A Mathematical Model of the Risk of Nuclear Terrorism

By
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This article presents a mathematical model for measuring the global risk of nuclear theft and terrorism. One plausible set of parameter values used in a numerical example suggests a 29 percent probability of a nuclear terrorist attack in the next decade. The expected loss over that period would be $1.17 trillion (undiscounted), or more than $100 billion per year. Historical and other evidence is used to explore the likely values of several of the key parameters, and policy options for reducing the risk are briefly assessed. The uncertainties in estimating the risk of nuclear terrorism are very large, but even a risk dramatically smaller than that estimated in the numerical example used in this article would justify a broad range of actions to reduce the threat.

Keywords: nuclear terrorism; mathematical model; nuclear theft; black market; calculating risk

The two most important policy questions about nuclear terrorism are (1) How big is the risk? and (2) What policy measures would be most effective in reducing that risk? The answers to these questions cannot be calculated reliably as the factors that affect the risk of nuclear terrorism are simply too uncertain and volatile. Informed observers, for example, have made estimates of the probability of a nuclear terrorist attack on a major city in the next decade that range from 1 to 50 percent (Allison 2004; Kristof 2004; Hegland and Webb 2005).

The use of a mathematical model cannot eliminate these uncertainties, but it can make explicit the assumptions about the key factors affecting the risk and provide a tool for assessing the effectiveness of alternative policies. In this article, I propose a simple mathematical model for estimating the risk of nuclear terrorism. After supplying a numerical example, I explore

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several of the model's key parameters, with an emphasis on the four means terrorists might use to acquire a nuclear bomb or materials: outsider theft, insider theft, the black market, and provision by a state. The model strongly suggests that the most promising policy options are based on a forward defense, combining strengthened counterterrorism policies that reduce the number of groups contemplating nuclear violence and their likely effectiveness with an urgent global campaign to secure or remove the nuclear stockpiles from the world's most vulnerable sites.

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Only a limited number of past efforts have explicitly modeled the global risk of nuclear theft and terrorism. Some previous mathematical models of nuclear terrorist risks assumed that each facility with potential bomb material had a fixed probability of theft, so that the total probability increased linearly with deployment of more facilities (Avedon 1997), or that the risk posed by each category of nuclear material was proportional to the quantity of material in that category (Zebrowski 1984). The model presented here is based on the more realistic assumption that a limited number of nuclear terrorist groups undertake a limited number of theft attempts. This means that the relationship between the risk and the quantity of facilities or materials is much less direct than in previous models. Any model is based on a particular intellectual frame, and the uncertainties introduced by different model structures are typically far larger than the uncertainties in the values of the parameters (Linkov and Burmistrov 2003). This article, however, makes no attempt to assess these uncertainties.

Introducing the Model

At any given time, there will be N_n terrorist groups that have decided to attempt nuclear violence and that are capable and sophisticated enough to have some nonzero probability of success.

Each year, each particular group j of these N_n groups will have some probability $P_{a(j)}$ of launching a significant attempt to acquire a nuclear weapon or the nuclear materials essential to making one. $P_{a(j)}$ is quite likely to be different for different groups.

The expected number of acquisition attempts per year, A, can be found by summing the probabilities of deciding on such an attempt by all the groups that might do so.[1]

$$A = \sum_{j=1}^{N_n} P_{a(j)}.$$

These acquisition attempts will have probability $P_{o(j)}$ of being based on carrying out or instigating an outsider theft attempt at a facility or transportation leg, probability $P_{i(j)}$ of being based on instigating a theft attempt by insiders with authorized access to the facility or transportation leg, probability $P_{b(j)}$ of being based on attempting to purchase such items from others who have stolen them on some kind of nuclear black market, and probability $P_{n(j)}$ of being based on deliberate provision of such items by a nation-state in possession of them. (Acquisition attempts are divided into these four categories because the policy prescriptions for reducing the probability of success for each of type of acquisition attempt are different.[2]) In this model, these are the only possible paths for an acquisition attempt.

Each acquisition attempt k will have some probability of being successful—$P_{os(j,k)}$, $P_{is(j,k)}$, $P_{bs(j,k)}$, $P_{ns(j,k)}$. These probabilities, too, are likely to vary from one group to the next and from one acquisition attempt by that group to the next.

In the event that an acquisition attempt is successful, there will be some probability, $P_{w(j,k)}$, that the group that acquired the items will be able to transform them into a workable nuclear explosive capability that would in fact detonate (including transporting them to the location where the group would work on this transformation, if necessary). Once the group has a usable nuclear capability, there will be some probability, $P_{d(j,k)}$, that they will decide to, and be able to, deliver the bomb to its intended target and detonate it.

The probability $P_{s(k)}$ that any given acquisition attempt k will be successful, and will ultimately lead to a terrorist nuclear attack, is given by summing the probabilities of occurrence and success for each of the types of acquisition attempts and multiplying the result by the probabilities of success in transforming the stolen items into a usable nuclear capability and delivering that capability to a target:

$$P_{s(k)} = (P_{o(j)} \times P_{os(j,k)} + P_{i(j)} \times P_{is(j,k)} + P_{b(j)} \times P_{bs(j,k)} + P_{n(j)} \times P_{ns(j,k)})(P_{w(j,k)} \times P_{d(j,k)}).$$

Hence, the overall probability, P_c, of a terrorist nuclear catastrophe somewhere in the world in any given year is given by

$$\begin{aligned} P_c &= 1 - \prod_{k=1}^{A} (1 - P_{s(k)}) \\ &= 1 - \prod_{k=1}^{\sum_{j=1}^{N_n} P_{a(j)}} (1 - (P_{o(j)} \times P_{os(j,k)} + P_{i(j)} \times P_{is(j,k)} + P_{b(j)} \times P_{bs(j,k)} + P_{n(j)} \times P_{ns(j,k)})(P_{w(j,k)} \times P_{d(j,k)})). \end{aligned}$$

This probability can be converted into the risk of nuclear terrorism, R_c, by multiplying it by the consequences of the event, C_c

$$R_c = P_c \times C_c.$$

Now the problem boils down to considering the factors that affect the various terms in the equations for P_c and R_c. Different policy prescriptions for dealing with the danger of nuclear terrorism amount, in effect, to different perceptions concerning which of the factors in these equations offer the most promise for risk reduction resulting from government policies.

A Numerical Example

Suppose, as one plausible estimate, that the factors in the equations for P_c and R_c have the following numerical values:

Number of plausible nuclear terrorist groups, $N_n = 2$
Yearly probability of an acquisition attempt by a particular group, $P_{a(j)} = 0.3$
Probability of choosing an acquisition attempt based on outsider theft, $P_{o(j)} = 0.2$
Probability of choosing an acquisition attempt based on insider theft, $P_{i(j)} = 0.3$
Probability of choosing to attempt to purchase black market material, $P_{b(j)} = 0.3$
Probability of choosing to attempt to convince a state to provide material, $P_{s(j)} = 0.2$
Probability that an outsider theft attempt will succeed, $P_{os(j,k)} = 0.2$
Probability that an insider theft attempt will succeed, $P_{is(j,k)} = 0.3$
Probability that a black market acquisition attempt will succeed, $P_{bs(j,k)} = 0.2$
Probability that an acquisition attempt from a state will succeed, $P_{ss(j,k)} = 0.05$
Probability of being able to convert acquired items to nuclear capability, $P_{w(j,k)} = 0.4$
Probability of delivering and detonating bomb once acquired, $P_{d(j,k)} = 0.7$
Consequence of terrorist nuclear attack, C_c = \$4 trillion

In this example, the number of plausible nuclear terrorist groups in the world is small, but greater than zero. For simplicity, assume for the sake of this example that the various probabilities are the same for all groups in the set N_n and for all acquisition attempts of a given type by those groups.

The consequence figure is intended to include both the immediate destruction caused by a terrorist nuclear blast (Bunn, Wier, and Holdren 2003, 15-19) and at least a portion of the knock-on economic and political effects in the target country and worldwide. UN Secretary-General Kofi Annan (2005) has estimated that the ripple effects of such an event would push "tens of millions of people into dire poverty," creating "a second death toll throughout the developing world." After such an attack, the world as we know it would be changed profoundly. It is difficult to monetize all of the potential consequences, but it is clear that their magnitude would be large.

With these values, one would expect a significant acquisition attempt roughly once every other year:

$$A = \sum_{j=1}^{2} 0.3 = 0.6.$$

The probability that such an acquisition attempt would be successful, and would lead to the detonation of a terrorist nuclear bomb somewhere in the world, would be in the range of 5 percent.

$$P_{s(k)} = (0.2 \times 0.2 + 0.3 \times 0.3 + 0.3 \times 0.2 + 0.2 \times 0.5)(0.4 \times 0.7) = 0.056.$$

The yearly probability of nuclear terrorism would be just over 3 percent.

$$P_c = 1 - \prod_{k=1}^{0.6}(1 - .056) = 1 - (.056)^{0.6} = 0.034.$$

The probability of nuclear terrorism over a ten-year period, $P_{c(10)}$, would be just under 30 percent.

$$P_{c(10)} = 1 - (1 - 0.034)^{10} = 0.29.$$

The overall risk, or expected cost, of nuclear terrorism per decade would be \$1.17 trillion (without discounting),[3] or well over \$100 billion per year.

The expected losses, $E(L)$, resulting from a successful theft of a nuclear weapon or enough nuclear material for a bomb (which can also be thought of as the expected value of preventing such an event) would be more than \$1 trillion, in this example, given the significant chance that such a theft would lead to actual nuclear terrorism.

$$E(L) = P_{w(j,k)} \times P_{d(j,k)} \times C_c = 0.4 \times 0.7 \times \$4 \times 10^{12} = \$1.12 \times 10^{12}.$$

Assumptions similar to those proposed in this example would support estimates of a 30 to 50 percent probability of nuclear terrorism over the next decade. (By chance, the 29 percent over ten years estimate in this numerical example is identical to the average estimate of the probability of a nuclear attack over the next ten years in a poll of selected international security experts by Senator Richard Lugar in 2005.) They would also support arguments that if policy options are available that could significantly reduce this risk, it would be worth spending large amounts of money and political capital to implement those policies (Weinzierl 2004). If the probability of success in turning the stolen items into a usable nuclear capability, and the probability of success for each of the types of acquisition attempt were both cut in half, then the yearly probability of nuclear terrorism would be 0.8 percent, and the ten-year probability would be 8 percent.[4] A probability of 1 percent over ten years, advocated by some analysts, would require reducing these factors even further, or reducing the yearly probability of an acquisition attempt (because the groups judged the prospects of success to be so poor that they focused their efforts in more promising areas). Even with only a 1 percent probability over ten years, the expected cost per decade would be $40 billion (without discounting), or $4 billion per year. Readers who may disagree with some of the numbers used in this example are free to use the model with numbers of their own, to develop and analyze their own risk assessments.

Assessing Some of the Factors

The number of plausible nuclear terrorist groups

The number of terrorist groups interested in getting and using nuclear weapons—and with enough capability to have some chance of success in doing so—is likely to be small. A reasonably strong case can be made that this number was zero from the advent of the nuclear era to the late 1980s (when both Aum Shinrikyo and al Qaeda began to take shape). Today, it appears that N_n is in the range of one to two. This category may include al Qaeda (with some of its derivatives),[5] and possibly also some subsets of Chechen terrorists (Bunn, Wier, and Friedman 2005).

[A] strong case can be made that under all but a few circumstances, states are extremely unlikely to transfer a nuclear weapon or weapons-usable nuclear materials to a terrorist group deliberately.

N_n is presumably affected by at least four factors: (1) the motivation for large-scale terrorism; (2) the characteristics and evolution of particular terrorist leaders and groups; (3) the effectiveness of counterterrorist efforts, particularly those that identify and disrupt terrorist groups with nuclear ambitions; and (4) potential nuclear terrorists' perceptions of the utility of nuclear explosives compared to other weapons, including the relative difficulty of their acquisition and use. Some policies for reducing N_n would attempt to address the root causes of terrorism or improve the targeting and effectiveness of counterterrorist efforts. Other policies would focus on deterring terrorists from seeking nuclear weapons, either by threatening the destruction of the offending group and its sponsors or by emphasizing the difficulty of acquiring nuclear weapons.

To assess the effectiveness of such policies, one could introduce factors reflecting the fraction of terrorist groups who were no longer in the set N_n because of their implementation. That approach, however, might understate the potential effectiveness of these policy approaches by focusing only on their chance of removing groups from the N_n set entirely, without taking into account their possible effect on reducing the effectiveness of the groups that remain. Successfully addressing many of the root causes of terrorism, for example, might still leave Osama bin Laden seeking a nuclear capability, but with much less chance of success because of greater difficulty in recruiting the relevant people and raising the necessary funds. Similarly, counterterrorist efforts might substantially reduce the probability that such groups would be able to mount a successful effort to gain and use a nuclear explosive capability without being interrupted in the process. This potential effect could be taken into account by introducing factors representing a policy's effect on the terrorists' probability of success.

If, for example, one uses the values in the numerical example above, and considers a counterterrorism policy that removes 20 percent of the groups from N_n and reduces the remaining groups' probability of success by 40 percent, then

$$N_n = 1 \times 0.8 = 1.6$$

$$A = \sum_{j=1}^{1.6} 0.3 = 0.48$$

$$P_{s(k)} = 0.034 \times 0.6 = .02$$

$$P_c = 1 - (1 - .02)^{0.48} = .0098$$

$$P_{c(10)} = 1 - (1 - .00472)^{10} = .094$$

In other words, although the hypothetical increased counterterrorist effort in this example was only modestly successful, the effort would reduce the ten-year probability of nuclear terrorism threefold, from 29 to 9.4 percent.

The annual probability of an acquisition attempt

The probability that a group seeking nuclear weapons will launch a significant acquisition effort in any given year is difficult to assess. The history of known acquisition attempts is discussed in more detail below; but it is clear that the known number of cases is small, in the range of three to six over the past fifteen years. If the known cases represented the total number of actual cases, and one concluded that for most of that period $N_n = 2$, then a reasonable estimate of $P_{a(j)}$ for the nuclear terrorist groups observed in recent times would be 10 to 20 percent per year. If, on the other hand, a substantial number of acquisition attempts took place that were never detected, then the figure might be higher, in the range of 30 to 40 percent per year, as in the numerical example above.

$P_{a(j)}$ is presumably influenced substantially by a group's assessment of the probability of success. Many groups are likely to behave somewhat opportunistically, launching an acquisition attempt when they perceive a favorable chance of obtaining a nuclear weapon or nuclear material—acting in an ongoing strategic game with governments attempting to make the most devastating types of attacks more difficult (Woo 2002). Hence, policy measures to reduce the chance of a successful acquisition—and to reduce terrorists' perception of that chance—would presumably reduce $P_{a(j)}$ for most groups.

The probabilities of outsider and insider theft attempts

Terrorists will presumably choose the method of nuclear acquisition that they deem most likely to work. The probability that a particular group will undertake an acquisition attempt based on an outsider or insider theft, $P_{o(j)}$ and $P_{i(j)}$, therefore, will be closely related to their perception of $P_{os(j,k)}$ and $P_{is(j,k)}$—the probability that outsider and insider theft attempts would succeed.

The historical record shows no confirmed incidents of terrorist outsider attacks on nuclear facilities or transports that were clearly intended for the purpose of stealing nuclear weapons or materials.

The historical record shows no confirmed incidents of terrorist outsider attacks on nuclear facilities or transports that were clearly intended for the purpose of stealing nuclear weapons or materials. This suggests that $P_{o(j)}$ is small. This is something of a puzzle, as some nuclear facilities around the world—particularly research reactors fueled with highly enriched uranium (HEU), a potential nuclear bomb material—have no more than a night watchman and a chain-link fence for their security (Bunn 2002). Such arrangements could readily be defeated by attack capabilities terrorists have demonstrated in other contexts, suggesting that for some facilities, $P_{os(j,k)}$ may be quite high.[6]

Over the years, however, there have been a number of incidents—from terrorists attacking a U.S. nuclear weapons base in Germany in 1977 to terrorist teams carrying out reconnaissance at Russian nuclear warhead storage facilities in 2001—that collectively suggest that $P_{o(j)}$ is not zero.[7] There have also been documented cases of outsider thefts of nuclear material not instigated by terrorists—though in the known cases, these outsiders had help from insiders, a situation that would be classified as an insider theft in the simple model used here.[8] Of course, overt frontal assaults are not the only options available for outsider theft attempts; covert outsider thefts (such as tunneling into a vault from outside, as has been done in a number of bank robberies in recent years), or thefts based on deception, are also possibilities that must be anticipated by policy makers.

As with $P_{o(j)}$, $P_{i(j)}$ is presumably small. While there are a number of confirmed insider thefts in the historical record, none of the confirmed cases of successful theft appear to have been instigated by terrorists. A case was revealed in a Russian criminal trial in 2003 in which a Russian businessman was attempting to instigate an insider theft by offering $750,000 for stolen plutonium for sale to a foreign client; this may have been terrorist linked (Anonymous 2003a, 2003b, 2003c).

The risk of outsider or insider theft is dominated by those facilities or transport legs where nuclear weapons or weapons-usable nuclear material exist that have the weakest security—because terrorists and thieves are more likely to choose those points of attack and more likely to succeed if they do. The probability of successful outsider theft depends on the security levels at the various sites or transport legs and the levels of capability the terrorists could bring to bear to steal what they wanted from them. Terrorists are likely to face substantial uncertainties on both points—but the information available to defenders about what capabilities terrorists might have is far more limited. No one really knows how clever a plan, with how many attackers, what weapons, or what capabilities, terrorists might be able to bring to bear to accomplish a nuclear theft.

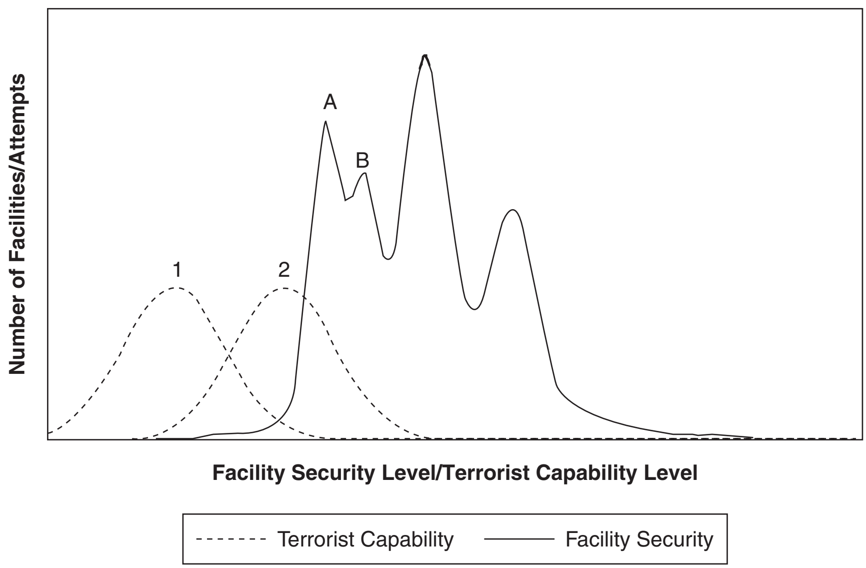
For an insider theft attempt, terrorists would also have to estimate their chances of insinuating one or more operatives into the staff or convincing one or more of the existing staff to take part (perhaps through bribery, blackmail, or ideological persuasion).

Until a terrorist group has an insider at a particular facility, crucial information regarding security measures focused on insiders is likely to be quite limited, as these measures are more difficult to observe from outside the facility.

Nuclear security levels in any particular country are likely to cluster around the measures that each country's rules require. Since there are no binding global rules, security levels vary widely from one country to the next, making the global distribution of nuclear security a lumpy sum of national distributions (Figure 1).[9] A given terrorist group would have an estimate of the capability it could bring to bear to execute an outside theft attempt, with some uncertainty, such as the distributions labeled "1" and "2" in Figure 1. Only where the distributions of capability and facility security overlap—that is, where there was a substantial probability that the group's capability could overcome a facility's security—would the chance of a successful outsider theft be significant.

If all countries faced an identical and fixed terrorist threat—for example, the distribution labeled "2" in Figure 1—then the probability of successful outsider theft could be reduced dramatically by upgrading security or removing the nuclear material from the facilities and transport legs in the countries labeled "A" and "B." Since current cooperative nuclear security programs are focused on

FIGURE 1
LUMPY GLOBAL DISTRIBUTION OF FACILITY SECURITY LEVEL AND TERRORIST CAPABILITY



providing integrated security upgrade suites designed to address both threats, the probability of insider theft might also be substantially reduced at the same time.

If, in the numerical example above, security upgrades managed to cut the probabilities of success for outsider and insider theft in half, and were also successful in reducing the chance of black market purchase by 40 percent (because such upgrades would reduce the chance of future insider and outsider thefts supplying a nuclear black market but they would not address already-stolen material), and these reductions led to a 20 percent decline in the annual probability of a serious acquisition by each group, then the previous 29 percent ten-year probability of nuclear terrorism would be cut by more than half, to 14 percent. If Figure 1 represents anything close to reality, modest investments in upgrading a few of the most vulnerable facilities worldwide may well reduce $P_{os(j,k)}$, $P_{is(j,k)}$, and $P_{bs(j,k)}$ by even larger factors. The possibility of dramatic risk reductions from modest investments in upgrading security at, or removing material from, the world's most vulnerable facilities has provided the rationale for cooperative programs to upgrade nuclear security in Russia and elsewhere, for proposals for a "global cleanout" of all nuclear materials from the most vulnerable facilities worldwide, and for calls for upgrading nuclear security worldwide to an effective global standard (Bunn and Wier 2005; Bleek 2004; Allison 2004).

Two points that might reduce the effectiveness of modest security investments should be kept in mind, however. First, while terrorists have demonstrated some degree of global reach, there is little doubt that their capability to operate in some countries is higher than in others. Hence, more substantial investments in nuclear security are likely to be necessary in Pakistan, for example, than they would be if comparable facilities were located in Canada. (In Figure 1, one might argue that Canada faces a threat distribution like the one labeled "1," while Pakistan faces one like the distribution labeled "2," or worse yet, a lumpy and unknown distribution with some outliers of capability going well beyond distribution "2.")

Second, intelligent and adaptive adversaries may react to security upgrades not by giving up but by increasing their capabilities—recruiting more people, buying better weapons, and developing more sophisticated tactics. If nuclear facilities need only defend against a handful of outsiders with limited armament, or one insider, relatively simple and low-cost security upgrades will be sufficient. If, on the other hand, nuclear facilities must withstand large teams of well-trained and well-armed militants, and the risk of large insider conspiracies is high, then the security measures needed to reduce the risk of theft to an acceptable level would be expensive and complex.[10] There are presumably some constraints on terror groups' ability to increase their capabilities, but no one knows for sure where the upper bound lies.

A site with enough nuclear material for a thousand bombs poses little more risk than a site with enough for ten bombs; therefore, total quantity of nuclear material is not a good indicator of theft risks. (A large annual throughput of nuclear material at a processing site, however, could be important, making it easier for insiders to squirrel away small amounts at a time without detection.) Increasing the number of facilities and transport legs with nuclear weapons or weapons-usable nuclear material would increase the chance that there will be one low enough on the tail of the security distribution for terrorists to be able to defeat it. Moreover, with a smaller number of facilities to defend, higher security can be achieved at lower cost. The number of personnel with the access needed to steal material or help others do so is also important, as the larger this group is, the greater are the chances of a bad apple among them.

The probabilities of black market acquisition attempts

Trying to buy nuclear weapons or materials from the nuclear black market appears to be an especially common choice for terrorist groups seeking nuclear capabilities. Both Aum Shinrikyo and al Qaeda have pursued this method of acquisition (Bunn, Wier, and Friedman 2005). Based on the historical record, therefore, $P_{b(j)}$ appears to be fairly large. The probability of success in acquiring nuclear weapons or materials on a nuclear black market, $P_{bs(j,k)}$, can be broken into two component probabilities: the probability of a potential seller coming into possession of such goods and the probability that the seller and the buyer will succeed in finding each other and making the transaction.

The principal source of black market nuclear material is likely to be nuclear theft, by outsiders or insiders not directly connected to terrorist groups.[11] Numerous cases of theft of weapons-usable nuclear material, apparently with the intention of selling the stolen nuclear material on the black market, have occurred. The International Atomic Energy Agency (IAEA; 2005) has documented eighteen seizures of stolen HEU or separated plutonium confirmed by the states concerned. More incidents have occurred, but the states in question have not been willing to confirm them.

Improved nuclear security measures would reduce the probability of additional thefts of HEU and plutonium in the future. But undetected nuclear thefts that may have occurred already pose an additional challenge. None of the documented seizures to date are suspected to have involved nuclear material stolen long before. Nuclear workers in the former Soviet Union who may have stolen nuclear material a decade ago and squirreled it away for a rainy day are now making a living wage, suggesting that if they did not sell this material before, they may not now. On the other hand, if improved security measures make it more difficult to steal nuclear material, already-stolen material could become more valuable. Overall, these factors suggest that the fraction of the black market problem arising from already stolen nuclear material is small—but it is probably not insignificant.

Would-be sellers obtaining a nuclear weapon or the materials to make one is only the first step. They would then have to make contact, and succeed in closing a transaction, with buyers from a terrorist group—a task that is not likely to be easy. None of the known cases involving stolen HEU or plutonium appear to have involved a real buyer or come close to a successful transaction. This may be the product of selection bias; it could be that competent thieves connected to buyers are the ones who do not get caught and whose cases are therefore unknown. If selection bias only distorts the picture modestly, however, the known cases suggest that the problem of making the connection between potential buyers and sellers—with the risks each faces that the other may be a scam artist, killer, or government agent—is a major barrier on this path, and the chances of success in such a transaction are relatively low (Bunn and Wier 2004, 27). The 20 percent chance of successful black market acquisition may seem too high given the large number of past attempts to pawn off worthless items as nuclear bomb material. But the commercial availability of hand-held devices that can confirm the presence of HEU or separated plutonium in a container suggests that sophisticated buyers will become less susceptible to scams over time.

How could the probability of successful black market acquisition be further reduced? The measures for preventing outsider and insider theft already discussed apply in this scenario as well. Additional measures should be taken to make the barriers to successful transactions between buyers and sellers even higher than they already are. Intelligence and law enforcement agencies could run additional stings and scams, posing as either buyers or sellers of nuclear material, to catch participants in this market, collect intelligence on market participants, and increase the fears of real buyers and sellers that their interlocutors may be government agents. Well-publicized anonymous tip hotlines, rewards, and similar measures could encourage conspirators or those they try to sell to or buy from to report to the authorities. All potential source states and likely transit states should have units of their national police force trained and equipped to deal with nuclear smuggling cases, and other law enforcement personnel should be trained to call in those units as needed. Current efforts to establish radiation detection at key border crossings may also reduce the probability of a successful black market acquisition, forcing smugglers to pursue riskier routes (Wier 2002).

The probabilities of acquisition from nation-states

The last option for attempting to acquire a nuclear weapon or weapons-usable nuclear materials is from a state in possession of such items. President George W. Bush is among those who see this acquisition path as the dominant danger. "Rogue states," he has said, "are clearly the most likely sources of chemical and biological and nuclear weapons for terrorists" (Bush 2001). This belief determines the policy prescription: if the principal danger of terrorists acquiring weapons of mass destruction is that hostile states might provide them, then the key element of the solution is to take on those hostile states and make sure that they do not provide them. This is the idea that animates the preemptive doctrine laid out in the administration's 2002 National Security Strategy and that was fundamental to the rationale for going to war with Iraq.

It is certainly *not* correct, as is sometimes argued, that only terrorists with help from a state could possibly put together the capability to get and use a nuclear bomb (Bunn and Wier 2004, 25-26). Indeed, a strong case can be made that under all but a few circumstances, states are extremely unlikely to transfer a nuclear weapon or weapons-usable nuclear materials to a terrorist group deliberately. Such a decision would mean transferring the most awesome military power the state possesses to a group over which it has little control. If the terrorists actually used the transferred capability against the United States or one of its allies, there would be a substantial chance that the source of the weapon or material would be traced back to the country of origin. The resulting retaliation would be overwhelming, almost certainly removing the government that decided on such a transfer. Hence, prior to the U.S.-led invasion of Iraq, the U.S. intelligence community unanimously concluded that it was unlikely Baghdad would sponsor any type of unconventional attack on the United States except if "ongoing military operations risked the imminent demise of his regime" or if he intended to "extract revenge" for such an assault (Waas 2006).

This is why the probability of success for an attempt to acquire nuclear weapons or materials from a nation-state, $P_{ns(j,k)}$, was assumed to be quite low (5 percent) in the numerical example above. As there is no historical evidence of such an attempt, it may be that the 20 percent probability of terrorists choosing to pursue this route used in the numerical example above is too high—though the absence of publicly available confirmation of such incidents does not prove that they have not occurred.

Steps to reduce the probability of a nuclear transfer from a state to a terrorist group would include (1) convincing Pyongyang and Tehran, with a package of carrots and sticks, that it is their national interests to verifiably abandon their nuclear ambitions; (2) persuading all states that the United States could trace the origin of nuclear material used in a terrorist nuclear attack and would be very likely to launch a devastating retaliation against the state that provided such items; (3) ensuring that states in a position to make such transfers do not become sufficiently desperate to make nuclear transfers seem the last chance for regime survival or retaliation; and (4) improving border controls through efforts such as the Proliferation Security Initiative (PSI). But as discussed below, border controls are unlikely to have more than a modest effect on the risk of such transfers.

Beyond Acquisition

Once terrorists have acquired a nuclear weapon or the materials to make one, the policy options available to reduce the danger of nuclear terrorism become far more limited. The great advantage of policies focused on keeping nuclear weapons and materials locked down at their source is the certainty of location; rather than searching for a needle in a haystack, the nations in control of these items know where they are. But once a nuclear weapon or the nuclear material to make one has walked out the door, it could be anywhere, and the problems of finding and recovering it multiply a thousandfold.

Intelligence efforts focused on detecting the recruitment and activities involved in making a crude nuclear bomb should be expanded, but the operations needed to make a bomb could be small and difficult to detect (Bunn and Wier 2006 [this volume]). As one U.S. government study put it, "a small group of people," without any "access to the classified literature," using "only modest machine-shop facilities that could be contracted for without arousing suspicion," could potentially make a crude nuclear bomb, if they obtained the necessary nuclear material (U.S. Congress 1977, 140). Efforts to rebuild failed states, avoid future failed states, and help countries gain control over areas the CIA refers to as "stateless zones" could help limit terrorists' access to sanctuaries where they could work on a bomb program, but such a program would also have a significant chance of being carried out undetected in a machine shop in any country in the world.

Efforts to install nuclear detectors at key border crossings, to make it more difficult for terrorists to transport such items from wherever they acquire them to a safe location where they can work on them, should continue—but the nuclear materials for a bomb would easily fit in a briefcase, their radiation is weak and difficult to detect, and nuclear terrorists and smugglers are likely to pick routes that are not monitored by nuclear detection equipment. Attempting to protect the United States from nuclear terrorism by detecting and stopping nuclear contraband at the border is like a football team defending at its own goal line—but with that goal line stretched across thousands of kilometers, much of it unguarded wilderness, and with millions of people and vehicles legitimately crossing it every year (Allison 2004; Wier 2002).

Moreover, new efforts should be made to deter terrorists from using any mass destruction capabilities they acquire. We should make the case within the communities from which terrorists draw support that the use of nuclear weapons to murder innocents on a mass scale is morally illegitimate. The benefit of such policies, however, will always be difficult to assess.

Finally, some investments in preparing for the consequences of a terrorist nuclear attack are worth making, including (1) resilient arrangements to ensure continuity of government and of critical private business operations, (2) surge capacity for treating massive numbers of burn and radiation victims, and (3) better plans to shelter or evacuate people from the projected path of the radioactive fallout. But the irreducible consequences of an attack that could turn the heart of any major city into a modern Hiroshima—and which the terrorists could use to exert blackmail or spread panic by claiming to have a second or third bomb—are vast. Prevention must be the top priority.

Conclusion

The model presented here cannot, in itself, eliminate the huge uncertainties in estimating the risk of nuclear terrorism. But as this article has attempted to show, the use of such a model can break the problem into one of estimating a series of parameters for which (in many cases) at least some basis for judgment exists, focusing debate and highlighting the basis for disagreements. It also makes it possible to identify policy options to modify each of the parameters to reduce the risk and to explore quantitatively what the effect of such policy options might be.

The uncertainties in estimating the risk of nuclear terrorism are large. But the very uncertainty of the danger highlights what we do not know—including the possibility that a major nuclear theft could be in the planning stages at any time. There is, in short, no time to lose.

Notes

1. This assumes a maximum of one serious acquisition attempt per year per group, adequate for the purposes of this simple model. One easy way of relaxing this assumption would be to use a smaller unit of time, such as a month or a week, and adjust estimates of $P_{a(j)}$ accordingly.

2. In many cases, outsiders and insiders might work together—for example, an insider might tell outsiders about the details of the site's security arrangements and possibly disable some security measures to facilitate an outsider attack. In this simple model, such combined insider and outsider attacks are treated as one subset of insider theft because two of the most important differences between outsider and insider thefts—the need to convince at least one authorized insider to participate and the possible knowledge of the confidential details of the security system that an insider could bring—apply in such combined cases as they do in cases involving only insiders.

3. The effect of discounting over a ten-year period would be less than the uncertainty in the consequences estimate. Discounting would also require determining the appropriate approach for discounting catastrophic loss of life in future years, which is a matter of considerable debate.

4. Normally, one would differentiate an equation such as that presented here, or use a Monte Carlo simulation given particular probability distributions of the value of each parameter, to examine the sensitivity of each of the parameters. These are not especially useful approaches here, as the shapes of the

distributions for the parameter are entirely unknown, and the model is so simple that the probability of an acquisition attempt being successful and leading to nuclear terrorism is simply linear with slope one for each of the main parameters—the combined probability of success of the various types of acquisition attempts, the probability of being able to make a working bomb, and the probability of delivering and detonating the bomb. The number of terrorist groups and acquisition attempts enters the equation somewhat differently, and the outcome is somewhat less sensitive to changes in that parameter. Hence, rather than using differentiation or Monte Carlo simulation, in this article I simply use plausible shifts in the parameters as examples of the impacts of different changes.

5. Although the central al Qaeda organization has been heavily damaged since 9/11, it is a more plausible candidate for nuclear terrorism than the many small jihadi groups it has inspired. Nevertheless, given the relatively modest total resources that might be required to make a crude bomb if a terrorist group got the necessary nuclear material, nuclear terrorism by some jihadi group whose capabilities are not currently well known cannot be entirely ruled out. In this simple model, al Qaeda could be treated as one entity, or, perhaps more realistically, the central organization and some of the more capable jihadi groups might be treated separately; this would increase N_n, but since the chance of success of the more minor groups would be very small, it would not drastically increase the overall estimated risk.

6. Terrorists may have limited information about nuclear matters, including which sites have weapons-usable nuclear material and what their security arrangements are; they may believe (perhaps correctly) that nuclear theft by open frontal assault would lead to such an intense government response attempting to find and recover the stolen items that their chances of successfully turning them into a usable nuclear explosive capability would be substantially reduced; or they may have felt that they were not yet sufficiently prepared to make a bomb to pursue a theft option that would openly announce their intentions.

7. A detailed account of the 1977 incident, making the case that it was an attempt to steal nuclear weapons, can be found in Cockburn and Cockburn (1997). The base commander at the time, however, believes that it was merely an attack on the base, not an attempt to steal nuclear weapons. If theft had been the purpose, in his view, the terrorists would have brought a larger and more capable force for the job (interview with Maj. Gen. William Burns, U.S. Army, Ret., August 2002). For the 2001 incidents, see Anonymous (2001) and Koryashkin (2001). There have been a substantial number of other terrorist incidents involving nuclear facilities over the years—including one in which a group of armed terrorists overwhelmed the guards and took complete control of a nuclear facility under construction—but these other incidents do not appear to have been carried out with nuclear theft in mind. For a list of such incidents through the mid-1980s, see Kellen (1987).

8. For a detailed account of one remarkable case of this kind, in which the Russian military prosecutor concluded that "potatoes were guarded better" than the stolen nuclear material, see Bukharin and Potter (1995).

9. There are many reasons for these wide variations, based on differences in national culture, varying degrees of concern over the danger of nuclear theft, and the like. In particular, countries that do not believe nuclear terrorism poses a substantial threat to *their* security will have an incentive to underinvest in nuclear security; moreover, there is an "interdependent security" problem, in which a country's incentive to invest in nuclear security is reduced by its perception that much of the security threat emanates from the possibility of theft in other countries and would not be reduced by investing in nuclear security domestically (Kunreuther and Heal 2003).

10. Since defending against larger and more sophisticated threats is costly, there is a lively debate in several countries concerning what "design basis threat" (DBT) nuclear facilities with nuclear weapons or weapons-usable nuclear materials should be required to defend against. Incidents worldwide in which terrorists or criminals have demonstrated the ability to attack in large numbers, to use sophisticated weapons and planning, and to recruit or blackmail multiple insiders to participate in theft conspiracies suggest that the threats nuclear weapons and the materials needed to make them should be defended against are substantial (Bunn and Wier 2004, 14-15). Law enforcement and intelligence efforts that seek to ensure that especially large and sophisticated conspiracies would be detected before they could carry out their theft attempts are clearly complementary with nuclear security upgrades.

11. State decisions to provide nuclear weapons or the materials for them to terrorist groups are discussed separately below; state decisions to provide such items to black market middlemen, with no control over who they might then sell them to, seem so unlikely that they are not further considered here.

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