The Application of Gamma Spectrometric Techniques with Plastic Scintillators for the Suppression of "Innocent Alarms" in Border Monitoring for Nuclear and other Radioactive Materials

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Abstract

Border monitoring equipment for nuclear and other radioactive materials apply fixed installed, automated "portal monitors" at checkpoints such as road and rail border crossings, airports or seaports, to detect gamma and neutron radiation in order to alert the front line officer about the presence of nuclear and other radioactive materials. Although highly sensitive and reliable systems are available today, a major problem, particularly for truck and railroad monitors as well as for pedestrian monitors e.g. at airports are frequent "innocent alarms" caused by naturally occurring radioactive materials (NORM) and medical radioisotopes administered to patients crossing borders. Such "innocent alarms" require extensive investigation by the front line officer to verify the alarm and identify the radioisotope in order to prove the innocent nature of the event. In addition this usually requires a lengthy holdup of the persons and vehicles involved. New developments of gamma spectrometric techniques and advanced software can be applied to automatically suppress "innocent" alarms caused by commodities such as fertilizers, ceramics, colored glass, optical lenses or welding rods containing NORM, i.e. ^{40}K, ^{232}Th ^{226}Ra and U, even with low energy resolution plastic scintillation detectors as required for truck and train monitors. In addition pedestrian monitors, based on NaI scintillation detectors can be designed to simultaneously detect and identify the most frequently used medical radioisotopes in real time and indicate the "innocent" nature of the alarm to the front line officer. The paper describes detailed investigations with novel prototype truck and pedestrian monitoring systems at the Austrian Research Center Seibersdorf and the Vienna airport to evaluate the possibility to suppress "innocent" alarms while still maintaining adequate sensitivity for the detection of illicit nuclear and other radioactive materials.

Introduction

Numerous incidents in the past years involved illegal movement of nuclear materials and other radioactive sources across State borders. Even more frequently radioactive sources out of regulatory control have entered the public domain, in particular in metallurgical scrap, and sometimes caused significant radiation exposure. This creates a potentially serious hazard to public health as well as a thread of nuclear proliferation and terrorist activities. In 1995 the IAEA started a program to combat illicit trafficking in nuclear and other radioactive materials, which includes the operation of an international database on illicit trafficking incidents, which is now collecting reports from about 85 Member States [1].

Nuclear smuggling involving nuclear proliferation or nuclear terrorism is considered today as a "prime national security threat" in the United States and many countries all over the world, particularly after September 11. It is likely that front line inspectors will be the first law enforcement personnel to encounter radioactive materials. Law enforcement officers have therefore assumed a new important responsibility to detect and properly respond to special nuclear material and weapons of mass destruction, interdict hazardous radioactive materials and to protect themselves, their fellow citizens, the public and the environment from radiation hazard.

Illicit trafficking in nuclear and radioactive materials is not a new phenomenon. However, concern about a "nuclear black market" has increased remarkably in the last decade. In addition to the threat of nuclear weapons getting in wrong hands, radioactive materials are widely used in industry of medicine and much easier accessible for criminals than nuclear materials, which are generally under physical protection. However, combined with conventional explosives they create "radiation dispersion devices (RDDs)", nowadays often called "dirty bombs". Such technically quite simple devices, could lead to a nightmare of terror and widespread contamination, if exploded in the center of a large city or at an other strategic location. In fact such devices carry a comparable terroristic potential as nuclear weapons.

While monitoring systems for contaminated scrap metals in steel plants and scrap yards have been used routinely since many years, this has – until recently - not been the case for detection systems installed at border crossings, due to the fact that the measurement conditions at borders are essentially different. Large vehicle traffic limits the time for detection and response to a few seconds and repeated checks of the same vehicle are usually impractical. Border monitoring has to cover all kinds of traffic, on ground and at sea, passenger cars, lorries and busses and rail cars, as well as pedestrians, particularly at airports, and all kinds of sea going vessels including container ships. For the detection of shielded nuclear materials, such as plutonium, additional neutron measurement is essential. Frequent false alarms (alarms not caused by an increased radiation signal) and "innocent alarms" (true alarms caused by an increased radiation signal due to "innocent" naturally occurring or medical radioisotopes) may create unacceptable problems at borders and render the monitoring system practically useless. Therefore a compromise needs to be made between sensitivity of detection and false alarm rate. Technical specifications and recommendations for the detection of radioactive materials at borders have been published by IAEA [2].

Detection or discovery of nuclear or other radioactive materials at borders or inside States will require an immediate reactive response at the scene of the discovery, to regain control and to prevent further escalation of problems. Recommendations on response measures after detection of radioactive materials at borders have been published by IAEA [3]. The over-riding objectives and priorities of any response to illicit trafficking of radioactive materials are:

- to minimize any potential health hazards;
- to bring the radioactive materials under appropriate control; and
- to investigate, gather evidence and prosecute any offenders.

The scale of the response needs to be geared to the severity of the individual situation. In cases where there is no significant health hazard, no security implication or no proliferation threat, front-line officers and the routine response mechanisms of their respective agencies can deal with an incident simply yet effectively. This is termed an "operational response". In a more serious incident, there will be a need for a more elaborate response mechanism and the scale of the response will increase. In particular, the assistance of radiation safety professionals will probably be needed. It is therefore appropriate to consider a flexible approach, which can move from the immediate operational requirements into a "tactical response" mechanism involving other agencies.

Only in very serious situations, will the need arise to move to a "strategic level response". Such a response might be characterized by the activation of a district or national emergency response plan because of a significant potential hazard to the public and the environment. The decision, if a particular incident is to be considered a real case of illicit trafficking and which kind of response is required, will have to be made or at least initiated by the front line officer based on the first evidence. For this decision hand held gamma spectrometers play a crucial role. Quick characterization of the radioactive material on the spot is therefore of crucial importance and should be performed, if possible - at least in routine situations of operational response – by the front line officer, without loosing time to get outside expert assistance.

The Problem

Although highly sensitive and reliable systems are available today, a major problem, particularly for truck and railroad monitoring as well as for pedestrian monitoring e.g. at airports are frequent "innocent alarms" caused by naturally occurring radioactive materials (NORM) and medical radioisotopes administered to patients crossing borders. Such "innocent alarms" require extensive investigation by the front line officer to verify the alarm and identify the radioisotope in order to prove the innocent nature of the event. In addition this usually requires a lengthy holdup of the persons and vehicles involved. Innocent alarms due to NORM and low level contamination are most frequently observed when trucks and lorries are monitored, due to the large amounts of material involved. Fig.1 shows the frequency of gamma and neutron alarms observed within a duration of one month for the truck lane at the Austrian – Hungarian border Nickelsdorf, the border test site of ITRAP [4]. The intensity of the radiation signal triggering alarm is shown in terms of multiples of background.

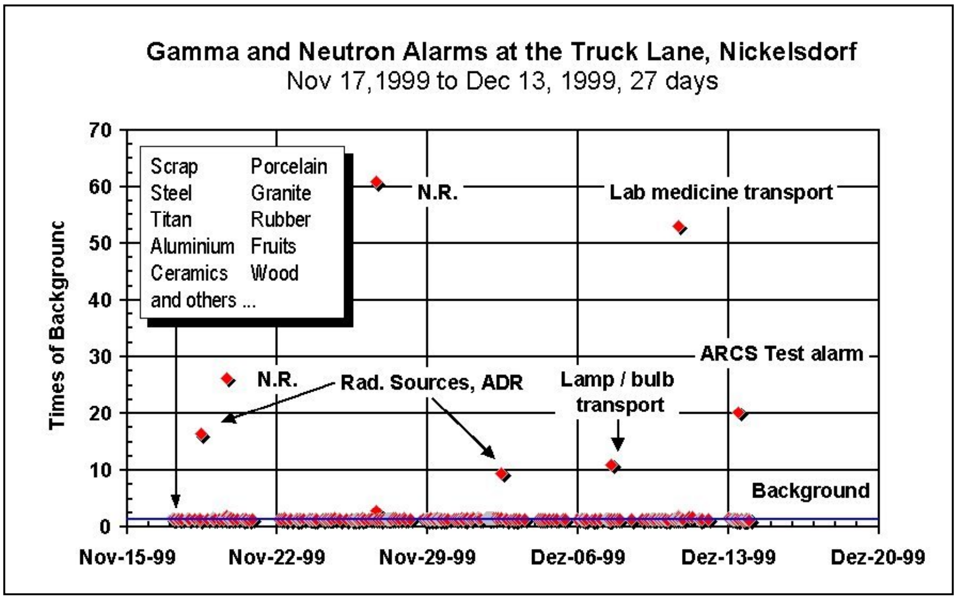


Fig. 1 : Frequency and intensity of alarms observed within one month at the ITRAP truck lane

It can be clearly seen that the vast majority of the alarms (red dots near the bottom line) comes from radiation signals considerably less than double background, i.e. - in this location - less than some 150 nSv/h. The alarms which have been analysed by hand-held isotope identifiers were caused essentially by four different categories of goods (see Table 1).

Alarms*	Reason	Max. observed multiple of background
10 per day	**Industrial Products and Raw Material e.g. ceramics, fertiliser, lamps, TV, etc**	**10 / some events with e.g. ceramics**
1 per week	**Agricultural Products e.g. fruits, vegetable, wood, etc.**	**5 / e.g. one event with a chicken transport**
1 per week	**Iron and Metal Transports e.g. Scrap, etc.**	**50 / e.g. contaminated metal plates**
1 per week	**ADR (legal) Transport of Radionuclides e.g. radio pharmaceuticals and industrial sources, etc.**	**60 / almost all legal transports**

*** Traffic approximately 1000 trucks per day**

Table 1: Categories of goods which triggered alarms at the ITRAP truck lane during an observation period of 6 months (totally about 200000 trucks)

According to these statistics the most frequent cause for innocent alarms in truck monitoring are naturally occurring radioactive materials (NORM), i.e. ^{40}K, ^{232}Th ^{226}Ra and U, contained in numerous industrial products and raw materials such as fertilizers, ceramics, construction materials and many others. In a typical situation one can expect a frequency of about one innocent alarm per 100 monitored vehicles, which in the case of the Nickelsdorf checkpoint means about 10 innocent alarms per day.

In every case of such an innocent alarm operational response by the frontline officer is required. This means that the vehicles has to be moved to a stand by position and a full investigation using hand held isotope identifiers conducted. In most countries where dedicated technical services within Customs – such as in Russia – do not exist, a significant frequency of innocent alarms can not be coped with in practice, which may render border monitoring useless and finally lead to shutting off the monitoring systems.

Gamma Spectrometric Techniques for the Suppression of "Innocent Alarms"

During the last few years intensive development has been devoted by several manufacturers of portal monitoring systems to the automatic real time suppression of innocent alarms based on gamma spectrometric analysis. The principle of this technique shall be described by the example of the AT-900 Advanced Technology Vehicle Monitoring System produced by EXPLORANIUM Radiation Detection Systems in Toronto, Canada.

Description of the instrument and spectrometric technique

The Exploranium AT-900 vehicle portal monitoring system normally consists of a two detector pillars each containing two plastic scintillators with a total volume of 49 l (3000 cu. in.), outside dimensions 178cm x 91 cm x 21 cm, mounted one above the other in each pillar. For neutron detection three He3 tubes of 5cm diameter and 100 cm active length with a pressure of 3 atm are used in each detector. This configuration is suitable for car and truck monitoring, the distance between the two pillars is generally 4 m. The output signals of all six He3 tubes located in both pillars, are summed up in the neutron channel, for gamma measurement the plastic scintillators in pillar A and B are analyzed separately.

Fig.2 shows AT-900 as normally used in truck monitoring for metal scrap with one detector assembly in each pillar and the length axis of the detectors horizontal. For border monitoring of trucks usually two detector assemblies are stacked above each other with the length axis vertical, in order to obtain a uniform search range up to a height of 4 m.

Fig. 2: AT-900 truck monitoring systems as normally used for scrap monitoring.

The detectors apply two 2“ photo multiplier tubes per scintillator with coincident signal processing. The console consists of a big split-screen color display as shown in Fig. 3.

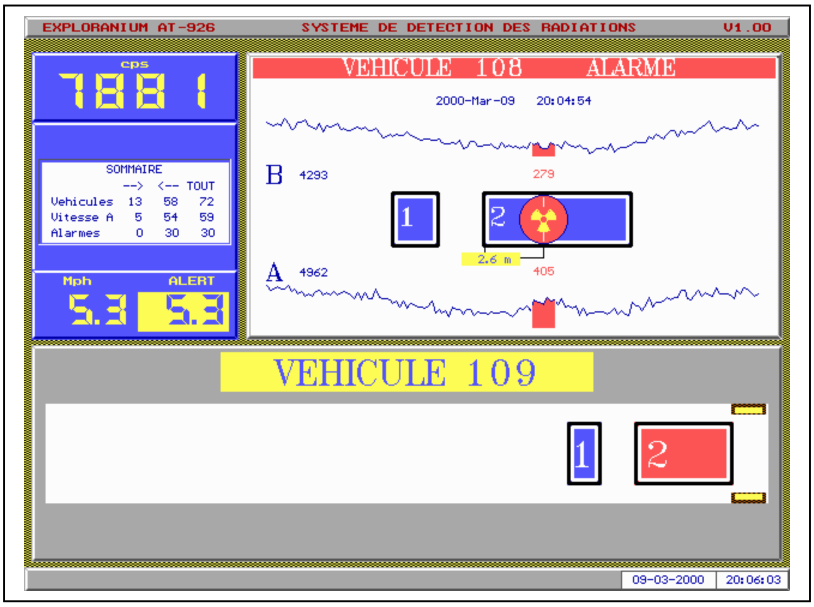
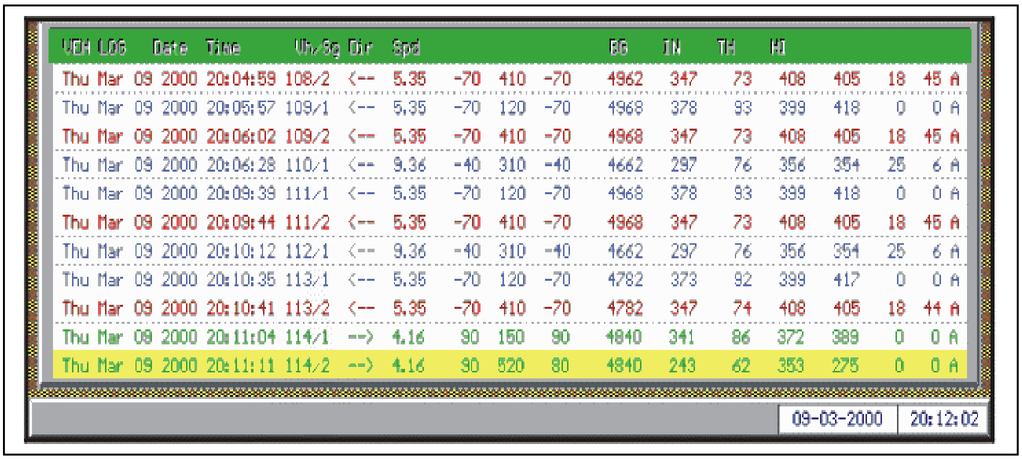


Fig. 3: Typical view of the console display after alarm

The display shows on the left side the total gamma count rate (cps) of both pillars, the vehicle speed and the daily summary of passed vehicles and alarms. The graphic plots the gamma count rate vs. time for both pillars A and B, and shows a schematic view of the vehicles (lorry with cabin (1) and freight space (2)), the position of the alarm with count rate above background (A and B) and the distance of the source position from the front of the freight space. Information about each radiation alarm with count rates, thresholds, speed and vehicle number, as well as system reset, errors, parameter changes and other critical items are displayed in real time on the vehicle log file and stored in a data base on hard disk for the last 30 days of operation. The displays screen of the vehicle log in shown in Fig.4.



VEH LOG	Date	Time	Vh/Sg	Dir	Spd				BG	IN	TH	HI			
Thu Mar	09 2000	20:04:59	108/2	<--	5.35	-70	410	-70	4962	347	73	408	405	18	45 A
Thu Mar	09 2000	20:05:57	109/1	<--	5.35	-70	120	-70	4968	378	93	399	418	0	0 A
Thu Mar	09 2000	20:06:02	109/2	<--	5.35	-70	410	-70	4968	347	73	408	405	18	45 A
Thu Mar	09 2000	20:06:28	110/1	<--	9.36	-40	310	-40	4662	297	76	356	354	25	6 A
Thu Mar	09 2000	20:09:39	111/1	<--	5.35	-70	120	-70	4968	378	93	399	418	0	0 A
Thu Mar	09 2000	20:09:44	111/2	<--	5.35	-70	410	-70	4968	347	73	408	405	18	45 A
Thu Mar	09 2000	20:10:12	112/1	<--	9.36	-40	310	-40	4662	297	76	356	354	25	6 A
Thu Mar	09 2000	20:10:35	113/1	<--	5.35	-70	120	-70	4782	373	92	399	417	0	0 A
Thu Mar	09 2000	20:10:41	113/2	<--	5.35	-70	410	-70	4782	347	74	408	405	18	44 A
Thu Mar	09 2000	20:11:04	114/1	-->	4.16	90	150	90	4840	341	86	372	389	0	0 A
Thu Mar	09 2000	20:11:11	114/2	-->	4.16	90	520	80	4840	243	62	353	275	0	0 A

09-03-2000 20:12:02

Fig.4: Display of vehicle log with time/date, speed, count rate and threshold data

Tests on suppression of NORM alarms using spectral information

In the following tests recently performed at the ITRAP laboratory test site of the Austrian Research Center Seibersdorf are described, which demonstrate in principle, that even with the poor energy resolution of plastic scintillators, alarms due to NORM, i.e. thorium, radium or potassium-40 can widely be suppressed without significantly loosing sensitivity for detection of nuclear materials or industrial isotopes. The principle of the method is to split the gamma spectra into three energy windows, a low window which includes low energy signals from SNM and medical isotopes, a medium energy window for most industrial sources and a high energy window which contains high energy gammas from ^{232}Th, ^{226}Ra and ^{40}K typically contained in NORM materials, as shown in Fig.5.

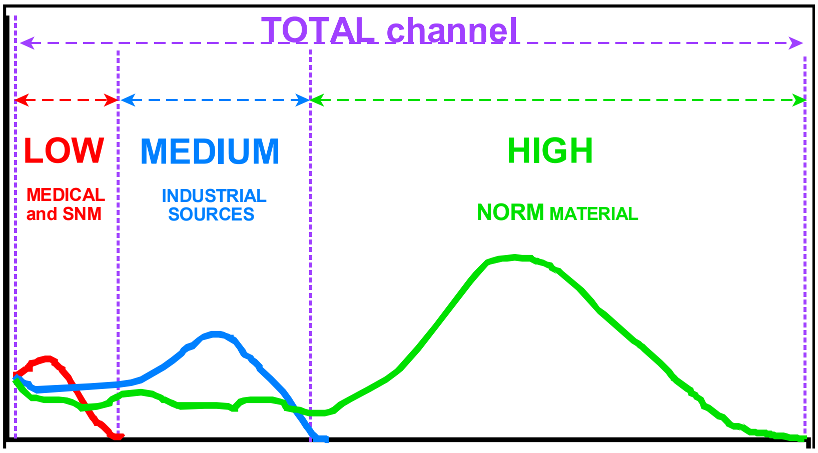


Fig.5: Gamma spectra of different radiation sources measured by plastic scintillators

Fig. 6 shows the actual count rate profiles (cps versus time in 0.1 s) of a weapon grade Pu source with an equivalent mass of 46 g, passing through the detector pillars with a speed of 18 km/h. The gray area between 50 and 60 on the abscissa, i.e. 5 and 6 s after triggering the optical occupancy sensor, shows the range when the source is near the detectors, just passing through the monitor. The blue line on top gives the total count rate in detector pillar A, which was closer to the source than B. One can also see the significant increase in count rate in the low energy range (above 0.2 MeV) in detector A, which indicates nuclear materials. The count rates in the high energy range (above 1.1 MeV) is significantly above background for both detectors, which indicates the presence of NORM. The logic for triggering alarms is shown schematically in Fig.7.

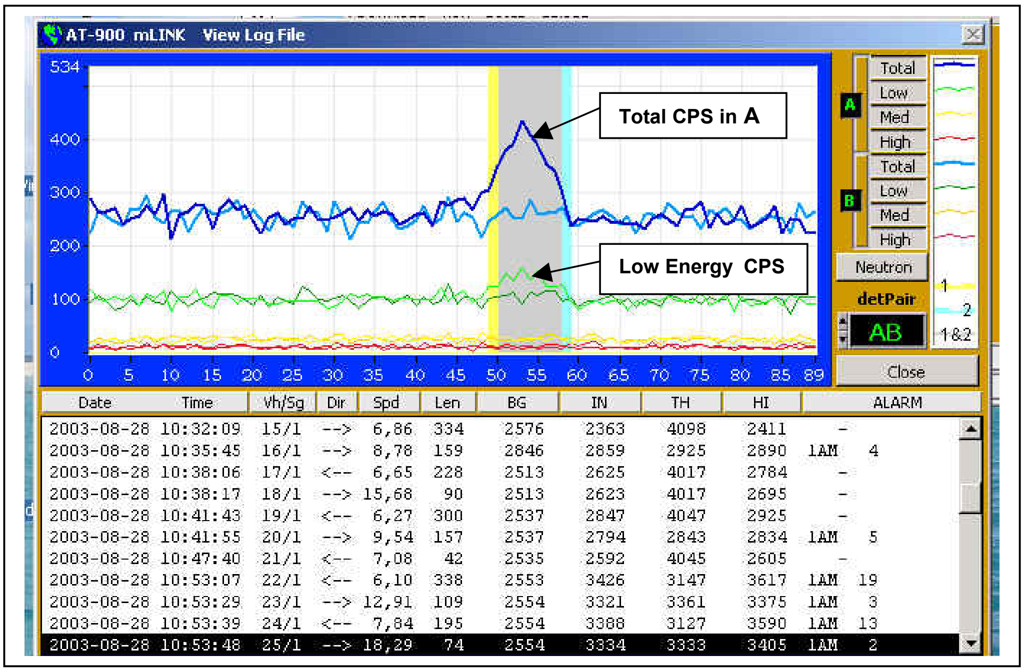


Fig. 6: Count rate profiles in three different energy ranges with a WG Pu source passing through.

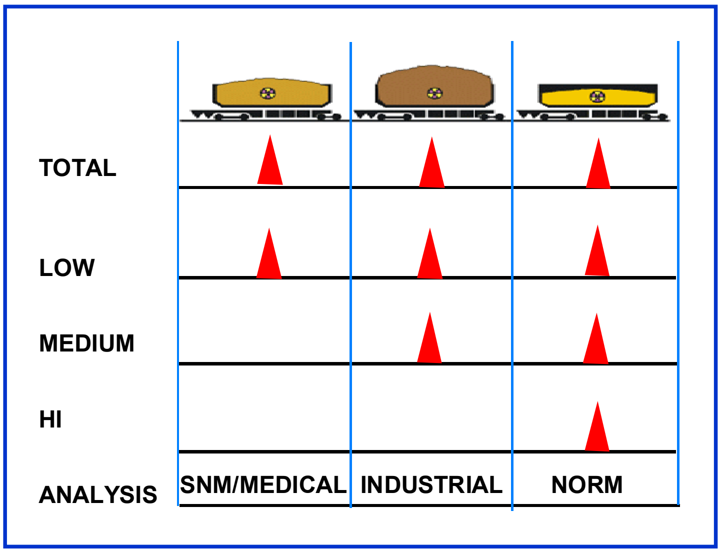


Fig.7: Discrimination logic for alarms due to SNM/Medical, Industrial and NORM

If the alarm threshold of the total count rate channel is exceeded, the logic compares the total counts with the counts in three energy windows. If increased counts are observed in the low energy window only, this indicates SNM or medical sources. An additional neutron alarm would verify SNM. If alarm occurs in total, low and medium window, it indicates industrial isotopes. If alarms are triggered in all four channels it indicates NORM and this alarm can be suppressed. In addition an equal distribution of count rates over the whole vehicle supports this decision.

Sensitivity tests with Pu sources without NORM suppression

First the sensitivity for detecting weapon grade Pu samples and ^{252}Cf neutron sources was tested under realistic border conditions, with the sources positioned in the trunk or the front of a car and driven through the detector pillars at different speed. Fig.8 shows the ITRAP test site with the two detector pillars of the AT 900 system (yellow) and the cars used for moving the sources through the monitor.
Table 2 is a list of the Pu sources used in this test.

Fig. 8: AT900 system (yellow pillars near the cars) installed at the ITRAP laboratory test site

Source	Equivalent Mass of WG Pu [g]	Neutron emission [n/s]	Gamma dose rate at 0.5m [µSv/h]
Pu93 O/2	10.25	680	unshielded : 0.20 + 1cm steel: 0.12
Pu84 O/2	21	1390	unshielded : 0.30 + 1cm steel: 0.13
Pu70 O/2	46	3060	unshielded : 0.70 + 1cm steel: 0.25
Pu61 O/2	64	• 4220	unshielded : 0.90 + 1cm steel: 0.30

Tab.2: Weapon grade Pu sources used in this test

Tab.3 gives the results of the drive through tests with the different WG Pu sources at different speed, without gamma spectrometric NORM suppression .

Source	Speed [km/h]	Background [cps]	Threshold [~ 5 σ in cps]	Signal [cps]	Alarm
Pu93, Pu84, Pu70, Pu61, 141 g 9350n/s, Transport box, in the trunk	10.97	n: 7 γ : 2790	n : 12	n: 18	n (neutron)
Pu93, Pu84, Pu70, Pu61, 141 g 9350n/s, Transport box, in the trunk	14.63	γ: 2799	3618	4110	γ (gamma)
Pu93, Pu84, Pu70, Pu61, 141 g 9350n/s, Transport box, in the trunk	12.91	n: 6	11	15	n
Pu93, Pu84, Pu70, Pu61, 141 g 9350n/s, Transport box, in the trunk	9.98	n : 5	10	12	n
Pu93, Pu84, Pu70, Pu61, 141 g 9350n/s, Transport box, in the trunk	12.19	n : 5	10	14	n
Pu93, Pu84, Pu70, 77 g, 5130 n/s 1 cm steel container, in trunk	9.99	γ : 2789	3601	4113	γ
Pu93, 10.25g, 680 n/s 1 cm steel container, in trunk	10.45	2789	2967	3076	γ
Pu93, 10.25g, 680 n/s 1 cm steel container, in trunk	10.97	2781	3142	3174	γ
Pu93, 10.25g, 680 n/s 1 cm steel container, in trunk	15.68	2787	3025	3194	γ
Pu93, 10.25g, 680 n/s 1 cm steel container, in trunk	11.55	2782	2856	2856	γ

Tab.3: Sensitivity tests with WG Pu sources without NORM suppression

This test demonstrates that weapon grade Pu sources can be detected – mostly by gamma alarms – down to an equivalent mass of 10 g with a speed up to 15 km/h.

Sensitivity tests with Pu sources with NORM suppression

In order to simulate materials containing considerable amounts of NORM a metallic ^{232}Th source of 59 g, producing a gamma dose rate of 0.2 µSv/h in 1 m distance was used. Driving this source trough the centerline of the detector pillars (2.7 m distance) would lead to an increase in background by about 30%, which is in the typical range of innocent alarms observed at the ITRAP tests (see Fig.1). In 1 m distance from one detector it would be about 300% increase in background. Table 4 summarizes measurements of the ^{232}Th source at different speed and distances from the detectors, without NORM suppression.

Source	Speed [km/h]	Distance Source – Detector [m]	Alarm
^{232}Th (59 g metallic)	6.45	2.7 (Centerline)	γ
^{232}Th (59 g metallic)	10.45	2.7 (Centerline)	γ
^{232}Th (59 g metallic)	7.80	2.7 (Centerline)	γ
^{232}Th (59 g metallic)	3.99	0.8	γ
^{232}Th (59 g metallic)	7.30	0.8	γ
^{232}Th (59 g metallic)	18.40	0.8	γ
^{232}Th (59 g metallic)	11.55	2.7 (Centerline)	no

Tab.4: ^{232}Th (59 g metallic) measurements without NORM suppression

The ^{232}Th source triggered alarm when moved through the centerline between the detector pillars (distance 2.7 m) up to a speed of 12 km/h. In closer distances it always triggered alarm. Table 5 shows results of the ^{232}Th measurements with NORM suppression activated.

Source	Speed [km/h]	Distance Source – Detector [m]	Alarm
^{232}Th (59 g metallic)	0.72	2.7 (Centerline)	no
^{232}Th (59 g metallic)	6.65	2.7 (Centerline)	no
^{232}Th (59 g metallic)	7.32	2.7 (Centerline)	no
^{232}Th (59 g metallic)	12.91	2.7 (Centerline)	no
^{232}Th (59 g metallic)	11.55	2.7 (Centerline)	no
^{232}Th (59 g metallic)	10.97	2.7 (Centerline)	no
^{232}Th (59 g metallic)	9.54	2.7 (Centerline)	no
^{232}Th (59 g metallic)	6.27	1.0	no
^{232}Th (59 g metallic)	5.10	0.7	γ
^{232}Th (59 g metallic)	4.14	1.0	γ
^{232}Th (59 g metallic)	8.13	0.6	γ

Tab.5: ^{232}Th (59 g metallic) measurements with NORM suppression

With NORM suppression activated the ^{232}Th source triggered no alarms when moved through the centerline between the detector pillars (distance 2.7 m) at any speed. Only at close distance to the detector, when the radiation signal reaches 300% background, alarm was triggered.

Finally with NORM suppression activated drive through tests with weapon grade Pu sources with an equivalent mass of 21 g and 46 g in 1 cm steel containers were performed. The results are shown in table 6.

Source	Speed [km/h]	Distance Source – Detector [m]	Alarm
Pu84 O/2, 21 g, in 1cm Fe	6.27	2.7 (Centerline)	no
Pu84 O/2, 21 g, in 1cm Fe	4.22	2.7 (Centerline)	γ
Pu84 O/2, 21 g, in 1cm Fe	9.98	2.7 (Centerline)	γ
Pu84 O/2, 21 g, in 1cm Fe	3.60	2.7 (Centerline)	γ
Pu84 O/2, 21 g, in 1cm Fe	3.14	2.7 (Centerline)	γ
Pu84 O/2, 21 g, in 1cm Fe	6.86	2.7 (Centerline)	γ
Pu84 O/2, 21 g, in 1cm Fe	5.35	2.7 (Centerline)	γ
Pu70 O/2, 46 g, in 1cm Fe	6.45	2.7 (Centerline)	γ
Pu70 O/2, 46 g, in 1cm Fe	9.54	2.7 (Centerline)	no
Pu70 O/2, 46 g, in 1cm Fe	4.88	2.7 (Centerline)	γ
Pu70 O/2, 46 g, in 1cm Fe	3.14	2.7 (Centerline)	n (neutron)

Table 6: Sensitivity of detecting WG Pu samples with 21g and 46g with NORM suppression

Conclusion

From the results of these preliminary measurements it can be concluded that gamma spectrometric suppression of innocent alarms due to NORM is feasible even with the rather poor energy resolution of plastic scintillation detectors. There seems to be no significant difference in sensitivity of detection for nuclear materials, medical and industrial radioisotopes with and without NORM suppression, except for ^{60}Co, which can not be fully distinguished from ^{40}K and ^{232}Th NORM. However, significant ^{60}Co sources will still trigger alarm, such as strong NORM sources with higher specific activities as usually occurring in natural materials. The gamma spectrometric technique has a great potential for solving the problem of frequent innocent alarms due to commodities containing low activity NORM. This can significantly improve the practical application of border monitoring for trucks and railcars, transporting large amounts of material with low concentration of NORM.

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