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Technologies for Detection of Nuclear Materials

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INTRODUCTION

In keeping with the theme of the Symposium, this overview focuses on detecting smuggled nuclear-materials at international transit points, which include national borders, customs check points, airports, export-import facilities—even post offices—wherever goods are transferred.

The first resources to draw upon for instrumentation would be equipment already developed in three related fields: nuclear-material assay and safeguards, commercial operations, and arms-control treaty verification. Yet, the requirements of civilian transit-point monitoring differ from these three fields, making much of that equipment not directly transferrable—although components could be adapted.

Detection equipment proven for domestic material assay and international safeguards is intended for use at well-guarded storage sites. While sharing some underlying detection principles, the monitoring of civilian packages and vehicles differs in important respects. Nuclear-material storage sites are government-controlled or regulated, while commercial transit is predominately a civilian activity. This difference affects, even limits, choices for radiation-generating interrogating sources. Moreover, domestic and international safeguards are carried out with a well-characterized range of declared materials in a controlled environment, whereas contraband consists *a-priori* of variable objects with fewer constraints at point of transfer.

Many nuclear-detection instruments have been developed for quantitative radiation measurements and for arms-control treaty verification. These instruments also might not be directly

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applicable at civilian transit-points, where detection of contraband is more important than quantification. Treaty-mandated equipment usually has a narrowly defined purpose where reciprocity and transparency are emphasized.

Synergisms can be exploited. Equipment developed for the detection of explosives, chemicals, illicit drugs, etc., might also be sensitive to nuclear materials; and, conversely, nuclear-material detectors can be tuned to sense other contraband. Fissionable materials are characterized by high density (and high atomic number), often requiring bulky or heavy shielding; so non-nuclear screening could discover extraordinarily heavy objects that need additional inspection.

To maintain nuclear control at transit points, a wide range of materials must be considered. Chief among these are fissile and radioactive substances, although some other materials are considered "sensitive" and "nuclear" in the context of possible societal threat or proliferation risk. Examples of the latter would be beryllium, lithium, fertile nuclear materials, and high-grade zirconium.

Nuclear detection methods are usually considered as either "passive" or "active." Passive detection relies on inherent radiation emanating from the nuclear material; active detection depends on radiation stimulated by concurrent external means. Often an active system can detect passive radiation, although not optimized for that purpose.

In general, active detection of radiation-induced fission would be a necessary and sufficient indicator of clandestine nuclear traffic. Fissile materials, especially weapon grade, pose the greatest proliferation risk. Plutonium, uranium, and thorium in any form or composition would be of particular concern. Because inherent spontaneous fission is not sufficient to cause high-probability detection of all of these materials, fission must be induced by external means.

In order to set goals for detecting smuggled nuclear materials, several questions arise. Is simple detection, identification, or quantification needed? Is imaging of the object's shape necessary or useful? What is the operative threshold for positive action?

A practical system for nuclear-materials detection should meet a number of constraints: fieldability, simplicity, cost, measurement time, confidence level, etc.

For this review, applicable passive and active methods will be discussed first. Next, appropriate systems will be examined, and finally various application scenarios for the systems will be described.

Because FSU technical developments have not been widely published in Western literature, recognition of many worthy contributions in the field will be inadequate. As a result, this review is more illustrative than comprehensive.

SIGNATURES

Intrinsic and induced radiation are signatures of nuclear materials. All fissionable materials produce passive radiation, albeit sometimes difficult to detect. Active techniques induce detectable prompt and delayed radiation, the most penetrating and useful being fast neutrons and gamma-rays.[1]

Delayed neutrons and gammas are also quite distinctive of fission, and with sufficient counting time allow identification of specific fissile materials. These methods are very useful for safeguards measurements. However, low emissivity makes delayed radiation less useful in situations where detection of smuggling is paramount.

With energies up to several MeV, prompt neutrons and gamma rays from fission provide unique signatures and are highly penetrating. They can be induced by slow or fast neutrons. Detection of smuggled fissionable substances is far more important than their specific characterization.

Compared to safeguards measurements for spent nuclear-reactor fuel, a simplifying factor in detecting nuclear smuggling is the absence of high radiation background; the signal from clandestine nuclear material would have to compete only with natural background sources.

PASSIVE METHODS

The primary detectable emanations from nuclear materials are x-rays, gammas, and neutrons.[2,3]

Neutrons

Of the materials having proliferation concern, only plutonium has readily detectable spontaneous neutrons. Although Pu-240 issues about 10^6/s-kg, weapon-grade Pu has typically 2.5×10^6/s-kg, with a fission spectrum characteristic of fast neutrons. Detection of any unnatural neutron emanation would be useful in countering smuggling.

If chemically impure or non-metallic, isotopically high-grade uranium could emit neutrons from alpha reactions. For this reason, a higher probability of detection by passive neutron (and gamma) radiation exists for fresh (as well as spent) nuclear-reactor fuel than for nuclear-weapons materials.

Gammas/X-rays

Gamma and x-ray radiation from weapons-grade materials are rather low in energy and weak in intensity, and thus are easily absorbed before escape or missed by most detectors.

Pu-239, the dominant fissile component in weapons-grade plutonium, issues primarily a 414-keV gamma at the rate of 3.4×10^7/s-kg, while the much smaller Pu-241 component at 208 keV emits at the rate of 2.0×10^{10}/s-kg. The latter decays to a more intense but less energetic source of Am-241, whose specific gamma activity is 4.6×10^{13}/s-kg.

U-235, the fissile component in weapons-grade uranium, emits 185-keV gammas at the rate of 4.3×10^7/s-kg, while the fertile component, U-238, has a highly detectable gamma ray at 1001.1 keV but a low emission specific rate of 1.0×10^5/s-kg.

To detect the most important nuclear materials by passive methods, neutron measurements alone would be inadequate; both neutron and gamma/x measurements need to be made. A strategy that allows a broad spectral-energy response band would also sense radiation from radiological sources.

Passive methods generally have low cost, good durability, and useful simplicity in maintenance and operation. But passive nuclear-detection methods cannot ensure that all fissionable materials would be detected at check points: For weapon-grade materials, relatively straightforward shielding could easily mask the signal sufficiently to avert detection.

ACTIVE METHODS

Active stimulation of fission (or other radiative indicators) is necessary to detect smuggled nuclear materials, especially those of weapon quality. Induced fission is marked by the emission of energetic neutrons and gamma rays that have high probability of emerging from all but the most massive containers.

In active techniques the controlling factor is the means of inducing fission. Generally this is by neutrons, either fast or thermal. Accelerators or radioactive sources can supply neutrons.

Radioactive Neutron Sources

One category of radioactive neutron source could be classified as "continual." Examples are spontaneous fission Cf-252, which is not accompanied by intense gamma rays, and standard alpha-active sources such as Pu-Be.

Another category of radioactive neutron source is "switchable." This capability has been demonstrated at Argonne for the switchable radioactive neutron source (SRNS)[4] and, I understand, has been more fully developed in the FSU. When not needed as a neutron source, the SRNS can be switched off. This helps in reducing potential personnel exposure. In addition, the source could be remotely controlled, even pulsed at repetitive rates.

Accelerator Neutron Sources

Accelerators can be used to produce abundant, controlled neutron fluxes. Conveniently small and fieldable units have been developed. Either steady-state or pulsed operation could be useful for these applications.

LINACs are prolific gamma-ray and neutron radiation sources, but the large accompanying gamma background[5] makes this type of generator difficult to use in many transit-point environments.

Among the most useful high-intensity sources are pulsed-fast-neutron accelerators (PFNA), which can be raster-scanned across large objects.[6] Very capable generators have been manufactured in Eastern and Western nations.

A type of accelerator neutron source that makes a useful compromise between fieldability, cost, and utility is the Associated-Particle Sealed-Tube Neutron Generator (APSTNG).[7,8] Still being developed and improved, it's availability is relatively limited. Based primarily on time-of-flight measurements of inelastic neutron scattering, the associated-particle technique provides a useful 3-dimensional mapping of chemical components in objects with the size typical of luggage and shipping packages. Inelastic scattering cross-sections are reasonably high and uniform for all chemical elements above boron. Also, the 14-MeV source neutrons and the reaction-product radiation are highly penetrating. The APSTNG is effective in sorting the characteristic reactions from background, delivering information on ratios of chemical constituents. These ratios are definitive in identifying explosives and other contraband. Since fission and capture radiation are also detectable, the associated-particle technique offers sensitivity and versatility to the full range of potential smuggled goods.

Although more expensive than passive methods, active neutron-generating techniques alone have the capability of detecting all nuclear materials. In addition, some active techniques such as PFNA and APSTNG also distinguish explosives and other contraband. While active interrogation induces some residual radioactivity, short bursts of fast neutrons coupled with high detection efficiency would minimize the effect.

DETECTORS

While there are many gamma and neutron detectors[9], fieldability requirements would tend to narrow the list of candidates. For example, gamma detectors that require liquid-nitrogen coolant would be discouraged. More likely, sodium-iodide and bismuth-germanate scintillators would be preferred. For neutron detection, He-3 moderated arrays might be most useful as long as time-of-flight requirements do not need to be met, in which case unmoderated detectors containing B, Li, He-3 or a proton-recoil gas would be acceptable.

Many detectors have been developed and used in nuclear safeguards. While some, such as portal monitors, might be adaptable for civilian transit points, quantitative materials assay or isotopic measurements are not needed in this application. Detectors optimized to cope with the high radioactivity of spent reactor fuel would be too elaborate.

Hodoscope arrays[10] have proven performance for nuclear-material detection under extreme background conditions. Arrays with up to 360 channels have been implemented in the United States and France to measure and cineradiographically image fission-induced radiation. Both gamma-ray and neutron hodoscopes have been developed, and an integrated system has been used to simultaneously detect gamma and neutron beams. Some of the (fast) neutron detectors employed have been fission-ionization, Hornyak-button scintillator, and gas-proportional counters. The gamma detectors are relatively small NaI(Tl) crystals placed in tandem behind the neutron detectors. Such arrays, because of redundancy, efficiency, and moderate cost, are well suited for nuclear-material monitoring at transit points. Hodoscopes have been applied in both passive and active modes of operation.

Particularly versatile are scintillators that have electronically separable gamma and neutron responses. The separation can be based on either pulse amplitude or pulse shape differences. Shape separation was used in the Los Alamos BC454/BGO phoswich detector[11]. In portable commercial ^{6}Li-loaded Ce glass or ^{6}LiI(Eu) scintillator units,[12] both glass (GS-20) and thin 2-in. scintillation crystals show adequate separation of gamma and neutron regions from Cf-252, while giving good efficiency for gamma rays. Such detectors, employed in hodoscope arrays, could be used in a scanned-image mode.

SYSTEMS AND APPLICATIONS

Active units with well-shielded stationary equipment would be valuable at major border traffic crossings. Small portable passive systems would have utility at other transit points. Hand-held units can be used for spot checks and confirmatory, close follow-up inspection. Passive methods would add worthwhile complementary value to a broad-based system centered around active techniques.

Passive neutron/gamma vehicle-monitoring systems could play an important supplementary and complementary role. Well-engineered systems have been developed for nuclear-materials control applications. They would not contribute to detection of explosives and other contraband.

A high-efficiency, stand-off passive-radiation monitoring system is the crystal-lens spectrometer[13], which can detect in one minute a few grams of unshielded Pu-239 or U-235 at a distance of 25 m. Its excellent high signal/background capability results because a large cone of radiation is focused by the lens onto a single small detector. A tandem pair of lenses would be needed for simultaneous detection of both U-235 and Pu-239 with a single detector.

Either radioactive or accelerator sources of neutrons can provide the necessary stimulation of fission for active systems. Pulsed-fast-neutron systems are examples of relatively large stationary units that would be suitable for customs warehouses, airports, marshalling yards, etc. Associated-particle systems might be better for airports and border checkpoints.

There are several possibilities for synergistic operation of detection systems. Although smuggling of an actual nuclear warhead is highly unlikely, its threat potential is the most significant. The detection of explosives and fertile nuclear material, in association with fissile material, is therefore a useful adjunct. Because contraband involved in smuggling is not limited to nuclear materials, a system that detects many types of contraband would be more cost-effective. Inasmuch as neutron probes provide limited spatial resolution, concurrent x-ray imaging could augment identification of objects.

Thus, an optimal system at transit points to monitor smuggling would consist of a versatile neutron-source system which interrogates simultaneously for fissionable materials and other contraband and which is linked directly and synergistically to an x-ray imaging system.

For inspection of cargo containers that cross international borders (including transport by ship), Khan[14] has carried out extensive reviews. Container-inspection systems are relatively large, exemplified by the SAIC-developed PFNA system.[15]

The large number of potential international check points is one of the key problems in coping with smuggling. Monitoring systems thus need to be standardized and user-friendly. For air-transported materials, the major transit points are fewer in number and traditionally subjected to close and sanctioned scrutiny. For light-weight packages in the postal system, passive radiation monitors might be adequate (except at major postal cargo distribution centers). Customs stations at border crossings have vehicular and pedestrian traffic to monitor: Monitoring of pedestrians and passenger vehicles would probably be limited to passive systems: Driverless trucks, however, could be subjected to active interrogation with a moving scanner.

The development of monitoring systems for civilian application has benefited from, and could contribute to, government-controlled applications—including weapons-materials transparency, arms-control treaty verification[16] of inventories, dismantlement of nuclear warheads and missiles, and civilian demining.

CONCLUSIONS

The detection of smuggled nuclear materials at transit points requires monitoring unknown samples contained in relatively large closed packages. The contention of this review is that high-confidence nuclear-material detection requires induced fission as the primary mechanism, with passive radiation screening in a complementary role. This combination of operating modes would have sufficient capability to cope with the vast majority of objects and means of evasion.

Specific technologies that could meet the requisite confidence levels are active techniques—such as PFNA, APSTNG, and SRNS—which induce the defining fission process unique to nuclear materials.

With the right choice of equipment, even small quantities of nuclear materials are subject to high-probability detection at transit points. Moreover, the equipment chosen to detect nuclear materials could benefit from a synergistic linkage with detectors of other contraband, and, conversely, detection of other smuggled goods can be improved by optimization of apparatus that searches for nuclear materials. A good example is the potential coupling of x-ray imaging equipment with the associated-particle chemical-element detection system.

Certainly the experience gained with equipment used at established nuclear-storage sites is valuable in preparing for applications at civilian transit points. At the same time, the applications are sufficiently different that the storage-site experience will have to be adapted, along with other experience in nuclear-material detection, to result in systems suitable for specialized use in detecting smuggling at check points.

For screening postal mail and packages, passive monitors are probably more cost-effective. When a suspicious item is detected, a single active probe at the facility could be used to determine its threat potential. Unless active systems become produced in sufficient quantities to compete with passive monitors, this two-stage screening/interrogation role for active/passive equipment is more economic for cargo at border crossings. However, active equipment designed to rapidly and simultaneously detect and image nuclear and non-nuclear contraband would provide the highest confidence in countering the smuggling of dangerous goods. In fact, to make cost-effective the widespread monitoring of nuclear smuggling, it will probably be necessary to develop a system capable of simultaneously detecting most categories of contraband, including explosives and illicit drugs.

With control of nuclear materials at known storage sites being the first line of defense, detection capabilities at international borders could establish a viable second line of defense against smuggling.

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