Devabhaktuni Srikrishna, Amalavoyal Narasimha Chari, Thomas Tisch
Comments to sri at devabhaktuni.us
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Nuclear Detection: History and Facts

Contents

Brief History of Nuclear Terrorism and Clandestine Nuclear Attack

The attacks of September 11 launched nuclear terrorism[1] into the national political debate[2] by raising awareness that the ambitions of terrorists and non-state actors have been increasing. With the steady, worldwide proliferation of fissile material, in particular highly enriched uranium (HEU), the likelihood that HEU can be used in nuclear terrorism or clandestine attack by a nation-state has also been rising. Whereas Plutonium-based nuclear weapons require more sophisticated implosion designs, the technical knowledge to make a simple, low-yield, gun-type atom bomb using HEU has been in the public domain – access to knowledge alone is unlikely to present much of a barrier to a determined terrorist group.[3] Terrorist groups only need to acquire approximately 50 kilograms (100 pounds or 2.5 liters) of HEU to make an improvised nuclear device.[4]

Anticipating the possibility of a nuclear event[5] after the attacks of September 11, 2001, according to news reports the "Ring Around Washington" was constructed to detect a nuclear weapon smuggled into the capital.[6] The early solution proved operationally unworkable to the military over a longer term—so the US backed off from the ring detection approach leaving the capital vulnerable once again.[7] The ring may have represented a haphazard attempt to secure the nation's capital and perhaps served as a warning to would-be attackers. It is questionable how much incremental security it provided at the time given all the alternative routes such as airplanes entering Reagan National Airport, the Potomac river, nearby seaports, and many others.

HEU was first manufactured in the United States during World War II, and 60kg of 80% enriched HEU[8] used to make the first fission bomb dropped on Hiroshima killing 140,000 people. The design was considered so simple as to not require testing or pre-qualification. Only 1% of the U-235 fissioned and the blast yielded 13 kilotons[9] to 18 kilotons[10] of TNT equivalent. The theoretical risk of nuclear terrorism or clandestine attack with highly enriched uranium (HEU) has existed since critical mass quantities of HEU were first produced for a nuclear bomb over sixty years ago, in contrast to other types[11] of nuclear terrorism. US national intelligence estimates throughout the 1950s and 1960s provided warnings about the possibility of “clandestine” delivery of nuclear weapons by foreign nuclear states via commercial ships or airplanes.[12] The easiest way to make a nuclear weapon is to steal or obtain approximately 50 kg[13] of highly enriched uranium (HEU) from existing stocks (1.5 – 2 million kilograms[14]). The cheapest and stealthiest way to deliver a nuclear weapon into a metropolitan area is by using commercial or private transportation that today goes unchecked by the military (including ground, air, and sea pathways).

An estimate by former US Defense Secretary Perry puts the risk of nuclear detonation on US targets at 50% in ten years, and Defense Secretaries McNamara, Rumsfeld, Gates, and Vice President Cheney have provided similar warnings.[15] The CIA, FBI, and Pentagon meet weekly to assess progress on how the US can identify (attribute) the perpetrators of a nuclear terrorist attack[16], and the FBI director Mueller has warned that it was only a matter of time and economics before terrorists will be able to purchase nuclear weapons.[17] US government and military leaders are participating in contingency planning exercises for a terrorist nuclear attack, and possible steps include the suspension of civil liberties.[18] Perry, Carter, and May offer a vivid description[19] of the consequences and tough decisions that would have to be made by the US government in the days following a Hiroshima-sized act of nuclear terrorism or clandestine nuclear attack (the “day after”[20]). People within approximately a few miles of the detonation would either die instantly or shortly thereafter by radiation sickness, and those downwind of the blast would be subject to cancer-causing radiation.

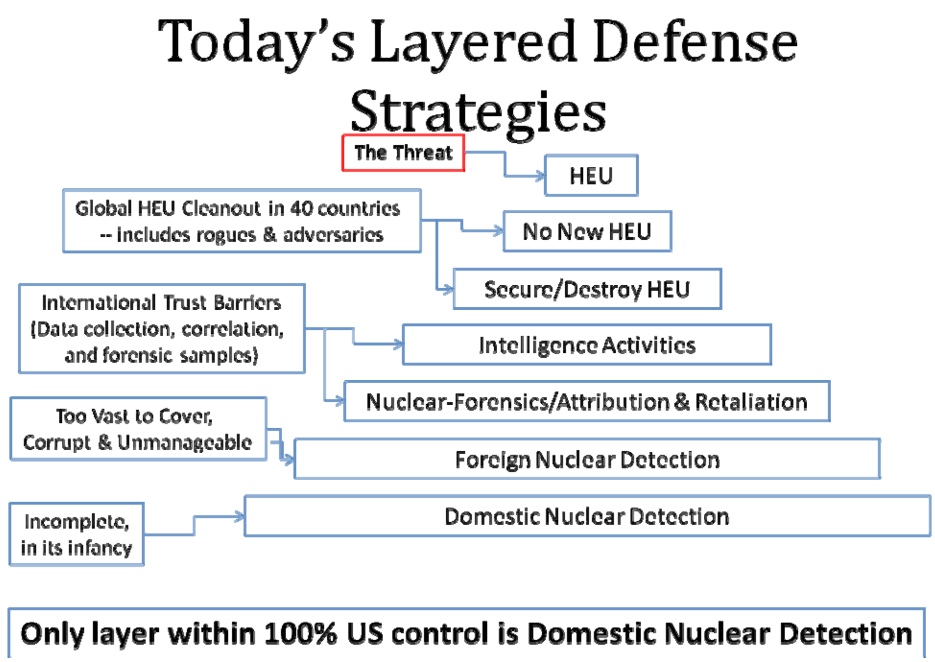
We need to "do something" to prevent nuclear terrorism for 50 if not 100 years anticipating new trends in nuclear proliferation, and not simply looking backward at the last 50 years as a blueprint for the future – 50-100 years should be the standard by which we judge whether or not our efforts and course of action are sufficient. In this paper, we are concerned with highly enriched uranium that has not been reprocessed – hence contains no penetrating U-232 radiation that can be easily detected from a distance. With radiological threats (and deterring them) it is likely possible to detect them using a thin, sloppy deployment of detectors because their radioactivity is so huge that they can be “seen” from long distances.

Detection should not be seen as taking away from the mission of locking down and destroying weapons-usable fissile materials (HEU included), only complementing it. If it happens and no new material is produced by adversarial or rogue nations – that's a dream come true, but it is too optimistic. With proliferation of enrichment technology, we ma not be able to rely on locking down materials alone in the next 50 years. A lot of things can change that necessitate additional preventative layers.

The capability for attribution of HEU used in an attack may be useful to trace the source after the first attack to shut it down and prevent follow on attacks. Attribution is unlikely to be a 'stick' or deterrent that is strong enough to compel nations to secure their stocks of nuclear material to the 50 or 100 year standard. For example, being able to trace the source of fertilizer or military high explosive doesn't do much to prevent it from being misused in improvised explosive devices – it's not clear that attribution can make the critical difference. Even the US Air Force had had a "bent spear" incident in 2007 where they lost track of nuclear weapons for 36 hours.[21]

The second problem with attribution is that there are cases where nuclear forensics may not even work in the case of HEU – the case of "fresh fuel" with insufficient number of uranium isotopes to uniquely identify the fuel, the incompleteness forensic sample databases.

All said and done, today our best hope to stop a plot involving HEU may still be intelligence, law enforcement, and investigation – whose worldwide coverage is necessarily incomplete.



Conceptually, domestic nuclear detection of HEU has the potential to serve as the last layer in a multi-layered defense against a terrorist nuclear attack[22] – the need rises in proportion to the likelihood that the other layers may fail. The remaining layers consist of nuclear detection in foreign territory, dissuasion through nuclear forensics/attribution followed by threat of retaliation against the source nation, intelligence efforts to disrupt nuclear terrorism plots and smuggling, securing of existing weapons/stockpiles, destroying stocks of nuclear material, and finally nonproliferation treaties to prevent the worldwide spread of weapons-usable nuclear material and production technology. In the event that attackers or smugglers ever acquire HEU, domestic nuclear detection is meant to dissuade their attempts with policies designed to detect and intercept their attempts to smuggle shipments of HEU and transport an HEU-based weapon to its target in the US, whether the transport vehicle is in a foreign country headed to the US, already inside the US, or approaching the borders.

Can we can build a nuclear detection architecture (or other alternative approach) that together with the above efforts will suffice for the next 50-100 years to prevent the HEU threat?

Nuclear Detection Tradeoffs

HEU cannot always be detected at stand-off distances (10-100 meters)

> *"The future force will be organized, trained, equipped, and resourced to deal with all aspects of the threat posed by weapons of mass destruction.* ***It will have capabilities to: detect WMD, including fissile material at stand-off ranges;*** *locate and characterize threats; interdict WMD and related shipments whether on land, at sea, or in the air; sustain operations under WMD attack; and render safe or otherwise eliminate WMD before, during or after a conflict."*[23]
>
> -- Quadrennial Defense Review (2006),

The implication is that with sufficient research[24], long term solutions for detecting nuclear materials in transit will lead to detection capabilities at stand-off ranges (long-distance) much like radar, sonar, or other remote detection techniques. This is unlikely to be possible without the use of a dedicated source of radiation to interrogate the target with. The possibilities are either a directed muon beam or neutron beam,[25] which may turn out to be unsafe for people or living beings. This is more likely to be useful on the battlefield in hostile environments, rather than for civilian use on a daily basis.

Without a dedicated source of radiation to penetrate the target, any form of passive detection of shielded HEU, including increased-sensitivity gamma-ray imaging[26], is fundamentally limited by the radiation emanating from the source—even for an ideal detector with 100% detection efficiency. Due to physical limits based on distance (proximity) and time (duration of exposure) required for detectors to integrate radiation from the source HEU, fixed and handheld detectors at borders are rendered incapable of detecting HEU when a small but sufficient amount of shielding is used to mask its natural radioactivity (a shield composed of lead, steel, or concrete that is 1-10 centimeters thick should suffice).[27]

The inability to detect HEU from a distance, at "stand-off ranges" without a dedicated source of radiation to interrogate the target, reduces the barrier to HEU trade on the black market since kilogram quantities of HEU can be freely transported to almost any destination worldwide. HEU enriched from naturally occurring uranium ore contains a low level of natural radioactivity making it is easy for nuclear smugglers to evade detection by military and intelligence agencies today.[28]

The current state of nuclear detection can be described as one where critical mass quantities of HEU can be shielded and freely transported to almost any destination, easily bypassing[29] the limited radiation detection systems in place at US borders.[30] Due to the low radioactivity of HEU which can be further attenuated by shielding (lead or concrete), a proposed network of fixed radiation detectors[31] dispersed throughout a city or area will not suffice to detect HEU[32], leaving the city wide open to attack by non-state actors or terrorists should they obtain a weapon.

When masked by shielding, HEU derived directly from uranium ore (not from spent reactor fuel) requires long periods of exposure time and short distance for passive detection outside a portal. The only reliable, practical passive detection is likely to be embedded detectors inside vehicles that have sufficient exposure time and short enough distance to integrate the HEU signal. We can't change the laws of physics, and the best we can hope to do is what the laws of physics let us do. Don't expect fundamentally new techniques to emerge that can remotely detect shielded HEU

1. at a distance of greater than a few meters and time shorter than several minutes,
2. without a radiation source to interrogate/probe the vehicle, and
3. within a form factor and cost that makes widespread deployment practical.

The only known exception to the above statement is when the HEU was produced from nuclear reactor feedstock or in facilities previously contaminated by reactor feedstock. In this case, there may be traces of U-232 present that emit highly penetrating gamma rays useful for detection through the shielding. In this special case, shielded HEU can be detected from a greater distance of possibly several meters or over shorter timescales using fixed or mobile detectors.[33] U-232 is likely to be present in HEU from enrichment programs by the US/USSR and other nations which engaged in large scale HEU production during the Cold War, but it is unlikely to be present in HEU produced by clandestine nuclear programs. HEU from clandestine enrichment programs is most likely to have been produced directly from uranium ore, without reprocessing inside a nuclear reactor which means it won't have shield penetrating gamma emissions from U-232.

Operational and Response Requirements

Reduction in false-positive rates has been billed as the major challenge to building usable nuclear detection, as summarized by the Department of Energy,

> "A detection system whose sensitivity is set very low in order to have high confidence of detecting nuclear material will have a correspondingly higher false positives rate from commonly occurring sources of radiation. Recent developments by the Domestic Nuclear Detection Office (DNDO), including installation of Advanced Spectroscopic Portals, are aimed at addressing this challenge. It is important to emphasize that developing appropriate procedures to be followed after an alarm is triggered—the so-called "concept of operations"—is

> as important to building a successful detection system as the physical characteristics of the detectors themselves."[34]

Since responding to a positive detection event is costly, requiring further investigation of the vehicle, the false-positive rate of any detection system needs to be sufficiently low, while also maintaining sufficiently useful detection with low or zero false-negatives.[35] For daily traffic volumes of a half million, the false-positive rate would need to be on the order of one in a million (0.0001%) or less to avoid experiencing a false-positive episode every day, given the traffic volumes discussed earlier for the Washington DC area. False-negatives need to be low enough to deter attackers and catch all perceived attempts, and there needs to be no way a knowledgeable attacker is capable of increasing false-negative rates to arbitrarily high values (for instance through use of shielding)—false-negative rates perhaps need to be less than 5% in all cases.

False-positives/negatives represent only one aspect of the set of metrics that completely define and quantify the success or failure of a security initiative such as the DC NDZ. Additional reliability metrics cover the detection of HEU, transportation pathways covered by detection, operational security, enforcement upon detection, and the minimum safe distance. Poor design, implementation, or operation leading to lack of sufficient performance along any of these metrics will lead to a failed NDZ.

- <u>Safe Distance:</u> The size of the weapon, the prompt effects (fireball), the fallout carried downwind of the detonation, and the sensitivity to casualties dictate how far the ring has to be from the target. A safe distance ensures the capital is immune from all HEU weapons that are likely to be employed by attackers.
    - At what distance does the target remain from the nearest point of non-inspected area where a blast could take place?
- <u>Physical Detection Reliability:</u> This characterizes how often the NDZ fails to correctly identify HEU (ideally never).
    - How often can HEU pass through a detector undetected (false-negatives), or evade a detector?
    - How often does a detection event occur that does not contain HEU (false-positives)?
    - What is the minimum detectable quantity of HEU in the presences of arbitrary shielding?
- <u>Pathway Coverage:</u> Ideally, there should be no loopholes.
    - Which regions or areas does it protect?
    - What transportation pathways may operate securely?
    - What transportation pathways are not securable?
    - What transportation pathways are not covered?
    - How often can HEU enter the NDZ by avoiding detectors and overcoming barriers?
- <u>Response Capacity:</u> This determines how the attacker could overwhelm the system. It should be large enough to deter all reasonable attempts by non-state actors.

  - How many simultaneous attempts can it detect and block? One? Two? Ten thousand?
  - For example, an attacker could use conventional explosives or techniques to break through the NDZ physical barrier and then transport the nuclear device inside the NDZ. How many simultaneous detector failures or attacker-initiated barrier penetrations can be tolerated before no response can be offered and security is lost?
- <u>Operational Detector Reliability:</u> Ideally, the system failures rates should be zero
  - How often do the detectors fail to operate?
  - How easy is it for detector information to be compromised with false output by intruders or operators themselves?
  - How easy would it be for the barriers to be penetrated by the attacker?

Synthesizing the requirements described above, the outstanding “applied research challenges” involve developing reliable products to fulfill the vision of a DC NDZ.

- <u>Reliable Detection Portals:</u> Create detection portals through which ground transportation (pedestrians, animals, cars, buses, trains) and air passengers/cargo can be screened safely, efficiently, and reasonably quickly for HEU. False positive rates need to be in the range of less than 1 in a million. Similarly false-negative rates need to be low enough to deter attackers. Combination of passive detection of nautral radioactivity of gamma/neutron (for unshielded HEU) and passive muon detection at portals (to detect shielding) is the primary candidate for this, but it remains to be seen whether these technique are infeasible in large-scale. They would have to be safe, reliable, and easy enough to operate thousands of portals for a metro.
- <u>Passive In-Vehicle Detectors:</u> Develop low-cost energy-selective passive tamper-proof detectors that can be embedded in vehicles and can be wirelessly queried at checkpoints to verify the absence of HEU in the vehicle. These can function as a supplement to passive portals, and are unlikely to substitute. False-negative rates need to be low enough to deter attackers. False-positive rates need to be sufficiently low to support the scale of the deployment, likely in the millions. Form-factor and power requirement need to be targeted to the application (cargo containers, trucks, cars, etc).
- <u>Active Interrogation:</u> This would be a solution for scanning ultra-large vehicles or that cannot fit through portals or vehicles with dense shielding requiring active interrogation (not simply containers). Both neutrons and muons are candidates. These would need to be like power-tools that can be used to thoroughly analyze these vehicles.
- <u>Secure Systems:</u> The detector system design needs to make these systems and the information they generate immune to being compromised by operators or intruders.
- <u>Large-Scale Management:</u> Since thousands of these systems would be operating in a city, they would need to be remotely manageable to detect and respond to operational failures such as loss of power, equipment malfunction, etc.

- Future Proofing and Extensibility: The NDZ should be designed to enable drop-in equipment and software upgrades without requiring severe operational or deployment changes in order to secure against future threats as the threat model evolves, technological improvements become feasible, or complementary technology becomes available.

Other theoretical threats beyond HEU include bombs based on plutonium (inherently easier to detect than HEU, since they emit many times more gamma rays and neutrons), fusion bombs, and neutron bombs. These require much greater testing, verification, and access to knowledge/materials and may be more likely to be attributable, so they are less likely to be as significant a threat as HEU.

In principle, the passive muon portals and active neutron/muon interrogation techniques can be applied to plutonium just as easily as HEU. Plutonium can also more easily detected using passive neutron detection techniques.

Spot Checking versus Portal Inspection

When complete screening is costly or prohibitive, randomized search is often used in terrorism security. To deter subway bombings with conventional explosives, New York City Police are conducting randomized search of passengers in different subways stations at unannounced times just like police checkpoints are used to screen drivers for blood alcohol concentration (BAC) on Friday/Saturday nights, and trace-testing for explosives are conducted at airport check-points on randomly selected travelers:

> *Officers set up inspection posts at least 35 times a year in each of the city's 468 subway stations, said Paul J. Browne, the department's chief spokesman. He said the operations went on 24 hours a day, sometimes in the middle of the night, and for several hours at a time. More than 300 posts are set up each week, for a total of more than 30,000 checkpoints since the program began.*
>
> *Terrorism experts said the program's effectiveness was not so much that it is a tight barrier to keep terrorists out of the subways, but that its fluid nature could keep any attack planners off balance. Trumpeting the program publicly is also a deterrent, they said.*
>
> *"Understanding that checkpoints only last for three or four hours and are concentrated during the rush hours," he said, "the department's own figures reveal that as few as 2 or 3 percent of the 1,000 subway entrances may have checkpoints at any given time."…*
>
> *Mr. Sheehan said that having officers checking bags at every station all the time would certainly be more effective, but added, "That is difficult to do."*
>
> *"That would require a tremendous commitment," he said. "It's cost-prohibitive in terms of cops and money. But if we have to do it, if the threat requires, we can do it."*[36]

Unpredictable, randomized searching on subways may create the impression that all stations/trains are searched by police at least some portion of the time—this might serve to raise the attacker's perceived risk of the being caught. It might cause the attackers to look for softer targets (through a displacement effect[37]), as which was the case with terrorist use of explosives on airplanes after explosive screening measures were introduced.[38] Based on the risk profile of the attacker, the probability of being searched has to appear to be greater than some number (say >5%), making it not worth the attacker's time/investment to attack the subway, and driving him/her to instead focus on other targets.

As an interim measure, short of fully ensuring no HEU enters an NDZ, randomized searching of ground transport may be accomplished provided that technology becomes available for US agents to screen for HEU on the spot throughout the NDZ without requiring the vehicle to be rerouted to a portal. This would require a thorough search of the vehicle—on demand—to uncover shielded HEU. To avoid transporting the vehicle to a portal, this randomized search would need some form of publicly acceptable stand-off detection (no health risks) to conduct randomized searches for HEU, perhaps relying on active interrogation using muons or neutrons—lead, concrete, or steel shielding makes it possible for attackers to conceal HEU from passive radiation detectors.

The primary drawback with randomized techniques is that, despite the odds, attackers may not be deterred from attacking national symbols like the capital (DC) or Wall Street (NYC) using HEU-based atomic weapons. If the probability of failure is 'p' per attempted attack, the attacker can succeed with a probability '1-p.' Determined attackers can compensate for this by attempting multiple simultaneous HEU attacks and achieve an arbitrarily high probability of at least one attack succeeding. If the rate of random searchers is perceived to be too low, it may not deter an attack. Determining the correct rate of random searches is subject to the risk profile and resources of the attacker, which is variable and unknown a priori. They can also fractionalize the material by dividing it up into a large number of smaller pieces and transporting them separately, so that the interception of any given piece will not adversely impact the overall project – and although it may alert authorities to the potential existence of the project, it may not cause sufficient alarm if the quantity smuggled is so small that it is dismissed. For these reasons, while the probabilistic dissuasion of the random inspections of New York subways might work to some extent to deter the entry of pre-fabricated bombs, it is very questionable whether this approach would work with nuclear materials that can be independently transported and post-assembled.

Randomized search would also have to be uniformly applied across all possible pathways (road, air, sea, etc.), leaving no stone unturned. Several pathways simply can't be searched effectively such as private jets, oil tankers, sailboats, or large cargo ships (before they arrive at the dock). For these, randomized techniques may not work requiring true barriers to entry.

Worst-case scenarios in which domestic nuclear detection might be useful

Given how hard and costly it would be to create a domestic nuclear detection system that works reliably, in what circumstances would it be worthwhile as a last line of defense?

Terrorists or non-state actors seek and obtain atomic capability

In a 2007 survey of 100 American foreign policy experts, respondents were asked to identify nations likely to transfer nuclear technology to terrorists in the next 3-5 years—the responses[39] were North Korea[40] (73%), Pakistan[41] (44%), Iran (40%), Russia[42] (12%), India (2%), Israel (1%), US (1%). Little is known with certainty about the exact composition, motivations, and loyalties of non-state actors, and often cited examples include Al Qaeda, Hezbollah, Quds Force[43], Liberation Tigers of Tamil Eelam (LTTE), Chechnyan Rebels, Lakshar-e-Toiba, Aum Shinrikyo. Since non-state actors neither represent nor are not loyal to any particular nation, the threat of retaliation on a nation-state in response to an attack is unlikely to be effective in deterring a non-state actor such as Al Qaeda.[44]

The proliferation of HEU to nation-states, next to semi-autonomous or unaccountable insiders, and ultimately to non-state actors remains outside the direct control of the US and is likely to accelerate over time.[45] According to the Quadrennial Defense Review (2006),

> *"The prospect that a nuclear capable state may lose control of some of its weapons to terrorists is one of the greatest dangers the United States and its allies face[46]… Based on the demonstrated ease with which uncooperative states and non-state actors can conceal WMD programs and related activities, the United States, its allies and partners must expect further intelligence gaps and surprises.[47]"*

Former CIA director George Tenet has estimated that it takes $100 million to be your own nuclear power.[48]Another estimate of the resources required to carry out a nuclear terrorism plot is roughly $5-6 million: non-state actors could employ a small number (on the order of a dozen) of technically capable people and use $3-5 million to illegally purchase HEU on the black market. [49] They could use it to threaten or kill hundreds of thousands of people in a metropolitan area from the direct radiation (fireball), and potentially harm millions of people who are located downwind of the blast. [50] Losses would be measured in trillions of dollars[51]. By comparison the US GDP is on the order of $13 trillion.[52]

Powerful sub-groups within nations may end up cooperating with terrorists directly or indirectly, and their motivations may differ from the national policy or rational interest of the nation's people.[53] These groups include the scientific bureaucracy (such as AQ Khan[54] in Pakistan), military, and national leadership.[55] In extreme cases the threat of transferring nuclear material to non-state actors itself was used in negotiations between US and North Korea[56]. Nations such as North Korea or Iran which perceive their delivery systems to be vulnerable to an overwhelming US first strike[57] may elect to deliver or store their atomic weapons in a clandestine manner on US soil, despite the incremental risk of losing control of these weapons.

According to a British Ministry of Defense analysis (2007-2036),

> *"The proliferation of nuclear weapons possession beyond the existing powers, particularly to weak and unstable states, will increase the risks of more uninhibited, assertive and intemperate behaviour by these polities while reducing their susceptibility to conventional methods of coercion. Also, the possession of nuclear weapons by states, whose capacity for ensuring their security and safety may be inadequate, will increase the risk of these technologies and associated materials being incompetently handled or acquired by third parties, including non-state actors such as criminals and terrorists."*[58]

HEU gets loose from stocks by thieves or insiders

We are in 100% agreement with the aims of a global cleanout of HEU, and efforts should be strengthened to down-blend and eliminate HEU stocks – which would address the most thorny issue. Doubts remain about its feasibility due to the factors outside of domestic control:

1. Will that ever happen since it depends on the cooperation of 40 nations, some potentially hostile?
2. Can we be sure that HEU production in "rogue" nations or by non-state actors (like AQ Khan's network) will never happen in the future?

The IAEA nominally defines a significant quantity of HEU to be 25kg[59]. HEU can be split into much smaller quantities (sub-kilograms) and smuggled around the globe, and should therefore be considered significant.[60] Fortunately there has not yet been a nuclear detonation by non-state actors, but the threat is real and increasing as long as HEU can be stolen by or transferred to terrorists from even one of these facilities.[61] In the last 20 years the IAEA reported 16 smuggling incidents involving HEU and Plutonium. There were at least three incidents involving kilogram quantities of HEU[62], and a total of 30.8 kg of HEU involved in known smuggling incidents (stolen, lost or seized). [63] A plot to smuggle an undisclosed amount of HEU to Iran was disrupted by British authorities in early 2006 after the material had been obtained through the black market in Russia.[64] In 1992, Russian authorities foiled an attempt to steal 18.5 kg of HEU, which may have been enough for a nuclear weapon.[65] Also in 1992, 1.5kg was stolen by insiders of a nuclear facility in increments of 25-30g, falling within the materials accounting precision of the facility in order to evade detection.[66] Three gram-quantity cases of HEU smuggling have been reported from 2001-2006 in the former Soviet Union countries.[67] One can only speculate on how many more smuggling incidents go undetected by authorities. A US government report argues that *"undetected smuggling of weapons-usable nuclear material has likely occurred"* at sites in Russia.[68] The detection rate of trafficking incidents by Russian security officials was estimated to be only 30-40%, and may be as low as 10%.[69]

Stockpiles of HEU are prime targets for mercenaries, smugglers, and terrorists, and it is imperative that the HEU in every stockpile worldwide is secured from falling into the wrong hands.[70] The most worrisome scenarios are that HEU can be stolen from stockpiles by terrorists or nations seeking nuclear capability, transferred to them by sympathetic insiders[71] from any one of the growing number of nations possessing HEU, or fall into the hands of terrorists after the collapse of an unstable national government (such as Pakistan[72], North Korea, or formerly as had happened with the Soviet Union)—all it would take is roughly 50 kg out of the 1.9 million kg in worldwide stockpiles to fall into their hands. One probabilistic model puts the likelihood of terrorist attack at 29% in the next decade by making assumptions about a finite number of terrorist groups trying to acquire fissile material from a fixed number of stockpiles.[73]

The security and accounting of these large military and civilian HEU stockpiles has been questioned, and has in several instances found to be unsatisfactory according to government and international watchdog agencies. As of 2006, according to the GAO the US has spent $2.2 billion since 1993 to upgrade security for sites Russia and other countries that house nuclear material and weapons, but the long-term sustainability of these US-funded programs is in question[74] and many more sites remain to be secured. Recent progress has been reported that two year efforts resulted in agreements between Russia and the US to ensure that Russia takes full responsibility for securing their nuclear materials by 2013.[75]

By the end of FY2005, the number of secured sites in Russia was estimated to be only 54%[76] – implying that about half of those buildings haven't received security upgrades – and up to 100 more sites do not have state-of-the-art security.[77] By one estimate, 500 tons of HEU in Russia is under uncertain security.[78] Insiders can exploited the fact that the material within an operating nuclear facility cannot be accounted for to an accuracy perhaps better than 2-4% ("Material Unaccounted For" or MUF) to steal small amounts of material at a time to evade detection.[79] Even with security upgrades, the stockpiles may still remain vulnerable to theft through a sufficient number of sophisticated enough attacks—the only real guarantee that material can't be stolen is if it is completely destroyed or down-blended to LEU.

Even if 100% of the existing HEU stockpiles in Russia and other HEU-possessing nations were to be secured, nations may begin to create new HEU stocks without international control.[80] In the past, uranium enrichment facilities required tremendous coordination, know how, and resources on the order of billions of dollars. These technical barriers are eroding and the cost of uranium enrichment is dropping over time due to technological trends such as the growing accessibility of high-precision lasers and high-speed gas centrifuges.[81] There is a rising demand for Uranium for power generation and weapons programs, and the number of nuclear states is growing over time. An increasing amount of low-enriched uranium[82] (LEU) being produced and distributed worldwide for nuclear power generation can in theory also be enriched into HEU—the opposite of down-blending.

The intelligence community fails

What is the likelihood that a terrorist plot to create an HEU-based atomic weapon is well underway and the US intelligence community doesn't know about it? While overestimation also happens, we found that over 50 years the underestimation of adversary's nuclear capabilities happens more often than we would like until a nuclear test is performed--when the capability is objectively baselined. Unlike with most nations, underestimation of terrorist nuclear capabilities is catastrophic. Nations can simply be deterred by threat of retaliation, terrorists can't.

Based on the historical accuracy of US intelligence estimates on foreign nuclear weapons programs, we cannot expect that these estimates by DoD, CIA, DoE, and State-Dept to be much more accurate than to within +5 to -5 years in (1) predicting progress of HEU enrichment programs in foreign countries, (2) determining whether or not foreign groups have attained nuclear weapons capability, and (3) estimating when they are likely to test them. This has proven to be the case in the last 50 years since Nazi Germany, and the forecast accuracy has not been improving over time.[83] Iraq[84] was no exception to the rule, both before/after the Gulf Wars of 1991[85] and 2003.[86] Intelligence on terrorist acquisition of nuclear materials or capabilities is even harder to estimate since non-state actors are much more numerous, employ more distributed networks of procurement and operation, and are possibly harder to infiltrate.

A terrorist nuclear capability or clandestine attack will likely come as a surprise, and advance warning of less than a few years will be unlikely. We can expect non-state actors to obtain HEU from theft, smuggling, or clandestine HEU enrichment programs and for this to go undetected for perhaps 3-5 years, and for suspicions about true capabilities of non-state actors to remain unresolved for the similar (if not longer) periods of time. Eight countries shown in Table 1 have produced nuclear weapons, five countries in Table 2 have attempted and failed to obtain nuclear weapons capability, although many other nations can opt to do so in a time-frame of a few years or less based on their possession of fissile material. In each case, intelligence analyst views/estimates (assembled through a combination of human intelligence, communications intercepts, satellite imagery, and smuggling intercepts) have routinely been off by 3-5 years when predicting progress towards nuclear weapons capability.

Due to the great perceived value that policy makers place on knowing about foreign nuclear programs in advance, combined with the extreme secrecy with which nations carry out their nuclear programs, the US intelligence predictions and conclusions often tolerate the use of insufficient and inconclusive evidence.[87] This leads to false-positives meaning that nuclear capability is "assumed" to have been achieved ahead of actual schedule (France, India, South Africa, North Korea, and Iraq in 2003). There are also false-negatives meaning that in several cases, the US was taken by surprise on the date the nation actually achieved its nuclear weapons capability (Israel, Pakistan), performed a nuclear test (Russia), or after definite information was obtained about progress towards nuclear weapons capability from a US-led invasion (Nazi-Germany, Iraq in 1991).

Obtaining reliable intelligence on terrorist progress toward nuclear weapons is likely to be even harder, given the large number of such groups and their distributed, global networks.

Table 1 Accuracy of US intelligence forecasts for nations that achieved nuclear weapons capability

Successful Nuclear Weapons Power	**Plans to Build a Nuclear Weapon**	**Achieved Nuclear Weapons Capability (date and type, Pu or HEU)**	**Forecast Inaccuracy: The years that the US estimates were off by. MC = "most conservative" ML = "most likely" Estimate must be earlier than or off by one year**	**Surprise Upon Achieving Nuclear Weapons Capability: Years of underestimation or overestimation on the day that nuclear capability was achieved MC = "most conservative" ML = "most likely"**
USSR	August 1, 1945[88]	August 29, 1949[89] (Pu)	-2 to +1 years (MC) and 0 to +4 years (ML) spanning 6 years [90]	+1 year (MC) and +4 years (ML), [91]
France	November 30, 1956 [92]	February 13, 1960[93] (Pu)	-2 to -1 years (MC) -1 to -2 years (ML) spanning 2 years [94]	0 years, expected two years before first actual bomb assembly and test [95]
China	January, 1955[96]	October 16, 1964[97] (HEU)	-1 to +1 years (MC) -0 to +6 years (ML) spanning 13 years[98]	0 years, based on Chinese preparation of test site shown by satellite imagery[99]
Israel	1955[100]	November 1, 1966[101] (Pu)	-4 to +1 years (MC) and -4 to +2 years (ML) spanning 8 years[102]	+1 year (MC) and +2 years (ML)[103]
India	September, 1971[104]	May 18, 1974[105] (Pu)	-6 to -2 years (MC) and -2 to -6 years (ML) spanning 7 years[106]	0 years, expected to be imminent for at least a decade until first bomb assembly and test, but it was a surprise on the day of the test[107]
South Africa	1974[108]	November, 1979[109] (HEU)	-2 to 0 years (MC) and -2 to +5 years (ML) spanning 12 years[110]	0 years, expected a test was imminent based on satellite imagery for at least two years before first bomb assembly[111]
Pakistan	January 20, 1972[112]	January, 1986[113] (HEU)	-6 to -1 years (MC) -5 to -1 years (ML) spanning 10 years[114]	+1 year, expected a Pu program instead of HEU [115]
North Korea	late 1970s[116]	1990s[117] (Pu)	insufficient knowledge to calculate the inaccuracy, but estimates span 11 years[118]	0 years, expected to be imminent for well over a decade until first test; first assembly unknown[119]

Table 2 Accuracy of US intelligence forecasts for states that have not yet achieved nuclear weapons capability

Attempted Nuclear Weapons Power	Plans to Build a Nuclear Weapon	Cause for Failure	Forecast Inaccuracy: The years that the US estimates were off by. MC = "most conservative" ML = "most likely" Estimate must be earlier than or off by one year	Surprise on the day the weapons program failed: years of underestimation that nuclear capability would have been achieved had it been allowed to continue MC = "most conservative" ML = "most likely"
Nazi Germany	September 25, 1939[120]	Allied Invasion, April, 1944[121]	at least 0 to -2 years (MC) and at least 0 to -2 years (ML) spanning 2 years[122]	would not have been achieved in any predictable time-frame[123]
Iran	1987[124]	Still In Progress	at least -2 to -7 years (MC) and at least -2 to -7 years (ML) spanning 15 years[125]	n/a
Libya	1970[126]	October, 2003, Exposed by Interception of Centrifuges[127]	at least -8 to -18 years (MC) and at least -8 to -18 years (ML) spanning 10 years[128]	5 years (MC) and 10 years (ML)[129]
Iraq (pre Gulf War of 1991)	September, 1975[130]	Coalition Invasion, March 1, 1991[131]	at least -4 to +5 years (MC) and at least -2 to +5 years (ML) spanning 8 years[132]	-3 years (MC) and 2 years (ML)[133]
Iraq (post Gulf War of 1991)	September, 1975[134]	Sanctions, Inspections, and US/British Invasion beginning March 19, 2003[135]	at least 0 to -3 (MC) spanning 13 years[136]	would not have been achieved in any predictable time-frame[137]
Taiwan	September, 1969[138]	Exposed by High-Level Defection, Dec 1987, Col. Chang defected and reported that Taiwan had begun to build a small-scale Pu extraction facility[139]	estimates span several years[140]	n/a

The conventional wisdom is that although nuclear intelligence is not perfect today, detection of the activities of non-state actors with regards to HEU can improve by demanding more from the intelligence community. As suggested by the Presidential Commission on WMD intelligence[141] these improvements include intelligence collection, analysis and reporting, and operations and management of intelligence organizations including multiplying human intelligence (HUMINT) capabilities.[142] Improvements in intelligence will no doubt be useful—even if US intelligence was operating near-perfectly[143] per the Presidential Commission recommendations, the odds are that there will still be undetected clandestine nuclear programs or activities involving non-state actors across the world (false-negatives) or that inconclusive evidence may lead to incorrect suspicions (false-positives).[144]

To use an analogy, let's suppose a government agency was commissioned to predict something as fundamentally uncertain as whether a fair coin will land up heads or tails. Due to the inherent uncertainty in coin tosses, no matter how hard the government tried or how many resources they spent they would not be able to be better than 50% right. In fact, they could achieve 50% accuracy simply predicting heads every time. If these coin tosses had large consequences (heads = clandestine HEU program exists; tails = clandestine HEU program does not exist), then if the government predicts heads when tails is true they will be branded as acting too conservatively. If they predict tails when in fact the truth is heads (or vice-versa), they will have made a huge mistake.

Foreign HEU production is concealed from the international community

Historically, all dual-use technologies have spread all over the globe eventually. If a nation opts to pursue HEU enrichment programs and weapons programs in locations that are undisclosed or inaccessible to international monitors, they are not hard to conceal.[145] This is why China and Pakistan exceeded US intelligence estimates of the rate of their progress toward a nuclear weapon, and the South African program was not possible to be tracked closely. While plutonium is highly radioactive and an operating nuclear reactor is required[146] to produce it, HEU enrichment and HEU bomb assembly is not usually amenable to external monitoring by satellite or monitoring devices outside the weapons facilities when the location of the facility is not known. [147] In a foreign country, HEU enrichment programs and HEU possession can be concealed[148] under any building or underground in a tunnel[149], and they are fundamentally unverifiable.[150] This continues to be the case today with HEU enrichment programs of Iran[151] and North Korea[152]. This loophole was effectively exploited by Iraq following the 1981 Israeli bombing of the Osirak reactor, when they decided to pursue a clandestine uranium enrichment program that went undetected until after the end of the first Gulf War in 1991.[153]

Over 50 years of history of intelligence, dozens of case studies have exposed that there is fundamental uncertainty about HEU production capabilities that is related to the ease with which HEU production and smuggling operations can be concealed. The outcome of intelligence gathering on HEU enrichment and weapons production is governed by immutable physical laws that apply to ease of concealment and distribution of HEU production and weapons programs, in particular enrichment techniques like gaseous centrifuge cascades and HEU itself.[154]

> *Looking to dissuade any U.S. consideration of using military strikes against Iranian nuclear sites, Tehran cautioned Friday that it could disperse its facilities to protect them. "We have a large country … and for centrifuge machines a room … is enough," said Ali Asghar Soltanieh, Iran's representative to the International Atomic Energy Agency in Vienna. Centrifuge work "could be performed, could be installed anywhere and could be protected," he added.* [155]

In contrast to older techniques, a gas-centrifuge plant to produce 50kg of HEU annually could be concealed in a building 50 meters long by 25 meters wide and consume only 200 kilowatts of electricity.[156] Such a plant would not be distinguishable from air or space from other industrial buildings, nor would it leak quantities of gas to the atmosphere that would aid in remote detection to localize the position of the plant.[157]

Pakistan (AQ Khan) has proved that sensitive nuclear technology can be exported to many nations (Libya, Iran, North Korea[158]) without the knowledge of US intelligence for many years. Disruption of the AQ Khan network was the result of diligent efforts by US, British, and other intelligence agencies.[159] However this tactical success[160] ultimately highlights a larger failure to prevent widespread, clandestine proliferation of HEU enrichment technology. Intelligence is essential and may impede the rate of nuclear proliferation, but it is unlikely to be good enough to completely stop states and non-state actors from acquiring nuclear weapons.[161]

Iraq demonstrated that they had maintained a clandestine HEU enrichment and weapons program for many years, and would likely have had a nuclear weapon had the US-led invasion of Iraq not uncovered and halted the program in 1991.[162] Iran continues to show that they can carry out an unverifiable HEU program on their territory in defiance of international pressure and the NPT and international inspection regime.[163]

The US first learnt of possible North Korean HEU program in 1998 or 1999 that was based on a dozen to two dozen centrifuges and centrifuge designs supplied by the A.Q. Khan network from Pakistan, and later through an interception of aluminum centrifuge tubes in 2003.[164]After initial US concern about underground North Korean HEU enrichment in 2002[165], North Korea maintained ambiguity about the status of their HEU program. This has not been resolved for many years, and is potentially leading to a US reassessment[166] about existence or capability of North Korean HEU program without any fundamentally new evidence since 2002 that would prove the non-existence of this program.[167]

The nation whose HEU was used in an attack cannot be uniquely identified

We cannot guarantee that after a terrorist or clandestine attack not delivered by missile or aircraft, the nation(s) who supplied the HEU in an attack may be correctly identified or traced—as a consequence, this makes the threat of retaliation by the US military almost a moot point. In order to serve as incentive for nations to ensure the physical security and accounting of their HEU stocks, nuclear forensics would have to help pinpoint the source of the HEU in the event of an attack. [168] This information could then be used to trace how it got loose, who exactly was responsible, and what retaliatory or corrective actions should be taken. [169] Simply being able to trace the source of fertilizer or military high explosive in an IED attack doesn't do much to prevent it from being misused in improvised explosive devices – it's not clear that attribution can make the critical difference in compelling nations to secure their stocks of nuclear material to a higher standard.

Even with the weekly meetings being devoted to this question by the CIA, FBI, and the Pentagon the President's decision to retaliate or apply pressure on the source nation will likely be a difficult one due to the ambiguity of attribution.[170] In the absence of sufficiently reliable human intelligence about the perpetrators of the attack or the HEU supply chain that was involved, it's borderline impossible to narrow down the source of the material among any one of several possible nations each with clandestine nuclear programs. [171] This is due to four technical reasons summarized below.

The first barrier to forensics is not specific to HEU, and applies to Pu equally. Samples are not exchanged between most nation-states who have HEU stocks – at least today – and there is no reason to believe this is going to get much better except without intelligence gathering.

1. Without a complete database of HEU samples, there is no basis for comparison of a forensic sample.

Second, unlike Pu there are comparatively few isotopes of Uranium (U-234/235/238) to provide an unambiguous fingerprint based on their relative composition – the "signal" may not be as discernable due to measurement error.

2. For HEU produced in a centrifuge directly from natural uranium ore, you have to rely on the ratio of U-234/235 which may lead to inability to distinguish between multiple HEU stockpiles. For "fresh" fuel the daughter products of the Uranium isotopes may have not accumulated in significant quantities to be useful in calibrating the age of the material.

Third, if you are "lucky" and the HEU has been produced through reprocessing, there may be trace contamination of U-232, U-233 , and U-236 as well. This should in theory make it easier to identify the sources.

3. Somehow this was not the case in 2006 between US and Russia. There still remain public differences of opinion between the US and Russia about the origin of HEU in the Georgian smuggling incident of 2006. In press reports Russians claim it's impossible to attribute if it was produced a long time ago, but the US opinion was that it came from Russia due to the presence of U-234 and U-236 contaminants. Which is true?

Finally, if we don't have a sample of a HEU from a stock at least in theory we could attempt to estimate the composition produced by a particular enrichment facility based on knowledge of its cascade/network design facility in order to check if there is a match.

4. Problem is that if the network design is not known accurately, or if the amount of U-234 was intentionally altered by the producer it may be nearly impossible to estimate.

A 2006 incident of a Russian smuggling HEU apprehended by Georgian authorities is a perfect example of the difficulty of reaching international agreement on the source of loose HEU, even when the HEU samples are made available to each nation.[172] The judgment of US scientists was that it likely came from Russia based on the presence of U-234 and U-236, whereas Russian scientists could only estimate that the uranium was reprocessed over a decade ago.[173] Russian scientists further insisted that there is no evidence the material originated in Russia, and *"if this uranium was produced in the 1940s-50s, it will be extremely difficult to identify the country of origin"*[174] Had this been material recovered by a nation post-blast, the disagreement about its origins would have made it extremely difficult to make decisions to prevent further attacks whether by taking steps to seal up the material leak or threaten retaliation.

In an HEU-based nuclear explosion, all physical evidence[175] is incinerated except the unexploded HEU that remains after a blast, from which the relative composition of uranium isotopes can be used as a partial signature. In the event of recovery of smuggled HEU prior to an attack,[176] other forensic tools (chemical, physical, can provide some insight into the point of origin of the materials). Even with a national attribution program intended to gather "smoking gun" evidence after a blast[177], there remain fundamental physical constraints to reliably attributing the HEU to the source nation after an attack or even upon interception of the HEU before an attack. In some cases, isotopic analysis of unexploded HEU after an actual nuclear blast may be used to positively verify whether or not the HEU matches the fingerprint from a well-characterized HEU stockpile.[178] It might therefore be used to help exonerate a trusted nation-state that has a transparent nuclear program (example: US and Canada), but not to attribute or confirm the HEU came from a particular nation-state which could then be targeted.[179]

The presence of U-232, U-233[180], and U-236 in the unexploded HEU indicate contamination from reactor feed-stocks. This was the case for HEU produced in gaseous diffusion plants during the Cold War by the US, Britain, and the former Soviet Union.[181] In contrast, HEU enriched from natural uranium ore that is not contaminated by feedstock from nuclear reactors will not have any of these uranium isotopes—likely to be case with more recently established enrichment programs based on gas centrifuges[182] suspected to be in Pakistan, Iran, or North Korea. The remaining isotopes[183] whose relative composition is useful for fingerprinting are only U-234 and U-235, and therefore the isotopic ratio of U-234 to U-235 of samples from the source nation's stockpile is the critical measurement that can be used for attribution of a future attack. U-234 is present in natural uranium in very small amounts compared to U-235. Enrichment techniques involving laser isotope separation (LIS) or electromagnetic isotope separation (EMIS), will deplete U-234 relative to U-235, whereas U-234 will be enriched relative to U-235 with enrichment based on gaseous diffusion, gas centrifuges, thermal diffusion, or aerodynamic enrichment. The exact ratio of U-234 to U-235 depends on specifics of how the cascades stages used for enrichment are networked[184] and will be hard to estimate without knowledge (intelligence) of the exact details.

The ratio of U-234 to U-235 in unexploded material (post-attack) cannot be used to perform reliable attribution if any of the following hold true,

1. nation-states maintain clandestine nuclear programs and do not voluntarily and verifiably divulge the isotopic composition of their entire HEU stocks, or
2. intelligence fails to uncover the technical details of the process used to enrich the HEU as would be the case with a clandestine enrichment program, or
3. nation-states with clandestine nuclear programs[185] intentionally alter the isotopic composition so as to make their HEU impervious to attribution or to provide a false attribution signature.

Clandestine uranium enrichment programs that are not transparent to international inspections are a major risk because concealment and lack of access to the facilities makes it difficult or impossible to fingerprint HEU produced by these programs. [186] Since a national attribution database[187] based on the isotopic composition of other nations' nuclear materials (nuclear fingerprints[188]) can only be populated either through intelligence or measurement after nuclear tests, such as the 2006 test by North Korea[189], these databases are likely to remain incomplete,[190] especially in the case of clandestine HEU programs, simply due to gaps in intelligence and measurement. These limitations increase the risk that insiders of a nation-state with a clandestine nuclear program can sell or transfer HEU to non-state actors with impunity[191]: in one hypothetical scenario the Iranian Revolutionary Guard supplies terrorist groups like Hamas and Hezbollah with HEU or a weapon itself.[192] As long as the uranium enrichment processes and the HEU employed by other nations remains unknown, analysis of the isotopic composition of the unexploded uranium remaining after an attack with an HEU-based atomic bomb may not be sufficient to determine the source nation of the HEU. [193]

Even if nation-states cooperate to construct an internationally verifiable database of HEU fingerprints (samples) from all known stockpiles worldwide,[194] the limited number of uranium isotopes present in these samples makes it physically impossible to unambiguously deduce the stockpile from which the material came. Since the victim nation can potentially narrow down the likely sources of the attack only to the list of nations whose HEU sample compositions are unknown, such a database can maximize the potential repercussions to someone with access to HEU and possibly influence their decision whether to make that material available to terrorists. Creating such a comprehensive database requires all nations to contribute samples of all their HEU stocks, without spoofs, in an internationally verifiable manner—which seems unlikely since it faces the same set of trust, transparency, and cooperation issues between nations.[195]

Foreign nuclear weapons programs evade intelligence

Short of observing a nuclear test[196], the only reliable, objective means to determine the status of HEU enrichment and weapons programs by untrustworthy foreign nations is to have access to 100% of the territory that could be used in weapons production and to be able to search the territory thoroughly without obstruction, as the US had the opportunity to do during Project Alsos[197] in Nazi Germany and with the Iraq Survey Group[198] after the Gulf War of 2003. The absence of positive evidence of a terrorist or clandestine nuclear program is not any indication that such a program does not actually exist (false negatives), which was the case early on with the nuclear programs of all the nuclear weapons states. Some types of evidence are reliable, while others that warn of the existence, status, or location of HEU nuclear programs run the risk of being misleading (false positives).

Of the sources of intelligence listed in Table 3, the nuclear tests by nuclear weapon nation-states (except Israel and South Africa) have been the most definite source of intelligence and information about their nuclear weapons programs. There is no reason to believe this will be any different with non-state actors. . The major difference is that nuclear tests by nations-states are likely to be conducted at underground or unpopulated sites whereas a “nuclear test” by a terrorist group could be conducted in a populated area with large civilian and economic casualties.

Inspections of nuclear facilities help, but they are not always a good indicator and suffer from false-negatives. The host country can attempt to mislead the inspectors (Israel in 1963-1964[199]), relocate equipment or material during the visits (Iraq after the 1991 Gulf War[200]), stall or delay inspections (North Korea[201]), or conduct weapons activities at completely different locations (as feared in Iran[202]). In rare instances, human intelligence has been invaluable to provide accurate, advance warning such as the defections that led to uncovering Taiwanese[203] and Israeli[204] programs. Intercepts of materials, documents, communication, have been of questionable value and less often provided conclusive information—as was the case with dual-use aluminum rocket tubes destined for Iraq that were mistaken to be centrifuge parts.[205]

Table 3 Reliable and unreliable sources of intelligence on foreign nuclear weapons programs

Method	Intelligence Provided	Requirements/limitations	Selected Examples
Nuclear Test	Reliable confirmation of nuclear capability	may be too late, especially in the case of a non-state actor	Soviet Union, France, China, India, Pakistan, North Korea
Alsos-style inspections of foreign territory without restrictions for HEU production/presence, once control has been gained through an invasion.	Reliable.	Requires knowledge of which territory the facility is in. In case of non-state actors in a friendly country, also requires access to be granted in foreign territory.	Nazi-Germany[206] and Iraq[207]
Sting Operation	Reliable.	Likely to catch a small fraction of actual activity	Georgian HEU smuggling incident[208]
Forensic evidence from analyzing materials originating in the source nation near a nuclear facility.	Reliable.	Requires receiving and analyzing materials from or with exposure to gaseous, liquid, or solid contaminants in or near a facility that identify weapons (materials) production. Susceptible to spoofing.	Discovery of traces of highly enriched uranium on the clothes of Iraqi hostages released in 1990[209]
Human Source with High-Level or insider access	Unreliable. Can provide detailed plans, locations, assets and progress to date.	Not always available, often needs to be planted several years in advance. Needs to be authenticated as true.	Taiwan[210], Israel[211], and China[212] (success); Complete lack of visibility into Indian, Soviet, and Iranian programs (failure).
Satellite image of Plutonium Reactor or nuclear complex.	Unreliable.	Works for nuclear reactors or for preparation of test sites. Works only when the reactor or power lines are above ground, and its location is known. Does not work for Uranium enrichment or weapons production where a reactor is not required (centrifuges).	Soviet Union[213] and China[214], (success) and India[215] (false-negative); South Africa[216] (false-positive)
Parts or material Intercept	Unreliable.	Likely to catch only a small fraction of actual traffic	Iraqi dual-use aluminum tubes[217] (failure); centrifuges in Libya[218] (success)
Inspections	Unreliable.	Inspectors can be misled or material/equipment relocated.	Israel[219], North Korea[220], Iraq[221], Iran[222].

Policy Recommendations

What are the US government policies to prevent nuclear terrorism with HEU?

The US government is pursing six preventive[223] defense policies:

1. **No new HEU:** Stop enrichment of Uranium into HEU. This defense includes all diplomatically driven[224] efforts for WMD interdiction such as the Proliferation Security Initiative[225] (PSI) funded to $50 million in 2005 and preemptive[226] military nonproliferation initiatives such as the Operation Iraqi Freedom[227]. The US State Department spent $197 million on nonproliferation initiatives in 2005[228] and requested $209 million for FY2007[229]. This includes approximately $50 million in voluntary contributions to the International Atomic Energy Agency[230] (IAEA) which verifies compliance of nations with the Nonproliferation Treaty[231] (NPT). The Iraq War to preempt clandestine efforts by Saddam Hussein to obtain weapons of mass destruction,[232] and in particular a nuclear device[233] based on HEU[234], began on March 20, 2003. Its cost was estimated to be $53 billion through the end of FY2003 during which President Bush declared end of major combat operations on May 1, 2003.[235] A cumulative $378 billion will have been spent on the Iraq War through FY 2007.[236] In order to dissuade nations from producing new HEU and building new dual-use (civilian-military) nuclear facilities used in uranium enrichment[237], the US will be providing a matching contribution of $50 million (of the total $200 million) to support an international effort to create a "nuclear fuel bank" that will offer an internationally assured supply of Low Enriched Uranium (LEU) for civilian use (power-generation).[238]
2. **Securing existing HEU:** If HEU remains in a stockpile, reactor, or weapons complex then take steps to ensure a terrorist can't gain access to it.[239] This is achieved by destroying the HEU or down-blending it to LEU[240] which make the material unusable in a weapon (unless it is re-enriched), or securing the existing HEU in stockpiles. Specifically the FY 2008 budget request for the US fissile material disposition program[241] is $610 million of which $66.8 million is to be used for disposition of US-surplus HEU.[242] The FY 2008 budget request to secure nuclear sites, convert reactors, and repatriate fuel from reactors worldwide is for $492 million. A total of $2.2 billion has been spent by the US to improve security at foreign sites as of 2006[243], and $1.6 billion in Russia alone since 1993[244].
3. **Intelligence:** tracking down individuals, disrupting plots, and destroying facilities involving HEU smuggling, production, and weaponization. The annual intelligence budget for the US was in the range of $26.6 billion in FY 1997, rising to an estimated $44 billion in 2005[245] and $48 billion in 2007[246].
4. **Forensics, Attribution, and Retaliation:** Threaten negative diplomatic, military, economic consequences against nation(s) responsible for providing or deploying the material in the event an attack actually taking place. If the HEU was stolen, work constructively with the nation to shore up security of HEU stocks after the leak has been pinpointed. The credibility of these post-attack measures as deterrents and corrective actions hinge on being able to use post-detonation

forensic evidence to reliably determine where the material came from, and nuclear attribution programs are reportedly funded in the US at a level between $8 and 18 million in FY 2007.[247]

5. **Foreign Detection:** From 1994-2005, the DoE, DoD, and State Department have spent $178 million to aid 36 foreign countries in deploying radiation detection equipment, primarily Russia as part of a "Second Line of Defense."[248] Of Russia's 350 border crossings, international airports, and road/rail crossings), the US has spent $40 million through 2006; approximately 200 of these crossings are expected to have detection equipment installed by the end of 2007, and the remaining are expected to be completed for an additional $100 million over four years.[249]
6. **Domestic Detection:** For the case when attackers or smugglers ever acquire HEU, deter their attempts with policies designed to detect and intercept their attempts to smuggle shipments of HEU and transport an HEU-based weapon to its target in the US, whether the transport vehicle is in a foreign country, already inside the US, or approaching the borders. The US budget for domestic nuclear detection in FY 2007 was $480 million with a request of $562 million for FY 2008.[250]

If the traditional approaches including nonproliferation efforts, intelligence for interdiction/attribution, and military campaigns to eliminate clandestine nuclear programs fail to sufficiently reduce the risk of HEU spreading to terrorists, rogue states, and non-state actors, then additional steps are needed to prevent proliferation of HEU from spiraling out of control. According to the Quadrennial Defense Review (2006),

> *"The principal objective of the United States is to prevent hostile states or non-state actors from acquiring WMD. This involves diplomatic and economic measures, but it can also involve active measures and the use of military force to deny access to materials, interdict transfers, and disrupt production programs."*[251]

What are limitations of US policies?

As implemented today, none of these defense policies alone may solve the problem. Even in combination they can fail altogether to prevent nuclear terrorism by a small, sufficiently financed, motivated, terrorist group[252] or the clandestine delivery of a nuclear weapon by a nation-state. Each layer of defense deserves to be strengthened, enhanced, and further supported with additional funding to the extent that marginal security benefit can be derived. Even so, there remain serious gaps today in the US government policies for these defenses. These gaps are likely to result in failures to prevent nuclear terrorism or clandestine attack. Although the six-layer defense outlined above has succeeded in preventing nuclear terrorism or clandestine attack to-date[253], the threat continues to grow with time. We analyze the limitations of these policies in subsequent sections.

There is no consensus on what needs to be done to make each of the layers to completely watertight, and there remain several vulnerabilities in each of the layers as implemented. Nonproliferation of HEU and securing existing stockpiles are slowed by negotiations and trust barriers between the growing numbers of nuclear-capable nations. Both the intelligence and attribution of HEU to a nation are error-prone or impossible because they are subject to fundamental physical and logistical constraints which are created by foreign entities, outside the control of the US. Today, there are unfortunately many ways for a terrorist to smuggle HEU across the border into a nation like the US whether by land, sea, or air. A few of the loopholes include private jets, sail boats, off road vehicles, and underground tunnels. It is much harder to ensure accountability of US-funded nuclear detection efforts to secure foreign borders and nuclear smuggling corridors when compared to 100% domestic approaches. Corruption or forcible removal of foreign security guards can compromise the detection network, and risk also include the difficulties of remote management, maintenance, and upgrades, and inter-agency coordination.[254] Preventing the failures in the first five layers depends heavily on factors beyond the control of the United States, and therefore unlikely to be fixed anytime in the next 50-100 years. Changes will be required to efficiently transport goods and people while ensuring the transportation network is not misused by non-state actors to position highly enriched uranium within the nation's capital or other major metros.

Today's approaches to domestic nuclear detection being deployed individually or jointly by the Domestic Nuclear Detection Office[255] (DNDO), Customs and Border Patrol[256] (CBP), the Defense Threat Reduction Agency[257] (DTRA), and the Department of Energy[258] (DoE) are incomplete[259] resulting in a large number of false-negatives[260] or otherwise hinge on inflated expectations for future developments in nuclear detection technology[261] for domestic search[262] or reconnaissance in enemy territory[263]. The DoD[264] and DNDO[265] requirements for stand-off detection of HEU at greater than 100m or even 1km are unlikely to be fulfilled without active radiation directed at the target, and therefore they do not translate to application outside the battlefield in large-scale civilian environments. Screening cargo containers at sea ports[266] and land border crossings[267] covers a tiny fraction of the larger problem, and terrorists or smugglers are more likely to try one of the remaining pathways that are unsecured since those present a lower risk of being caught (displacement effect). Surrounding the HEU with lead, steel, or concrete makes it much harder to detect HEU at a distance (shielding).[268]

What does the Nonproliferation Treaty have to do with nuclear terrorism and HEU stockpiles?

The proliferation of nuclear weapons among nations and the proliferation of fissile materials used in nuclear weapons are not governed by the same rules.[269] With 184 signatories who have voluntarily agreed to be non-nuclear weapons states and five nuclear weapons states (P-5) [270], the Nonproliferation Treaty (NPT) has so far been successful in moderating the chain reaction[271] that is weapons proliferation to ten nations down from a peak of 23 nations with active weapons programs during the Cold War[272]. It does not explicitly stop nations from producing fissile material and maintaining stockpiles for civilian purposes like power generation (sometimes used as a cover for a weapons program).[273] In order to dissuade the construction of new dual-use (civilian-military) production facilities for HEU by nations such as Iran, the IAEA is leading an effort to create an assured nuclear fuel supply for LEU[274] that can be used for power-generation purposes only.[275]

As drafted, the NPT does not constrain the proliferation of HEU itself which President Bush[276] refers to as a "loophole," and the IAEA's assured nuclear LEU supply is too late by five decades: as of 2003 1900 metric tons of HEU are currently spread across 50 countries.[277] Over 55% of the world's HEU is in Russia, and 35% in the United States.[278] As of 2004, the US Government Accountability Office reports that there were at least 128 facilities worldwide with more than 20kg of HEU onsite.[279] As of mid-2006, the International Panel on Fissile Materials estimates that the global stockpile of HEU amounts to 1400-2000 metric tons.[280]

Strengthening, accelerating, and providing full financial support for international efforts to prevent new HEU production[281], destroy existing HEU stocks, and deny access to HEU[282] is essential. The US-sponsored Global Threat Reduction Initiative, launched in 2004, set out a 10-year goal for converting or shutting down 106 research reactors that run on HEU, but this goal does not include 61 additional reactors that use HEU.[283]

To date, these efforts begun after the Cold War have remained incomplete for a number of reasons.[284] International efforts have been protracted for decades and remain incomplete due to barriers of trust, transparency, and cooperation between nations (such as US-Russia[285] or US-Pakistan) or lack of inter-agency collaboration[286] within the US government.

Had there not been international nonproliferation agreements[287] (like the NPT) that have been achieved through voluntary cooperation of nations capable of producing HEU, the number of nations actually producing HEU weapons may have been much greater than it is today. A nation's compliance with these voluntary agreements is audited by outside inspections of declared nuclear activities[288] and also by on-demand "special inspections,"[289] "snap-inspections,"[290] and location-specific environmental sampling aimed at detecting undeclared nuclear activities (voluntary Additional Protocol[291]). Nations can refuse these international inspections or access to sites if they are concerned about their national security interests.[292] As of early 2007, only 111 states and Taiwan of the 188 states party to the NPT have signed an Additional Protocol and only 78 of these have ratified it.[293]

NPT inspections of declared facilities or on-demand inspections of suspect sites like the Additional Protocol are not strong enough to completely stop HEU proliferation in uncooperative nation-states or NPT signatories who are intent on deceiving the international community by carrying out nuclear weapons and/or uranium enrichment programs at secret locations.[294] Prior to the first Gulf War, Iraq was a signatory to the NPT yet fell into this category.[295] The growing list of countries considered to be major nuclear proliferation risks[296] includes Iran[297], North Korea[298], and Pakistan[299] and they are either confirmed to have or may have internationally unverifiable HEU enrichment programs. At this time, the efficacy of the NPT is under review in light of clandestine nuclear programs uncovered in Iran, Libya, the AQ Khan network, and North Korea's withdrawal from the NPT.[300] Intelligence gaps about these clandestine programs are likely to grow in the future as more nations may undertake clandestine programs either in response to worldwide nuclear proliferation or for political reasons. For example, Iran's proliferation efforts may inspire its neighbors including Syria and Saudi Arabia to pursue nuclear capabilities,[301] or South Korea could initiate nuclear weapons development in response to North Korea's program.[302]

So what do we do about nuclear detection?

In 2005, the Secretary of Defense designated US Strategic Command as the focal point for integrating and synchronizing efforts to combat WMD, with Defense Threat Reduction Agency (DTRA) as primary support and the Army's Chem-Bio-Radiological-Nuclear (CBRNE[303]) 20th support command to "respond-to" and "render-safe" any WMD threat. [304] To achieve these goals, the DTRA[305] will need to operate a reliable national detection system to detect HEU across all transportation pathways (vehicles) accessible to terrorists within Nuclear Defense Zones (NDZs) surrounding each metropolitan area and military base. Actionable information on HEU content and integrity of the NDZ operations in each city, with near-zero false-negatives or false-positives, needs to be generated by DTRA and made accessible to the Army, Navy, and Air Force by securely reading out and processing detector readings for each vehicle. As an alternative or supporting function to the DTRA, the National Security Agency (NSA) may be in a stronger position to fulfill the large-scale, distributed, secure computational requirements to reliably operate a national nuclear detection system.

The "Global Nuclear Detection Architecture" [306] proposed in the DNDO charter is a mirage, and reliable detection on a global scale is not achievable in the near term—a domestic, metropolitan nuclear detection architecture is a more solvable problem that can result in a reliable nuclear detection system around primary targets.

Defense Research & Engineering (DR&E) should be charged with the responsibility of engineering a national nuclear detection architecture and reliable detection portal (RDP) capable of detecting HEU in every vehicle. This involves addressing the "applied research challenges" listed in the previous section. This activity can be kicked-off as part of a national security presidential directive (NSPD), similar to how research for tamper-proof nuclear weapons was initiated in NSPD 28 and the Domestic Nuclear Detection Office (DNDO) was established in NSPD 43. [307] Congress should require that DR&E invest in nuclear detection systems at least at a level comparable[308] to missile defense spending which is currently $10 billion[309] annually (out of a total annual DR&E budget exceeding $70 billion) and projected to remain around that level for over a decade.[310]

DTRA (and possibly NSA) will need to operate a large-scale secure network to monitor all the detectors across each of these pathways to reliably pinpoint the location of smuggled HEU. DR&E should work out operational aspects and trial a system to gain a handle on costs/phases/timeline of implementation on a large scale, such as in DC or New York.

Existing policy for nuclear detection is not aggressive enough, as Senator Kyl points out,

> *"Finally, I would like to consider the proposition that the US is approaching the issue of nuclear detection at far too leisurely a pace… If a nuclear 9/11 is in fact the greatest existential danger facing this nation, then we must ensure that we are*

> *acting in a manner proportionate to the threat. That includes providing adequate funding, adequate authority, and adequate attention to the relevant agencies of our government."*[311]

Conclusion

Security policies that ignore the adversary will not be successful. With the current gaps in our security against "clandestine nuclear attack" or "nuclear terrorism," the US Department of Defense should come to terms with how this is consistent with its mission[312], *"To provide the military forces needed to deter war and to protect the security of the United States. Everything we do supports that primary mission. Nothing less is acceptable to us, or to the American people."*[313] In comparison to the historical focus on regional threats and security,[314] all military service branches should conduct a comprehensive review and reassessment of their collective capability in dealing with the global threat of nuclear terrorism perpetrated by transnational, non-state actors or clandestine attack from hostile nation-states. They should identify all the changes, needed for the US to be reliably secured against this threat, and then work to fund/implement those necessary changes.

1. Complete Intelligence Coverage: For example, consider multiplying the budget and operations for intelligence on clandestine nuclear networks and programs to ensure sufficient coverage in all risk areas—this has shown success with the dismantling of parts of the AQ Khan network—remains to be seen if this has been fully dismantled.[315] Failures and setbacks shave shown intelligence improvements are unlikely to be enough.
2. Global HEU cleanout: Make it a priority to convince all nations to secure and destroy their HEU, and convert to using LEU instead for research & power generation. This is outside of the US control and will never be sufficient until all HEU can be fully eliminated.
3. Reliable Nuclear Detection: We described the concept of a "Nuclear Defense Zone" (NDZs) to protect cities, metropolitan areas, and military bases. The NDZ starts with an impenetrable barrier around a city or base perimeter (ground, water, and air) and permits vehicles to enter only if they can be guaranteed to be free of HEU. Most forms of ground transportation can be screened at entry points of the NDZ using reliable detection portals (RDPs), provided the portal detection technology can be proven to handle millions of vehicles per day. Detection solutions for some transportation pathways are intractable, such as ships at seaports co-located near cities or private aircraft not screened at airports. These need to be relocated far away from populated centers.

International measures alone may be insufficient to halt the physically unverifiable activities of uranium enrichment and black market trade of HEU in foreign countries. Outbound investments in foreign intelligence gathering, international nonproliferation efforts to stop production of new HEU, securing HEU stockpiles, detection of HEU at foreign borders, and finally post-attack attribution/planning should all be redoubled to achieve maximum dissuasion and prevention. The problem of containing and securing 10-20 parts per million of HEU stocks across fifty countries is unachievable in a reasonable time-frame, especially as the number of nations capable of producing HEU is rising. Advance warning of a nuclear terrorist attack of less than a few years is unlikely—we find that over the last 50 years, US Intelligence estimates on foreign nuclear capability have been accurate to only +/- 5 years, are chronically incomplete, and unreliable. We also find that post-blast evidence after an attack will be unable to reliably identify the source of HEU in order to shut down the supply HEU chain, assign responsibility, or deter aggressors. The scale of foreign nuclear detection required far exceeds that of US domestic nuclear detection, and is likely to take much longer to achieve if ever.

To complement the national border, reliable, concentric city-wide and metropolitan HEU detection programs may be necessary to dissuade smugglers and terrorists from transporting and positioning HEU in or near a populated area or megalopolis. A Hiroshima-sized bomb built from HEU could cause hundreds of thousands of deaths, casualties in the millions, and trillions of dollars of economic damage. The cheapest and stealthiest way to deliver a nuclear weapon into a metropolitan area is by using one of many commercial or private transportation pathways that today go unchecked by the military (including ground, air, and sea pathways). The easiest way to make a nuclear weapon is to steal or obtain approximately 50 kg of highly enriched uranium (HEU) from existing stocks.

The Department of Defense should be determine how to verify that every vehicle within tens of miles of a major city or military base (a "Nuclear Defense Zone") is free of significant quantities of fissile nuclear materials—including all forms of HEU. Proliferation of HEU continues, increasing the risk that it may be exploited for nuclear terrorism by non-state actors or clandestine attack by a nation-state to deploy a fissile nuclear weapon against US or international targets. The DoD has to step up to the threat of clandestine attack and nuclear terrorism with foreign HEU. DoD must apply all its resources to the problem as outlined using DTRA, DRE, Army, Navy and Air Force in an integrated program that incorporates the work of DNDO.

Intelligence is unlikely to be able to identify and stop all inbound threats arising from HEU. Attribution of the source of the HEU using nuclear forensics on the unexploded material used in an attack may not be reliable and may be ambiguous especially when the potential sources include countries with clandestine nuclear programs. To dissuade smugglers from trying to acquire and use HEU, the DoD will need to learn how to efficiently verify that every vehicle within a safe radius of a major metro area is free of significant quantities of fissile nuclear materials including all forms of HEU—a Nuclear Defense Zone (NDZ).

To dissuade adversaries from planning clandestine nuclear attack or nuclear terrorism, the DoD should be prepared to intercept all shipments of HEU before they enters an NDZ by any pathway that is within the capability of these adversaries. Actionable information on HEU content at the borders of an NDZ needs to be mined by DTRA (or NSA) and be made accessible to Army, Navy, and Air Force which then needs to take control of the HEU. DR&E (Defense Research & Engineering) should own the responsibility of engineering a reliable NDZ capable of detecting HEU in every vehicle using a combination of passive gamma/neutron detectors, passive muon drive-thru portals and active interrogation of large vehicles with muons or neutrons. Detection solutions for some transportation pathways are intractable, like ships at seaports co-located near cities, and they need to be either relocated far away from populated centers or removed entirely.

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[175] Sidney Niemeyer and David K. Smith, *"Following the Clues: The Role of Forensics in Preventing Nuclear Terrorism"* (Arms Control Today, July/August 2007) <http://www.armscontrol.org/act/2007_07-08/Clues.asp>

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[179] After the first nuclear test by China, the US was only able to conlude though a process of elimination that the HEU used for the bomb did not come from the USSR, and only therefore China has produced its own HEU—which was a surprise to the US at that time. See page 169, Jeffery T. Richelson, *"Spying on the Bomb"*.

[180] p. 37, Michael Miller *"Nuclear Attribution As Deterrence,"* (Nonproliferation Review, Vol 14, No 1, March 2007) <http://cns.miis.edu/pubs/npr/vol14/141toc.htm>

[181] p. 107, Kenton J. Moody, Ian D. Hutcheon, Patrick M. Grant, *"Nuclear Forensic Analysis"* (London: Taylor & Francis, 2005)

[182] p. 113, Kenton J. Moody, Ian D. Hutcheon, Patrick M. Grant, *"Nuclear Forensic Analysis"* (London: Taylor & Francis, 2005)

[183] p. 107, Kenton J. Moody, Ian D. Hutcheon, Patrick M. Grant, *"Nuclear Forensic Analysis"* (London: Taylor & Francis, 2005)
[184] p. 102-107 and 113, Kenton J. Moody, Ian D. Hutcheon, Patrick M. Grant, *"Nuclear Forensic Analysis"* (London: Taylor & Francis, 2005)
[185] p. 50-51, Miller
[186] p. 50-51, Michael Miller *"Nuclear Attribution As Deterrence,"* (Nonproliferation Review, Vol 14, No 1, March 2007) <http://cns.miis.edu/pubs/npr/vol14/141toc.htm>
[187] Michael May, Jay Davis and Raymond Jeanloz, *"Preparing for the Worst"* (Nature, Vol 443, 26 October 2006) ; p. 50-51, Miller
[188]Debra Decker, *"Who Pays When the Bomb Goes Off?"* (Foreign Policy, December, 2006) <http://www.foreignpolicy.com/story/cms.php?story_id=3653> ; Oxford Analytica, *"U.S. Asks Countries For Nuclear Fingerprints"* (Forbes, June 6, 2007) <http://www.forbes.com/business/2007/06/05/nuclear-russia-weapons-biz-cx_0606oxford.html>
[189] Jon Fox, "D.P.R.K. Test Spurs U.S. to Discuss Nuclear Attribution" (Global Security Newswire, October 20, 2006) <http://www.nti.org/d_newswire/issues/2006_10_20.html#C3C7D926>
[190] "Carter, speaking here yesterday, said the U.S. catalogue of nuclear fingerprints is incomplete. 'That is, there would be circumstances where a bomb would go off and we couldn't pin down where it came from,' he said…" See Jon Fox, "D.P.R.K. Test Spurs U.S. to Discuss Nuclear Attribution" (Global Security Newswire, October 20, 2006) <http://www.nti.org/d_newswire/issues/2006_10_20.html#C3C7D926>; D E. SANGER and THOM SHANKER, *"U.S. Debates Deterrence for Nuclear Terrorism"* (New York Times, May 8, 2007) <http://www.nytimes.com/2007/05/08/washington/08nuke.html?hp>
[191] p. 46-49, Michael Miller *"Nuclear Attribution As Deterrence,"* (Nonproliferation Review, Vol 14, No 1, March 2007) <http://cns.miis.edu/pubs/npr/vol14/141toc.htm>
[192] "in the case of Iran, suppose that Iranian Revolutionary Guard Corps officials got control of some nuclear assets and if there was a continuing power struggle in Tehran -- led to them actually, physically getting control of this and then using it for purposes of selling to an overseas group or a foreign group. And the Iranian Revolutionary Guard Corps, you know, has very extensive contacts with Hamas and Hezbollah and others; they have a very strong commercial inclination, they control large areas of commercial activity in Iran; they have a record of corruption and then we know that there are these power struggles. So that all contributes to a scenario in which you could envision them engaged in some kind of a sale effort." in Mark Fitzpatrick, *"Nuclear Black Markets: Pakistan, A.Q. Khan and the Rise Of Proliferation Networks"* (Federal News Service, May 9, 2007) <http://www.cfr.org/publication/13308/nuclear_black_markets.html>
[193]See "An Iranian bomb that took out a U.S. city might not be traceable to its source if it had first been put in the hands of terrorists smuggling it into the country the same way large quantities of illegal drugs are routinely brought in." JAY AMBROSE, *"Abizaid's risky proposition"* (Scripps Howard News Service, September 18, 2007) <http://www.scrippsnews.com/node/26914>
[194] Michael May, Jay Davis and Raymond Jeanloz, "Preparing for the Worst" (Nature, Vol 443, 26 October 2006)
[195] p. 50-51, Michael Miller *"Nuclear Attribution As Deterrence,"* (Nonproliferation Review, Vol 14, No 1, March 2007) <http://cns.miis.edu/pubs/npr/vol14/141toc.htm>
[196] About the origins of the US long-range nuclear test detection efforts, see p. 77-87, Jeffery T. Richelson, *"Spying on the Bomb"*, In particular, there appears to be an historical parallel in the efforts and debates to develop nuclear detection and long-range nuclear test detection, see "Long Range Detection Committee" on p. 80-81. Except that a test with non-state actors would likely be on a real target, not in a desert or on an island. As of 1957, a National Intelligence Estimate concluded that the US had "excellent capability (90-100%) for detecting airbursts of 10 kilotons or greater, a good capability (60-90%) with respect to 5-10 kiloton airbursts, and a fair one (30-60%) for 3-5 kiloton bursts. There was a poor capability (0-30%) for airbursts less than 3 kilotons." See p. 131, T. Richelson, *"Spying on the Bomb"* (Norton, New York, 2006)
[197] p. 51-61, Jeffery T. Richelson, *"Spying on the Bomb"* (Norton, New York, 2006)
[198] p. 498, Richelson
[199] p. 259-261, Richelson
[200] p. 447-469, Richelson
[201] Dan Pinkston, "*The Status of North Korea's Nuclear Inspections*" (Center for Nonproliferation Studies, February 26, 2002) <http://cns.miis.edu/pubs/week/020226.htm> ; David E. Sanger, "NORTH KOREA

ASSEMBLY BACKS ATOM PACT" (New York Times, April 10, 1992) <http://www.fas.org/irp/news/1992/18511682-18516144.htm>

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[203] p. 367, Richelson

[204] p. 360-367, Richelson

[205] p. 49, Lawrence H. Silberman and Charles S. Robb, *"The Commission on the Intelligence Capabilities of the United States Regarding Weapons of Mass Destruction"* (Report to the President of the United States, March 31, 2005) <http://www.wmd.gov/report/wmd_report.pdf>

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[208] LAWRENCE SCOTT SHEETS and WILLIAM J. BROAD, *"Smuggler's Plot Highlights Fear Over Uranium"* (New York Times, January 25, 2007) <http://www.nytimes.com/2007/01/25/world/europe/25nuke.html> ; Elena Sokova, William C. Potter, and Cristina Chuen, "*Recent Weapons Grade Uranium Smuggling Case: Nuclear Materials are Still on the Loose"* (Center for Nonproliferation Studies, January 26, 2007) <http://cns.miis.edu/pubs/week/070126.htm> ; Justin Reed, *"HEU Smuggling Sting Raises Security Concerns"* (Arms Control Today, March 2007) <http://www.armscontrol.org/act/2007_03/HEU.asp>

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