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US program to address nuclear terrorism threats:

Surveillance of fissile materials and weapons at the US borders

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1. <u>Introduction</u>

Ferguson (2004) identifies four possible scenarios involving nuclear terrorism: (1) stealing of a nuclear weapon from one of the nuclear-weapon states - the least likely but most destructive-, (2) stealing of highly-enriched uranium (HEU) or Pu for use in an improvised nuclear device (IND) - the most likely and gravest threat-, (3) an attack on a nuclear power plant, (4) a radiological dispersive device or “dirty bomb”. In this report I will concentrate on the first two scenarios: the use of a stolen nuclear weapon, and the fabrication of an IND out of stolen or otherwise acquired weapons-usable nuclear materials, both with the potential to be most catastrophic.

The US strategy to address the nuclear terrorism threat is based on a layered approach to safety where several techniques are used in conjunction:

- The first and most important step is to secure materials at their origin. For example, since HEU is considered the most likely material that terrorists would use in an attack, it is essential to secure it at its source, mainly in Russia.
- The next would be to strengthen intelligence capabilities to detect black markets and possible transport of fissile materials across the world.
- It is then important to install detection equipment at ports of embarkation around the world, but this depends on the degree of friendliness and anti-terrorist cooperation between the country of origin and the US.
- And as a final step we have detection equipment at the arrival ports in US soil.

Even when only concentrating on detection techniques for fissile materials at the US border, each possible technology has a finite probability of detection, so again a combination of techniques is needed.

Three detection techniques can be used at the ports:

- Passive screening for detecting gamma and neutron emission from cargo containers.
- Active screening using X-ray imaging to detect high density material.
- Active interrogation by inducing fission with a neutron beam.

2. Detection of fissile materials and weapons at the US borders

2.1 Scope of the problem

To give an idea of the importance of the cargo-transported commerce, the fraction of US imports and exports that are shipped by sea cargoes is more than 90%. In particular, 6 million cargo containers arrive at US ports per year. If we focus just on the west coast alone, the traffic amounts to 11,000 per day, which is equivalent to 8 per minute (24/7). Given the economic importance of this activity, the current maritime shipping system has been designed for speed and efficiency.

However, post-9/11 security concerns have resulted in a revision of the cargo screening procedures that are currently in place. Many studies today show that the current screening methods are very deficient in handling present security risks, especially in the case in which a terrorist could be trying to use one of these cargo containers to smuggle nuclear materials or weapons into the US. Policy analysts such as G. Allison (2004) believe that a nuclear terrorist attack on a Western city (US, US interests around the world, Europe) either using a real nuclear detonation or a radiological dispersive device (RDD) is not a matter of if, but of when. In his book, Allison analyzes current US vulnerabilities in its screening procedures and points out that if terrorists today try to ship a certain amount of nuclear material from anywhere in the world to a given address in the US, they will have a probability of greater than 95% that the material will arrive to its destination completely unscreened and undetected.

Apart from huge personal, psychological and environmental loss, a nuclear detonation will affect the economy of the US and the world in an unprecedent way. Therefore, port security is essential to the world safety and economy.

The cargo containers are large (8.5 ft by 8.5 ft by 20 or 40 ft). The 20-ft containers can hold up to 20,000 kg of merchandise. It would be easy to hide ~10 kg of fissile material that is needed for a nuclear detonation. In addition, the container material itself would attenuate any radiation given off by the nuclear materials, making passive detection very difficult especially for the lowest-energy radiation that is emitted (fissile materials ^{235}U and ^{239}Pu give off low-energy gamma radiation). In the next section I briefly describe what nuclear materials are to be detected and the types of radiation they emit; that type of information is necessary to select appropriate detection techniques. I will concentrate on materials that can cause a nuclear detonation (fissile materials) and exclude from this analysis other radioactive isotopes that could be used in radiological dispersal devices (RDDs), also called “dirty bombs”.

2.2 Radiation emitted by fissile (weapons-usable) materials and possible ways of detecting them

The two fissile isotopes used in building a nuclear weapon are ^{235}U and ^{339}Pu. Fissile is a more restrictive term than fissionable. Fissile materials can fission with either thermal or fast neutrons, and can sustain a chain reaction, therefore are weapons-usable. Fissionable materials in general undergo fission when they interact with fast neutrons but not necessarily when they interact with thermal neutrons, and are not capable of sustaining a chain reaction.

The so-called “weapons-grade material” is that usually containing $\geq$ 93% fissile isotopes. Weapons-grade plutonium typically contains 94-96% ^{239}Pu (and 4-6% ^{240}Pu). However, other materials with lesser concentrations in these fissile isotopes are also considered “weapons-usable” and therefore are also of interest in the detection. For example: highly-enriched uranium (HEU) which is that containing $\geq$ 20% of ^{235}U, or weapons-usable plutonium, which contains < 60% ^{239}Pu and > 24% ^{240}Pu. The only plutonium concentration that is considered to be proliferation-resistant is the so-called reactor-grade Pu or spent-fuel standard Pu (containing ~1% Pu isotopes and mixed with highly-radioactive fission products in the spent fuel).

In general, fissile materials share a number of characteristics, which allows for specific methods for their detection. However not all the methods are applicable for the screening of cargo containers:

(1) Fissile materials are radioactive, therefore they can in principle be passively detected by studying their gamma-ray energy spectra. This method works well in analyzing a piece of material with very little or no shielding. However, since the main radiation emitted by weapons-usable material is low in energy, these radiation signatures get quickly attenuated by even thin pieces of shielding, such as lead or steal.

(2) Fissile materials are very dense, and therefore can attenuate certain radiations that are incident on them; this feature allows active interrogation with X-rays (X-ray imaging). The presence of high-density materials within a cargo container may raise an alarm at the ports which may instigate further screening, this time by “active interrogation”.

(3) Fissile materials can be fissioned, so that they can be actively interrogated by subjecting them to a beam of gamma rays or neutrons that will induce a limited amount of fission whose signatures can be detected.

In particular, the radioactive signatures of uranium and plutonium materials are described in the following paragraphs.

2.2.1 Uranium material

^{235}U has a very slow decay rate ($T_{1/2}$ = 7.2 x 10^8 yr) and it emits a 185-keV gamma ray with very low mean free path (it can be stopped by one inch of lead). This gamma ray will be shielded by the cargo container material, so it makes passive detection very difficult.

However, weapons uranium materials always contain > 6% ^{238}U, which has an intense gamma radiation at relatively high energies of 1 and 2.6 MeV. The problem with ^{238}U is that this isotope is found in the background, so one of the questions would be how to distinguish the ^{238}U in the weapons material from the ^{238}U in the background.

Another possibility for detection is that the weapons material also contains ^{232}U as an impurity (usually in the range of parts-per-trillion to parts-per-billion). This isotope is not part of NORM (naturally occurring radioactive materials) so its presence if detected is a clear indication of weapons material.

In addition to gamma radiation, ^{235}U also emits neutrons at a relatively slow rate of 0.055 n/s/kg.

2.2.2 Plutonium material

^{239}Pu also has a very slow decay rate ($T_{1/2}$ = 2.4 x 10^4 yr), although not as slow as ^{235}U. It emits quite energetic gamma rays at 642 and 687 keV. The neutron emission rates are high: 15 n/s/kg for ^{239}Pu, and 440 n/s/kg for ^{240}Pu.

<u>3. Active neutron interrogation of cargo containers</u>

The active neutron interrogation technique is currently the most promising option for detecting fissile material in cargo containers. Its goal is to provide with a “yes or no” answer regarding the presence of illicit weapons-usable materials without having to open up the container. This technology is presently under research and it has not yet been deployed in the field, although a prototype is being prepared for field-test in the near future. Experimental work (Norman, Slaughter) and computer simulation research (Pruet) using Monte Carlo techniques are underway by a research group at Lawrence Livermore National Laboratory, headed by S. Prussin, D. Slaughter and E. Norman.

The main issue to be addressed here is that when trying to detect fissile ^{235}U and ^{239}Pu in heavily-shielded material such as in cargo containers, normal techniques of passive gamma detection and active X-ray imaging will not work. In this particular research, an active interrogation is performed using a beam of high-energy neutrons that would induce limited fission in case fissile material is present within the cargo, and that would generate in turn a specific identifying signal. The neutron beam must be sufficiently intense to be able to penetrate thick cargo containers (8.5 by 8.5 ft by 20-40 ft, with a weight of up to 27,000 kg and a maximum density of 0.6 g/cm^3). The original idea was to use neutrons of 14 MeV; however, they react with ^{16}O in the air thereby generating radioactive ^{16}N that interferes with the intended fissile material measurement. Therefore the neutron beam energy was reduced to 7 MeV, which is high enough to induce fission but low enough to avoid generating ^{16}N.

The screening is done by looking at the “beta-delayed gamma rays”. The detection principle consists in that, if there is fissile material inside the cargo, the neutrons will induce fission. Some of the fission products will undergo β^- decay and will populate certain excited states in the products of the β^- decay. These excited states decay by emission of gamma rays, which can be detected and will be used as a signature for the presence of fissile materials.

The minimum requirement for the detection system to be feasible is that the β-delayed gamma rays have an energy that is high enough to be able to penetrate very thick cargos and be readily detected through lots of shielding.

The proof-of-concept is reported in the work by Norman *et al*. where the authors experimentally demonstrate that high-energy ($E_\gamma \geq 2.5$ MeV) delayed γ-rays emitted during the decay of short-lived (less than 1-2 minutes half-live) fission products can be used for detection of fissile materials within the cargo container materials. One of the physics facts that facilitates the analysis is that gamma-rays between 2.5 and 6 MeV (typical energies of emission from beta-delayed fission products) behave in very similar manner (have similar mass attenuation coefficients, cm^2/g) when traveling through different materials, such as Al, Fe, Pb. So the detection of beta-delayed gamma rays is going to be independent on the material used for shielding. But they key point is that the background radiation emits gamma rays at energies usually below 2.5 MeV, so these high-energy signatures allow the experimenters to discern the presence of fissile weapons materials because they “stand out” against a low background spectrum.

So far the proof-of-principle was developed by using high-resolution, very expensive Germanium detectors (the highest-resolution detectors in the market), which cost between $25,000 and $50,000 a piece. If they were to be implemented in the cargo screening problem worldwide where hundreds of them would need to be deployed, the cost of the system would rise to billions of dollars, and the project would not be feasible.

But a breakthrough development was achieved when the experimenters realized that the fissile materials such as ^{239}Pu were giving off a characteristic wedge-shape radiation extending up to high energies of 6 MeV, and this shape could be detected by cheaper, low-resolution but high-efficiency scintillator detectors. With these detectors, it is expected that the system could be deployed as a practical detection technology worldwide.

One of the most recent papers (Slaughter) introduces the “nuclear car wash” prototype, based on scintillator detectors.

4. Practical constraints in the active interrogation technology

For the detection technology to be practical, the following requirements have been established:

- A scan time of one minute or less
- A detection probability of ≥ 95%
- A false positive and alarm rate less than one in 1000.
    - A false-positive alarm occurs when the normal background has a count rate that is above the threshold discriminator. A high number of false alarms is detrimental to the economic viability of the detection system.

5. Feasibility and cost estimate

Some of the key issues related to the practical implementation of the active interrogation technology are as follows:

5.1 Cost

5.1.1 Materials and operations costs

- Materials. Each active interrogation system is composed of two elements: a neutron generator and the scintillator detectors (20-ft long) to register the emitted beta-delayed gamma radiation. According to E. Norman, an estimate of the cost of one of these detectors is between 1 and 10 million dollars.

- Operations. The application of the active interrogation technology will influence operation costs if the scanning time is longer than one minute (disrupts the economy), or if there are too many false positive alarms.

5.1.2 Large-scale implementation

There are 6 million containers arriving to the US per year. The problem of screening all this traffic seems at first look daunting. However, it gets simplified by noting that containers are shipped mainly from 10 large ports in the world, and arrive to mainly 10 large ports in the US. The idea is to spread the interrogation systems by preferentially locating them along the busiest routes and at the critical ports. According to E. Norman estimates, about 100 of these interrogation systems would be needed to screen the whole commercial traffic that is incoming into the US. This estimate gives a total cost of $1 Billion.

5.1.3 The cost in perspective

If we compare this amount ($1 Billion) with other activities related to the fight against nuclear terrorism, it looks comparable to other costs, and in some cases it does not seem like a large amount. The following are costs *per year* of different programs:

- Cooperative Threat Reduction: $1 Billion
  - This important program (also called Nunn-Lugar program) has the objective of securing nuclear materials in former Soviet Union states. Some policy analysts consider it underfunded. Some efforts are currently directed at expanding the program to other regions.
- Department of Defense budget: $401 Billion, excluding the war in Iraq
- Department of Homeland Security budget: $30 Billion

- War in Iraq: $84 Billion (the total cost is set to reach $251 billion in April 2006, after three years since the attack started)
- Maintaining the security of >10,000 US nuclear warheads = $6.5 Billion
- US plan to develop new generation of nuclear weapons and increased nuclear spending: $7.5 Billion (each year at least for the next four years).

The possible cost of not doing everything we can to prevent a terrorist attack, even if low in probability, is very high:

- A nuclear detonation on a US city (for example, a 10 kT IND) would result in $100s Billions of economic loss (in addition to loss of life, displacement of more than 450,000 people, and contamination of 3000 mi^2 that would take years to recover, as estimated by www.globalsecurity.org)

5.2 Property rights and patents

The intention of the research team at Lawrence Livermore Lab in developing these active interrogation technologies is not to compete with industry. The goal at the lab is to develop a prototype that is then given to a private company that will commercialize it. This practice raises some policy issues.

It is in the best interest of the US and other countries that the vast majority of countries around the world have access to this technology. One step that the lab is following is to make the research information public by means of publishing in the open literature. One of the actual reasons behind the publication in the open literature is that it is a way to dissuade the terrorist by letting them know that we will be able to defeat their intents.

But by making the system commercial and have only one company monopolize its fabrication, the cost is likely to increase and might be prohibitive by poorer countries.

This issues are still unresolved and are subject to current debate.

5.3 Other challenges

- Intrusiveness: There might be opposition by the other party to be inspected by active interrogation means. Some materials may not be amenable to active interrogation because of neutron activation concerns, etc.
- Relationships between the US and the countries where ports of embarkation are located. Depending on the degree of friendliness between the two countries, exchange of intelligence information, technology and anti-terrorism cooperation will vary.

6 Conclusions and recommendations

- Active interrogation is currently the only means to detect fissile materials in cargo containers, since the shielding inside the cargo tends to absorb all the low-energy gamma radiation that is characteristic of these fissile materials
- Active interrogation is especially useful to detect HEU because its low energy gamma-radiation makes passive detection impossible. HEU is very important for homeland security because it is considered the most likely nuclear material to be used by terrorists
- The expected cost of $1 Billion dollars for the system seems comparable or lower than many other current anti-terrorist programs led by the US, so it seems like it would be cost-effective to implement.
- A cost-benefit study should be performed that would incorporate the active interrogation system within a layered system of techniques and approaches, from the source to the target:

- Depending on the perception of risk and consequences of a nuclear detonation, one could consider to soften the imposition of zero disruption to the US commerce that is assumed in current studies.

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