alarm probability (FAP) can be moderately high, because secondary screening can usually be accomplished within a modest time, but operational resources are required.

Statistical false alarms are related to measurement errors due to statistical fluctuations in the natural background, but are unlikely to be repeated in secondary. Assuming Gaussian statistics, a statistical false alarm probability of less than 0.1% can be achieved with an alarm threshold of 3-sigma.

Systematic or nuisance false alarms are caused by NORM [2], medical radionuclides [3], and/or legal radioactive shipments of man-made radionuclides. Nuisance alarms are more frequent than statistical alarms for cargo surveys and potentially require a higher alarm threshold to meet operational requirements. Some energy-based alarm algorithms can reduce the number of NORM alarms. The low-energy and point source nature of medical alarms make these alarms difficult to avoid by sophisticated alarm algorithms aimed at efficient HEU and WGPu detection. However, medical alarms can be easily handled when the source is located within a person that can be readily separated from the vehicle. Another type of nuisance alarm is caused by cross talk when a "hot" source potentially triggers simultaneous alarms in multiple lanes, but innocent vehicles can be easily released if an identical RPM in secondary does not subsequently alarm when the suspect vehicles are separately measured.

The mix and type of these alarms depends on the port of entry and the vehicle type. For example, a car is more likely to produce a medical alarm than a NORM alarm, because cars lack sufficient cargo capacity for enough NORM to exceed the threshold. In addition, the types of cargo handled by a port-of-entry are dependent on the port location (e.g., auto-industry cargo frequently occurs in Michigan).

Many ports use RPMs just prior to each primary inspection booth. Vehicles stop at a stop line and then roll slowly through the RPM prior to stopping at a booth. The velocity is not generally constant as the vehicle first accelerates from the stop line and then slows to stop at the booth. Some ports use a RPM at a chokepoint before the vehicles fan out for the inspection booths. Vehicles roll through the chokepoint without stopping nearby. Vehicle velocity is generally uniform while passing through a chokepoint RPM, and relating any spatial peak to a potential source location in the vehicle is then relatively easy. A chokepoint installation uses fewer sensors, but tracking alarming vehicles is more challenging. The slower vehicle speeds associated with a stop line allow longer measurement times, which achieve better counting statistics.

The RPM collects counts in brief time intervals that allow distinguishing the spatial profile of a point source from a uniform load of NORM. The alarm algorithms average several of these brief counts to achieve more optimal counting statistics. If the averaging time is longer than the source residence time, the signal is diluted with excessive background. If the averaging time is too short, valuable signal is ignored.

A sensor with an area of about one square meter is necessary to achieve adequate statistics for potential SNM sources. A RDD source could be readily seen with a much smaller sensor area because of the far greater source strength.

IV. SENSOR IMPLICATIONS

Selection of a survey sensor and its optimization require an understanding of the loaded-vehicle survey problem (i.e., large trucks and/or cargo containers). This problem is significantly different from the otherwise-empty-truck survey encountered at nuclear installations where the guards more time per vehicle and routinely open and examine cargo areas.

The limited survey time at ports of entry requires a large area sensor to maximize sensitivity. A small NaI(Tl) sensor will be far more sensitive to NORM nuisance alarms (due to the proximity to the outer layer of NORM) than to an interior source of concern surrounded by typical cargo. The number of medical alarms will be relatively independent of the sensor size, because medical sources are typically very strong.

Modeling a potential signal as a reduced-strength point source of the same radionuclide in an otherwise-empty-truck may be reasonable for photopeak detection, but does not account for the build-up of the low-energy component of the spectrum due to Compton scattering or the effects of the surrounding cargo on the spatial profile.

Positioning of the sensors between the deck and ceiling of the cargo container is most desirable under the loaded-truck scenario. The shielding due to surrounding cargo is potentially greater than that due to vehicle structural materials under the deck.

Intermodal containers impose weight and volume limits on the cargo. Thus, the average cargo density must be less than 0.4 g/cc when volume-limited. If the cargo is low-Z material, there is a significant build up of the low-energy component of the gamma spectrum due to Compton scattering within the cargo. The gross-count mode is significantly more sensitive than a photopeak mode for gamma rays observed through low-Z media. If the cargo is high-Z material, there will be low-attenuation pathways between dense cargo elements due to weight limits. In that case, nearly complete vertical coverage of the cargo container provides the best opportunity to detect a beam of escaping gamma rays. Vertical orientation of a rectangular plastic scintillator provides better vertical coverage and slightly improves the spatial resolution. For vehicle stability, heavy, dense cargo is generally loaded low, on the vehicle centerline, and concentrated over the dual axle wheels. This gives the upper panels a relatively unobstructed view of the load at the centerline.

Since energy-based algorithms are beneficial, a uniform response over the sensor area for equivalent energy depositions is desirable. Using photomultiplier tubes (PMTs) at opposite short ends of a rectangular scintillator and summing their pulse-heights aid this energy uniformity by reducing spatial differences in light collection efficiency (e.g., no difficult to view corners). A coincidence requirement between those PMTs allows use of a lower deposited-energy threshold. Using thin slabs of plastic scintillator compromises light collection uniformity, because more reflections occur as light travels toward the PMT. Since energy-ratio algorithms require good statistics for both the high-energy and low-energy spectral components, use of thicker plastic is beneficial, because many high-energy gamma rays will not interact in a thin sensor.

V. BASELINE DEPRESSION

As a vehicle passes through a RPM, the vehicle itself shadow shields gamma rays from the surrounding environment. This baseline depression has been characterized using empirical data [4]. Figure 1 illustrates the spatial profile due to baseline depression along with a potential increase from the depressed baseline due to a uniform NORM load. For a

large truck, the baseline typically drops significantly relative to the fixed background value as measured between vehicles. Much of the baseline depression is due to the effectiveness of the deck and structure of the vehicle at blocking gamma rays from the nearby environment (e.g., the roadway). The actual load preferentially blocks the radioactivity to the side of the vehicle, which often is a small component of the observed background. Any signal from a source within the vehicle increases from the depressed baseline value rather than the between-vehicle background value. Figure 1 shows identical signal increases for three scenarios. It is clear that some sources, which could cause an alarm when located between vehicles, might be unlikely to alarm when located within an otherwise empty truck, which depresses the baseline. Under the loaded-truck scenario, both shielding by surrounding cargo and the baseline depression significantly impact alarm sensitivity.

A few trucks contain NORM, which could increase detection probability by raising the effective baseline. However, if a higher threshold is used to avoid NORM alarms, detection probability for all vehicles decreases. Many vendor-supplied RPM alarm algorithms ignore the baseline depression and use a threshold calculated relative to the fixed baseline by a user-supplied sigma-value or multiplicative factor. Great care must be used in stating sensor capabilities using this type of algorithm. Merely walking a calibration source through a RPM does not reproduce the baseline depression that occurs for a large vehicle.

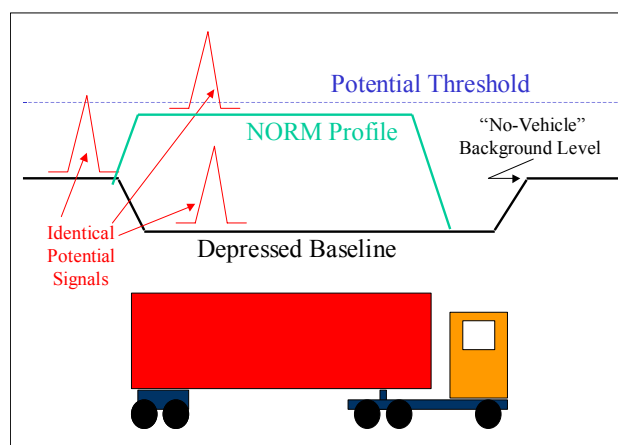


Figure 1. Schematic Diagram Illustrating Baseline Depression and the Potential Increase Due to a NORM Load.

It may be desirable to alarm on modest signals that are small relative to the amount the baseline is depressed. However, such signal increases do not regain the between-vehicle background value and would never exceed a higher threshold value. Simple alarm algorithms that ignore baseline depression are not sensitive to signals smaller than the baseline depression rate. Survey locations with higher background count rates experience the same fractional baseline depression, and the limitations scale accordingly. Lowering the background rate through use of less radioactive construction materials near the RPM would reduce this fundamental limitation.

Two alarm-algorithm approaches effectively take into account baseline depression and avoid this limitation. One uses spatial modeling to empirically produce an estimated depressed baseline. The sensitivity of a spatial model is limited by the minor baseline depression structure associated with the truck structure and loading (e.g., the dual axle wheels more effectively shadow shield the roadway). A narrow spatial filter can be used to model the baseline under point source peaks. Alternatively, one could attempt to fit a parameterized baseline depression model.

The other approach uses multiple energy thresholds and either predicts the profile of the baseline based on the profile in other energy bands or examines ratios between energy bands. The count ratio between energy bands is not nearly as depressed as the gross-count baseline, because the energy spectrum of the surrounding background closely matches NORM. Energy-based algorithms exist in several forms.

VI. NORM LOAD PROFILES

The spatial profile of an 18-wheel truck with a uniform NORM load will perhaps drop below the fixed background while the tractor is in the RPM, but then will increase to a constant value above the fixed background while the NORM cargo is in the RPM (see Figure 1). If the NORM is not uniformly distributed, the spatial profile will indicate the NORM loading. The maximum NORM rate becomes a problem for the simple fixed-background algorithm, which potentially forces the use of a higher threshold value than required to merely overcome statistical fluctuations. Whenever the alarm threshold is merely raised to avoid excessive NORM nuisance alarms, a smaller sensor could be used, unless complementary algorithms make better use of the measurement precision. Many NORM items are only very slightly radioactive, but the combined contribution of several tons of NORM produces an over-threshold increase in the gross count and causes alarms.

It can be difficult to rapidly obtain an energy spectrum from a single item in a NORM load. A plastic-scintillator-based RPM in secondary with several energy thresholds may provide as much or more useful energy information as a small handheld NaI(Tl) or HPGe sensor.

The broad increase due to typical NORM loads has two adverse affects on survey statistics. 1) A higher threshold decreases the detection probability for modest radiation sources. 2) The nuisance alarm rate increases, since some NORM loads must be sent to secondary, because they are more radioactive than typical NORM loads. A high nuisance alarm rate is undesirable, because it potentially ties up enforcement resources in secondary. The selection of a threshold is a compromise between these two adverse affects and depends on the local traffic in NORM.

The same two algorithm approaches used to overcome baseline depression (i.e., spatial and energy-based) can also handle this NORM problem. If the broad NORM increase is included in a baseline calculated to reveal narrow peaks, the threshold relative to that tracking baseline can be much smaller than it would be relative to either the fixed background or the depressed baseline. The energy-based approach works well, because the NORM load has the same broad energy profile as the natural background.

The spatial profile of a NORM load can be effectively used in secondary, where a slow and uniform drive through an RPM can be readily enforced. Any spatial peak is a potential point-source profile and warrants extra investigation. Spectral measurements of significant duration can more readily be made in secondary to aid in source identification. A large spectral sensor facilitates 1) rapid source identification and 2) scanning a NORM load for any source of concern having a different spectral and spatial profile.

VII. COMPARISON OF ALARM ALGORITHMS

A very useful method of quantitatively comparing potential alarm algorithms has been developed [5]. It uses a large empirical data set to calculate a false alarm probability (FAP) curve as a function of sigma-value threshold for each algorithm. The FAP curve is a strong function of each particular algorithm. The empirical FAP curve includes both statistical and systematic components. The systematic component dominates and includes NORM loads, medical alarms, and legal radiation shipments. An empirical data set of about 30,000 vehicles achieves adequate precision in the tail of the distribution used for the FAP. Using that FAP curve, one selects an appropriate sigma-value threshold to achieve an operationally acceptable FAP value. Then, using a subset of that empirical data, one can inject a calculated point-source signal and find the corresponding detection probability (DP) for each algorithm. The injected spatial profile corresponds to $\cos(\theta)/r^2$ and was placed on the vehicle centerline at a random point within each vehicle. The counts are distributed between energy bins to match experimental observations for HEU and WGPu. Four pseudo source strengths (e.g., producing 500-cps, 1000-cps, 1500-cps, and 2000-cps as the added count on a sensor panel at closest approach) were selected to illustrate DP values reasonably obtainable near the detection limits with a realistic background rate. Ultimately, one desires survey sensitivity to sources as low as reasonably achievable, because difficult scenarios and physical limitations exist.

Figure 2 shows such a probability-curve set for the fixed-background algorithm that ignores baseline depression. The FAP curve in Figure 2 is in the lower left-hand corner with small amplitude, because baseline depression has effectively left-shifted the FAP=1 point many sigma below the fixed background value. However, an 18.5-sigma alarm threshold (i.e., vertical arrow) is required to achieve the desired FAP value for comparison to the much more sensitive energy-based algorithm. A DP=23% is all that can be achieved for the 2000-cps pseudo source. The 1000-cps pseudo source cannot be detected with this algorithm at this FAP level, because the corresponding DP is minuscule.

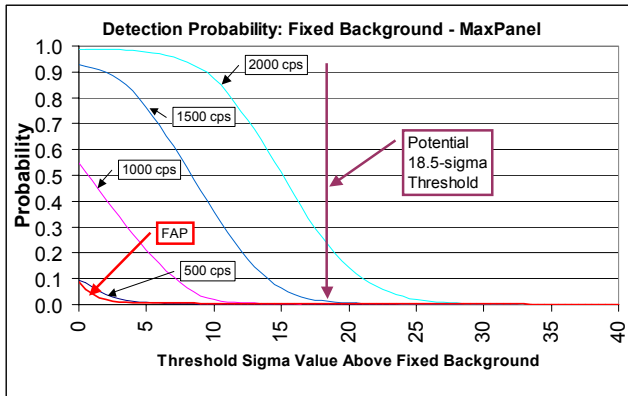


Figure 2. False Alarm Probability (FAP) and Detection Probabilities Using the Fixed Background Algorithm, which Ignores Baseline Depression.

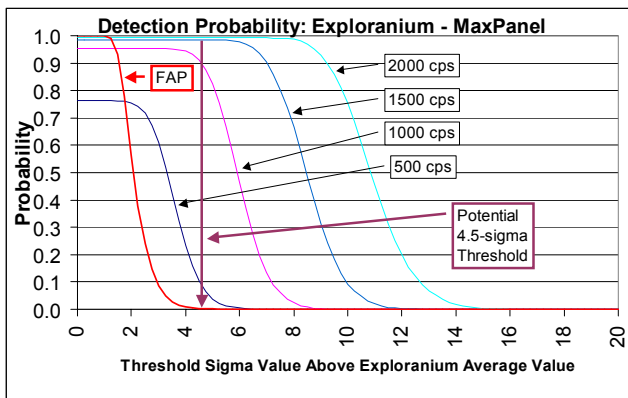


Figure 3. False Alarm Probability (FAP) and Detection Probabilities Using the Energy-Based Algorithm Accounting for Baseline Depression.

Figure 3 shows the same probability curve set for an energy-based algorithm [6]. The FAP curve in Figure 3 is right-shifted slightly, because the maximum value for the vehicle was selected (maximum panel and maximum deviation loca-

tion). However, a 4.5-sigma alarm threshold (i.e., vertical arrow) is required to achieve the same desired FAP value for comparison to the fixed background algorithm. This lower threshold value indicates that the sensor is not oversized, and that this algorithm is effectively using the available statistical precision. At the comparable FAP value, the energy-based algorithm achieves a DP=100% for the 2000-cps pseudo source and a DP=91% for the 1000-cps pseudo source. Clearly, the energy-based algorithm performance is superior to the fixed-background algorithm. This algorithm better controls the FAP by avoiding NORM alarms and adequately handles baseline depression.

VIII. SUMMARY

Vehicle surveys for radioactive materials can be implemented in an operationally acceptable manner at ports-of-entry. Large area plastic scintillators and gross-count neutron sensors are best suited for cargo surveys at borders. The effectiveness of cargo surveys using simple alarm algorithms is limited due to baseline depression and uniform NORM loads. Various alarm algorithms have been usefully ranked according to detection probability for various signal intensities while achieving a manageable false alarm probability using the same empirical data set. An energy-based algorithm was shown to be clearly superior to the fixed-background algorithm. The improvement in sensitivity achievable with an energy-based algorithm is highly desirable.

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