Devabhaktuni Srikrishna, A. Narasimha Chari, Thomas Tisch
email: sri at devabhaktuni.us, anchari at gmail.com, ttisch at mindspring.com

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Nuclear Detection: Fixed detectors, portals, and NEST teams won't work for shielded HEU on a national scale; a distributed network of in-vehicle detectors is also necessary to deter nuclear terrorism

<u>Nationwide nuclear detection systems consisting exclusively of portals at borders (drive-thru scanning at borders, container screening) and fixed or handheld detectors in the interior (customs agents, NEST teams) will not suffice to deter nuclear terrorists who are attempting to trade, assemble, or transport highly enriched uranium (HEU) in the worldwide transportation system.</u> Calculations of a link budget for passive detection of HEU and Plutonium (Pu) show that using emitted gamma rays and neutrons is physically limited by the sharp attenuation of its radioactivity with distance/shielding (2-4 feet or less)[1] and the time required to count a sufficient number of particles (several minutes to hours), although Pu may be easier to detect than HEU.

Even if the national border was completely covered with detectors, there is not enough time for passive detection of shielded HEU. Once across the border, terrorist vehicles carrying HEU can circumvent or pass by a network of fixed detectors in the interior for the same reasons. Transport carrying people or livestock can't be subject to active neutron or x-ray interrogation like cargo containers can be, and all types of vehicles can't be searched like air passengers are today. Many kinds of vehicles from light road vehicles to private jets to oil tankers are not screened for HEU,[2] analogous to locking the front door of a house while leaving the garage door wide open. To lock all doors of the house, available detection techniques need to be applied and combined in such a manner that they ensure uniform detection coverage across every transportation mode accessible to terrorists, thereby raising the risk that terrorists transporting HEU and Pu will be detected.

For the vast number of small vehicles (autos, boats, small planes), neutron and gamma detectors located inside the target transport are perhaps the only way that both shielded HEU and Pu detection can be detected. This ensures enough time to record any radioactivity coming from inside the vehicle before securely reporting their readings to a network of check-points (for example, in the same way E-Z pass collects highway tolls).

Today's detection efforts involving fixed/handheld detectors would be useful primarily for detecting unshielded HEU carried by people or animals; active neutron scanning or X-ray portals checking cargo containers may find reasonable quantities (Kgs) of unshielded or shielded HEU depending on the circumstances . In addition to bolstering and expanding these programs, commercially available detector technology should be directly integrated into smaller vehicles and used in conjunction with direct inspection or surveillance schemes for the smaller number of extremely large vehicles not amenable to detection (oil tankers, jumbo-jets).

Besides several hundred thousand casualties and injuries likely, the loss from a terrorist nuclear attack is estimated up to $1 trillion.[3] Back of the envelope estimates of costs for the US to implement an in-vehicle detector program are within $75 billion and possibly much less.

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[1] attenuation of radioactivity with distance is subject to an inverse-square law in free-space and is exponential with shielding

[2] Medalia, J., 2005, "Nuclear Terrorism: A Brief Review of Threats and Responses," CRS Report for Congress, The Library of Congress
http://fpc.state.gov/documents/organization/43399.pdf

[3] See [p. 7, O'Hanlon, 2002]

Nuclear Detection: Fixed detectors, portals, and NEST teams won't work for shielded HEU on a national scale; a distributed network of in-vehicle detectors is also necessary to deter nuclear terrorism ... 1
- The Problem ... 3
- Detection of Shielded HEU (passively) —just how hard? ... 6
  - Gamma Emissions of U-238, U-235, and U-232 ... 8
  - Neutron Emissions of U-238, U-235, and U-234 ... 9
  - Self-Shielding ... 10
  - External Shielding ... 10
  - Path Loss ... 10
  - Background and Detector Efficiency ... 10
  - Detector Area, Detection Time, Detection Distance ... 10
  - Nuclear Detection Link Budget ... 11
  - Detecting HEU with U-238 signal: Dependence on Detector Size ... 13
  - Detection times of a day at a half meter distance are required for ten centimeters shielding ... 13
  - U-232 makes detection easy, but is not always present ... 15
  - A few centimeters of lead shielding put detection times into minutes at distances of a meter ... 15
  - Fixed detectors on streets don't make sense, but in-vehicle detectors are useful ... 16
- Plutonium Detection—easier than HEU? ... 16
  - Neutron Detection ... 17
  - Gamma Detection ... 18
- Detector System Manufacturers ... 21
- DISARM: Detect and Intercept Shipments of Articles with Radioactive Material ... 22
- How good does the detection system have to be? ... 25
- What is required to secure each transportation mode? ... 30
  - Water ... 30
  - Air ... 31
  - Ground ... 31
- Operational Requirements For Assuring Compliance With DISARM ... 31
- How could DISARM be defeated? ... 34
- Economics of Industry Participation and Public Adoption of DISARM ... 36
- Conclusion ... 39
- References ... 41
- Appendix A: Representative Detector and System Suppliers ... 46
- Appendix B: How do we track trends in worldwide terrorism? ... 51

The Problem

Access to a sufficient amount of highly enriched uranium (HEU) is the only barrier preventing a determined terrorist group from building an atomic bomb, since the know-how to build a gun-type HEU-based bomb has been in the public domain for several decades [p. 28, Campbell, 2004], [p. 97, Falkernrath, 1998].[4] Improvised nuclear weapons (based on either HEU or Plutonium) are easier to build than military grade weapons, and they can be delivered to populated areas by modes of civilian transport such as road or sea which militaries are not equipped to defend [p. 100, Falkernrath, 1998], including cars, containers, trucks, boats, trains, helicopters, planes, or ships. A black market of procurement networks and easily concealable nuclear enrichment facilities is being formed [Reuters, 2004], [p. 326, Campbell, 2004]. If the security of HEU and Pu stockpiles cannot be guaranteed, then the second line of defense against nuclear terrorism is to deter would-be nuclear terrorists attempting to pursue construction and deployment of a nuclear weapon and to detect or discover special nuclear material (SNM) in transit through the civilian transportation infrastructure.

If nuclear detection has the potential to deter nuclear terrorism by increasing risk of failure of a nuclear terrorism plot, then the question becomes how do detection systems have to be designed in order to be effective? Today's approaches to nuclear detection rely primarily on fixed inspection portals at national borders[5] and sea-ports through which shipping containers or vehicles pass, fixed radiation detectors positioned at traffic choke-points within the national interior, or handheld detectors used by government agents or nuclear emergency search teams[6] (NEST) when specific intelligence is available. In FY 2006, $125 million or over half of the requested budget for the new Domestic Nuclear Detection Office was proposed for next generation detection portals [Chertoff, 2005]. The U.S. Department of Defense has speculated that at an estimated cost of a few billion to a few tens of billions of dollars, roughly 100,000-400,000 fixed detectors strategically placed in the interior both in and around cities along roads, ports, airports would be necessary to secure the US against a "clandestine nuclear attack" between 2004 and 2015 [p. 10, Defense Science Board, 2004].

The first problem with the DHS, DoD, and DoE initiatives involving portals, fixed detectors, and handhelds is that on a national scale there are many loopholes for terrorists to circumvent these systems including private jets, drug shipments, or oil tankers, etc. as described by a Congressional Research Report titled "Nuclear Terrorism: A Brief Review of Threats and Responses" (See [Medalia, 2005] and [p. 26, Bunn, 2004]). Today's radiation portals situated at ports and border crossings will only result in displacement of nuclear transport into many other sea, air, or ground transport mechanisms that avoid the portals. It is not enough to selectively inspect incoming cargo and vehicles at selected

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[4] For varying assessments of the risk of nuclear terrorism, see [Ferguson, 2004], [Allison, 2004], [National Intelligence Council, 2005], [Linzer, 2004], [Medalia, 2005], and [Howe, 2004]

[5] As part of its Second Line of Defense Program, the Department of Energy has targeted 330 high priority sites Russia and 21 neighboring countries for nuclear detection equipment. These include border crossings and high transit sites, only a small fraction of which (roughly 25%) have been installed and staffed with trained personnel. See [p. 45-46, Bunn, 2005].

[6] see [Nuclear Threat Initiative, 2005], [Kimery, 1995], and [The Week, 2002]

border checkpoints–the capability to detect nuclear materials *anywhere* within the transportation infrastructure is necessary to detect nuclear smuggling and transport.

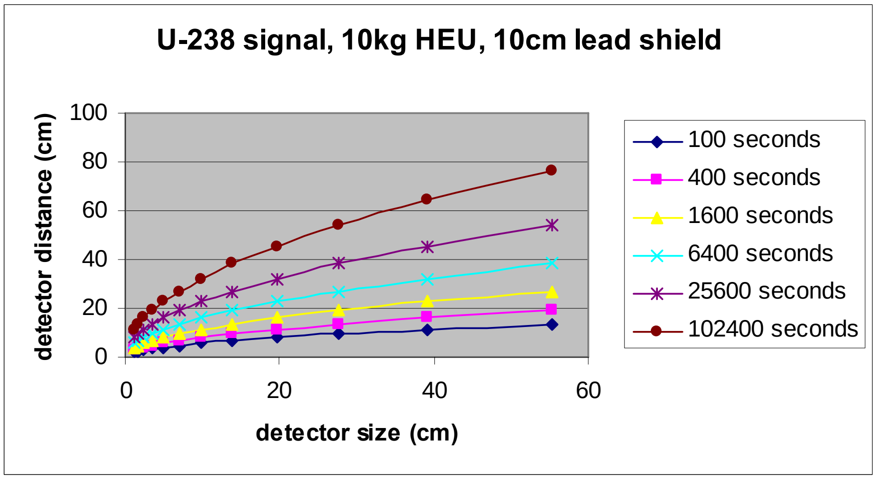

Figure 1 Time and distance required to detect a shielded HEU sample (10kg) using gamma rays

Second, a terrorist could surround HEU with shielding such as lead, concrete, or steel and render passive detection impossible beyond the range of 1 meter using gamma and neutron detection equipment. Shielding all but eliminates the low energy gamma rays (< 200 KeV) and also cuts down the rate of higher energy gamma and neutron emissions so much so that detection times for shielded HEU will necessarily be in the range of many minutes to hours, certainly not seconds. Shielding represents a challenge for detecting HEU with portals or handheld detectors even under ideal detector designs, with 100% detection efficiency, the use of collimation, or even the most advanced gamma detection technologies such as Compton gamma ray imaging[7] that are still under research (and therefore very costly and bulky).

An alternative to passive detection is to pass the target through a portal that uses highly penetrating active neutron interrogation[8] (or experimental muon detection[9] techniques). Active scanning may be suitable for some larger vehicles that carry cargo containers and do not transport living beings, but it is not suitable for the vast majority of vehicles which carry passengers, for which passive scanning or visual inspection are the only remaining options.

Finally, the Department of Homeland Security outlines the need for sensor technology and networks that reliably detect shielded HEU as it crosses national borders and travels within the interior [Kammeraad, 2004], and they indicate that they are funding research into new detection technologies to extend HEU detection to 100 m [see slide 11, Kammeraad, 2004]. Except possibly for very specific nuclear search applications where detection time is not a constraint, detection of shielded HEU based on its radioactivity is

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[7] For an overview of Compton gamma ray imaging, see [Vetter, 2005]
[8] See [Slaughter, 2003]
[9] See [Borozdin, 2003]

unlikely to reach ranges of 100m with acceptably low false-positive rates even with any sort of R&D breakthroughs in detector or portal technology. The constraints on detection have to do with the rate and energy of the natural radioactivity of HEU, its attenuation through shielding, its path loss due to the solid-angle subtended by the detector, and the presence of background radiation at the detector. The constraints on detection ranges and detection times stem from physics and it doesn't make sense to look to technological breakthroughs to deliver detection at distances of hundreds of meters.

Reliable detection of shielded HEU on a national scale will require a completely new nuclear detection architecture and system design that complements portals, fixed detectors, or handheld devices.[10]

We analyze what it would take to design a comprehensive detection system that applies today's portfolio of evolving detection technologies and assembles them into a system that is capable of reliably detecting even small amounts (few kilograms) of shielded HEU and Pu in transit. If the system is to retain enough flexibility to be engineered to deliver any desired level of security where cost and investment replaces physical limits as the determinant of the level of security, then it is not sufficient to simply expand and bolster today's initiatives involving fixed/handheld detectors and portals. We conclude that they will need to be complemented with new approaches involving in-vehicle detectors and inspection or surveillance.

We begin with the assumption that since nuclear terrorists are non-state actors, they won't have access to the weapons delivery vehicles of choice, namely the inter-continental ballistic missiles and air-force jets. In order to deliver a weapon into a city or populated area, terrorists would need to assemble or steal a nuclear weapon in a manner that exploits conventional transportation modes, analogous to how Al-Qaeda attacked the US with commercial airplanes on 9/11 and how they drove a rental truck full of explosives into the World Trade Center in 1993. Assembling or delivering the fissile nuclear material would necessarily involve use of private or government vehicles at multiple points during the development of the terrorist plot, including cars, containers, trucks, boats, trains, helicopters, planes, or ships. Therefore the likelihood of success of a terrorist nuclear plot is directly dependent on the ease with which they can transport nuclear materials without interception by law enforcement and military. Conversely, an increase in the cost and complexity of undetected transportation of fissile nuclear material will serve to dissuade terrorists from pursuing nuclear terrorism plots due to the increased risk of failure they would face. Securing the entire transportation infrastructure against being used to transport nuclear materials is, therefore, key to deterring nuclear terrorism.

Physical constraints of passive detectors are eased with proximity as well as prolonged exposure to the source. For the vast majority of vehicles which are small enough, it is possible to directly integrate emerging and commercially available radiation detector technology into each vehicle such that these detectors travel with vehicles and benefit from having enough time to record radioactivity before reporting their readings to a network of check-points (analogous to how E-Z pass collects highway tolls). One or more

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[10] See [Doyle, 2003] for a motivation of the need for a "nuclear dragnet for homeland security."

passive detectors can be mounted on or inside each vehicle, rather than exclusively at fixed locations or check-points (traffic lights, street lamps, or embedded in roads) where the opportunity for sufficient exposure at short enough distance is extremely limited. . We use DISARM to refer to a system designed to **D**etect and **I**ntercept **S**hipments of **A**rticles with **R**adioactive **M**aterials by placing detectors inside the vehicles that might be used to transport nuclear materials leverages the close proximity as well as prolonged exposure to the radioactive source in transit.

Under plausible shielding scenarios for HEU, the most effective solution involves energy-selective detectors mounted inside vehicles so that radiation coming from *inside* the vehicle is recognized and detected. These in-vehicle detectors would need to be deployed in all types of vehicles that cannot be actively screened: automobiles, trucks, commercial airplanes, trains, private jets, boats and ships, etc. In addition, these same detectors could also be deployed on shipping containers.[11] The larger the vehicle the more shielding it can contain. The smaller subset of vehicles which are too large for passive detection to ever work will need to be dealt with on a case-by-case basis either by requiring them to be screened using fixed portals or through other inspection and surveillance programs.

Detectors used in DISARM can be equipped with tamper-detection circuitry to prevent them from being disabled. Detector readings can be conveyed from the vehicle to a dispersed network of checkpoints (or queried on demand by law enforcement authorities). Checkpoints can be interspersed throughout the interior and around the periphery of the nation as well as around the perimeters of large populated areas. The checkpoints can be designed so that there is no ambiguity about which vehicle transmitted its detector reading. This could be achieved either by using commercially available short-range wireless communication technology between the detector and checkpoint or by designing the checkpoints to be pass-through like toll booths. By programming the checkpoints to discard the readings if the detector does not report anything suspicious, this would also respect personal privacy. One way to ensure deployment in all vehicles of a class is for federal regulations to mandate that all vehicles built after a to-be-determined model year have built-in radiation detectors, with a similar requirement applying to shipping containers as well as commercial and civil aviation airplanes. While it is unusual to call for new federal regulations, the seriousness of the threat and the technical difficulty of otherwise effectively detecting shielded HEU may well warrant this step.

Detection of Shielded HEU (passively) —just how hard?

Short of manual searching or active scanning with neutrons, the only option available for detecting shielded HEU in smaller vehicles, especially those with passengers, is passive detection which utilizes natural radioactivity of HEU as a signal to detect shielded nuclear materials or weapons.

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[11] For a detailed analysis of various passive and active monitoring schemes for cargo containers at seaports, see [Wein, 2005].

We analyze the fundamental physical constraints on passive detection of shielded HEU, and conclude that a fixed infrastructure-based architecture is all but hopeless. The conclusions discussed below are:

1. The useful radioactive emissions for passively detecting shielded HEU are gamma rays at 1MeV from decay of U-238, although neutrons may offer better or complementary detection options.[12] The gamma rays with energy below 200 KeV are practical for detecting only unshielded HEU since these are too easily attenuated with shielding.
2. The most effective detection solutions will place detectors with the largest possible area and most energy-specificity as close as possible and for as long a time as possible since
    a. At distances 10 meters or more, the solid angle subtended by the detector (~ detector area/distance^2) from a 50kg HEU source is likely to reduce the signal as much as any reasonable size shielding.
    b. With sufficient time for the detector to integrate photon counts within a narrow enough photon energy range, even signals below the background can be detected.
3. Due to limitations on both distance and time, a fixed detector infrastructure monitoring vehicles as they pass by can easily be overcome with sufficient shielding.

Advances in detection *technology* cannot alter the fundamental limits on detection that stem from the laws of physics governing attenuation (through shielding) and path loss. Increases in R&D spending aimed at better and more sensitive radiation technology are unlikely to lead to solutions that can detect SNM radiation sources from a great distance (hundreds or thousands of feet) or with short exposure times (seconds or minutes).
In characterizing the ultimate limits of passively detecting shielded highly enriched uranium (HEU), distance of the detector, integration time required, and area of detector can all be traded off against each other while energy-discrimination of the detector allows for precise identification the target material (HEU) in the presence of other benign radioactive sources. Throughout this entire section, our estimation methodology and approximations are based on the development in [Fetter, 1990a, 1990b]. An overview of nuclear detection techniques for homeland security is given in [McDonald, 2004]. For a highly engaging introduction to nuclear science, see [Shultis, 2002].

In our model, we assume the HEU core is shielded externally by lead. The linear attenuation coefficient, defined as the probability per unit distance that a gamma ray is scattered by a material, is a function of both the material and the energy of the gamma ray. Steel and concrete have linear attenuation coefficients at 1 MeV that are not all that different from lead, so the conclusions will be roughly similar even with other typical shielding materials. In addition to the external shield, the mass of HEU itself acts to shield gamma rays (self-shielding). The number of gamma rays that reach the detector is limited by the solid angle subtended by the detector from the source. Finally, detection

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[12] Although highly penetrating neutrons from HEU can be detected, current technology offers limited options for sufficiently small detectors that are also energy selective enough to rule out false positives from other benign neutron sources. Trace quantities of U-232 can sometimes be present, resulting in more penetrating gamma rays of up to 2.4MeV, but they cannot be relied upon to be present in all HEU samples.

involves reading enough counts of gamma rays to be able to ascertain a significant deviation from the background and the detector only detects a fraction of those gamma rays that are emitted due to detection inefficiencies. Each of these factors when put together forms a “link budget” and is explained below.

We use nuclear theory to estimate the maximum distance possible for passive detection of a lead-shielded HEU spherical core using both U-238 and U-232 signals. The distance is graphed against variables of interest including detector area, detection time, shield thickness, and mass of the HEU core. Detection distance depends on amount of HEU and its surface area, shielding, detector area, distance, and time available to detect the emissions. Maximum detection distance is dependent on these factors. Larger detectors might seem to yield better results. They will not be as portable as smaller ones that can be placed closer to the target. When the increased background radiation of larger detectors is also taken into consideration, the increase in solid angle subtended by the detector will only result in detection distances growing in proportion to the square root of detector size.

Although we also explore neutron emissions of HEU, for our detailed analysis, we focus on the 1 MeV gamma emissions of U-238 for two reasons. First it is technologically feasible to implement portable gamma detectors of sufficient energy selectivity. Second it is analytically tractable to analyze gamma detection under different masses and shielding scenarios, and this helps expose the factors that matter most when designing a system. Further investigation could reveal that there are more optimal detection solutions under these constraints (possibly even a combination of neutron and gamma detection), but our survey of gamma and neutron techniques shows that the basic conclusions are unlikely to change regardless: *detection probability is sensitive to proximity and duration of exposure of the detector to the source requiring distance of not more than a few meters and detection times in the minutes to hours.* The problem of effectively detecting highly enriched nuclear materials whether through neutron- or gamma-detection is a hard one.

Gamma Emissions of U-238, U-235, and U-232

Uranium consists of multiple isotopes. By definition highly enriched Uranium (HEU) has more than 20%[13] of the isotope U-235 which is fissile, and weapons grade Uranium contains over 90%[14] U-235. Radioactive decay of U-235 results in gamma rays at 185 KeV, but shielding too easily attenuates these and so they are not useful for detecting shielded HEU. HEU also contains the isotope U-238—the more highly enriched, the less the percentage of U-238. A conservative assumption for detection using U-238 emissions is that HEU or weapons grade Uranium contains at least 5% U-238 by weight. U-232 may also be present in trace quantities (parts per trillion).[15]

According to [Fetter, 1990a], U-238 emits 81 gammas per second per gram at 1.001MeV, and we use that value denoted by **N**. This number can also be derived using first principles and nuclear data, but results in only a slightly higher value based on data from

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[13] See [p. 107, Ferguson]

[14] [p. 255, Fetter, 1990b]

[15] [p. 256, Fetter, 1990b]

[National Nuclear Data Center, 2004]. Radioactive decay of U-238, which has a half-life of 4.47 billion years, will result in Thorium-234 which in-turn decays to a meta-stable (excited) state of Protactinium-234. Meta-stable Protactinium (half life of 1.17 minutes) quickly decays to U-234 most of the time, but 0.16% of the time it relaxes to a more stable state of Protactinium-234 (half-life of 6.75 hours) before eventually decaying to U-234. Gamma rays at 1.001MeV will be emitted due to the transition of meta-stable Protactinium to Protactinium with a probability of 0.837%. Therefore an estimate of the number of 1.001MeV gamma rays emitted by U-238 is 104 per gram per second (= 1 mole / AMU of U-238) x (ln 2 / half-life of U-238) x 0.837%.

U-232's decay chain produces even more penetrating gamma rays than U-238. The most important gamma emitter in the U-232 decay chain is Tl-208 which emits a 2.6 MeV gamma ray when it decays. These gamma rays can be effectively used to detect the presence of HEU if U-232 is known to be a contaminant, even to the effect of a few hundred parts per trillion [Gosnell, 2000]. We can similarly arrive at the rates for U-232, the most penetrating of which has emissions at 2.614MeV at a rate of 2.68 x 10^{11} gammas per gram per second also as reported by [Fetter, 1990a].

Neutron Emissions of U-238, U-235, and U-234

The neutron "link budget" is not easily amenable to analytical approximation as it is for gammas. For a comparison with gammas, we present the basics of neutron emissions and attenuation here in the specific case of weapons grade Uranium (WgU). The lack of energy specific neutron detectors with sufficient portability is currently a technological limitation [McDonald, 2004].

- Weapons grade Uranium (WgU) emits neutrons at the rate of roughly 1/s/kg with an energy distribution centered around 1 MeV—primarily due to spontaneous fission of Uranium isotopes, with each of 234, 235, and 238 contributing roughly equal numbers of neutrons given their relative composition in WgU (see Table 2, Fetter, 1990b).
- These energetic neutrons also have mean free path lengths of 2-6 cm in most shielding materials (tungsten, lead, etc.) whereas 1 MeV gammas are only ~1cm by comparison (Tables B-2/B-3, Fetter, 1990b).
- A 12 kg WgU sample with tungsten tamper emits 30 neutrons per second in addition to 30 1 MeV gamma rays per second at the surface of the sample. The path loss through free space is equivalent for both forms of radiation.
- The background rate of neutrons (per meter-squared per second) is about 50 (for hand-held or portable detectors) whereas the background rate for 1 MeV gamma rays (per meter-squared per second) is cited as being between 17 (for hand-held) and 860 (for portable detectors).

Although neutrons may pass through shielding further than 1MeV gammas, the difference is small enough that detection of shielded WGU using neutrons is likely to be subject to comparable constraints of short distance (2-4 feet) and long observation times (several minutes to hours) like gammas.

Self-Shielding

Gamma rays may be scattered as they escape from the HEU core, losing some fraction of their energy and making them less useful for detection. Fundamentally, the more surface area per gram of material, the more gammas escape. The number of gammas that escape without scattering can be calculated precisely with radiation shielding theory and depends on the geometry of the core. But for a sphere of radius **r** and linear attenuation coefficient **μ**, it can be approximated by the self-shielding attenuation coefficient **G** that describes the fraction of gammas emerging without scattering,

$$\mathbf{G = (1-e^{-4\mu r/3}) / (4\mu r/3)}.$$

External Shielding

Our model of the shield is a spherical shell of thickness **x** surrounding the HEU core, whose effects we approximate as being the same as a sheet of the same thickness. For an external shield material of thickness **x** and linear attenuation coefficient **λ**, the well known formula for the fraction of gammas emerging without scattering is

$$\mathbf{F = e^{-\lambda x}}$$

Path Loss

The solid angle subtended by a detector of area **A** at a distance **d** from the center of the Uranium core is approximately

$$\mathbf{P = A/4\pi d^2}$$

Background and Detector Efficiency

Some fraction of the received gamma rays will not be counted due to inefficiencies in the detector. The efficiency is denoted by **ε**. The detector will also receive gamma rays from both its surroundings and the cosmic rays collectively termed “background” and denoted by **b**, which is dependent on the bandwidth of the channel in which the detector measures counts. Therefore, a high-resolution detector with a large number of channels will have a small value of **b**. As a result, the average rate of background will be

$$\mathbf{B = Ab}$$

and **Bε** counts will be registered by the detector due to background. In our calculation, we assume a high-purity Germanium detector with a 2keV bandwidth. Other types of detectors may have a higher bandwidth that would result in a greater background rate.

Detector Area, Detection Time, Detection Distance

The total signal received at the detector is therefore given by

$$\mathbf{S = NGFP}$$

Signals below the background can be detected when the total counts due to the signal exceeds the fluctuations in the background. If a source is present, the former grows linearly with time while the latter is proportional to the square root of time. If **S** is the signal received at the detector and t is the time over which counts are integrated, then the $\mathbf{S\varepsilon t}$ will be the counts due to the signal, while the standard deviation of fluctuations in the background will be proportional to $\mathbf{(Ab\varepsilon t)^{1/2}}$. Therefore the signal can be detected after the following criterion when the average signal exceeds a multiple, **m**, of standard deviations of the background

$$\mathbf{S\varepsilon t > m\,(Ab\varepsilon t)^{1/2}}$$

Solving for t, we arrive at the time required for detection is

$$\mathbf{t > m^2Ab/(S^2\varepsilon)}$$

In our calculations below, we use **m=5**.

Nuclear Detection Link Budget

To illustrate these calculations, an example is shown in the following table for the detection of roughly 50kg of HEU with 10cm lead shielding assuming a detection distance of 100cm. The third column presents a link budget through detection of the 1 MeV gamma ray emitted by U-238 showing that detection of the core under these conditions would require nearly three hours assuming a gigantic 1 square meter solid-state detector (if one existed). The fourth column presents a similar link budget for detection using the 2.6 MeV gamma ray emitted by U-232 (a trace contaminant that may or may not be present in HEU) that requires just 31 seconds to detect the core using a much smaller 30 square centimeter detector.

CORE	**Symbol**	**HEU**	**HEU**
Detectable Isotope		**U-238**	**U-232**
Gamma Energy (MeV)		1.00	2.6
Production Rate (per gram per second)	**N**	81.00	2.68E+11
Density (grams per cubic centimeter)		19.00	19
Weight fraction of isotope		0.06	1.00E-10
Inner Radius (cm)		0.00	0.00
Outer Radius (cm)	**r**	8.50	8.50
Linear Attenuation Coefficient (per centimeter)	**μ**	1.41	0.87
Thickness (cm)		8.50	8.50
Weight (grams)		48851.60	48851.60
Weight (kg)		48.85	48.85
Total Gamma Rate		217633.86	1309222.79
Beta		1.33	1.33
Self-Shielding Attenuation (dB)	**G**	-12.04	-9.94
SHIELD		Lead	Lead
Density (grams per cubic centimeter)		11.35	11.35
Linear Attenuation Coefficient (per centimeter)	**λ**	0.77	0.50
Inner Radius (cm)		8.50	8.50
Outer Radius (cm)		18.50	18.50
Thickness (cm)	**x**	10.00	10.00
Weight (kilograms)		271.69	271.69
Shielding Attenuation (dB)	**F**	-33.44	-21.71
DETECTOR		Handheld HPGe	Handheld HPGe
Area (square cm)	**A**	10000.00	30.00
Efficiency	**ε**	0.16	0.16
Bandwidth (KeV)		2	2
Background at this Bandwidth (per sq. cm per sec.)	**b**	0.0017	0.0003
Background detected (per second)	**Aεb**	2.72	0.00
Detection threshold (number of standard deviations)	**m**	5.00	5.00
TIME TO DETECTION			
Distance (cm)	**d**	100.00	100.00
Path Attenuation (dB)	**P**	-10.99	-36.22
Total Attenuation: self + shield + path (dB)	**G + F + P**	-56.47	-67.87
Total Gammas at Detector (per second)		0.49	0.21
Gammas detected (per second)		0.08	0.03
Time to detection (seconds)	**t**	11017.52	30.80
Time to detection (minutes)		183.63	0.51
Time to detection (hours)		3.06	0.01
DISTANCE TO DETECTION			
Detection time (seconds)		11017.00	30.80
Self + Shield Attenuation		-45.48	-31.65
Total Gammas outside (per second)		6.17	894.63
Detection distance (cm)		100.00	100.00

Detecting HEU with U-238 signal: Dependence on Detector Size

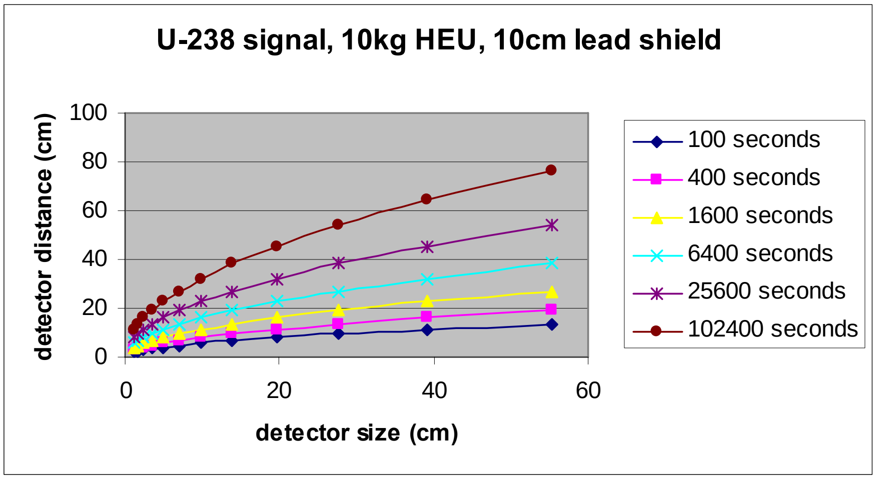

Figure 2

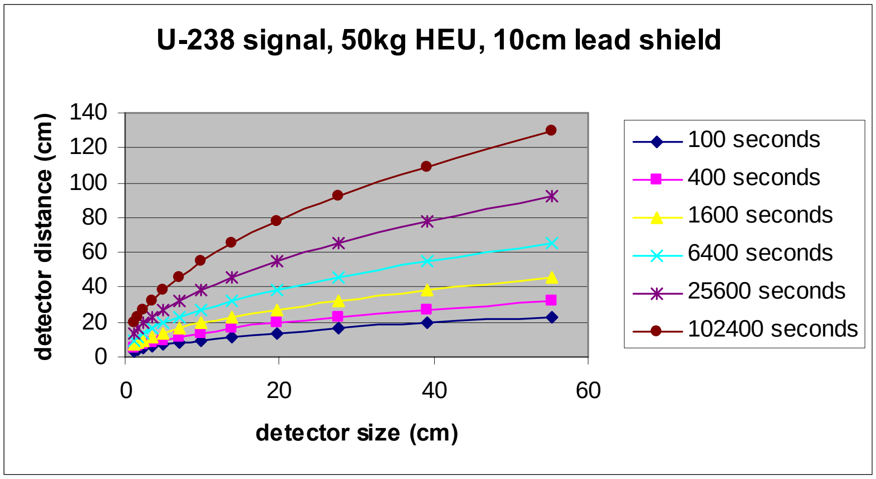

Figure 3

Detection times of a day at a half meter distance are required for ten centimeters shielding

The graphs in this section indicate that 7-10cm of lead shielding requires on the order of a day using U-238 based detection even at distances of 0.5-1m. So detection of heavily shielded HEU looks hopeless at distances greater than 1 meter, and only begins to become feasible below 1m.

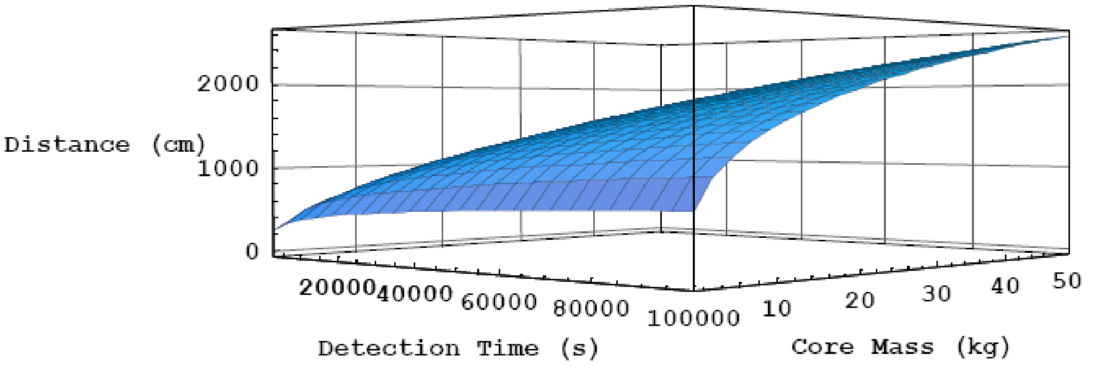

Figure 4 Detection Distance For No Lead Shielding, 1800-100000 seconds of HEU using U-238 signal, 100 sq. cm. detector area (10cm x 10cm). Mass of core varies from 1-50 kg

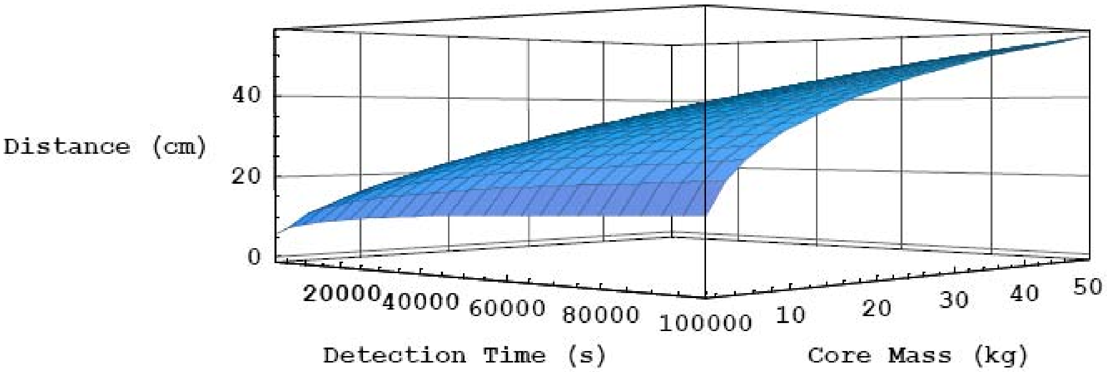

Figure 5 Detection Distance For 10cm Lead Shielding, 1800-100000 seconds of HEU using U-238 signal, 100 sq. cm. detector area (10cm x 10cm). Mass of core varies from 1-50 kg

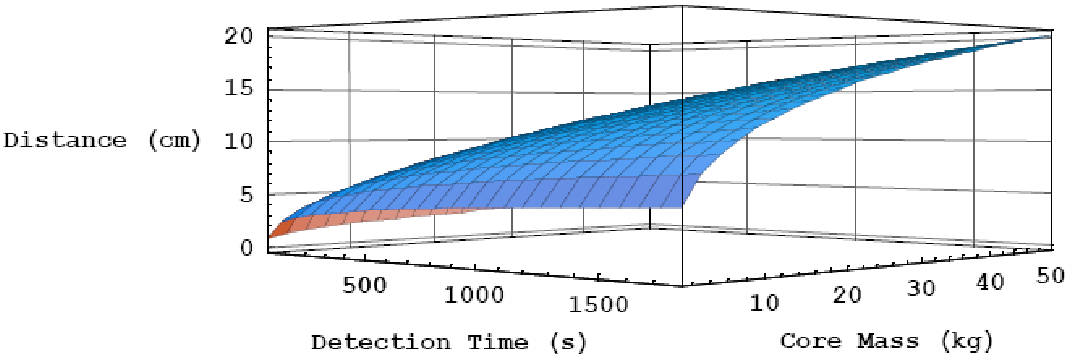

Figure 6 Detection Distance For 10cm Lead Shielding, 1-1800 seconds of HEU using U-238 signal, 100 sq. cm. detector area (10cm x 10cm). Mass of core varies from 1-50 kg

U-232 makes detection easy, but is not always present

If trace quantities of U-232 are present, detection is much easier and can be achieved at several meters distance even with 10cm of lead shielding and for a few kilograms of HEU. The catch is that U-232 is not guaranteed to be present in HEU. From here onwards, we refer to detection with U-238 only.

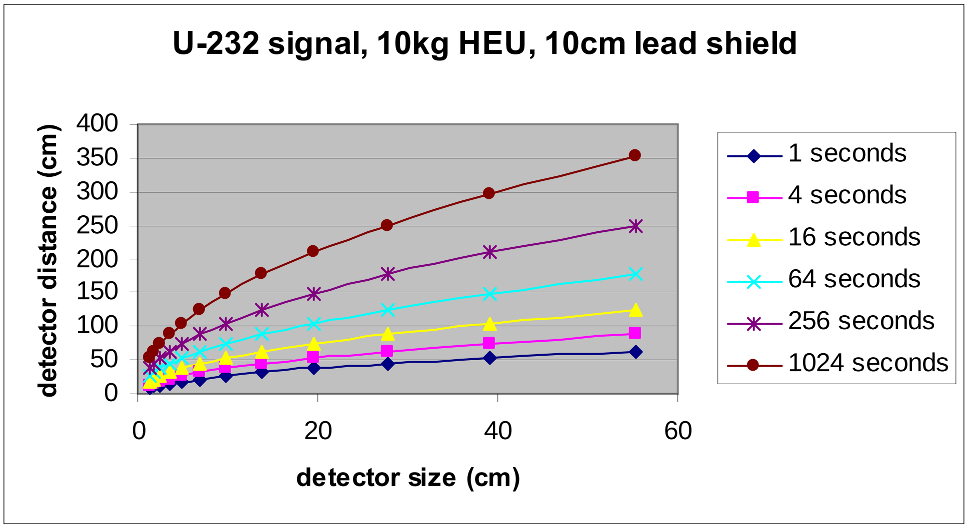

Figure 7

A few centimeters of lead shielding put detection times into minutes at distances of a meter

Detection times on the order of minutes can be achieved at distances of a meter or more only when shielding is less than a 2-3 centimeters. Beyond that, detection times need to be taken to tens, hundreds, or thousands of minutes depending on the shielding and size of the core

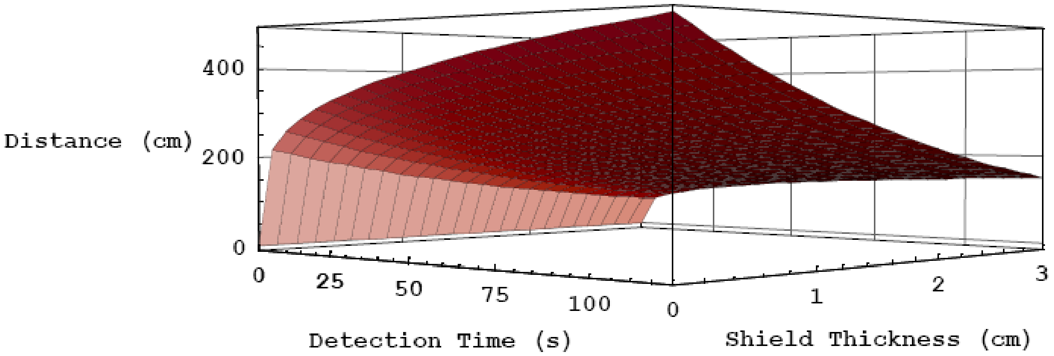

Figure 8 Detection Distance for 0-120s, 0-3 cm lead shielding of 48kg HEU using U-238 signal, 100 sq. cm. detector area (10cm x 10cm)

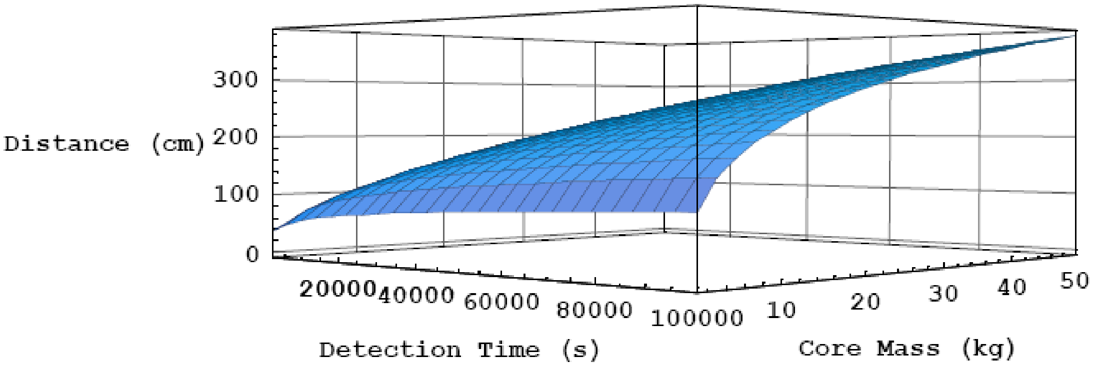

Figure 9 Detection Distance For 5cm Lead Shielding, 1800-100000 seconds of HEU using U-238 signal, 100 sq. cm. detector area (10cm x 10cm). Mass of core varies from 1-50 kg

Fixed detectors on streets don't make sense, but in-vehicle detectors are useful

If either the U-238 signal or neutrons or both are to be relied upon, we conclude that any practical and robust detection scheme is going to require detection times in the range of several tens of minutes to hours. This immediately rules out the use of fixed detector infrastructure to look for signals in vehicles passing by—there will not be enough time to integrate the signal from signals from a moving vehicle. Improving detector efficiency from 16% to 100% would not even double the detection distance since the detection distance is proportional to the fourth root of the efficiency--improvements in detector efficiency result in more background radioactivity counts and because activity from the source has an inverse square law falloff with distance from the source.

Requiring operation of one or more detectors continuously inside the vehicle that ensure proximity and sufficient photon integration time will serve to raise the risk of detection for a terrorist transporting HEU. If an in-vehicle detector were present, hundreds of kilograms of shielding would be required to evade detection, which would make it more likely that the terrorist would have to use a heavier vehicle to transport the HEU. If these larger vehicles are then screened with more invasive (active) techniques that amplify the U-238 signal, the terrorist would probably give up trying.

Plutonium Detection—easier than HEU?

Even reactor-grade (i.e., not weapons-grade) plutonium can be used to achieve a yield of a few kilotons. More generally, plutonium of any isotopic composition can be used to construct an implosion assembly with kiloton yield. The bare critical mass is a function of the isotopic composition. Also, the probability of pre-detonation (resulting in a fizzle) varies depending on the composition. Furthermore, "the technical problems confronting a terrorist organization considering the use of reactor-grade plutonium are not different in kind from those involved in using weapons-grade plutonium, but only in degree." [Mark 1990]

Since reactor-grade plutonium might be more readily available, it might represent a material of choice for would-be nuclear terrorists. However, they would still be faced with the technical difficulty of constructing an implosion system. Below we consider the limits of detection of plutonium of various grades (from super-grade with 98% Pu-239 through MOX-grade with only 40% Pu-239) based on the natural neutron and gamma ray emissions.

The isotopic compositions of different grades of plutonium are as listed in the table below [Mark 1993]:

	Super-grade	**Weapons-grade**	**Reactor-grade**	**MOX-grade**	**FBR Blanket**
Pu-238 (%)	0	0.012	1.3	1.9	0
Pu-239 (%)	98	93.8	60.3	40.4	96
Pu-240 (%)	2	5.8	24.3	32.1	4
Pu-241 (%)	0	0.35	9.1	17.8	0
Pu-242 (%)	0	0.022	5	7.8	0

Neutron Detection

In general, isotopes of plutonium undergo spontaneous fission far more readily than uranium isotopes, resulting in much higher rates of neutron emission. The table below lists the approximate number of neutrons per second per kilogram generated due to spontaneous fission for each grade of plutonium. These numbers are can be readily derived from the isotopic composition of each grade of plutonium, the half life of each isotope, the branching ratio for spontaneous fission, and the number of neutrons produced per fission.

Super-grade Pu	**Weapons-grade Pu**	**Reactor-grade Pu**	**MOX-grade Pu**
18400	54000	349000	487000

The dominant contribution to the neutrons for all of the grades comes from the spontaneous fission of Pu-240. Reactor-grade and MOX-grade plutonium have an order of magnitude higher percentage of Pu-240 compared to weapons-grade plutonium, and their neutron emissions are larger by a corresponding factor. Regardless of the grade of plutonium under consideration, the production rate of neutrons from spontaneous fission is about 4 orders of magnitude greater than for weapons-grade uranium (of the order of 1 per second per kilogram).

The mean energy of the neutrons produced by fission is about 2 MeV (just as for weapons-grade uranium). Mean interaction-free paths for common shielding materials are in the 2-6 cm range and materials containing lighter elements such as boron or lithium can have much shorter mean-free paths. The mean free path for absorption of neutrons is much larger than the mean interaction-free path. The neutron background is about 50 per meter-squared per second, just as for neutrons from weapons-grade uranium.

In comparing neutron detection of weapons-grade uranium versus neutron detection of any grade of plutonium, we can conclude that any grade of plutonium is several times easier to detect than weapons-grade uranium for the following reasons:

- The rate of neutron production is 4 orders of magnitude higher for any grade of plutonium
- The energies of the neutrons produced are identical
- The path loss through shielding and through free space are identical
- The background rates of neutrons at the detector are identical

As noted earlier, the dominant contribution to the neutrons for all of the grades comes from the spontaneous fission of Pu-240. It is possible to reduce the Pu-240 content by a factor of 400-4000 resulting in a corresponding reduction in the neutron emission rate. This purification of plutonium can be achieved through multi-stage atomic-vapor laser isotope separation techniques. This would have the effect of reducing the neutron emissions. It has been estimated [Fetter 1990c] that this would add a cost of $5MM for 4 kg of weapons-grade plutonium.

Gamma Detection

Plutonium has several gamma ray emissions, notably those at 645.98 KeV and 769 KeV (from the Pu-239 decay chain) and those at 662 KeV and 722.47 KeV (from the Pu-241 decay chain). In addition, there is an energetic neutron-induced 1.597 MeV gamma ray that may be useful for detection. We focus here on the detection of the 769 KeV gamma ray from the Pu-239 decay chain and present a side-by side comparison of detection of plutonium of various grades and the detection of weapons-grade uranium based on the 1.001 MeV gamma ray from the U-238 decay chain. We conservatively assume that for detection of WgU, the 1.001 MeV gamma ray from U-238 is the most useful emission for detection purposes – if trace U-232 contaminants are present, there may be a more penetrating 2.6 MeV gamma emission. Since U-232 contaminants may not be present, we focus on the 1 MeV gamma emission for the purpose of reliable detection.

CORE	**Weapons-grade Pu**	**Reactor-grade Pu**	**MOX-grade Pu**	**Weapons-grade U**
Detectable Isotope	Pu-239	Pu-239	Pu-239	U-238
Gamma Energy (MeV)	0.769	0.769	0.769	1.001
Production Rate (per gram per second)	252	252	252	81
Density (grams per cubic centimeter)	19.84	19.84	19.84	19
Weight fraction of isotope	0.933	0.603	0.404	0.055
Inner Radius (cm)	0	0	0	0

Outer Radius (cm)	4	4	4	4
Linear Attenuation Coefficient (per centimeter)	2.07584	2.07584	2.07584	1.41
Thickness (cm)	4	4	4	4
Weight (grams)	5316.061867	5316.061867	5316.061867	5090.986667
Weight (kg)	5.316061867	5.316061867	5.316061867	5.090986667
Total Gamma Rate	1249891.202	807807.497	541217.6265	22680.3456
Beta	1.333333333	1.333333333	1.333333333	1.333333333
Self-Shielding Attenuation (dB)	-10.4419936	-10.4419936	-10.4419936	-8.764533496
SHIELD	Lead	Lead	Lead	Lead
Density (grams per cubic centimeter)	11.35	11.35	11.35	11.35
Linear Attenuation Coefficient (per centimeter)	1.012	1.012	1.012	0.77
Inner Radius (cm)	4	4	4	4
Outer Radius (cm)	14	14	14	14
Thickness (cm)	10	10	10	10
Weight (kilograms)	127.3500267	127.3500267	127.3500267	127.3500267
Shielding Attenuation (dB)	-43.95060157	-43.95060157	-43.95060157	-33.44067511
DETECTOR	Handheld HPGe	Handheld HPGe	Handheld HPGe	Handheld HPGe
Area (square cm)	10000	10000	10000	10000
Efficiency	0.16	0.16	0.16	0.16
Background (per square centimeter per second)	0.00734	0.00734	0.00734	0.0017
Background detected (per second)	11.744	11.744	11.744	2.72
Detection threshold (number of standard deviations)	5	5	5	5
TIME TO DETECTION				
Distance (cm)	100	100	100	100
Path Attenuation (dB)	-10.98989639	-10.98989639	-10.98989639	-10.98989639
Total Attenuation: self + shield + path (dB)	-65.38249156	-65.38249156	-65.38249156	-53.195105
Total Gammas at Detector (per second)	0.361928727	0.233915351	0.156719406	0.108677382
Gammas detected (per second)	0.057908596	0.037426456	0.025075105	0.017388381
Time to detection (seconds)	87552.78707	209603.5524	466950.1646	224900.5983
Time to detection (minutes)	1459.213118	2493.392539	7782.502744	3748.343305
Time to detection (hours)	24.32021863	58.22320899	129.708391	62.47238841

DISTANCE TO DETECTION

Detection time (seconds)	300	300	300	300
Self + Shield Attenuation	-54.39259516	-54.39259516	-54.39259516	-42.2052086
Total Gammas outside (per second)	4.54582481	2.937976806	1.968395738	1.364987919
Detection distance (cm)	24.19428654	19.45049481	15.92071912	19.11096693

This analysis shows that even at 10cm lead shielding both weapons-grade and reactor-detection of any of the grades of plutonium considered above using only the 769 KeV gamma emission from the Pu-239 decay chain is easier than detection of WgU using the 1.001 MeV gamma ray from the U-238 decay chain. This may be attributed to the following observations:

1. U-238 comprises only about 5% of WgU, whereas Pu-239 comprises anywhere from 40% to 93%, depending on the grade of plutonium. As a consequence, plutonium generates 1 to 2 orders of magnitude (10-13 dB) more gammas (per kg per second) at 769 KeV than WgU generates at 1 MeV
2. The 769 KeV gamma rays have a higher linear attenuation coefficient and are more strongly attenuated than the 1 MeV gamma rays. As a result, the shielding attenuation is about 12 dB greater for the plutonium emissions.
3. The background count of gamma rays is about 5 times higher at the lower energy (769 KeV) compared to 1 MeV.

These two effects counteract each other, the former favoring easier detection of plutonium, the latter favoring easier detection of uranium, with the end result that of either weapons-grade or reactor-plutonium considered is slightly more detectable than weapons-grade uranium, while MOX-grade plutonium is a little harder to detect than WgU.

Note that we assumed that trace quantities of U-232 are absent in the uranium sample and that the most useful emission for reliable detection is the 1 MeV gamma ray from the U-238 decay chain. If trace quantities (ppb) of U-232 were present, the detection problem would be much easier for uranium, since the 2.6 MeV gamma ray is very penetrating. This analysis also only considers plutonium detection using the 769 KeV gamma emission from the Pu-239 decay chain. Including the other gamma ray emissions for plutonium listed previously will only make the plutonium detection problem easier. From this analysis we conclude that any grade of plutonium will be no harder to detect (and perhaps easier to detect) than weapons-grade uranium, based on gamma ray emissions alone. We conclude that a national detection system that is capable of detecting weapons-grade uranium in transit through the transportation system will be capable of also detecting similar quantities of plutonium.

Detector System Manufacturers

Well over 50 companies and laboratories--systems, instrument and technology developers—are involved in producing nuclear detectors worldwide as listed in "Appendix A: Representative Detector and System Manufacturers." The market has been estimated by some manufacturers at around $500M/ year. Current offerings can be broadly summarized in the following table:

	Broadband Detection	**SNM Discrimination**
Portal Type [moving target or scanner]	- Large Detector areas/volumes -- Typically designed to work at 5-10m distances - Rapid detection of high activity sources - Slow speed detection of low activity sources - Specs typically 8Km/hr max speed through portal - Price $10K-$50K (low range or personal portals); much higher for large vehicle portals	- Higher Sensitivity - Add SNM specificity or spectrum analysis - Otherwise same as broadband - Computational systems and other automation - Mobile Scanners fit in this category; some with GPS location and wireless communications - $ 50K +
Hand-held [Stationery Target]	-Typically High Activity Sources [e.g. Cs, Co] - Small detector volumes/areas - Some designed for permanent placement (e.g. in-container, some with wireless) - Some meet IAEA specs for SNM detection - Work at < 1-2 m range - 30KeV – 1.5MeV range - Price $1-$2K	- Higher Sensitivity - Add SNM specificity or spectrum analysis - Otherwise same as broadband - Price $5- $15K

As detector volumes reach into the millions or tens of millions of units a year, we can reasonably expect that the detector performance will improve and costs and prices will come down dramatically. Progress in detector technology is likely to result in improvements in cost, form factor, sensitivity, and discrimination. For example, room temperature Cadmium-zinc-telluride gamma detectors have recently been developed [Physorg.com, 2005] and semiconductor neutron detectors are described in US Patent 6,075,261.

DISARM: Detect and Intercept Shipments of Articles with Radioactive Material

Today's nuclear detection systems consist primarily of scans at borders and ports for a small fraction of cargo containers and vehicles. Maintaining the status quo implies a reliance on intelligence and military to catch nuclear terrorists and smugglers in the act. One option is to bolster existing container security schemes to include 100% of all cargo and equip customs/border patrol with energy selective detectors that can reduce false-positive rates—those improvements are likely to deter some attempts and probably not others due to the vast majority of loopholes across the borders. Another option is to distribute a network of fixed detectors with the possibility of detecting fissile material that is contaminated with U-232 using its highly penetrating gamma rays—this approach is like probabilistic insurance because some but not all HEU contains U-232.

How do we create a comprehensive deterrent to smuggling fissile nuclear materials? We propose an in-vehicle detector architecture that we refer to as DISARM (**D**etect and **I**ntercept **S**hipments of **A**rticles with **R**adioactive **M**aterial) which can be used to offer greater likelihood of detecting shielded HEU traveling uniformly through the transportation system, when used in conjunction with expanded initiatives for fixed/handheld detectors, portals, as well as inspection or surveillance schemes for the largest vehicles not amenable to detection. The goal is to interdict smuggling of all or part of an HEU device to defend against both trafficking and delivery to substantially increase the risk for terrorists building and deploying a nuclear weapon.

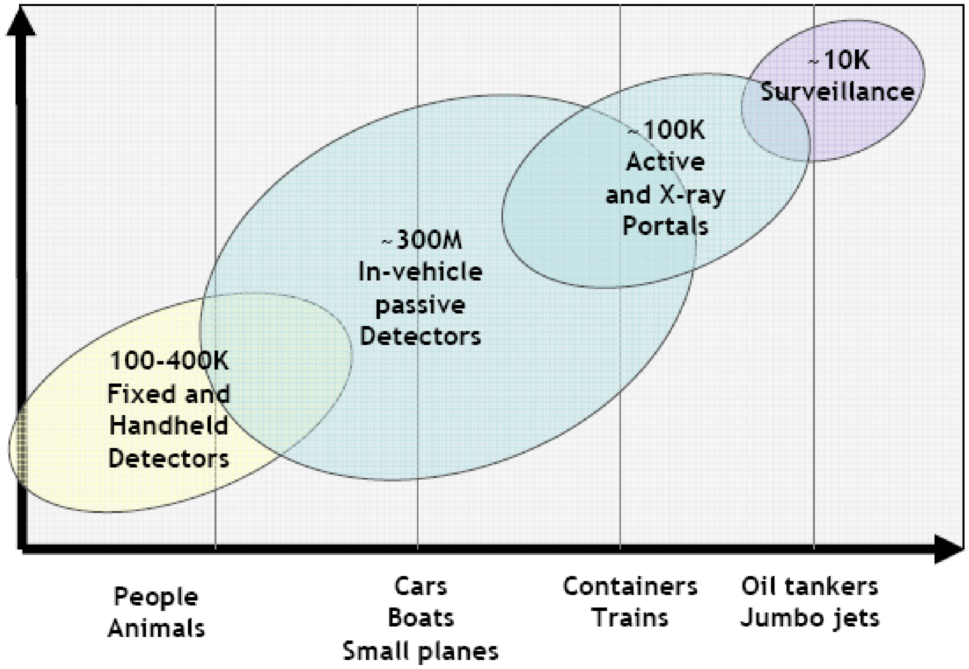

Figure 10 Achieving uniform coverage for nuclear detection across transportation modes

The salient aspects of the DISARM proposal are as follows:

- *In-vehicle detectors:* Nuclear detectors passively searching for the characteristic radioactivity need to be co-located inside any moving vehicle that is capable of transporting shielded HEU and that is either not inspected or actively screened with neutrons. These would include automobiles, trucks, trains, planes, boats, shipping containers, etc. as well as smaller trailers that may be towed by these vehicles. These detectors can be small, mass-produced, and built from the same commercially available and emerging technologies that can be used for handheld and portable detectors, but will be capable of reliable detection of nuclear contraband by virtue of both extremely close proximity and prolonged exposure (minutes to hours to weeks) to the radiation source. A sufficient number of detectors per vehicle continuously powered by the vehicle's batteries or power supply are necessary in order to ensure time to enough count particles from nuclear materials inside the vehicle.
- *Fixed and mobile infrastructure:* A network of detector-readout checkpoints can be deployed liberally throughout highly populated areas [including at transportation chokepoints, around critical infrastructure such as government buildings and bridges, as well as around the perimeters of major metros]. The checkpoints would employ short-range wireless communications to remotely query vehicles and cargo approaching the checkpoint and determine its detector readings. The checkpoints need to be designed such that the received detector reading can be unambiguously associated with the correct vehicle. This is achieved either by using wireless technology whose range is short enough to remove ambiguity of which vehicle originated the reading or by designing the check-point to have the vehicle pass through like a toll-booth or with sufficient proximity to the vehicle. The checkpoints could be designed to generate alarms for further inspection if either the detector reading is reported to be above a threshold, or if the detector fails to report a reading.
- *Incentives to participation:*
    - *Expedited passage:* Vehicles and cargo that can be verified to be carrying on-board detectors would be granted rights to expedited passage while those not similarly equipped might be subjected to manual search, which might be time-consuming and intrusive.
    - *Driver-warnings:*[16] A secondary benefit of in-vehicle detectors for drivers and owners of vehicles can be achieved if detector readings are designed to be conveyed to the driver on their dashboard such that they warn of any radioactive material that has been planted inside the vehicle by a potential terrorist or smuggler or picked up unknowingly contaminated material. This provides an incentive for the driver or owner to ensure that detectors are functioning.
    - *Subsidies:* To promote detector installation, the federal government should provide powerful financial incentives to corporations and private parties to participate in the program and install detectors in their vehicles and containers.
- *Federal regulations for vehicles and containers:*

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[16] This idea was suggested to the authors by Michael May when this material was presented at the Center for International Security and Cooperation, Stanford University on October 11, 2005.

  - *New vehicles:* Federal regulations should mandate that all motor vehicles after a to-be-determined model year be required to ship with an embedded radiation detector equipped with short-range wireless communications capabilities. Similar regulations should apply to shipping containers [Wein et al, 2005].
  - *Old vehicles:* Federal regulations should mandate that older vehicles and containers be retrofitted (through after-market installation) to carry on-board detectors.
  - *Vehicle Licensing:* Routine inspections of vehicles for licensing purposes would be expanded to encompass radiation detector functioning (similar to smog certification).
- *To achieve uniform detection coverage, the above proposals complement today's initiatives in perimeter screening systems*:
  - *Portals:* Portals employing active scanning technology can be useful to screen larger heavily shielded containers (in airplanes, trains, trucks) for which use the number of passive detectors required would become too large. These can be located at seaports, truck weigh-stations, rail-stations, and airports to screen cargo.
  - *Fixed and handheld detectors:* SNM carried by people or animals is unlikely to be shielded heavily if at all due to constraints on weight, hence fixed and handheld detectors at border crossings and within the interior are likely to be useful.
  - *Inspections & surveillance:* Securing against transport of nuclear weapons inside large vessels such as oil tankers or jumbo jets (outside cargo containers) is an important aspect of the detection problem not likely to be amenable solely to detector approaches. Due to the combination of their potential for shielding of radiation as well as the proximity of airports and harbors to populated centers, these larger vessels must be safeguarded by monitoring and controlling access through inspection and video surveillance so that terrorists simply can't use them to deliver nuclear weapons.

Stephen Flynn [Flynn, 2004] offers a promising (and similar) proposal aimed at container security. The DISARM proposal generalizes Flynn's basic model. Flynn suggests that containers could be outfitted with internal sensors that detect gamma and neutron emissions from a nuclear weapon or dirty bomb. When the container arrives at a terminal, an inspection unit would interrogate sensors inside the container and the sensor data would be securely transmitted over a secure Internet link to customs authorities along the route. Flynn's in-container approach effectively exploits proximity and prolonged exposure of the detector to the container contents. It is likely to be capable of detecting the presence of even shielded HEU or other radioactive materials. We believe this idea can be extended to all modes of transport as envisioned in our DISARM proposal. Along the lines of Flynn's proposal, two companies have introduced radiation detection systems that place detectors inside shipping containers and in conjunction with communication systems. RAE Systems of San Jose, CA has a case study discussing their results deploying an in-container solution [RAE Systems, 2005]. RFTrax of Allyn, WA discusses a battery powered radiation sensor [RFTrax, 2005a] and a remote monitoring communication system that integrates GPS, Internet, RFID, and GSM wireless communication technologies [RFTrax, 2005b].

How good does the detection system have to be?

To make it difficult to dissuade the terrorist from trying to transport SNM, there needs to be uniformly high risk of failure in transporting SNM across all transportation modes available to the terrorist. Securing only a subset of accessible transportation modes will result in terrorists resorting to the next available alternative, like locking some doors of a house and leaving other doors open. For instance, preventing the movement of HEU through US ports will not necessarily make it more difficult to transport HEU if it remains easy to use airplanes or ground transport instead. Even if land border crossings and airports were secured from HEU, terrorists could simply bring nuclear materials into a neighboring country's ports and then smuggle it into the US in the same way tons of drugs cross international boundaries every year.

Today's radiation portals situated at ports and border crossings will only result in displacement into many other sea, air, or ground transport mechanisms that avoid the portals. For completeness, we both list and analyze below the set of possible classes of vehicles spanning 2-3 orders of magnitude in their physical dimensions:

1. Water:
    a. oil tankers
    b. cargo vessels
    c. cruise ships
    d. yachts
    e. sail boats
    f. motor boats
    g. canoes
2. Air:
    a. jumbo jets (passenger and cargo)
    b. private jets
    c. propeller planes
    d. helicopters
3. Ground:
    a. trains (passenger and cargo)
    b. trailer-trucks (oil tankers, trailers, flatbeds)
    c. four-wheelers (trucks, cars)
    d. three-wheelers (automated or manual rickshaws)
    e. two-wheelers (motorcycles, scooters)
    f. trailers in tow by two, three, or four wheelers.
    g. anything carried by people on foot or animals (horses, cows, camels, elephants, etc.), or even carts pulled/pushed by them.

Even with an effective nuclear detection network in place, skeptics might contend that a terrorist could remain undeterred by accepting even heavy risk detection in transport of HEU. While that is a possibility, we believe it is unlikely. In its report, the 9/11 Commission points out that,

> "Just increasing the attacker's odds of failure may make the difference between a plan attempted, or a plan discarded. The enemy also may have to develop more elaborate plans, thereby increasing the danger of exposure or defeat." [p. 383, Kean, 2004].

The basis of this statement is that terrorists[17], just like their target nation-states, are subject to limited resources. When terrorists consider a particular mode of attack, accessibility of the required resources, and likelihood of a successful attack, and the cost of discovery in light of counter-measures will be primary considerations. Studies in behavioral psychology have further established that when making economic tradeoffs "people have a tendency to overweight outcomes that are considered certain, relative to outcomes which are merely probable."[18] Since terrorists are people making economic tradeoffs, increasing the risk of failure from zero to non-zero across every option available to terrorists will bring about a disproportionately large deterrence effect compared to an approach that improves any one option but does nothing to introduce any risk in other options.

The degree of deterrence that could potentially be achieved by efforts to increase the risk of failure for terrorists is illustrated by examining terrorist use of conventional explosives and the role that screening of passengers and luggage for conventional explosives has played. Critiques of airport screening measures have primarily focused on less than perfect detection probability, i.e. whether or not a weapon or explosive will pass through the screening process at the airport. For instance, [p. 52, Szyliowicz, 2004] remarks on the "porousness" of airport screening by citing the United States GAO finding (July 2002) that fake weapons and explosives had passed through airport screeners a quarter of the time at 32 major airports [p. 2, Dillingham, 2002].

Contrary to popular disbelief, the deterrence effect resulting from "annoying" airport screening procedures has likely turned out to be much greater than would have been predicted simply by a multiplication of the detection probability by the rate of incidents prior to introduction of these measures. Commercial passenger airplanes have historically been a high-visibility target for terrorists, yet statistics indicate that the incidence of aircraft bombings have all but ceased over the past decade. We employ data from the RAND-MIPT database ([MIPT, 2002], [RAND, 2003]) of worldwide terrorism incidents from January 1, 1968 until March 12, 2003.[19] In the figure below, we chart the time series of cumulative fatalities and incidents across four decreasingly inclusive categories,

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[17] See [Enders, 1993] for a seminal analysis of terrorists as rational actors in the economic sense.

[18] See [p. 20, Kahneman, 2000]. This work is based on Prospect Theory by Daniel Kahneman and Amos Tversky—Kahneman was awarded the Nobel Prize in Economics for this discovery. See [Kahneman, 2002]

[19] In "Appendix B: How do we track trends in worldwide terrorism?," we survey the publicly available databases that track terrorism incidents including the RAND-MIPT database from which the data in this study was drawn.

1. ALL: all terrorist incidents
2. EXPLOSIVES: explosives were used or detonated
3. AIRPORT/PLANE: explosives in an airport or onboard an airplane
4. AIRPLANE: explosives onboard an airplane.

From 1989 onwards, ALL fatalities and fatalities from EXPLOSIVES not only increase, but so does their rate as shown by the increasing steepness of the slope (the apparent discontinuity on the ALL graph represents the deaths of nearly 3000 victims on September 11, 2001). In contrast, we observe that fatalities for AIRPORT/PLANE and AIRPLANE remain nearly constant after 1989, with AIRPLANE fatalities rising by only 14 over the course of 14 years.

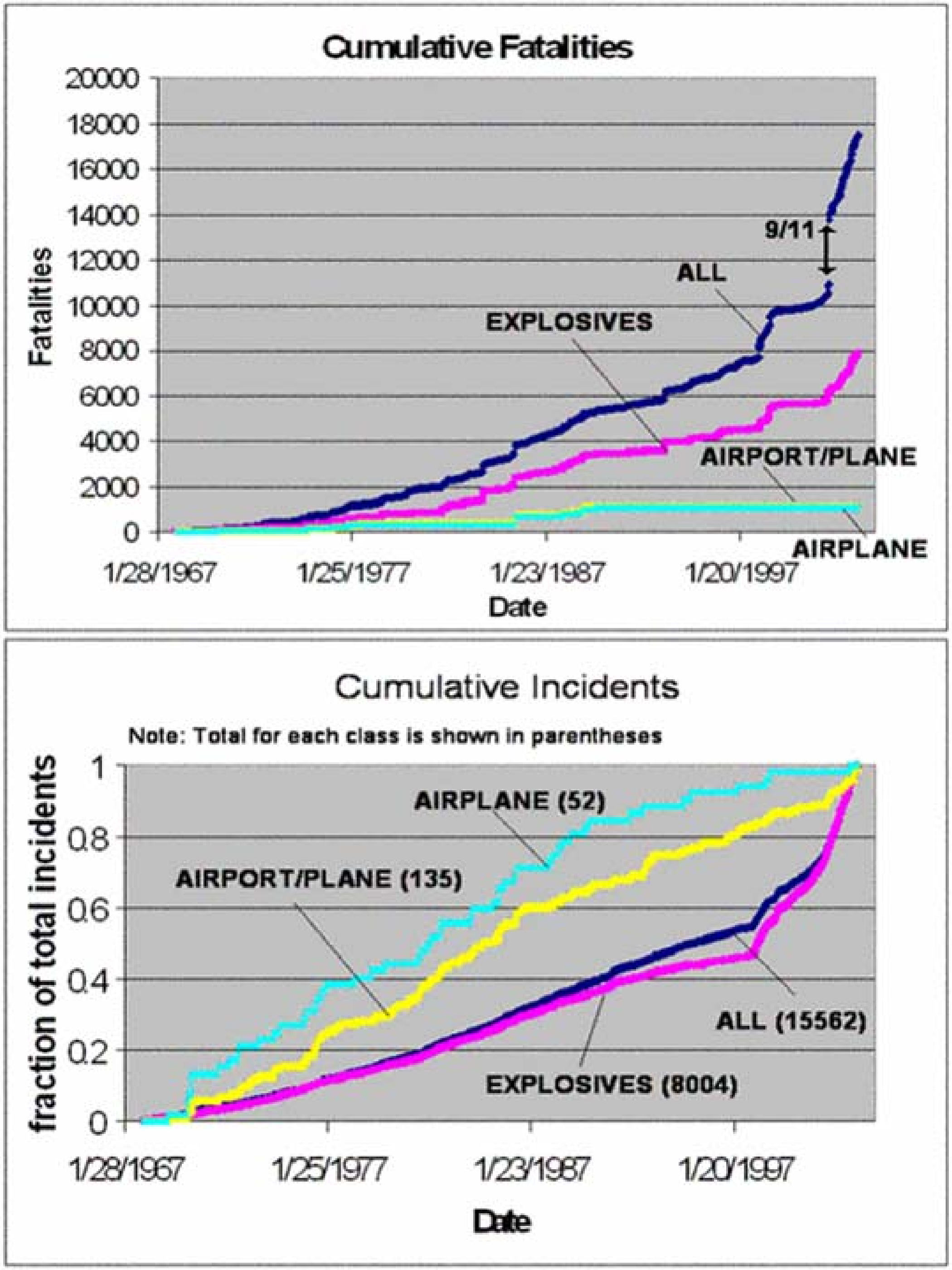

Figure 11

Upon a closer examination of the data for categories AIRPORT/PLANE and AIRPLANE, we find two extended periods of comparatively low fatalities preceded by periods of much greater intensity. In the table below, we show these periods along with the fatalities for each category. Periods II and IV have much smaller fatalities for AIRPORT/PLANE and AIRPLANE when compared to the corresponding statistics during periods I and III. However, during all periods, including I and II, the number of fatalities in EXPLOSIVES or ALL showed no signs of slowing down. We conclude that during periods II and IV, there was a "displacement[20]" from airplanes as terrorist bombing targets onto other environments.

Period	**Dates**	**Length (years)**	**ALL**	**EXPLOSIVES**	**AIRPORT/PLANE**	**AIRPLANE**
I	09/02/1974 to 03/27/1977	2.5	593	391	296	283
II	03/28/1977 to 08/07/1984	7.5	2027	1250	51	7
III	08/07/1984 to 03/10/1989	4.5	2050	1520	708	700
IV	03/10/1989 to 03/12/2003	14	12302	4492	26	14

Table 1: Fatalities for each category and time period

Despite continuous increase in fatalities for ALL and EXPLOSIVES, the presence of two periods of accelerated fatalities followed by extremely low fatalities for AIRPORT/PLANE and AIRPORT is telling. We attribute this trend to expansion of airport screening programs,

- First, following frequent hijackings beginning in the late 1960s, a variety of security measures including metal-detectors and X-Ray machines to screen carry-on baggage were introduced in the United States as part of the Air Transportation Security Act of 1974 [Malotky, 1998]. Indeed, a reduction in skyjackings in the United States could be attributed to the introduction of metal detectors in 1973, while also increasing incidents not protected by the detectors such as those involving hostages [Enders, 1993]. In light of the trends in the graph and table, it is likely that introduction of airport security measures worldwide contributed primarily to the reduced number of fatalities in period II.
- Second, following an intense wave of fatalities during period III primarily due to use of explosives in airports/airplanes culminating in the Pan Am airliner explosion over Scotland[21], increased vigilance and better procedures to sniff and screen for explosives in airports appears to be directly responsible for the period of low fatalities beginning in 1989 and continuing on into the present era. The end of this period was also marked by the United States Aviation Security Improvement Act of 1990 [Bush, 1990].
- Finally, over the 1990s, increasingly better detection techniques and a greater degree of automation to screen for explosives were introduced at airports worldwide [Malotky, 1998] thereby continuing to raise the bar for terrorists who sought to employ explosives aboard airplanes.

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[20] for more on the use of the term "displacement" in the terrorism context, see [p. 2, O'Hanlon, 2002]

[21] The bombing killed 259 people on board and 11 people on the ground [MIPT, 2002]

As shown in the graph, during periods II and IV, there was also a significant reduction, but not elimination, in terrorist attempts to deploy explosives in airports and airplanes, even though overall terrorist incidents using explosives continued to rise at an accelerated pace. These data suggest two important conclusions: 1) airport screening of explosives, although imperfect, has successfully prevented fatalities despite a significant number of continued attempted attacks at airports. 2) The screening measures have been successful in deterring a much greater number of attempts that would have taken place had the screening not been present.

Lessons learnt about deterring terrorism from the case of conventional explosives are all the more valuable in light of the fact that terrorist incidents involving alternate modes of attack (without explosives) that were not fully appreciated by aviation authorities have become responsible for much greater fatalities, as had happened with the attacks of September 11, 2001. We conclude that deterring transport of HEU requires a uniform increase in the risk/cost/difficulty of transporting these materials across *all* accessible transportation modes, both across borders and inside the interior.

What is required to secure each transportation mode?

Securing each form of transport from transport of nuclear materials (HEU) poses a unique set of challenges, which we touch upon in this section. We also discuss special challenges posed by larger vehicles and vessels and suggest ways to monitor their contents. Large vessels would need to either be certified as free of HEU, or they must maintain a safe distance from populated areas to provide sufficient isolation from a nuclear blast on the vessel. This is analogous to how the US military closely monitors and disallows the approach of foreign military vehicles (submarines, ships, airplanes, missiles) around national borders. See the section on “Weapon Delivery” in [Medalia, 2005] for a discussion of the ways a terrorist nuclear weapon could be imported into the United States.

Water

Cities have historically been built around ports. Ships of all sizes routinely sail into harbors that are close by. Ships can easily carry a nuclear weapon or nuclear contraband. Screening of cargo for nuclear materials (active and passive) has had its own set of challenges (see [Hecker, 2002]). Large vessels like oil tankers are more difficult, since it is likely to be physically impossible to screen for something inside due to the attenuation of the surrounding oil, see [pp. 7-8, Medalia, 2005]. Such large, thick vessels may need to be certified through initial inspection at the embarkation point followed by constant surveillance while in transit. Otherwise they would be forbidden them from approaching populated cities altogether in case they cannot be certified as being free of nuclear materials. For all other types of ships, one or more on-board radiation detectors (matched to on physical dimensions of the yacht) and remote check points located at sea (as described in DISARM) would be the ideal approach to certify them as free of radiation at check points at sufficient distance from the city. If all “floating” vessels were successfully secured, the only remaining option for delivery of nuclear material would be underwater using submarines, which certainly raises the cost and complexity of HEU transport.

Air

In several respects, airplanes pose an even greater challenge than ships since they can rapidly approach any target, see [p. 6, Medalia, 2005]. It is important to ensure that airplanes can't get close to populated areas, and for the ones that do it is necessary to certify that they are free of nuclear materials. Just like oil tankers, jumbo jets can be initially certified and constantly monitored to prevent nuclear material from being loaded onboard or otherwise disallowed from approaching within the distance of populated areas. Just like container screening at sea ports, air cargo screening for nuclear material (active and passive) is an important step in this direction but to our knowledge is not being pursued aggressively. Just like yachts, private jets and helicopters also would need to implement DISARM with a sufficient number of detectors per aircraft. A mechanism for preventing aircraft that have not been certified as free of nuclear materials from landing near populated areas must be put in place.

Ground

Perhaps the biggest challenge with ground transport is the sheer numbers of vehicles that must be dealt with. Trains, being the largest, require inspection and surveillance to ensure they are free of nuclear materials just like oil tankers and jumbo jets. Rail cargo would have to be screened (actively and passively), and even entire train cars may have to be screened regularly. The same holds for trailers on large trucks and 18-wheelers, just like how trucks with trailers are weighed at weigh stations along the highways. Otherwise they would need to participate in a DISARM program with a number of detectors sufficient to cover the length, width, and height of the trailer. Smaller trailers towed by cars would need their own detectors to participate in the DISARM program, and would likely need to be powered by the towing vehicle to ensure operation of the detector. Just as with water-borne transport, if all ground transport was secured the only option left for terrorists to transport HEU would be underground tunnels which significantly raises the cost and complexity, and would still have to surface at some point near the target.

In theory, people on foot or animals (horses, cows, camels, etc.) can carry unshielded or lightly shielded HEU through forests and other areas. If the only alternative left to the attacker is to use people or animals for transport, the primary purpose of increasing the cost/complexity of transporting shielded HEU to a sufficiently high level would have been served. Even HEU-laden people and animals could be made susceptible to detection by using a sufficiently ubiquitous fixed infrastructure. Carts capable of carrying shielded HEU would still have to be screened.

Operational Requirements For Assuring Compliance With DISARM

One of the key questions in mandating uniform adoption of an in-vehicle detector system is ensuring that all vehicles are compliant. A disabled detector would produce no communication with a checkpoint, and raises suspicions prompting further manual inspection. What if an attacker tries to tamper with or reprogram the built-in detector? To prevent this, we propose that

- The detector would have to be powered by either a self-contained battery or input power supplied from the vehicle itself.
- In-vehicle detectors would contain a radio to enable them to transmit their readings as they pass by specially designed checkpoints or on-demand to specially equipped law-enforcement vehicles.
- The detector is authenticated from its point of manufacture and public-key infrastructure (PKI) can be used to authenticate the detector's readings.
- The detector housing would be tamper-proof conforming to standards such as FIPS 140-2 [National Institute of Standards, 2005]. The FIPS standard includes requirements on tamper detection (physical evidence of tampering), as well as requirements on tamper mitigation circuitry.

These four concepts permit law-enforcement officials to determine whether the detector readings indicate that a bomb could be present, or to further investigate if the detector is not readable. This can help ensure compliance with the in-vehicle detector program.

Securely transmit detector readings on-demand to law-enforcement (mobile readers or readers at checkpoints)

We envision that mobile or fixed readers will be used to remotely read in-vehicle detectors at borders and checkpoints. The reading could be triggered either manually or automatically, and there would have to be no ambiguity of which vehicle originated the reading. The in-vehicle detector can be equipped with a short-range wireless network interface card using commercial off-the-shelf radio technologies (e.g., Wi-Fi or other), whose range is short enough to eliminate the ambiguity. When the reader chooses to interrogate the detector, it sends a signal to the detector querying its readings. The detector can respond with the current reading, the background and, perhaps, the readings history over the last 24 hours. This will allow the reader to assess the likelihood of presence of HEU aboard the vehicle. Data transfer between reader and detector can be authenticated using public-private keys and encrypted using a suitably robust encryption scheme, such as AES.

Location of checkpoints

Checkpoints, fixed or mobile, will need to be installed at vehicle intersections and traffic choke-points and other places to ensure each vehicle can be queried often enough. This would include, but not be limited to:

- Perimeters of major metros and highway toll booths
- National borders (sea and land)
- Major ports
- Airports
- Train stations
- Other elements of the transportation infrastructure (subway stations, bus stations, etc.)

- Randomly located checkpoints or reading areas should be thrown in from the start as they substantially increase the uncertainty of detection points and therefore deterrence

False Positives and False Negatives

Reducing false positives in nuclear detection has become a national research priority for the DNDO.[22] Numerous reports in the media have highlighted false positives and negatives in nuclear detection on those systems deployed in major metros like Washington D.C. and New York.[23] In 2001 just after the 9/11 attack, the Bush Administration ordered a large-scale operational trial of nuclear sensors around a perimeter of Washington DC [see Gellman, 2002b and Crowley, 2005] to detect and intercept a nuclear weapon entering the area through roads and rivers. However the US government apparently gave up on this “Ring Around Washington” as it was eventually shut down due to a large number of false positives (detection of benign radioactive sources) and false negatives (failure to detect real signatures). While it represented a haphazard attempt to secure the nation’s capitol and perhaps sent a signal to would-be attackers, the incremental security it provided is questionable given all the alternative routes such as by all the airplanes entering Dulles National Airport or nearby sea ports. Similarly, according to one New York official, the city employs over 20,000 handheld and stationary nuclear detectors which go off all the time due to transport of medical isotopes [Ruppe, 2005].

In general, detectors may produce misleading readings due to a number of causes including

1. fluctuations in the natural radioactive background
2. the presence of other radioactive isotopes whose radiation cannot be distinguished from that being detected whose radiation lies within the discrimination band of the detector.
3. equipment malfunction

In the case of positive readings, where the detector detects a threat, further inspection will necessarily be called for. The cost of this inspection is directly tied to the feasibility of the DISARM program. The frequency of false positives experienced multiplied by the average cost of inspection is the total cost of dealing with false positives. Each factor in this product needs to be kept in check to make a feasible solution—the lower the better.

In accordance with the program outlined by the DNDO, we expect that acceptable levels of false positives can be achieved through judicious detector design and energy-specific detectors that can discriminate various radioactive signatures. By training local law enforcement in inspection, further reductions in cost due to false positives may also be achieved since federal agents or NEST team members will not be required to inspect suspicious detector readings.

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[22] See [Oxford, 2005] for the Advanced Spectroscopic Program to create more accurate energey discrimination of nuclear materials

[23] See [Gellman 2002a, 2002b], [Ruppe, 2005], and [Associated Press, 2005].

When operating within the physical limits of passive detection, false negatives may also arise due to equipment malfunction or when high background levels mask the signal. Like false positives, we expect false negatives can be overcome in with judicious detector design.

How could DISARM be defeated?

Just about any security scheme can be circumvented with enough ingenuity, money, and effort, so the security scheme fulfils its role if it increases the attacker's risk of failure. In this section we analyze the "loopholes" that a terrorist might try to use to work around DISARM, and how by doing so that increases their risk of failure. Each of these "loopholes" can be countered by additional engineering to achieve the desired level of security for some cost.

Decoy Vehicles (Binding of Detector Reading)

Binding a detector reading received at the checkpoint to the right vehicle is a key problem that needs to be systematically addressed, and DISARM security is dependent on how well binding can be implemented. If the vehicle transmitting the short-range wireless signal cannot be uniquely determined, then an attacker can simply destroy the detector inside the vehicle carrying the nuclear material and leverage a nearby vehicle's reading to pass through a checkpoint unnoticed. Alternatively, if the detector reading can be authenticated digitally and bound to the vehicle itself rather than the detector, then this is not a problem. Hence security of DISARM is tied directly to how well the reading can be physically localized or authenticated.

For road vehicles, one way to ensure that the readings are bound directly to the vehicle being read is to use something similar to an E-Z pass tollbooth. Using a suitably designed short-range wireless communications system, a check-point that permits fast reading can be incorporated into streets beneath the vehicle or on the side of the road, such that the reading the vehicle providing the reading can be uniquely identified.

Destroy, Tamper With, or Relocate the In-Vehicle Detector (Tamper Resistance)

The checkpoint recognizes non-compliance with DISARM through the absence of a response from the detector, eliciting a more detailed inspection. Implementation of a tamper-detection standard (like Federal Information Processing Standard 140-2) to detect either tampering or removal/relocation of the detector would allow it to immediately shut down. Therefore the security offered by DISARM is dependent on the integrity of the tamper detection standard.

Shielding the Detector (Placement, Solid-Angle, and Number)

Rather than shield the nuclear material, an in-vehicle detector itself can be shielded directly from the interior of the vehicle. The difficulty with which the attacker can effectively shield the detector is dependent on the attacker's knowledge of the detector locations, the amount of shielding required, the number of detectors in the vehicle, the size of the detector, and ultimately the solid angle cross section the detectors subtend with the interior of the vehicle. The tradeoff is one of cost and form factor. If detector technology becomes cheap and easily integrated, multiple detectors or even detector strips along the length of the vehicle can make it hard to shield.

Divide and Conquer (Minimum Detectible Quantity)

Buy a detector or a car with a detector, then work to optimize the amount of material and shielding such that it is the most material that does not set off the detector. Then transport it in these quantities and collect it at some final destination where it could be assembled into a WMD and never ship the assembled WMD or assembled SNM package.

Splitting up the nuclear material and transporting it multiple times increases the odds of being caught by that factor, and complicates the operation and its logistics. Therefore, the smallest amount of nuclear material that can be carried in any detector-equipped vehicle determines how effective DISARM can be.

Switch Vehicles (Minimum Detection Time)

An idea related to divide and conquer is to overcome DISARM by switching vehicles before the detection time of the detector is reached. This also complicates the operation by necessitating the use of shielding to increase the detection time up to the point where the switch can be made. Hence detection time becomes a key limit to DISARM security. Increasing the detector's solid angle around the vehicle decreases the minimum detectable quantity.

Avoid or Disable Checkpoints (Number, Predictability, and Security)

Naturally, if a path can be charted to avoid checkpoints then DISARM can be circumvented. So the security of DISARM is limited by the distribution of check points that query the in-vehicle detector. The quality of the physical and digital security for the information gathered by checkpoints determines the security of DISARM. One way to further increase security is to make the checkpoints effectively mobile and thereby increase uncertainty as to their whereabouts.

Power-down the In-Vehicle Detector prior to approaching the check-point (Uptime of detector)

If the detector could be disconnected from its power source prior to approaching a check-point for the minimum duration required to detect the nuclear material travelling in the vehicle, then the vehicle can pass through a DISARM check-points circumventing detection. Therefore each check point needs to verify that the detector has been operational for a sufficiently long time prior to reporting its reading, and violation of this condition should raise suspicion. It would also be useful to if the check-point can determine during what time intervals, if at all, the detector has been powered down through lack of a power source during the past several days or weeks.

Economics of Industry Participation and Public Adoption of DISARM

The E-Z Pass electronic toll-collection system [E-ZPass] offers an example of incentives to spur participation and adoption.

> When you establish an E-ZPass prepaid account, you receive a small electronic tag that attaches to the windshield inside your car. Within the tag is an electronic chip that contains information about your account. Each time you use a toll facility where E-ZPass is offered, an antenna at the toll plaza reads the vehicle and account information contained in your tag. The appropriate toll is then electronically debited from your prepaid account. A record of your transactions will be included in your periodic statement.

E-Z Pass customers enjoy the benefit of expedited passage through toll-collection booths. If the inspections process is slow and time-consuming as it might be at border checkpoints, the ease and speed of an E-Z Pass-like system would act as a powerful incentive to adoption and installation of detectors, whether by automotive manufacturers or by the after-market.

Stephen Flynn [Flynn 2004] suggested a similar incentives-based scheme in connection with speeding the adoption of container security initiatives by shipping companies and seaports. Two other examples of relevant programs are the CBP’s NEXUS and FAST (Fast and Secure Trade) initiatives [Bonner 2003]. Participation in these programs is voluntary and the incentive for participation is expedited clearance through border checkpoints for individuals (NEXUS) and cargo (FAST). Individuals choosing to participate in NEXUS voluntarily provide background information and biometrics that are used to screen against international crime and terrorist databases. They are provided with a SMART card that can be waved through a border checkpoint.

Proposed incentives and regulatory framework

With DISARM, a network of checkpoints would be established within the transportation infrastructure as well throughout the perimeters of the major metros. Vehicles passing these checkpoints would be either automatically read using a combination of readers and detectors or would be subject to manual inspection, perhaps using a man-portable radiation detector. Vehicle manufacturers would be required to install detectors in all vehicles, beginning in a particular model year, to achieve the radiation safety benefits.

After-market installation of detectors in older model vehicles would be required, but as an interim measure could be facilitated by the incentives to speed passage through checkpoints. Owners of older vehicles would be given the incentive to install detectors since vehicles not equipped with detectors would be subject to a more time-consuming manual inspection, resulting in longer delays. After-market installation of detectors could be monetarily subsidized by the DoT or through tax incentives. The Transportation Security Administration within the Department of Transportation could administer the regulatory framework. Identification and maintenance of malfunctioning in-vehicle detectors will be a necessary component of a DISARM program—therefore detector design that minimizes maintenance (both frequency and costs) is desirable.

Drivers and owners of vehicles can benefit from in-vehicle detectors whose readings are designed to be appropriately summarized and conveyed to the driver on their dashboard.[24] Driver-readable detectors inside vehicles can warn of any highly radioactive material such as Cesium-137 or Cobalt-60 that has been maliciously planted inside the vehicle by a potential terrorist in order to contaminate the occupants, which is a possible way for terrorists to create public panic by inflicting harm, see [p. 783, Steinhausler]. These detectors might also catch unintentionally or unknowingly contaminated normal materials. They can also be used to detect of fissile material such as HEU being smuggled in the vehicle without the driver's knowledge, especially in delivery or cargo vehicles. The information provided by these detectors is likely to be valuable enough that there is an incentive for the driver or owner to ensure that detectors are functioning properly.

In addition, the President's budget request for FY 2006 includes the establishment of a Domestic Nuclear Detection Office (DNDO) within the Department of Homeland Security [DHSFY06]. Coordination between these agencies as well as CBP (Customs and Border Protection) would be necessary.

Precedents for regulation

There are several precedents for mandating the installation of detectors in vehicles and requiring the inspection of vehicles at major transportation choke-points. Some examples:

- To prevent automotive accident deaths due to tread separation and under-inflation, tire pressure sensors in all four wheels of light vehicles will be required in the US by 2007, see [Crawley, 2005] and [Plungis, 2005]. At a cost of $40-$70 per vehicle, 100 lives are expected to be saved annually.
- DoT regulations on the installation of seat-belts in the context of Federal Motor Vehicle Safety Standards [FMVSS].
- The Clean Air Act of 1970 that led to the introduction of catalytic converters and the phase-out of tetra-ethyl lead (TEL) [CAA1970]
- EPA's regulations on vehicle emissions testing
- The proposed Vehicle Infrastructure Integration initiative by the DoT [VII]

Respecting Personal Privacy

Unlike E-Z Pass which uniquely identifies the driver/vehicle but is also opt-in from the driver's perspective and can even be disabled, the mandatory inclusion of an always-on device inside each vehicle that will communicate to a state-controlled infrastructure can

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[24] This idea was suggested to the authors by Michael May when this material was presented at the Center for International Security and Cooperation, Stanford University on October 11, 2005.

raise personal privacy concerns. If privacy is made an important consideration in system design, the DISARM checkpoints can be designed to respect privacy by discarding information about vehicles that do not set off the in-vehicle detector. Compare this to the extent that other security measures have already intruded on people's privacy.

- The FAA requires the inspection of bags as well as passengers at airports through manual procedures as well as through x-ray inspections.
- Video surveillance systems are pervasive on America's streets and highways for traffic monitoring, citations, public safety, and other applications. For example, see [New Orleans, 2005].
- Cell phones are required (under E-911 provisions [E911]) to be able to maintain and transmit location information.
- More than 65% of 2004 model year cars in the US were equipped with "black boxes" that record events. Privacy advocates fear that in the future these devices could be used to record location information and vehicle trajectories [Jones, 2004].

By comparison, the commonplace security measures listed here, a DISARM program explicitly designed to discard information about vehicles which do not set of the in-vehicle nuclear detector would be respectful of personal privacy.

DISARM Startup Costs

Given that the economic losses due a nuclear attack could spiral easily well into the trillions of US dollars, at what cost would it be appropriate to startup a DISARM program? To help gain a preliminary understanding of the most important cost drivers, we develop back-of-the-envelope estimates based of overall system cost to deploy a DISARM-based solution. An in-container detector capable of detecting nuclear (gamma and neutron) radiation as well as other kinds of (conventional) explosives would cost an estimated $250 [Flynn, 2004], which is comparable (three to four times) the cost of tire sensors that will be mandatory in all light vehicles in the US by 2007 and are expected to save 100 lives annually, see [Crawley, 2005] and [Plungis, 2005]. We use $250 as a conservative estimate – when dealing with the volumes relevant to the DISARM proposal, the costs are expected be much lower due to volume manufacturing and design, perhaps even approaching the cost comparable to the tire air pressure sensors. At the conservative price of $250 per detector system, to equip roughly 50 million containers worldwide plus 250 million vehicles in the US with these detectors would cost about $75 billion.

The next major component of the system cost is the cost of deploying checkpoints, but this turns out to be much less in comparison to the cost of detectors. Since the checkpoints incorporate communications technology, but not detectors, once again we conservatively approximate the cost of deploying a checkpoint by of the order of the cost of a Wi-Fi base-station (< $10,000 today), and the number of checkpoints based on an assumption of 10 base-stations per square mile. If we were to secure the 100 most densely populated areas, each with an area of 50 square miles, the total number of base-stations required is 100*10*50=50,000. The total cost to deploy these checkpoints is therefore $500 million = $0.50 billion, which is insignificant compared to the cost of the in-vehicle detectors.

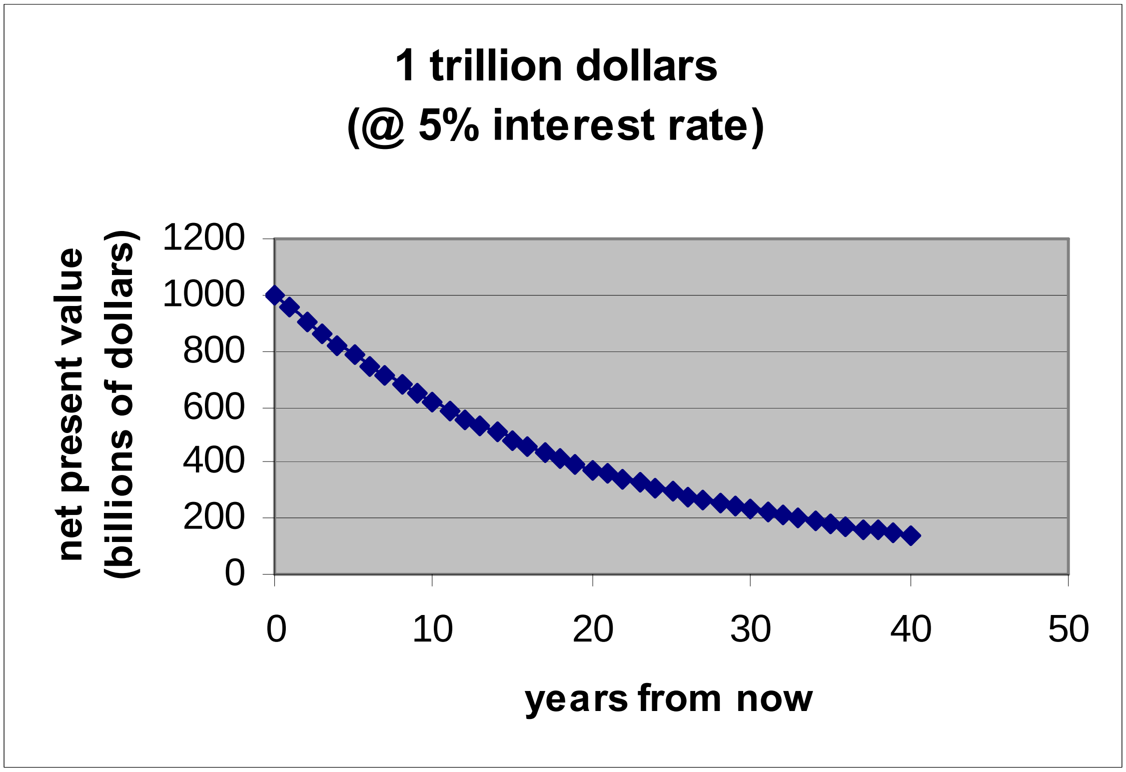

Figure 12 A future loss of $1 trillion in today's dollars

Our rough analysis suggests that in-vehicle detectors will comprise the bulk of the costs of the system, to be borne by vehicle owners and users and probably with some government subsidies or tax incentives. In either case, the startup cost involved (about $75 billion) is easily justifiable given the substantial risks and the trillion dollar economic impact that would be caused by a future US $1 trillion terrorist nuclear attack even in terms of today's dollars. For comparison, the new NHTSA rules on tire pressure sensors would add an additional $40-70 to the cost of a car (compared to about $250 for a radiation sensor with DISARM) and are expected to save about 100 lives annually.

Conclusion

Detecting and intercepting terrorist nuclear weapons is a challenging problem, especially on a national and worldwide scale. Our analysis shows that although current and planned architectures represent positive steps and may offer some short-term deterrent value, they are unlikely to be perceived as credible. New architectures involving in-vehicle detection (DISARM) will most likely be required to overcome the problems with current architectures. DISARM programs using existing technology to screen smaller vehicles in conjunction with active screening and inspection of larger vehicles will likely create a strong deterrent for potential nuclear terrorists by uniformly raising the cost and risk of transporting shielded HEU. Broad adoption of a DISARM architecture will drive down the program's costs over time.

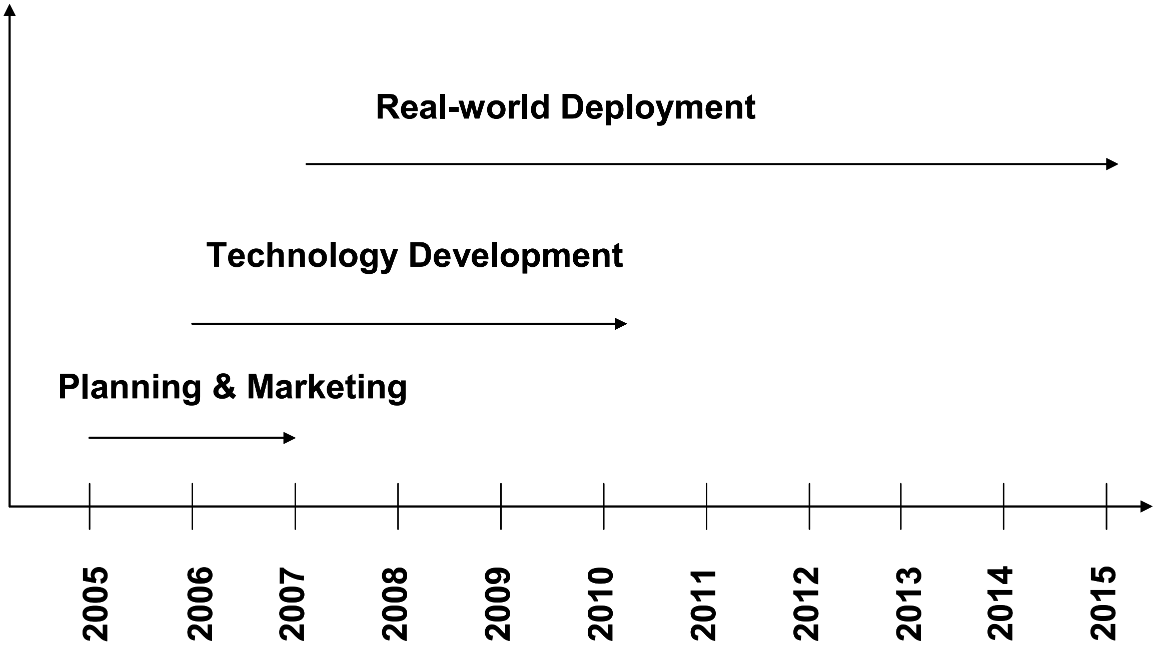

Figure 13 Estimated Timeline for DISARM

At the time of this writing, we are aware of no organization (public or private) that is committed to making a DISARM-like system a reality. We envision a three-stage approach to deployment of DISARM as illustrated in the timeline below. The first stage is to plan and market the DISARM program in consultation with key stakeholders. Within government this includes municipal, state, and national governments, specifically law enforcement, military, coast guard, and transportation authorities such as the DoT/FAA. In private industry this includes shipping and transportation companies, auto and vehicle manufacturers.

Second, a parallel effort in system and technology design & development against specified goals to achieve:

1. Detectors designed to be capable of detecting sufficiently small quantities of HEU & Pu when used inside vehicles such as cargo containers (ship/rail/road), automobiles, boats, and airplanes and can also be manufactured cost-effectively in large volumes.
2. System design to assure infrastructure and security can be designed to work with sufficient coverage and frequency of data collection to be useful to law enforcement.
3. Projected manufacturing and installation costs meet targeted goals over time.
4. False positives, equipment failure rates, labor or cost, and other operational concerns are manageable.
5. The DISARM program costs can be estimated and fall within a budget that is justified by the value-added.

6. Last but not least, the DISARM program in conjunction with complementary initiatives involving fixed/handheld detectors, portals, and inspection/surveillance together create enough risk of interception of nuclear materials to deter nuclear terrorists.

Integration of the technology into the real-world will likely to begin with shipping containers (land/sea/air) initially. It might subsequently be rolled out in the freight and package/mail delivery and public sector transportation system, and then be introduced into other transportation sectors such as automobiles through legislative mandate. The system can eventually be deployed worldwide.

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Appendix A: Representative Detector and System Suppliers

	Name	**Offerings**	**Products**
1	Alrad Instruments Berkshire, UK http://www.alrad.co.uk	Detectors	Distributor of others' products
2	American Science and Engineering, Inc.[AS&E] Billerica, MA www.as-e.com	Detectors, Instruments & Systems	Xray inspection systems
3	Applied Scintillation Technologies Harlow, UK www.appscintech.com	Scintillation Detectors	
4	Aracor Sunnyvale, CA http://www.aracor.com/	Xray Inspection systems	Xray inspect., industrial CT scan
5	Atlantic Nuclear Corp. Canton, MA USA www.atnuke.com	Nuclear material safety	Distributor of others' products
6	BAE SYSTEMS plc London, UK www.baesystems.com	Systems supplier & Integrator	
7	BIL Solutions (formerly BNFL Instrument, Ltd.) www.bilsolutions.co.uk BIL, Inc. [USA Head Office] Santa Fe, NM	System Integrator	Vehicle Portal Systems etc
8	Berkeley Nucleonics, Inc. San Rafael, CA www.berkeleynucleonics.com	Radiation Instruments & systems	Radionuclide Detection & Identification
9	Bruker Daltonik GmbH 04318 Leipzig, Germany www.bdal.de	Chem & Rad Instruments	NBC instruments Handheld detectorsSVG2
10	Canberra Industries Meridien, CT USA CANBERRA Industries (Canberra EURISYS) Saint Quentin En Yvelines Cedex, Francehttp://www.canberra-hs.com	Detectors, instruments & systems	Portal Monitors, Handheld units, other
11	Centronic Croydon, UK www.centronic.co.uk	Detectors and sensors	Semiconductor detectors & others
12	EADS - European Aeronautic Defence & Space Co. Defence Electronics Division Ryle, Netherlands www.eads.net	System integrator	

13	Exploranium [SAIC acquired December, 2003-see SAIC] Operated as SAIC Canada Missisagua, Ontario Canada		See SAIC
14	Fluke Biomedical Radiation Management Services (acquired Cardinal Health/Victoreen) Cleveland, OH USA www.flukebiomedical.com/rms	Worker health monitoring	Detectors, Instruments & Services
15	GammaSight Technologies, Inc. Newport News, VA, USA http://www.gammasight.com/	Nonintrusive inspection of closed spaces	pulsed gamma ray system to find NBC material
16	Hopewell Designs, Inc. Alpharetta, GA USA http://www.hopewelldesigns.com/	Detector test irradiation standards	
17	Innovative Survivability Technologies Goleta, CA www.istsurvive.com	LLNL licensee for ARAM	Area radiation monitoring
18	L.Q.C. s.I. La Escala, Spain http://www.radal.com/	Radiation detectors & alarms	Wall-mount radiation alarms
19	Lockheed Martin Company Maritime Systems and Sensors Manassas, VA USA www.lmco.com	NBC detection systems	Metroguard™" system
20	Ludlum Measurements Inc. Sweetwater, TX www.ludlums.com	Radiation Instruments and systems	-portal monitor -Conveyor monitors
21	MGP Instruments (part of Synodys group) www.mgpi.com	Radiation Instruments & systems	-Monitoring -Dosimetry -Surface Contamination
22	Nucsafe, Inc. Oak Ridge, TN www.nucsafe.com	Detectors & systems	Neutron & γ detecting panels & instr.
22	Nuctech Company Limited Haidian District, Beijing , China PRC http://www.nuctech.com/en/index.php	Instruments & systems	Xray Container & vehicle scan -Rad monitor
24	Orobotech Yavney, Israel [Billerica, MA in US] www.orbotech.com	Detector technology	CZT detectors for medical imaging, other
25	Passport Systems Acton, MA www.passportsystems.com	Detector technology & systems	Nuclear Resonance Fluorescence

26	Polimaster Ltd. Minsk, Belarus www.polimaster.com	Radiation Instruments & systems	-Polismart γ and n detectors
27	Quintell of Ohio LLC Beachwood OH [no website]	Patent owner-cfTannenbaum 6/21/05 remrk	Possibly developing system
28	Rados (part of Synodys group) D22761 Hamburg, Germany www.rados.com	Systems	RTM910 Gamma Scan Vehicle Portal System
29	RAE Systems Sunnyvale, CA www.raesystems.com	Instruments & systems [see also Polismart]	-Rad detector -Hand Held - In-container (remote readout)
30	Rapiscan Systems (combining Aracor, Ancor, Metor) Hawthorne, CA www.rapiscansystems.com	Systems	-Portal, fixed & mobile systems -active & passive methods
31	RFTrax, Inc. Allyn, WA USA www.rftrax.com	RF interrogated sensors	RAD-CZT sensor remote readout (containers)
32	S.E.A. GmbH Dülmen, Germany www.sea-duelman.de	Instruments & systems	
33	SAPHYMO Massy, France www.saphymo.com	Instruments & systems	Vehicle, package & container scanning
34	Science Application International Corp. [SAIC] San Diego, CA http://www.saic.com/products/security	Instruments & systems	Exploranium™ portals, detectors, mobile units
35	Target Systemelectronic GmbH Solingen, Germany www.target-systems-gmbh.de/	Instruments & systems	Handheld & integrated γ & n detectors
36	Technical Associates Canoga Park, CA www.tech-associates.com	Instruments and systems	
37	Thales Security Systems UK Ltd. Chessington, Surrey, United Kingdom www.thales-security.com	System Integrator	

38	Thermo Electron Radiation Measurement and Protection Erlangen, Germany www.thermo.com	Instruments & Systems	"Safety-guard" Portal Radiation Monitor
	Thermo Electron Corporation Franklin, NJ Radiation Measurement Div, Albuquerque, NM http://www.thermo.com	Instruments & systems	Matrix Mobile Radiation Detection System (Matrix MRDS)
39	Transgalactic Instruments 1000 Sofia, Bulgaria www.tgi-sci.com	Instruments	γ radiation spectrometer
40	TSA Systems, Ltd. Longmont, Colorado, USA http://www.tsasystems.com/	Instruments & Systems	Vehicle Portal Monitors
Some Detector Material Developers and Manufacturers			
1	Argonne Nat'l Lab Argonne, IL USA www.anl.gov	Detector Technologies	
2	Brookhaven Nat'l Laboratory Nonproliferation and National Security Dept (N&NS) www.bnl.gov		CZT, Xenon, other sensors
3	Brookhaven Nat'l Laboratory Nonproliferation and National Security Dept (N&NS) www.bnl.gov/nns		RADTEC detection test facility
4	EV Products Saxonburg, PA USA www.evproducts.com	Radiation detectors	CZT semi-conductor materials, products
5	Imarad [Israel] – See Orbotech Above		
6	LND, Inc. Oceanside [Long Island], NY www.lndinc.com	Custom nuclear detectors	Ionization chambers, GM Tubes, neutron detectors
7	ORTEC (a brand of AMETEK, formerly an EGG sub) Oak Ridge, TN http://www.ortec-online.com	Detectors & instruments	
8	Radiation Monitoring Devices, Inc. (RMD, Inc.) Watertown, MA www.rmdinc.com	Detectors & Instrument Research	

9	Sandia National Labs Albuquerque, NM USA www.sandia.gov		Neutron & γ detection microsystems
10	Scientific Production Center ASPECT 141980 Dubna, Moscow Region, Russia http://aspect.dubna.ru/english	Detector Materials	Plastic scintillators
11	Yinnel Tech, Inc. South Bend, IN	Detector Materials	CdZnTe
12	Non-Proliferation and Arms Control (NPAC) Technology Working Group (TWG) Fieldable Nuclear Detectors [FND] Focus Group	Facilitate R&D to improve FND	
13	Princeton Plasmas Physics Lab (US DOE) PPPL Tritium Systems Group www.pppl.gov	Detection subsystem	

Appendix B: How do we track trends in worldwide terrorism?

The United States State Department chronicles terrorist incidents annually in its publication, Patterns of Global Terrorism [US Department of State]. According to this chronology, international terrorists conducted 199 incidents in 2002, a drop of 44% from the previous year. However, analysis based on the RAND-MIPT terrorism incident database [MIPT, 2002] shows the total number of incidents in year 2001 as 1532 and year 2002 as 2631, thus representing an increase of over 70%. In each instance, they employ their chosen criteria decide what incidents are recorded as terrorism as shown in Table 1.

United States State Department (Incident Review Panel's definition)	**RAND** (Research Team's definition)
"An International Terrorist Incident is judged significant if it results in loss of life or serious injury to persons, abduction or kidnapping of persons, major property damage, and/or is an act or attempted act that could reasonably be expected to create the conditions noted." [p. 83, US Department of State, 2002]	"For the purpose of this database, terrorism is defined by the nature of the act, not by the identity of the perpetrators. Terrorism is violence calculated to create an atmosphere of fear and alarm to coerce others into actions they would not otherwise undertake, or refrain from actions they desired to take. Acts of terrorism are generally directed against civilian targets. The motives of all terrorists are political, and terrorist actions are generally carried out in a way that will achieve maximum publicity. [RAND, 2003]"

Table 2 Definitions of what constitutes a terrorist incident

It appears that an order of magnitude more incidents were tracked by RAND when compared to the State Department in 2001/2002, and these definitions alone offer little insight into the cause of this discrepancy between the two databases. In addition to RAND and the US State Department, other public databases for terrorist incidents exist within government and academia. One such database is ITERATE [Vinyard Software, 2003] that chronicles terrorism incidents from 1978 onwards[25]. However, we found that the RAND-MIPT database represents the most comprehensive, longest running, publicly available database of worldwide terrorist incidents, and provides a detailed summary of the incident in a format that is uniform across all incidents including description, fatalities, injuries, location, type of weapon used, terrorist organization responsible, to name a few.

In this paper, we employed[26] data from the database of terrorism incidents that has been kept by RAND and later MIPT continuously since January 1, 1968[27]. Current until March

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[25] Available for a fee

[26] With the aid of purpose-written automated (Perl) scripts, the entire contents of the RAND-MIPT database was downloaded, parsed, and arranged in a tabular spreadsheet (MS Excel). Having the incident data in this format enabled generation of charts and tables shown in this paper.

12, 2003, the contents of the RAND database have been made available by the MIPT on their website [MIPT, 2002]. In Figure 1, we chart the growth of terrorism incidents according to the RAND-MIPT database.

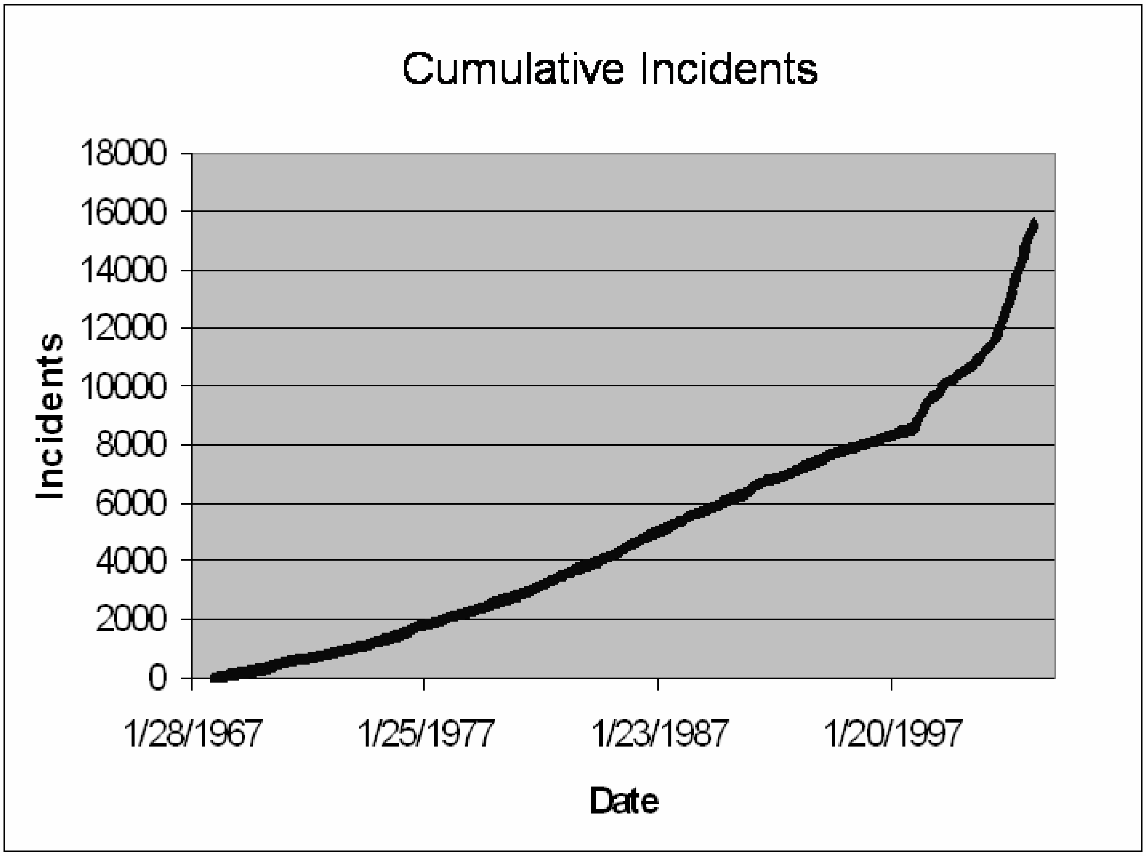

Figure 14

At the time of writing, this site was still a beta version. With over 15,000 incidents recorded, the database system is not yet absolutely perfect. For instance, at least two well-known incidents appeared to be missing in the RAND database that can be attributed either to bugs in the web-based software system[28] or simply delayed in their process of tracking and following up on incidents[29]. These bugs are being fixed. Nevertheless, the RAND-MIPT database of incidents remains a useful chronology upon which we can draw reasonably accurate conclusions.

Terrorism is frightening for several reasons, perhaps in large part due to the uncertainty inherent in the terms we use to describe it such as its causes, its perpetrators, the methods they employ, their targets, etc. To place terrorism in context, consider that the total number of terrorism fatalities worldwide from January 1, 1968 through March 12, 2003

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[27] Through 1997, only international terrorist incidents were recorded by RAND. From 1998 onwards, both domestic and international incidents were recorded.

[28] bombing of the USS Cole on October 12, 2000 [RAND, 2003]

[29] bombing of Indian Parliament on December 12, 2001 [BBC News, 2001]

as calculated from the RAND Terrorism database [RAND, 2003] were less than half of total automotive accident-related fatalities that occur in the United States every year [NHTSA, 2003]. However, in contrast to automotive accidents, terrorism is rising rapidly and there are no actuarial tables upon which uncertainty can be managed or mitigated. Furthermore, when gaming out plausible scenarios for terrorist incidents, the fatalities and cost could potentially skyrocket beyond anything witnessed to date [Associated Press, 2002].