Terrorist Nuclear Weapon Construction: How Difficult?

Matthew Bunn and Anthony Wier

The ANNALS of the American Academy of Political and Social Science 2006; 607; 133
DOI: 10.1177/0002716206290260

Terrorist Nuclear Weapon Construction: How Difficult?

By
MATTHEW BUNN
and
ANTHONY WIER

The likelihood of a nuclear terrorist attack depends in part on the ability of terrorist groups to acquire, construct, and detonate a nuclear device. This article attempts to determine the difficulty of such an endeavor by examining the underlying physical facts about nuclear fission, nuclear materials, and nuclear weapons design. The facts bear out a simple conclusion: while the danger should not be exaggerated, a nuclear terrorist attack is potentially within the capabilities of a well-organized and sophisticated terrorist group. A nuclear attack might be one of the most difficult missions a terrorist group could hope to try, but if a highly capable group acquired a stolen nuclear bomb or enough nuclear material to make one, there can be few grounds for confidence that they would be unable to use it.

Keywords: nuclear weapons; terrorism; fission; nuclear materials; weapons design

Could terrorists actually make and detonate a nuclear bomb? Convincing the public and policy makers of the true danger of nuclear terrorism demands an answer, but only a terrorist nuclear catastrophe could provide proof that no critic could assail.

Unfortunately, as government studies have repeatedly concluded, the answer is yes: even without direct help from a state with nuclear weapons, a capable and well-organized terrorist group with access to enough weapons-usable nuclear material might well be able to make at least a crude nuclear bomb. At the same time, the danger should not be exaggerated: an attack by nonstate terrorists using an actual nuclear explosive—self-made or stolen—would clearly be among the most difficult types of attack to

Matthew Bunn is a senior research associate at the Project on Managing the Atom in the Belfer Center for Science and International Affairs at Harvard University's John F. Kennedy School of Government.

Anthony Wier is a research associate at the Project on Managing the Atom in the Belfer Center for Science and International Affairs at Harvard University's John F. Kennedy School of Government.

DOI: 10.1177/0002716206290260

carry out. Moreover, while only sketchy information is available about the nuclear efforts of al Qaeda and the Japanese terror cult Aum Shinrikyo—the two most capable and well-financed terrorist groups to pursue nuclear weapons so far—none of the glimpses of their efforts indicate that either group has yet put together the capabilities needed to make a nuclear bomb (Bunn, Wier, and Friedman 2005).

In setting the basic parameters of the nuclear threat the world faces, the laws of physics are both kind and cruel. Kind, in that the essential ingredients of nuclear weapons do not exist in noticeable quantities in nature and are very difficult to produce. Cruel, in that, while it is not easy to make a nuclear bomb, it is not as difficult as many believe, once those essential ingredients are in hand (Holdren and Bunn 2002; Serber 1992).[1] To understand why, one must consider some of the underlying physical facts about nuclear fission, nuclear materials, and nuclear weapons design.

Nuclear Fission and Nuclear Materials

All nuclear weapons rely on the process of nuclear fission.[2] In fission, a heavy atomic nucleus splits into two lighter nuclei plus two to four free neutrons, accompanied by the release of energy. Because each fission releases neutrons that could induce further fissions, if there is enough nuclear material present in an appropriate configuration, it is possible to create a chain reaction. The smallest amount of nuclear material required to sustain a chain reaction in that configuration is called a "critical mass." Adding even a small amount of nuclear material to the critical mass will create a situation in which each fission causes more than one additional fission, leading to the runaway chain reaction needed for a nuclear explosion. Such a system is said to be "supercritical." The critical mass decreases with the square of the density, so if the nuclear material can be crushed to twice its normal density, only a quarter as much material would be needed. By the same token, as the energy released in a nuclear explosion turns the nuclear material to an expanding gas, the nuclear reaction quickly shuts itself off. The key to making a nuclear bomb is getting enough nuclear material together fast enough so that a substantial amount of explosive energy is released before the bomb blows itself apart and the reaction stops.

Among the hundreds of nuclides found in nature and the thousands producible by technology, only a few are capable of sustaining such an explosive nuclear chain reaction.[3] Two isotopes of uranium have this property (uranium-233, or U-233; and U-235), as do all of the isotopes of plutonium (most importantly plutonium-239, or Pu-239; Pu-240; Pu-241; and Pu-242). A few isotopes of still heavier elements could also sustain an explosive nuclear chain reaction, but uranium and plutonium are the only known elements to have ever been used in a nuclear bomb.

U-235 is the only nuclear-explosive nuclide that occurs naturally in significant quantities. When natural uranium is mined, only 0.7 percent of it is U-235, while more than 99 percent is U-238, which cannot sustain an explosive chain reaction.

To make nuclear weapons material from natural uranium, the concentration of U-235 must be increased by separating it from the U-238, a process known as "enrichment." Because both of these are isotopes of the chemical element uranium, they have essentially identical chemical properties, and separating them is a technically demanding process; the details of efficient enrichment technologies remain tightly controlled. For fission explosives, nuclear-weapon designers prefer the efficiency provided by uranium enriched to contain more than 90 percent U-235, and uranium in this concentration range is called "weapon-grade." But this label is to some degree a misnomer, as nuclear weapons can readily be made with less enriched material; the bomb that incinerated the Japanese city of Hiroshima, for example, was made from uranium with an average enrichment of 80 percent (Anonymous 1998).

In international practice, all uranium with a concentration of U-235 of 20 percent or more is referred to as highly enriched uranium (HEU); since it is possible to make nuclear explosives from any of this material, all of it is subject to special safeguards measures (Glaser 2005).[4] Material with U-235 concentrations between 0.7 percent and 20 percent is referred to as low-enriched uranium (LEU). The radioactivity from uranium, whether HEU or LEU, is so weak that uranium metal is routinely handled by hand; smuggling of HEU is thus extremely difficult to detect (especially if the smugglers employ even a modest amount of shielding to hide the radiation).

The radioactivity from uranium, whether HEU [highly enriched uranium] or LEU [low-enriched uranium], is so weak that uranium metal is routinely handled by hand; smuggling of HEU is thus extremely difficult to detect.

Unlike uranium, plutonium is virtually nonexistent in nature. Plutonium is produced when U-238 absorbs neutrons in a nuclear reactor.[5] When plutonium is produced in a reactor, it is, by the nature of the process, intimately mixed with U-238 and fission products, and in that form it cannot be used to make a nuclear weapon. It must first be separated, or *reprocessed,* from the fission products and the uranium. The term *separated plutonium* is used when this has been accomplished to a degree such that the plutonium will support a nuclear explosion. Plutonium is more radioactive, easier to detect, and somewhat harder to handle than uranium; terrorists using plutonium to make a bomb might make use of crude "glove boxes"—made, for example, from rubber gloves and polyethylene sheeting—to avoid exposure to plutonium particles.

Although all plutonium isotopes can support a fast-fission chain reaction and nearly any combination of them is usable for making a nuclear weapon,[6] nuclear-weapon designers prefer to work with plutonium containing more than 90 percent Pu-239 (which is accordingly called "weapon-grade"). In a reactor used primarily for electricity generation, the fuel is left in the reactor long enough that substantial portions of the Pu-239 produced absorb additional neutrons, creating Pu-240, Pu-241, and Pu-242. Such "reactor-grade" plutonium might contain roughly 60 to 70 percent Pu-239.

Here, too, however, the phrases *weapon-grade* and *reactor-grade* are misnomers, as separated plutonium of any isotopic composition other than those with very large fractions of Pu-238 is "weapon-usable." Reactor-grade plutonium is less attractive for weapons use because it generates more neutrons (which can set off a chain reaction earlier than the bomb designers intended), heat, and radioactivity. All of these factors can be addressed, however, with different degrees of success at different levels of sophistication. At the lowest level of sophistication, any state or subnational group capable of making a crude bomb from weapon-grade plutonium would also be capable of making a crude bomb from reactor-grade plutonium, though the explosive yield would likely be much lower. If, for example, reactor-grade plutonium were used instead of weapon-grade plutonium in a first-generation, Nagasaki-type design, the device would have an ensured, reliable yield of nearly a kiloton (and therefore a radius of destruction roughly one-third that of the Hiroshima bomb); even if a stray neutron set off the chain reaction at the worst possible moment, more neutrons could not make the yield worse (Mark 1993).[7] At the other end of the sophistication spectrum, advanced nuclear weapon states can make weapons with reactor-grade plutonium having yield, reliability, weight, and other characteristics comparable to those made from weapon-grade plutonium (U.S. Department of Energy 1997, 38-39).

Plutonium separation is effected by chemical means, which is possible because plutonium displays different chemical behavior than the other elements with which it is mixed. Because the separation process can be chemical rather than based on isotopic masses, it is technically easier, in principle, than uranium enrichment. But the process is made greatly more difficult by the intense radiation emanating from the commingled fission products. This intense radioactivity makes it extremely difficult to fix problems with reprocessing plants as they arise (a problem that has led some commercial plants even in advanced nuclear states to close soon after they opened, such as the U.S. West Valley facility and the Windscale reprocessing facility in the United Kingdom).

In short, producing either HEU or plutonium is a technically daunting enterprise. It is extremely unlikely that a subnational terrorist group would be able to make its own nuclear bomb material. The U.S. Department of Defense (1998, II-V-60) has stated that "90 percent of the overall difficulty in making a nuclear weapon lies in the production of special nuclear material," noting that more than 90 percent of the Manhattan Project budget supported material production.

Given these underlying physical realities, it is virtually inconceivable that a terrorist group would be able to produce separated plutonium or HEU on its own. The terrorists' main path to the bomb is getting the essential ingredients of nuclear weapons (or a nuclear weapon itself) after they have already been produced by a state. A state could transfer nuclear weapons or materials to a terrorist group deliberately, but this is unlikely given the potential for retaliation if it were traced back to the program of origin. A more likely scenario is one in which states transfer materials or weapons inadvertently by failing to protect stockpiles adequately from theft (Bunn 2006 [this volume]).

Terrorists might attempt to steal such items themselves or to purchase them from others who have done so. Unfortunately, world stockpiles of separated plutonium and HEU now amount to more than twenty-three hundred tons (Albright and Kramer 2005)—enough for more than two hundred thousand nuclear bombs—and these materials exist in hundreds of buildings in more than forty countries, under security arrangements ranging from excellent to appalling (Bunn 2002). The International Atomic Energy Agency (IAEA; 2005) has documented eighteen cases of seizure of stolen plutonium or HEU that have been confirmed by the states concerned; the obvious question is how many more thefts have not been detected.

The form of material most useful for constructing a nuclear bomb is pure HEU or plutonium metal. A terrorist group relying on stolen nuclear material, however, might well find that what it acquires is in a different form. Nuclear material in oxide form (as is commonly used in the nuclear industry) can be used directly in nuclear explosives without conversion to metal, but much larger quantities are required. Alternatively, chemical processes for converting either plutonium oxide or uranium oxide to metal have been widely published and are not unduly complex. Nevertheless, such conversion would be an additional hurdle for terrorists to clear.

Another quite plausible form in which terrorists might acquire nuclear material is in the form of research reactor fuel containing HEU. The U.S. Department of Energy has compiled data indicating that 128 research reactors or associated facilities worldwide hold twenty kilograms or more of HEU (U.S. Congress 2004, 28). Unlike the massive fuel assemblies used in most power reactors (which usually contain only LEU), research reactor fuels are typically found in fuel elements that are small and easy to handle—often less than a meter long, several centimeters across, and weighing a few kilograms.

While many types of research reactor fuel exist (including, in some cases, weapon-grade HEU metal), a common fuel is a mixture of uranium and aluminum, with aluminum cladding. To separate the uranium from the aluminum, such fuel could be cut into pieces, dissolved in acid, and the uranium separated from the resulting solution by well-known processes. Converting the chemical forms of uranium that would be recovered by these means to metal would also involve straightforward processes, all of which are published in the open literature and require only modest commercially available equipment. Hence, while the need for such processing would require an additional set of expertise and equipment, it would probably not pose an insurmountable challenge to terrorist groups. It is worth noting that the chemistry involved in converting opium poppies to heroin—an industry with which al Qaeda reportedly has substantial connections—is probably roughly as complex as the chemistry required to separate uranium from research reactor fuel, and because of the toxicity of airborne heroin, primitive glove boxes of the kind that might be used to handle nuclear material are sometimes used in the illegal narcotics industry as well.

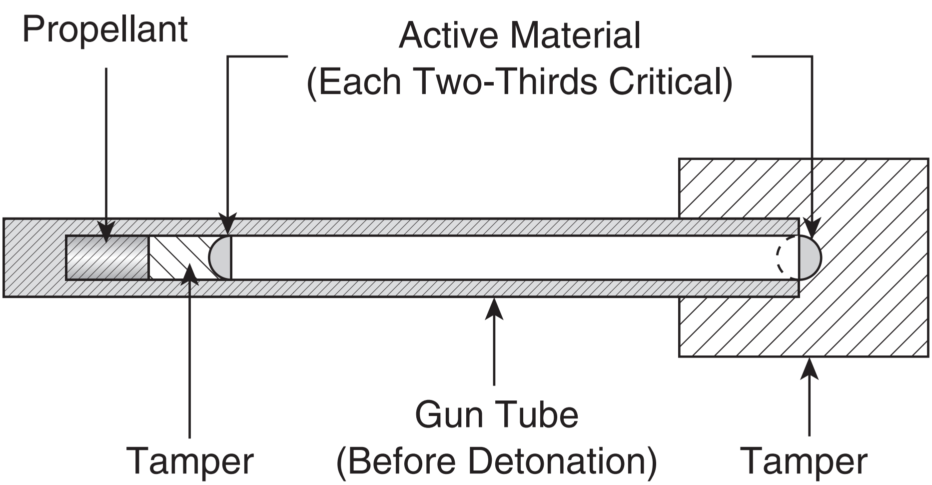
It is worth noting that the chemistry involved in converting opium poppies to heroin . . . is probably roughly as complex as the chemistry required to separate uranium from research reactor fuel.

Even "spent" research reactor fuel poses a serious proliferation threat; irradiated research reactor fuels usually remain very highly enriched, and most are not radioactive enough to prevent them from being stolen and processed for bomb material (Bunn and Wier 2004, 37). This stands in stark contrast to spent fuel from nuclear power reactors; while such fuel contains some plutonium, the massive, intensely radioactive fuel assemblies would be extremely difficult to steal and process to recover plutonium. Spent power reactor fuel poses more of a sabotage than theft threat.

Gun-Type and Implosion-Type Bombs

Those who discount the threat of nuclear terrorism often fail to grasp a crucial fact: the most difficult part of making a nuclear bomb is getting the nuclear material. As one leading critic argued, "Actually building [a crude nuclear weapon] is extremely difficult. A number of countries with vast resources and expertise, such as Iraq, have struggled unsuccessfully to produce one. It is difficult to imagine that a small terrorist group would find bomb-building any easier" (Kamp 1998). Similarly, the security chief of Russia's Federal Agency for Atomic Energy has publicly stated that "even having any nuclear material does not mean that an

FIGURE 1
GUN-TYPE BOMB, SHOWING HOW CONVENTIONAL EXPLOSIVES WOULD PROPEL ONE PIECE OF HIGHLY ENRICHED URANIUM (HEU) INTO ANOTHER TO SET OFF THE CHAIN REACTION



SOURCE: NATO.

explosive device can be made [by terrorists]. This is absolutely impossible" (Khinshteyn 2002).

Unfortunately, these arguments are simply incorrect. They conflate the difficulty of producing the nuclear material—the key step on which Iraq spent billions of dollars—with the difficulty of making a bomb once the material is in hand. These critiques also fail to make the crucial distinction between the technical and scientific challenge of building safe, reliable, and efficient nuclear weapons suitable for delivery by a missile or a fighter aircraft and the far simpler task of making a single crude, unsafe, and unreliable terrorist nuclear explosive that might be delivered by truck or boat.

The basic problem in making a fission bomb is getting a supercritical mass of material together fast enough so that the reaction does not blow the material apart before it can generate an appreciable explosive yield. Two basic types of bomb design accomplish this.

A *gun-type* weapon is the simplest type of nuclear bomb to build. The Hiroshima bomb, for example, was a cannon that fired a projectile of HEU into rings of HEU. The basic principles that need to be understood to make a gun-type bomb are widely available in the open literature (Serber 1992). Even when nothing of the kind had ever been done before, Hans Bethe, one of the technical leaders of the Manhattan Project, reported that the working principles of a gun-type bomb were "well taken care of" by one scientist and two of his graduate students during a summer study at Berkeley (Rhodes 1986).

The detonation of a gun-type bomb is very simple (see Figure 1). First, chemical explosives detonate, shooting one piece of HEU toward another. When the pieces are close enough together, they become critical; when they meet, they are substantially supercritical. (To get a good explosive yield, typical gun-type bombs include enough material to constitute two to three critical masses.) After neutrons begin the nuclear chain reaction, the reaction accelerates exponentially, so that each "generation" of fission splits more atoms and releases more energy than the one before. (A gun-type bomb might include a device known as a neutron generator to set off a shower of neutrons to begin the chain reaction at the right moment, but a terrorist device might dispense with this somewhat tricky part of the bomb design and rely on background neutrons to set off the chain reaction, as South Africa's weapons reportedly did.) The energy released heats the uranium and turns it into a gas, which begins to expand, reducing the density and shutting off the chain reaction. From beginning to end, the chain reaction takes only a few millionths of a second. The energy released in that time may be the equivalent of thousands of tons—or "kilotons" in nuclear lingo—of conventional explosives.[8] The small ball of nuclear material containing this energy reaches temperatures and pressures greater than those at the center of the sun, and the destructive effects are immense.

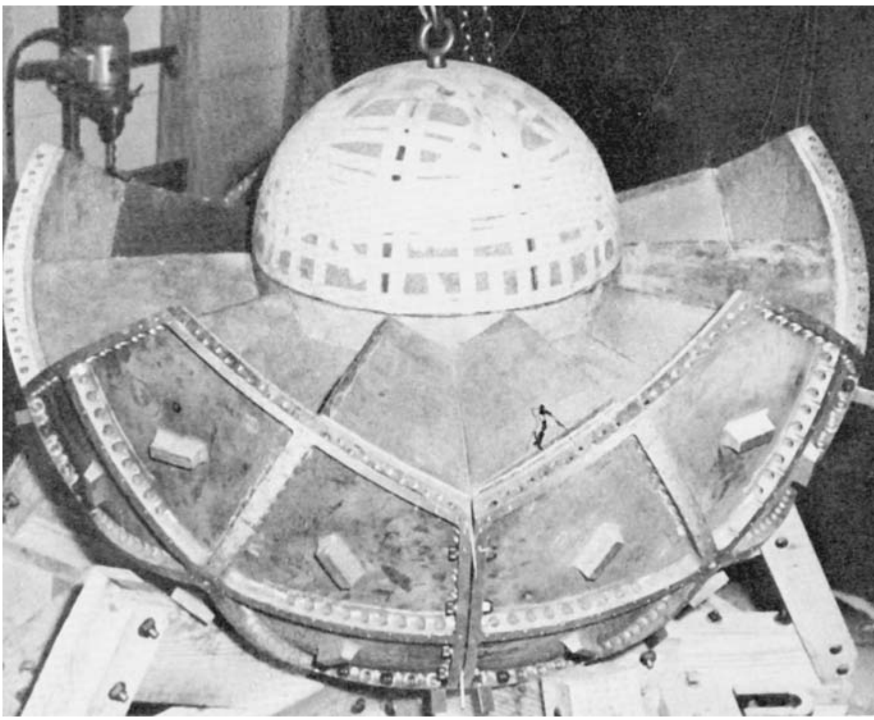
Simple and robust, a gun-type weapon allows the builder high confidence that it will perform properly without the trouble, expense, and exposure of a test explosion. Only a small fraction of the nuclear-explosive material used actually fissions in a gun-type weapon, so a substantial amount is required. The gun-type uranium bomb dropped by the United States on Hiroshima, for example, used just over sixty kilograms of HEU metal, of which less than 2 percent was fissioned (Sublette 2001). Because uranium metal is so dense, sixty kilograms of weapon-grade HEU metal could fit easily into a one-gallon container.

It is impossible to use plutonium to produce a substantial nuclear yield with a gun-type design because the rate of spontaneous fission is so high that the chain reaction will start as the two pieces in the gun get close to each other and blow the weapon apart before any significant yield results. Hence, if terrorists got plutonium, or if they got an amount of HEU too small for a gun-type weapon, they would have to attempt the more challenging task of designing and building an *implosion-type* weapon.

Implosion-type weapons, such as those used at Trinity and Nagasaki, use a set of shaped explosives arranged around a less-than-critical mass of HEU or plutonium to crush the atoms of material closer together. This increases the chance that whenever one of those atoms splits and releases neutrons, those neutrons will hit and split another atom—setting off a nuclear chain reaction (see Figure 2).

The amount of material needed for an implosion-type bomb is much less than is needed for a gun-type. Indeed, there is no fixed amount that is "enough for a bomb"—it depends on the speed of the explosives in the bomb and the sophistication

FIGURE 2
A MOCK-UP OF THE "FAT MAN" IMPLOSION DESIGN BEFORE THE TRINITY TEST, SHOWING THE EXPLOSIVE LENSES ARRANGED AROUND A SPHERICAL TAMPER/REFLECTOR SURROUNDING THE PLUTONIUM



SOURCE: Los Alamos National Laboratory.

of its design. (One unclassified reference suggests that weapons can be made with very small amounts of nuclear material [Cochran and Paine 1995].) The physical size of the nuclear material for an implosion bomb can be surprisingly small: six kilograms of weapon-grade plutonium, the amount used in the core of the implosion bomb dropped on Nagasaki, would fit in a soda can.[9] Roughly three times as much weapon-grade HEU would be needed for an implosion bomb using similar technology.

For a terrorist group, implosion bombs pose a significantly greater challenge than gun-type bombs. With an implosion bomb, precision timing in setting off the conventional explosives is crucial: if the explosives on one side go off much before the explosives on the other side, the nuclear material will be flattened rather than crushed to a smaller sphere, and there will be no nuclear explosion. For a group without prior experience, estimating how much compression their approach was likely to achieve would be a very difficult problem, possibly requiring a number of nonnuclear explosive tests. Such tests could increase the probability that such an effort would be detected (especially if they did not have a state sanctuary available as al Qaeda once did in Afghanistan). In addition, an implosion device using either weapon-grade plutonium or HEU requires a means for generating a burst of neutrons to start the chain reaction at the right moment, before the conventional explosion destroys the configuration that will sustain a nuclear chain reaction. Solving these technical challenges of implosion weapons was a major focus of the work at Los Alamos in the Manhattan Project (Rhodes 1986).

An implosion-type bomb does not, however, require as extreme a level of sophistication as is sometimes imagined. Today, with the knowledge that it can be done and substantial unclassified literature on the underlying physics, materials properties, and explosives (explosive lenses and other shaped explosive charges are now in wide use for conventional military and even commercial applications), the challenge, though still significant, would be less than during the Manhattan Project. Plastic explosives, for example, could readily be molded into the requisite shapes. And as long as a substantial degree of compression is achieved, the timing of the explosive detonations and the resulting shape of the inward-traveling shock wave do not have to be absolutely perfect.

There is, in short, a very real possibility that a technically sophisticated terrorist group, given sufficient effort, could make a crude implosion-type bomb.

A crude gun- or implosion-type weapon would be heavy—perhaps in the range of a ton—but not as heavy as even the first generation of military weapons, which required cases that enabled them to be dropped as gravity bombs (Mark et al. 1987). Such a bomb could easily be carried in a van or truck. Conceivably, the pieces of a bomb could even be put together at the target—as the bomb for the Trinity test was—in which case the nuclear-explosive materials and other components would be delivered separately. The number of possible pathways for smuggling a nuclear bomb or its ingredients into the United States is immense, and intelligent adversaries will choose whichever route remains undefended. All border controls can realistically hope to do is to make the easiest pathways more difficult, forcing terrorists to use riskier smuggling routes, increasing the chance of their interdiction.

There is, in short, a very real possibility that a technically sophisticated terrorist group, given sufficient effort, could make a crude implosion-type bomb—particularly if they got knowledgeable help, as al Qaeda has been attempting to do (Bunn, Wier, and Friedman 2005). While HEU poses a greater danger than plutonium, because of its potential use in a simpler gun-type bomb, it seems likely that a significant fraction of the small segment of terrorist groups that would have the technical sophistication and determination to both acquire substantial amounts of nuclear material and make a gun-type bomb would also be able to acquire the capabilities needed to make a crude implosion bomb—meaning that theft of separated plutonium would also pose a terrible danger.

Setting Off a Stolen Nuclear Weapon

A terrorist group that got hold of a stolen nuclear weapon would face somewhat different challenges. The difficulty of setting off a stolen weapon would depend substantially on the weapon's design. Many U.S. nuclear weapons are equipped with "permissive action links," or PALs, which are effectively electronic locks intended to make it difficult to detonate the weapon without inserting an authorized code. Modern versions are integral to the weapon, making it very difficult to bypass the locking device and "hotwire" the weapon to detonate. They are also equipped with "limited try" features that will permanently disable the weapon if the wrong code is entered too many times or if attempts are made to tamper with or bypass the lock (Stein and Feaver 1987; Feaver 1992; Cotter 1987). Older versions do not have all of these features and would provide somewhat less of an obstacle to a terrorist group attempting to detonate a stolen weapon. Figuring out how to do so would nevertheless be a considerable challenge.

In addition to PALs, for safety reasons many weapons are equipped with devices that prevent the weapon from detonating until it has gone through its expected flight-to-target sequence. An artillery shell, for example, might be designed so that it could not explode until it had sensed the intense acceleration of being fired from a cannon, followed by a period of free flight through the atmosphere. These features, if designed to be very difficult to bypass, can also pose a serious obstacle to a terrorist group attempting to detonate a stolen weapon.

Unfortunately, what little information is publicly available suggests that older Soviet-designed weapons, particularly older tactical weapons, may not be equipped with modern versions of such safeguards against unauthorized use. For instance, Bruce Blair, a former U.S. ballistic missile launch officer who has written extensively about U.S. and Russian nuclear command and control, reported that Russian tactical nuclear weapons "built before the early 1980s lack the safety locks known as permissive action links" (U.S. House of Representatives 1997). By one account, U.S. intelligence has concluded that Russian tactical weapons "often" have external locks "that can be removed, and many have none at all" (Nelan 1997). In both the United States and Russia, thousands of nuclear weapons, particularly older varieties, have been dismantled in recent years, and it is likely that most of the dangerous weapons lacking modern safeguards have been destroyed. But neither country has made any commitment to destroy all of these weapons. Nuclear powers such as Pakistan, India, and China are not believed to incorporate equivalents to modern PALs in their weapons, but many of these weapons are believed to be stored in partly disassembled form.

If they could not figure out how to detonate a stolen weapon, terrorists might choose to remove its nuclear material and fashion a new bomb. Some modern, highly efficient designs might not contain enough material for a crude, inefficient terrorist bomb; but multistage thermonuclear weapons, with nuclear material in both the "primary" (the fission bomb that sets off the fusion reaction) and the "secondary" (where the fusion takes place) probably would provide sufficient material. In any case, terrorists in possession of a stolen nuclear weapon would be in a position to make fearsome threats, for no one would know for sure whether they could set it off.

Official Assessments of Terrorist Nuclear Capability

Could resourceful terrorists design and build a crude nuclear bomb if they had the needed nuclear material? Unfortunately, repeated examinations of this question by nuclear weapons experts in the United States and elsewhere have concluded that the answer is yes—for either type of nuclear bomb. Many of these conclusions were drawn *before* the 9/11 attacks demonstrated the level of sophistication and careful planning of which some terrorist groups are capable. Indeed, perhaps the most authoritative unclassified treatment of the subject—in part because it represents something of a negotiated statement by experts with a range of views on the matter—was published in 1987 (Mark et al. 1987). A detailed examination by the U.S. Office of Technology Assessment, drawing on all the relevant classified information available in 1977, summed up the situation in a statement applying to both gun- and implosion-type devices:

> A small group of people, none of whom have ever had access to the classified literature, could possibly design and build a crude nuclear explosive device. They would not necessarily require a great deal of technological equipment or have to undertake any experiments. Only modest machine-shop facilities that could be contracted for without arousing suspicion would be required. The financial resources for the acquisition of necessary equipment on open markets need not exceed a fraction of a million dollars. The group would have to include, at a minimum, a person capable of researching and understanding the literature in several fields and a jack-of-all trades technician. (U.S. Congress 1977, 140)

A variety of other pre-9/11 official U.S. government studies similarly concluded that terrorist groups might well be able to make crude nuclear bombs of either the gun type or the implosion type (U.S. Congress 1977; U.S. Department of Energy 1997; U.S. Department of Defense 1998). In a classified November 2001 assessment, the Central Intelligence Agency's Weapons Intelligence, Nonproliferation, and Arms Control Center and the director of Central Intelligence's Counterterrorist Center judged that there was a real possibility that al Qaeda could develop a crude nuclear device (Commission on the Intelligence Capabilities of the United States regarding Weapons of Mass Destruction 2005, 271). As one such U.S. Department of Defense report (1998, II-V-58) concluded, "If fissile material is available, subnational or terrorist groups can likely produce an 'improvised nuclear explosive device' which will detonate with a significant nuclear yield." The same report elaborated,

> A terrorist with access to [greater than fifty kilograms] of HEU would almost certainly opt for a gun-assembled weapon despite the inherent inefficiencies of such a device, both because of its simplicity and the perceived lack of a need to test a gun assembly. . . . If the subnational group had only [Pu-239] or needed to be economical with a limited supply of HEU, then it would likely turn to an implosion assembly. (U.S. Department of Defense 1998, II-V-60-61)

Under some circumstances, setting off a nuclear explosion with HEU can be accomplished so quickly that the U.S. Department of Energy's internal security regulations require that security for U.S. nuclear sites where enough material for a bomb is present be based on keeping terrorists out entirely, rather than catching them as they leave the site, to avoid "an unauthorized opportunity . . . to use available nuclear materials for *onsite assembly* [italics added] of an improvised nuclear device" (U.S. Department of Energy 1994, I.3.a.1).

Nor has the question of terrorist nuclear capability been left to analysis alone; it has been subjected to "experiment" as well. For instance, in 1977, a Princeton undergraduate designed an implosion-type bomb for a senior paper. Freeman Dyson, the student's professor and a Manhattan Project veteran, gave him an A on the paper, after which the government promptly classified it (Phillips and Michaelis 1978). In one effort in the 1960s, the government asked two physicists fresh out of graduate school with no knowledge of weapon-usable nuclear materials, nuclear weapons, or explosives to design a nuclear bomb from scratch with only unclassified information. (There were ultimately a total of three participants, as one of the original two dropped out and was replaced.) They quickly decided that designing a workable gun-type bomb would be too easy to show off their technical skills in a way that would improve their subsequent job prospects; instead, they successfully designed a workable implosion bomb (Stober 2003).

In yet another example, Senator Joseph Biden (D-DE), when serving as chairman of the Foreign Relations Committee, asked the three U.S. nuclear weapons laboratories whether terrorists, if they had the nuclear material, could make a crude but workable nuclear bomb. The answer given was yes. Senator Biden (2004) reported that a few months later, the laboratories had actually built a gun-type device, using only components that, except for the nuclear material itself, were commercially available without breaking any laws. The device was actually brought into a secure Senate hearing room to demonstrate the gravity of the threat. These analyses and experiments offer a powerful rebuttal to the claim that it is "impossible" for terrorists to detonate a nuclear explosive successfully.

Conclusion: Could Today's Terrorists Set Off a Nuclear Bomb?

If nuclear terrorism is such a serious possibility, why have terrorists not yet done it (Kamp 1998)? The answer appears to be that there *are* a number of obstacles—from acquiring enough nuclear material to fabricating it into a bomb—that make such an attack difficult to accomplish. But it would be foolish to rest the world's security on the hope that terrorists will never overcome these obstacles.

Some analysts instead point to the weaknesses of today's most known terrorist group, al Qaeda. To begin with, many of the organization's recruits have little technical sophistication and expertise; al Qaeda reportedly concluded that its attempt to make nerve gas weapons by relying on the group's own expertise had "resulted in a waste of effort and money" (Cullison and Higgins 2001; Albright 2002). Though limited, available evidence does suggest a rather modest level of sophistication in al Qaeda's nuclear efforts (Bunn, Wier, and Friedman 2005). But a number of top al Qaeda personnel are technologically literate (Gunaratna 2003), and they may well succeed in recruiting other technically skilled individuals.[10] The most detailed unclassified analysis of al Qaeda's nuclear program concludes that it posed a serious threat while under way in Afghanistan and could still succeed elsewhere (Albright 2002).

Others assert that a group with al Qaeda's structure of small cells would not be well suited for an arguably large, long-term project like making a nuclear bomb, particularly given the substantial operational disruptions sustained since 9/11. This would undoubtedly make a bomb effort more difficult. Unfortunately, as already noted, repeated technical studies show that the group needed to design and fabricate a crude nuclear explosive, once the needed materials are in hand, might be quite small—possibly as small as a single al Qaeda cell.

Finally, some argue that in the absence of a stable sanctuary with large fixed facilities, it would be nearly impossible for a terrorist group to make a nuclear bomb. The overthrow of the Taliban regime and the removal of al Qaeda's Afghan sanctuary undoubtedly disrupted al Qaeda's nuclear efforts significantly. But two crucial points should be made. First, large fixed facilities are not necessarily required for putting together a crude nuclear explosive, and the time required may be distressingly short (as suggested by the U.S. Department of Energy's [1994] security regulations). The building that South Africa used to assemble its nuclear weapons, for instance, is a very ordinary-looking warehouse, with little external sign of the deadly activities that went on inside (Albright 1994).[11] Terrorists might well process nuclear material or manufacture a crude nuclear bomb on the premises of an apparently legitimate front company operating in a developed country. Second, a wide range of possible sanctuaries still exists. Indeed, in March 2004, former Director of Central Intelligence George Tenet expressed his concern regarding stateless zones in approximately fifty countries around the world where central governments have no consistent reach. In as many as half of those zones, Tenet said, terrorist groups were thriving (U.S. Senate 2004).

All of this leads us to a troubling conclusion: a nuclear attack might be one of the most difficult missions a terrorist group could hope to try, but if a sophisticated terrorist group acquired a stolen nuclear bomb or enough nuclear material to make one, there can be few grounds for confidence that they would be unable to use it.

Notes

1. Much of what follows draws heavily on these two works (Holdren and Bunn 2002; Serber 1992), the latter of which is the once-secret, classic introduction to the physics of nuclear weapons based on the notes from Serber's lecture to arriving scientists in the earliest days of work at Los Alamos.

2. Even modern thermonuclear weapons that get much of their energy from nuclear fusion—fusing light elements into heavier elements, rather than splitting heavy elements into lighter ones—rely on nuclear fission to trigger the fusion reaction (Holdren and Bunn 2002).

3. Nuclide is the general term for a species of atom characterized by the number of protons and the number of neutrons in its nucleus—that is, by its atomic number and its mass number. Thus, all of the isotopes of all of the elements constitute the set of nuclides. Each element in the periodic table is uniquely characterized by the number of protons that an atom of the element contains in its nucleus—called its atomic number. The number of protons determines the number and configuration of electrons surrounding the nucleus, which in turn govern the chemical properties of the element (for example, the chemical compounds it will form with other elements). Most elements occur in multiple forms, called isotopes of the element, which differ in the number of neutrons that each atom contains in its nucleus. The different isotopes of an element all have the same number of protons and hence the same chemical properties, but their differing numbers of neutrons give them different nuclear properties, including whether the nucleus of the isotope is stable or radioactive, what its half-life and emissions are if it is radioactive, and how susceptible it is to being split—fissioned—if struck by a free neutron.

4. While nuclear explosives in principle can even be made with material containing somewhat less than 20 percent U-235, the amount of material required increases rapidly as the U-235 concentration falls below that level.

5. Simply adding a neutron to U-238 would create U-239, but this quickly releases an electron (transforming one of the neutrons into a proton) to create neptunium-239, which then decays in a similar way to Pu-239.

6. The exception is plutonium containing substantial quantities of Pu-238, which generates such intense heat that it is not practical to make nuclear explosives from it; plutonium containing 80 percent or more Pu-238 is therefore exempted from international safeguards.

7. Indeed, one Russian weapons designer who had been tasked to examine possible terrorist weapon designs pointed out that terrorists might actually *prefer* reactor-grade plutonium, as this material generates so many neutrons that they would not need to bother with a neutron generator (otherwise a potentially tricky part of their bomb effort) to set off the nuclear chain reaction at the correct time (personal interview, 1996).

8. The explosion of one metric ton (1,000 kilograms) of TNT releases approximately 1 billion calories of energy, and the corresponding unit of measure—"one ton of TNT equivalent"—is defined as *exactly* 1 billion calories. A calorie is about 4.2 joules, so 1 billion calories—a ton of TNT equivalent—is about 4.2 billion joules or 4.2 gigajoules. A kiloton is then 4,200 gigajoules.

9. This comparison assumes the plutonium metal is in its alpha phase (19.6 grams per cubic centimeter), whereupon 6 kilograms occupies a volume of 306 milliliters compared to 355 milliliters for a 12-ounce soda can. If the plutonium were in its delta phase (15.7 grams per cubic centimeter), it would occupy 382 milliliters.

10. It is worth noting that Abu Khabab, an Egyptian trained in chemical engineering who was reportedly the leader of al Qaeda's nuclear, chemical, and biological weapons efforts, was possibly among those killed in a recent U.S. strike in Pakistan, though the identities of those killed are at the time of this writing in doubt (Anonymous 2006).

11. The weapons were assembled on the first floor of the building, which had approximately four thousand meters of floor space. South Africa consciously avoided equipping the building with features that would have made its importance obvious—such as high-technology satellite communications on the roof. The only distinguishing feature of the building is an earth embankment on one side, intended to block the building from view from the road within a large Armscor site.

References

Albright, David. 1994. South Africa and the affordable bomb. *Bulletin of the Atomic Scientists* 50 (4): 37. http://www.thebulletin.org/article.php?art_ofn=ja94albright.

———. 2002. *Al Qaeda's nuclear program: Through the window of seized documents*. Nautilus Institute Special Forum 47. San Francisco: Nautilus Institute.

Albright, David, and Kimberly Kramer. 2005. Global stocks of nuclear explosive materials: Summary tables and charts. In *Global stocks of nuclear explosive materials*. Washington, DC: Institute for Science and International Security.

Anonymous. 1998. *Special weapons primer: Nuclear weapon design*. Washington, DC: Federation of American Scientists.

———. 2006. Zawahiri escaped but relative killed in US air strike: Musharraf. Agence France Presse, February 12.

Biden, Senator Joseph. 2004. Avoiding nuclear anarchy. Paper read at the Paul C. Warnke Conference on the Past, Present, and Future of Arms Control, at Georgetown University, Washington, DC.

Bunn, Matthew. 2002. The global threat. In *Nuclear Threat Initiative Research Library: Securing the bomb*. Cambridge, MA/Washington, DC: Project on Managing the Atom, Harvard University/Nuclear Threat Initiative.

———. 2006. A mathematical model of the risk of nuclear terrorism. *Annals of the American Academy of Political and Social Science* 607:103-20.

Bunn, Matthew, and Anthony Wier. 2004. *Securing the bomb: An agenda for action*. Cambridge, MA/Washington, DC: Project on Managing the Atom, Harvard University/Nuclear Threat Initiative.

Bunn, Matthew, Anthony Wier, and Joshua Friedman. 2005. The demand for black market fissile material. In *Nuclear Threat Initiative Research Library: Securing the bomb*. Cambridge, MA/Washington, DC: Project on Managing the Atom, Harvard University/Nuclear Threat Initiative.

Cochran, Thomas, and Christopher Paine. 1995. *The amount of plutonium and highly-enriched uranium needed for pure fission nuclear weapons*. Washington, DC: Natural Resources Defense Council.

Commission on the Intelligence Capabilities of the United States regarding Weapons of Mass Destruction. 2005. *Report to the president*. Washington, DC: WMD Commission. http://www.wmd.gov/report/.

Cotter, Donald R. 1987. Peacetime operations: Safety and security. In *Managing nuclear operations*, ed. A. B. Carter, C. A. Zraket, and J. D. Steinbruner. Washington, DC: Brookings Institution.

Cullison, Alan, and Andrew Higgins. 2001. Files found: A computer in Kabul yields a chilling array of Al Qaeda memos. *The Wall Street Journal*, December 31, p. A1.

Feaver, Peter. 1992. *Guarding the guardians: Civilian control of nuclear weapons in the United States*. Ithaca, NY: Cornell University Press.

Glaser, Alexander. 2005. About the enrichment limit for research reactor conversion: Why 20%? Paper read at RERTR 2005: 27th International Meeting on Reduced Enrichment for Research and Test Reactors, November 6-10, Boston.

Gunaratna, Rohan. 2003. *Inside al Qaeda: Global network of terror*. New York: Berkley Books.

Holdren, John P., and Matthew Bunn. 2002. Technical background: A tutorial on nuclear weapons and nuclear-explosive materials. In *Nuclear Threat Initiative Research Library: Securing the bomb*. Cambridge, MA/Washington, DC: Project on Managing the Atom, Harvard University/Nuclear Threat Initiative.

International Atomic Energy Agency (IAEA). 2005. *Illicit nuclear trafficking: Facts & figures*. Vienna, Austria: IAEA.

Kamp, Karl-Heinz. 1998. Nuclear terrorism is not the core problem. *Survival* 40 (4): 168.

Khinshteyn, Aleksandr. 2002. Secret materials. Russian Centre TV, November 29.

Mark, J. Carson. 1993. Explosive properties of reactor-grade plutonium. *Science and Global Security* 4:111-28.

Mark, J. Carson, Theodore B. Taylor, Eugene Eyster, William Maraman, and Jacob Wechsler. 1987. Can terrorists build nuclear weapons? In *Preventing nuclear terrorism*, ed. P. Leventhal and Y. Alexander. Lexington, MA: Lexington Books.

Nelan, Bruce W. 1997. Present danger: Russia's nuclear forces are sliding into disrepair and even Moscow is worried about what might happen. *Time Europe*, April 7, p. 42.

Phillips, John Aristotle, and David Michaelis. 1978. *Mushroom: The story of the a-bomb kid*. New York: Morrow.

Rhodes, Richard. 1986. *The making of the atomic bomb*. New York: Simon & Schuster.

Serber, Robert. 1992. *The Los Alamos primer: The first lectures on how to build an atomic bomb*. Berkeley: University of California Press.

Stein, Peter, and Peter Feaver. 1987. *Assuring control of nuclear weapons: The evolution of permissive action links*. CSIA Occasional Paper no. 2. Cambridge, MA: Center for Science and International Affairs, Harvard University.

Stober, Dan. 2003. No experience necessary. *Bulletin of the Atomic Scientists* 59 (2): 56.

Sublette, Carey. 2001. Nuclear weapons frequently asked questions. http://nuclearweaponarchive.org/.

U.S. Congress, Government Accountability Office (GAO). 2004. *Nuclear nonproliferation: DOE needs to take action to further reduce the use of weapons-usable uranium in civilian research reactors*. GAO-04-807. Washington, DC: GAO.

U.S. Congress, Office of Technology Assessment (OTA). 1977. *Nuclear proliferation and safeguards*. Washington, DC: OTA.

U.S. Department of Defense (DOD). 1998. Section V: Nuclear weapons technology. In *Militarily critical technologies list*. Washington, DC: DOD.

U.S. Department of Energy (DOE), Office of Arms Control and Nonproliferation. 1997. *Nonproliferation and arms control assessment of weapons-usable fissile material storage and excess plutonium disposition alternatives.* DOE/NN-0007.Washington, DC: DOE.

U.S. Department of Energy (DOE), Office of Security Affairs, Office of Safeguards and Security. 1994. *Manual for protection and control of safeguards and security interests*. DOE-M-5632.1c-1. Washington, DC: DOE.

U.S. House of Representatives. 1997. National Security Committee, Military Research & Development Subcommittee. *Hearing on Russian missile detargeting and nuclear doctrine and its relation to national missile defense*. 105th Cong., 1st sess. March 13.

U.S. Senate. 2004. Select Committee on Intelligence. *Current and projected national security threats to the united states*. 108th Cong., 2nd sess. February 24.