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Detection and Characterization of Threat Materials

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Abstract

This paper characterizes the properties of chemical, biological, radiological and nuclear threat materials that enable their detection. Methods for detecting and distinguishing these materials, when concealed by innocuous substances, are presented. Challenges and research and development opportunities in the detection of threat materials are outlined.

Keywords

Threat material detection, explosives, narcotics, contraband, radiological and nuclear materials

1 Threat Materials

The threat of a material is caused by its chemical, biological, radiological or nuclear

(CBRN) properties. Radiological materials can be identified by the type and intensity of their emitted penetrating radiation. However, some radiation (alpha and beta) hardly penetrates matter, making it difficult to detect its source. Similarly, some nuclear materials do not emit easily detectable radiation. Typical explosive materials are characterized by their nitrogen (a bonding agent), oxygen (an oxidizer), hydrogen and carbon (fuel elements) content, but many innocuous materials have similar composition. Also, narcotics (a threat to human health) are organic materials with composition not too different from other organics. Many biological and chemical hazardous materials do not exhibit obvious distinguishable characteristics. In addition, the

presence of threat materials can be obscured by concealment within other harmless substances. Moreover, threat materials do not generally have any particular geometric shape or pattern. Nonintrusive detection of contraband and threat materials also requires reliable, fast and deployable detection equipment. Therefore, the detection of threat materials challenges conventional nondestructive testing and imaging techniques, which exploit a particular physical property to distinguish one material from another.

This paper examines the characteristics of each of those threat materials and reviews and assesses methods employed for their detection, when they are concealed within other innocuous materials. Since most effort has recently focused on detection of explosive materials, the paper starts by examining them, followed by a discussion on narcotics, then biological and chemical threat materials are considered. Finally, the detection of radiological and nuclear materials is discussed. The paper concludes by outlining the challenges of detecting threat materials.

2 Explosives

For a material to be explosive, it must rapidly decompose and release a substantial amount of energy. Most common explosives are nitrogen-based, in which nitrogen acts as a bonding agent that attaches itself to the other elements of the molecule. Such explosives contain oxygen, for oxidation. Hydrogen and carbon are also present in these materials as fuel. These four elements (N, O, H, and C) are common elements, present in many innocuous substances. Therefore, basic detection of explosives has often relied, not on the direct

detection of the presence of these elements, but on the detection of the metallic detonator, needed to trigger an explosive agent (high explosive material). A detonator is a low explosive contained within a metallic tube or a shell, ignited by an electrically heated wire or a fuse. Common metal detectors are used for detecting concealed detonators. Metal detectors rely on either electromagnetic induction or x-ray radiography. The latter method detects the presence of metals by their ability to absorb x-rays, due to their high mass density and large atomic number. Radiography also provides an image, which enables the detection a detonator by its geometric shape.

Metal detectors tend to have a high false-positive detection rate, since metals are common materials. Moreover, metallic detonators can be shaped in many forms. Most importantly, primary (predominantly plastic) explosives can be easily triggered, and as such may have a small amount of metal, or none whatsoever. These explosives are, therefore, not visible to metal detectors.

In the absence of metals, the detection of explosives has to rely on some unique material characteristics of explosives. Although the N, O, H, and C are common elements in many innocuous substances, their concentration in explosives tend to be unique; to the extent that nitrogen-based explosives have a mass density higher than that of most organic materials and polymers (in the range of about 1300 to 1800 kg/m³), but lower than that of most metals. Nevertheless, these four elements provide an effective atomic number that is not very different from water. As such, a material that appears to have an effective atomic number similar to that of water, but has a higher mass

density, is likely a suspect material. This is a necessary, but not sufficient, condition for the detection of nitrogen-based explosives, since some common polymers and organic materials have similar attributes. The concentration of nitrogen in explosives also tends to be higher than in other materials. For an explosive material to cause damage, it must have, upon decomposition, high specific energy. This in turn necessitates chemical structures and crystalline configurations that are particular to explosives. In addition to the above stated material properties, geometric shape can also be a useful supplementary indicator. Although there is no unique shape for an explosive material, given that plastic explosives are quite malleable, the presence of a contiguous region of a suspect material is a useful affirming indicator. Based on the above characteristics, a number of detection methods have emerged. A brief description of each is given below.

2.1 Vapor emission

The peculiar molecular composition of explosives gives their molecule a certain mass. Nitrogen-based explosives also tend to be volatile. Therefore, vapor emissions resulting from even trace amounts of explosives, can be used to determine the mass of the vapor molecules and ascertain their nature. The mass of a vapor molecule is determined by measuring the velocity of its ion, when accelerated at a constant voltage. This so-called ion mobility spectrometry is enabled by an ionization process facilitated by a small source of beta particles, such as ^{63}Ni . Alternatively, the presence of a nitro group in vapor is indicative of its nitrogen richness, and can be detected by taking advantage of its

affinity to absorbing electrons in an electron-capture device. Biological sniffers, such as dogs, provide the same detection ability. The artificial nose also functions with the same principle. Indirect detection of vapor emissions is also accomplished by analyzing a sample wipe with chromatography. Gases emerging from heating the sample are injected into an ion exchange column with the aid of a carrier gas. Gases emerge from this separation column at different times, depending on their ionic properties, enabling the detection of explosives.

Vapor detection is an effective means for detecting explosives, but is so sensitive that it can detect leftover residual amounts of explosives unrelated to the immediate presence of a threat. Environmental conditions, such as dust, humidity and temperature, also affect vapor emission. Moreover, some plastic explosives have a very low vapor pressure for effective detection. Tight sealing can also reduce the delectability of an explosive material.

2.2 Radiography and tomography

X-ray radiography and tomography detect an explosive material by its density and shape; and in advanced systems by its effective atomic number. Material mass-density is determined by the mass of each atom in the material and how compact its molecules are packed. This, in turn, determines the electron density. Since x-ray photons are absorbed and scattered by electrons, the more dense the material the more it interacts with x-rays. X-rays that are transmitted through a material are those that have survived interactions. As such the intensity of the transmitted radiation is a

density indicator. A radiographic image provides an overall indication of the density of the material traversed by a radiation beam. As such it results in a projection image, with each point on the image corresponding to a line in the object. This can lead to masking of the presence of a material and smearing out of its density indications. Dual-beam (two orthogonal projections) images can to some extent help unmask these indications, but computed Tomography (CT) completely unfolds the density information by numerically reconstructing a section image from many overlapping projections.

Dual-energy radiography and tomography provide information on the effective atomic number of the material. At high x-ray energy, the Compton scattering process (particle-like scattering of a photon with an atomic electron) is the dominant mode of interaction. Since the probability of Compton scattering is directly proportional to the electron density, and the latter in turn is proportional to mass density, radiographs and tomographs are density maps. At low-photon energy, the photoelectric effect dominates, where photons are fully absorbed in the atom and an electron emerges. The probability of this effect is strongly dependant on the atomic number, as well as the material density. A radiograph and a tomograph at low x-ray energy carry, therefore, material composition information as well as density information, while those at high energy provide only density indications. The combination of those two images is, therefore, a powerful tool for the detection of explosives by their density and composition, as well as shape.

The scattering of low-energy x-rays is also exploited in body scanners, where a pencil

beam scans the front and back surfaces of the body. This low-energy radiation is absorbed by metals, if present, while tissue and other low-density materials backscatter it with intensity proportional to their density. Sharp changes in the intensity of detected backscattered x-rays are used to outline the shape of suspect objects.

2.3 Crystalline and chemical structure

The common technique for crystal characterization is the diffraction of low-energy x-rays by Bragg scattering. However, such x-rays do not penetrate deep within matter. On the other hand, wavelike (coherent) scattering occurs at higher photon energy, in the form of Rayleigh (small-angle) scattering. With this mode of scattering, characteristic diffraction patterns can be observed in the distribution of transmitted photons. This requires, however, careful alignment of radiation beam and detectors to enable the observation of small-angle scattering.

The dielectric properties of a material also depend on molecular effects: the microscopic polarization effects produced by electronic, ionic, orientation and interfacial factors. Microwaves are strongly affected by the dielectric attributes of material. As such the intensity and spectrum of scattered or transmitted microwaves provide molecular information. However, microwaves are fully reflected by metals and are strongly absorbed by water. Nevertheless, the reflection of high-frequency (low wavelength) microwaves, the so-called millimeter waves, is used in some body scanners to provide a surface image and detect any material concealed under clothing. In this process, two antennas simultaneously rotate around the body and cover its surface

from all directions.

Lower-energy electromagnetic waves have wavelengths comparable to the lattice pitch. As such they can be used to characterize chemical and lattice structures, hence detect the peculiar structure of crystallized explosives.

Nuclear quadrupole resonance (NQR) is a technique that uses radiofrequency (RF) pulses to detect the presence of nitrogen in explosive materials. Nitrogen-14 has a nuclear spin greater than half, and as such has a nuclear electric quadrupole moment that affects the electric field of the surrounding electrons. This produces an electric quadrupole coupling, with a resonance occurring when the valence electrons align with some of the ^{14}N spins. The nature of the crystal structure determines the energy associated with this alignment, providing a specific signature for explosives. Applying an RF pulse at a frequency corresponding to the energy associated with this alignment disrupts this resonance. Therefore, after the cessation of the RF pulse, an indication signal corresponding to the presence and concentration of ^{14}N is obtained. Unfortunately, the NQR signal tends to be weak and is difficult to analyze. The detected signal is also affected by the presence of metal. Nuclear magnetic resonance (NMR) relies on a similar principle, except that an external magnetic field is applied. The interaction between the magnetic moment of a nuclei and the external field can result is a resonance. When an RF pulse, with a frequency appropriate to the type of nuclei and the molecular structure of the material, is introduced, the resonating nuclei absorb the RF energy. The ^1H - ^{14}N nuclear-dipole-moment cross coupling in explosive materials enables

their detection with NMR. Such an indication disappears, however, in the presence of a metal, as it strongly interferes with the applied field. Moreover, a uniform magnetic field distribution is required, which is difficult to achieve outside the laboratory.

2.4 Elemental analysis

Perhaps the most reliable means of detecting an explosive material, or for that matter any material, is to determine its elemental composition, i.e., identify its elements and their concentration. In the case of nitrogen-based explosives, the detection of nitrogen is paramount. Elemental analysis of bulk quantities, as is usually the case with threat material, is best accomplished by neutron techniques, because of their penetrability. When a thermal (low energy) neutron is captured by ^{14}N , it produces a characteristic high energy (10.8 MeV) gamma-ray. The intensity of the gamma-rays is inactive of nitrogen concentration. However, thermal neutrons are not directly generated, but are the result of slowing-down fast source neutrons. This results in bulky and inefficient devices. Moreover, thermal neutrons may leave some other elements radioactive, producing undesirable secondary radiation fields.

Highly energetic photons, generated by accelerators, are absorbed by ^{14}N , with resonance absorption at 9.17 MeV. Also the $^{14}\text{N}(\gamma, n)^{13}\text{N}$ reaction occurs at a photon energy greater than 11 MeV. The resulting ^{13}N isotope has a ten-minute half-life, decaying to ^{13}C (a positron emitter). The positrons are then annihilated by the electrons of the matter, giving rise to 511 keV gamma-rays (in a manner similar to that used in medical

positron-emission tomography). At higher energies (30 MeV), ^{12}N is produced, which has a half-life of 11 ms, and also decays by positron emission. High-energy photons provide more than one means of detecting nitrogen, but their generation is not that easy and their interaction probabilities are low, necessitating the use of intense sources.

Nitrogen detection alone is not sufficient for definite detection of an explosive, since nitrogen is commonly found in many materials. At least one of the other four elements present in nitrogen-based explosives should be detected, and its concentration should be determined. The easiest element to detect, among the four elements of explosives, is hydrogen. The hydrogen nucleus has about the same mass as that of a neutron, and as such is a very effective nucleus for slowing-down fast neutrons. The amount of slowed-down neutrons is therefore indicative of hydrogen concentration. The hydrogen concentration can also be determined by thermal neutron activation, since upon capturing a neutron by a hydrogen nucleus, characteristic 2.2 MeV gamma-rays are emitted.

The other two elements present in a nitrogen-based material, oxygen and carbon, hardly absorb thermal neutrons. However, they can be activated by fast-neutron inelastic scattering. At neutron energy above 5 MeV, characteristic gamma-rays are emitted promptly as follows: 6.13 MeV from ^{16}O and 4.43 MeV from ^{12}C . In addition, 2.31, 1.64 and 0.72 MeV are produced from ^{14}N . As such, inelastic scattering, which can be performed with common 14 MeV neutron generators, can activate and characterize three of the four elements of explosives. Though fast neutrons

do not activate hydrogen, they are slowed-down by it, and as such are also detectable by fast neutrons. Unfortunately, fast neutrons can also activate some other materials and leave residual radioactivity.

The activation probability by inelastic scattering is however low, necessitating the use of intense sources and/or long acquisition times. On the other hand, the scattering cross sections of fast neutrons have strong resonances for nitrogen, oxygen and carbon in the energy range of one to three MeV. This enables the determination of the concentration of these three elements by monitoring the transmission of fast neutrons in this energy range, and even providing radiographic images of their concentrations. However, a neutron energy source with a wide spectrum in the one to three MeV range is required, which is not an easy task.

3 Illicit Drugs

Narcotics, such as heroine and cocaine, are considered threat materials, due to their impact on health and society. These hard drugs tend to be rich in H, C, O, Cl, and to a lesser extent, N. These substances also tend to be much denser than most organics. As such, techniques used for the detection of explosives are also applicable to the detection of narcotics. In elemental analysis, Cl is detectable by thermal activation analysis, as it releases many distinguishable gamma-ray spectral lines.

Recreational drugs, such as marijuana, are known to be rich in potassium. One of the isotopes of the latter is ^{40}K , naturally active isotopes that emit 1.46 MeV (11%) and beta particles with maximum energy of 1.312 MeV (89%). The ^{40}K gamma-ray is used to passively

detect marijuana in large quantities concealed in shipment containers. On the other hand, the beta particles can be viewed as a contaminant, and used to detect the presence of leafy drugs in paper-cased postal parcels. Note that tobacco also contains ^{40}K , which can be used to detect its smuggling.

4 Biological and Chemical Threats

Biological threat materials include anthrax, ricin, viruses, bacteria and toxins. They are detectable by molecular recognition. This requires some form of assaying using techniques commonly employed in food, clinical and environmental testing.

Chemical threats, such as nerve choking, and blister agents, and chemical toxins, can also be identified, as in the case of explosives, by their vapor emissions, if present. Other common chemical analysis techniques can also be employed.

5 Nuclear and Radiological Materials

A nuclear material is a fissile material, such as plutonium-239, uranium-233, uranium enriched in ^{235}U or ^{233}U ; or a source material from which fissile materials can be produced, such as natural and depleted uranium, and thorium. Neptunium-237, generated in a nuclear reactor (by ^{235}U absorbing two neutrons) and in the production of plutonium, is also considered a nuclear material (as it can undergo fission) and its presence is indicative of the presence of uranium and/or plutonium. Radiological materials are characterized by being radioactive, emitting ionizing radiation (alpha, beta, gamma-rays, and neutrons). Nuclear materials are considered in a special category because of their particular threat.

Non-nuclear radioactive threat materials are typically characterized into three categories. The first category is that of isotopes used mainly in medical diagnosis or therapy, and includes: ^{18}F , ^{67}Ga , $^{99\text{m}}\text{Tc}$, ^{111}In , ^{123}I , ^{125}I , ^{131}I , ^{133}Xe , ^{201}Tl , ^{51}Cr and ^{103}Pd . The second category involves radionuclides employed predominantly in industrial applications and radiography; namely, ^{57}Co , ^{75}Se , ^{60}Co , ^{90}Sr , ^{133}Ba , ^{137}Cs , ^{192}Ir , ^{241}Am and ^{152}Eu . Naturally occurring radioactive materials are in the third category, which includes ^{40}K (found in fertilizer, kitty litter, tiles, ceramics, some plant vegetation), ^{226}Ra (resulting from uranium decay) and its daughters, ^{232}Th and its decay products, and ^{238}U in natural uranium (used in colored glass and in Fiesta ware). Although the last category does not involve threat materials, it is a source of false-positive indications, when inspecting for the presence of threat nuclear materials.

Radioactive materials are easily detectable by the associated emission of penetrating radiation; mainly gamma-rays and neutrons. No matter how well-shielded a material is, some amount of radiation will penetrate through, and produce a radiation field above the background level. Nuclear materials are mainly alpha emitters, but also decay by spontaneous fission but at very low level. Fission produces neutrons and gamma-rays, both can contribute to increasing the detected radiation level. Alpha particles tend also to produce neutrons when they interact with surrounding metal. The energy of the emitted gamma-rays can be used to identify radionuclides, since each radioactive nucleus has its own characteristic gamma-ray energy, dictated by its nuclear structure. The detection

of neutrons is mostly indicative of the presence of a nuclear material. However, alpha sources, such as ^{241}Am used in smoke (ionization) detectors, can also give rise to neutrons, by interacting with the encapsulating metal or ceramic material. Positron emitters, such as ^{18}F , are detected by the 511 keV gamma radiation associated with the annihilation of the positrons with the electrons of matters. Pure beta emitters, such as ^{90}Sr used in radioisotopic thermoelectric generators (RTG's) as well as thickness gauges and brachytherapy, are not detectable by their beta radiation which is easily absorbed. However, the beta-decay of ^{90}Sr produces ^{90}Yt , which emits detectable 2.18 MeV gamma-rays. Also the presence of ^{90}Sr in RTGs produce some heat, which when concealed can result in hot spots detectable by thermal (infrared) cameras. Note also that isotopes emitting non-penetrating radiation (alpha and beta particles), may also be detected by the associated contamination, if their sources are not well sealed. Surface swipes can be used for detecting the presence of these particles with common radiation contamination detectors.

6 Conclusion

As this paper indicates, there is a variety of techniques for the detection of concealed threat materials of various types. The challenge, however, is that one is dealing with rare events. Therefore, the false-positive detection rate tends to be high, leading to wasting time and resources; never mind people's irritation and aggravation. The false alarm rate can be reduced by relying on two or more orthogonal detection devices, i.e. those that rely on monitoring different physical attributes.

Relying on intelligence information prior to inspection also helps. Human judgment and alertness is crucial in proper interpretation of detection results. High-speed computing schemes, based on artificial intelligence and pattern recognition techniques, can also assist in reducing the false alarm rate. Ideally, a detection device should be nonintrusive and provide accurate and fast detection at a reasonable cost. Such features are not typically inclusive.

Addressing the above mentioned issues is a challenge to system developers. There is also room for instrumentation development to meet specific security needs. The report of the EU's <http://www.observatorynano.eu/project/catalogue/2SE/> outlines the demand for further research in the detection and characterization of different threat materials. Detection-technology development should also accommodate post-detection remedial actions, for safe and efficient handling of threats.

References

- [1] De Los Santos, A. (1994), Practical considerations for NMR in NDT applications. *Nondestructive Testing and Evaluation*, 11 (5) 305-311.
- [2] Falconer, D. G., Watters, D. G. (1994), Detection of chemical contraband using spectroscopic microwave imaging. *Proceedings of SPIE - The International Society for Optical Engineering Substance Identification Analytics*, 2093, 301-309.
- [3] Garroay A. N., Buess, M. L., Miller, J. B., Suits, B. H., Hibbs, A. D., Barrall, G. A., Matthews, R., Burnett, L. J. (2001), *Remote sensing by nuclear quadrupole resonance. IEEE Trans. Geoscience and*

- Remote Sensing*, 39 (6), 1108-1118.
- [4] Gardner, J. W., Bartlett, P. N. (1999), *Electronic Noses: Principles and Applications*. Oxford University Press, Oxford, UK.
- [5] Hussein, E. M. A., (2003), *Handbook on Radiation Probing, Gauging and Imaging*. Kluwer (Springer), Dordrecht, The Netherlands.
- [6] Hussein, E. M. A. (1992), Detection of explosive materials using nuclear radiation: a critical review. In *Aviation Security Problems and Related Technologies: Critical Reviews of Optical Science and Technology*, Makky, W. H. (Ed.). SPIE CR42, 126-136.
- [7] Hussein E. M. A., Waller, E. J. (2000), Landmine detection: the problem and the challenge, *Applied Radiation and Isotopes*, 53, 557-563.
- [8] Kolla, P. (1995), Detecting hidden explosives. *Analytical Chemistry*, 67 (5), 184A-189A.
- [9] IAEA (2007), *Combating Illicit Trafficking in Nuclear and Other Radioactive Material*, Reference Manual, IAEA Nuclear Security Series No. 6, Technical Guidance, International Atomic Energy Agency, Vienna.
- [10] Myers, J., Hussein, E. M. A. (2007), Natural beta emission for detecting concealed tobacco in parcels, *Nuclear Instruments and Methods in Physics Research B*, 263, 214-216.
- [11] Singh, K. A. (2009), *Security Technology Sector, First Year Progress Report*, Institute of Nanotechnology, Observatory NANO Project, <http://www.observatorynano.eu/project/cat>
- <http://www.observatorynano.eu/project/cat>, accessed March 2010.
- [12] TSA, *Imaging Technology*, Transportation Security Administration, U.S. Department of Homeland Security, http://www.tsa.gov/approach/tech/imaging_technology.shtm , accessed March 2010.
- [13] Yaar, I Pesachovand, E., Hussein, E. M. A., (2008) Passive Detection and identification of a concealed ²⁴¹Am source in transport, *Packaging, Transport, Storage and Security Radioactive Material*, 19, 189-196.
- [14] Yaar, I., Hussein, E. M. A., (2004), Passive detection of concealed ⁹⁰Sr radioisotope thermoelectric generators in transport, *Packaging, Transport, Storage and Security of Radioactive Material*, 15, 149-154.