Terrorism Potential for Research Reactors Compared With Power Reactors

Nuclear Weapons, "Dirty Bombs," and Truck Bombs

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If terrorists could steal 25 kg to 50 kg of highly enriched uranium fuel to be used for one or more large research reactors, they might be able to make a nuclear weapon from it. The same is not true of unburned fuel from power reactors because the uranium is not highly enriched and therefore not useful for making such weapons without a difficult uranium enrichment process. If terrorists could steal radioactive fuel that has been burned in either kind of reactor, they could probably make a radioactive dispersal device or "dirty bomb." If terrorists could use an airplane or truck bomb to crash through walls and fences protecting either kind of reactor and penetrate the reactor's containment or blow up in the pond where irradiated spent nuclear fuel is stored, they might be able to disperse radioactivity over an area the shape and size of which would depend not only on the effect of the crash or explosion but also on the direction and speed of the wind. The amount and degree of radioactivity of irradiated fuel is likely to be much greater in power reactors but the vulnerability of irradiated fuel is likely to be greater in research reactors.

Keywords: *nuclear weapons; terrorists; research reactors; power reactors; dirty bombs; truck bombs*

RESEARCH REACTORS

In statements about nuclear terrorism, there have been repeated expressions of concern about terrorists' attacks on nuclear power reactors but few about such attacks on research reactors. However, about half of the research reactors in the world contain highly enriched uranium that can be used for making nuclear weapons (International Atomic Energy Agency [IAEA], 2000). Highly enriched uranium (HEU) is enriched to 20% or more in uranium-235. Power reactors do not contain HEU, and their fuel cannot be made into nuclear weapons without enrichment of fresh fuel to HEU or separation of plutonium from spent fuel, major added technological undertakings.

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Typical small university research reactors that burn HEU may contain less than one fifth of the nuclear material necessary to make a simple Hiroshima HEU gun-type nuclear weapon, the easiest for terrorists to make. They are likely to have additional irradiated or unirradiated HEU, or both, stored near the reactor. All but two U.S. university research reactors have been converted from HEU to low-enriched uranium (LEU), which is not weapon-usable without enrichment (Travelli, 2000). There are much larger U.S. government research reactors that still burn HEU, but they are thought to be well protected from theft and sabotage (National Council on Radiation Protection and Measurement [NCRP], 2002; National Research Council [NRC], 2002). Conversion of research reactors around the world from HEU to LEU has not been as successful as conversion of university reactors has been in the United States. There are almost 100 research reactors around the world using HEU of 90% or greater enrichment, and about 20 more that use 50% to 90% HEU (IAEA, 2000). Many countries besides the United States have government or industry research reactors containing much larger amounts of HEU than the 2 kg to 5 kg that university HEU research reactors typically burn (IAEA, 2000).

Research reactors in many countries around the world came from the United States pursuant to the "Atoms for Peace Program" proposed by President Eisenhower in 1953. He suggested that the Soviet Union and the United States transfer enriched uranium to a new international organization (what became the International Atomic Energy Agency or IAEA). These transfers would form an "atomic bank" from which other countries could withdraw uranium for their peaceful nuclear programs (Eisenhower, 1953). By then, in addition to the Soviet Union and the United States, Britain had tested a nuclear weapon, and Belgium, Canada, France, Sweden, Norway, Switzerland, and Italy had the beginnings of national nuclear programs (some had reactors for peaceful purposes and some had them for both peaceful and weapons purposes). The likelihood that Eisenhower's proposed program would produce proliferation of nuclear weapons, not just of peaceful uses of atomic energy, was apparently not considered seriously by Eisenhower and his top advisers before the speech was given. The possible connection between peaceful uses and weapons came as a surprise to Secretary of State Dulles after the speech was made. No physicists with knowledge about nuclear weapons had been consulted before it was given (G. Bunn, 1992; Smith, 1987). Eventually, however, after modifying the original U.S. proposal, the United States, then the Soviet Union, and then France and other countries supplied research reactors and weapon-usable HEU to burn in them to many countries around the world. In addition, the IAEA was formed to provide information, assistance, training, and safeguards for the peaceful development of atomic energy.

In 1978, the U.S. government started a program to convert the uranium it had supplied from HEU to LEU to prevent the HEU from being used to make nuclear weapons. At a conference on research reactors after September 11, Armando

Travelli of Argonne National Laboratory, manager of the U.S. conversion program, had this to say (Travelli, 2002):

> In the past, our main concern [in the U.S. reactor conversion program] was that rogue nations or terrorist groups would develop nuclear weapons and that, by threatening to use those weapons, they would secure for themselves political and economic advantages that could drastically alter the world balance of power. . . . Today we know that if nuclear weapons were to fall in the hands of those who organized the September 11 attacks, there would be no threats or negotiations. . . . Innocent victims would die in a flash, without warning, killed by people driven by a twisted ideology and devoid of any respect for human life, including their own.

Research reactors versus power reactors for making nuclear weapons. There are many research reactors around the world. According to the IAEA (2000), there were 283 operating and 270 shutdown research reactors in 74 countries. The total of these two figures is higher than the total number of power reactors in operation and closed down around the world. Most reactors of both kinds use fresh fuel elements made of uranium. As we have seen, the LEU in power reactors is too low in its uranium-235 enrichment to be useful directly for making nuclear weapons. But, almost half of the operating research reactors in the world use HEU and most of those now shut down did so and may still contain HEU. There are hundreds of kg of HEU in operating and shutdown civilian research facilities in 58 countries, sometimes in quantities large enough in one facility to make a nuclear weapon (M. Bunn & G. Bunn, 2002). The total is enough to make many nuclear weapons.

The U.S. program begun in 1978 to convert reactors from HEU to LEU is called the Reduced Enrichment for Research and Test Reactors (RERTR) Program. Pursuant to it, 20 of the U.S.-supplied HEU research reactors outside the United States had been converted from HEU to LEU by March 2002. Except for one new HEU reactor in Germany, no new HEU research reactors have been built in the Western world since RERTR began. However, U.S.-supplied HEU reactors have not yet been converted in countries such as Argentina, Austria, Canada, France, Germany, Greece, Israel, Italy, Jamaica, Japan, Mexico, and Romania (Travelli, 2002).

In 1978, the Soviet Union launched its own program to reduce the enrichment of research reactor fuels it supplied to Eastern European countries and to Iraq, Libya, North Korea, and Vietnam. This program moved even more slowly than the U.S. program during the 1980s and 1990s. France also supplied large research reactors to other countries including Israel (uranium without enrichment) and Iraq (HEU fueled). According to the IAEA, government or industry research reactors with large HEU inventories were located in the year 2000 in Argentina, Australia, Austria, Belgium, Canada, Chile, China, Czech Republic, France, Germany, Greece, Hungary, Romania, Russia, South Africa, Switzerland, Taiwan, Ukraine, United Kingdom, United States, Uzbekistan, Vietnam, and Yugoslavia. Adding IAEA figures for operating research reactors to those that are shut down but may still house HEU fuel, there remain about as many HEU research reactors as LEU ones in the world (IAEA, 2000, 2002).

Delays in conversion of the HEU-fueled reactors to LEU fuel have resulted for technical and financial reasons. Designing LEU research reactor fuel that can accomplish the tasks that HEU fuel can accomplish has taken years of development that is still going on. Although the program started in 1978, funding was cut off for several years. There have been recent patent issues arising from the development effort that have held up some conversions (Civiak, 2002; Travelli, 2002). The similar Russian conversion program also was held up by funding problems and the need to develop an LEU fuel that would do essentially what the HEU fuels did for research purposes. Only recently, when funding became available from the United States, was it possible to conduct research on what LEU fuel could be substituted in Russian-built reactors. Thus, for many reasons, the conversion programs have not moved forward as fast as post–September 11 concerns suggest they should have.

As we have seen, to make a nuclear weapon from uranium, the weapon's uranium-235 content must be more than 20%. Moreover, a considerably higher percentage makes it easer to build a dependable weapon. This is particularly true for a terrorist group, which may not be well versed in the fine points of designing and manufacturing such weapons. Indeed, the higher the enrichment level of the HEU, the more manageable the weapon will be in size and the more likely to explode rather than fizzle. Assuming a simple Hiroshima gun-type nuclear weapon, something more than 50 kg (110 pounds) of HEU of 90% or greater enrichment in uranium-235 may be needed to make one nuclear weapon. More HEU would be needed if the uranium-235 enrichment level was lower than 90%. On the other hand, if 90% or higher enrichment in uranium-235 were used with a neutron reflector or in an implosion weapon using modern high-power explosives, the amount needed for a critical mass might be 15 kg to 25 kg.[1] According to DOE (1997),

> Several kilograms of plutonium, or several times that amount of HEU, are enough to make a bomb. With access to sufficient quantities of these materials, most nations and even some sub-national groups would be technically capable of producing a nuclear weapon.

Most research reactors do not contain 50 kg or even 15 kg of 90% or higher HEU, although some government and industry reactors do. However, combining the HEU within a medium-sized government or industry reactor with the inventories of fresh and irradiated fuel available at the site of the reactor might produce enough. Moreover, if more than one research reactor exists in a country, that country could use the combined fissile content of its reactors to produce one or more weapons in a nuclear breakout situation. Iraq was trying to produce a nuclear weapon out of fresh *and* irradiated HEU fuel rods from one

French-supplied research reactor and another Russian-supplied research reactor at the end of the Gulf War (Travelli, 2002; von Hippel, 2001).

In 2000, there were almost 100 research reactors in the world with HEU enriched to 90% or more (IAEA, 2000). An earlier IAEA estimate was that HEU research reactors still outnumbered LEU reactors in Africa, the Middle East, Eastern Europe, Russia, and in the industrialized countries of the Western Pacific rim, but not in Western Europe (Ritchie, 1997).

Research reactor fuel becomes very radioactive if it is irradiated continuously for a long time in a high neutron-flux environment. However, research reactor experiments are often of short duration and the reactor may be shut down between experiments. Some research reactors also may operate at low power. Moreover, the radioactivity of irradiated fuel reduces over time if it is not burned again. Used fuel in a research reactor pool may well include assemblies that are very radioactive, assemblies that are not radioactive at all, and others in between. Some *irradiated* fuel from research reactors may thus be usable for making nuclear weapons if the enrichment is high enough and the radioactivity is not too high, as was the case for the Iraqi bomb-making attempt.

Power reactors typically operate more than 75% of the time. They are maintained in continuous operation as long as possible because they are needed to supply power and they are typically not shut down to reload fresh fuel until some of the fuel in the reactor has been burned for so long that its radioactivity has significantly increased. Thus, the spent fuel taken from power reactors is usually highly radioactive and dangerous to handle even for terrorists willing to take greater chances with their lives. Close exposure to the fuel for a short period could produce radiation sickness followed by painful death. On the other hand, as we have seen, research reactor fuel may be highly radioactive in some cases and much less radioactive in others. An educated terrorist with a dose rate meter could tell what used fuel could be handled with lower risk.

There was great concern about a research reactor holding at least 50 kg of HEU in Vinca, Serbia, during the fighting in the Balkans but the HEU was recently returned safely to Russia. Not counting countries having nuclear weapons, research reactors with more than 20 kg of 90% HEU content exist in Argentina, Belarus, Belgium, Germany, Italy, Japan, and Ukraine. The reactors in Belarus and Ukraine were built when those countries were part of the Soviet Union. The research reactor in Belarus has more than 370 kg of HEU, including enough enriched to 90% to make several bombs. One reactor in the Ukraine also contains large amounts of 90% HEU. Up to two kg of 90% HEU was reported to have disappeared from a research reactor in the Abkhazia region of the former Soviet republic of Georgia during civil resistance there. HEU of somewhat lower U-235 enrichment level, probably stolen from one of the research reactors in Obninsk, Russia, was seized by police in Western Europe when arresting the alleged thieves, and LEU fuel rods were stolen from a research reactor in the Congo (M. Bunn, Holdren, & Weir, 2002; Civiak, 2002; Steinhausler & Zaitseva, 2002).

In sum, HEU from research reactors, particularly the larger ones operated by government and industry, could well be the source of the explosive material for a terrorist nuclear weapon if the nuclear fuel could be successfully stolen from the reactor. But the LEU burned in power reactors and in an increasing number of research reactors cannot be directly used to make nuclear weapons.

Research reactors versus power reactors for making radiological weapons. Radiological dispersal devices (RDDs), or "dirty bombs," are easier to make than nuclear weapons. One such potential device constructed by Chechens to scare the Russian authorities consisted of a container of radioactive material from medical or industrial sources attached to conventional explosives (Steinhausler & Zaitseva, 2002). The explosives were not exploded apparently because the Chechens wanted to gain Russian attention rather than cause major disruption by dispersing radioactive material. An RDD would probably not kill anyone not close enough to be killed by the high explosives. If effective as intended, however, it would disperse radioactive materials over a much wider area than the area in which people could be injured by the explosive force of the bomb. The size and shape of the area irradiated would depend on how large the explosion was, how well the radioactive particles were carried in the air, and what direction the wind was blowing. The dispersal could cause cancers eventually and, at the time, could cause panic in the irradiated area. It might require removal of the population from that area until the dispersed radioactive particles were cleaned away. The disruption to regular and business life and the economic loss could be great (NRC, 2002; Wald, 2002). In addition to being called dirty bombs, RDDs are sometimes referred to as weapons of "mass disruption" rather than "mass destruction."

Radioactive materials for making RDDs could probably be stolen from hospitals and industrial plants more easily than from research or power reactors. According to a committee of scientific experts, "Given the wide use of radiation sources in the United States and other countries, a determined terrorist would probably have little trouble obtaining material for use in an RDD" (NRC, 2002). However, typical hospital and industrial sources may contain only a few grams of easily available radioactive materials, and their dispersal by an explosion would be unlikely to cover a wide area. The area and concentration of dispersal of radioactivity might be too small and too low to cause major disruption. A knowledgeable radiological weapon maker who wanted major disruption would have to find a large quantity of radioactive materials.

He or she could perhaps find a large supply of Cobalt 90 or some similar radioactive material used in large quantities by industry or attempt to collect many grams of radioactivity from several industrial and hospital sources. Although small amounts of radioactive material from hospital and industry sources might be the easiest to acquire (large industrial sources are likely to be better protected), collecting many small sources from many places would likely be necessary. Doing so might well take longer and involve more risks of apprehension than stealing used fuel rods from a poorly protected, shutdown, university research reactor.

From a terrorist's point of view, the fact that the used fuel from such a reactor is likely not to be as highly radioactive as the spent fuel from a nuclear power plant may be an advantage. The NCRP (2002) had this to say about making radiological dispersion devices:

> The most likely scenarios involve the use of a solid radioactive material that would be of low enough activity that the construction and delivery of the RDD will not seriously inhibit the terrorist carrying out the attack. Large sources of penetrating radiation [such as irradiated power reactor fuel] are difficult to handle safely and without detection by authorities. Shielding materials that are adequate to protect both the individuals who construct the devices and those who are to deploy them complicate the design and fabrication of effective weapons. (p. 15)

Building an RDD from irradiated research reactor fuel may be within the reach of many terrorists, whereas making a nuclear weapon would take greater information and skill. The arrest of an alleged Al Qaeda terrorist who is reported to have studied how to make RDDs suggests the possible threat (Bridis, 2002).

Spent reactor fuel that has been recently removed from a power reactor will typically have been irradiated for a long time and will be too hot to handle even for suicidal terrorists. The same may be true of spent fuel from large government or industrial research reactors. If the gamma ray and neutron dosage is high enough, the radiation could affect the central nervous system fairly quickly and make the bomb maker unconscious. But this level of radioactivity typically results from the high burn-up that happens in power reactors and some large research reactors more often than in small university research reactors. Thus, for fashioning RDDs intended to frighten and disrupt, spent reactor fuel from small university reactors or from little-used government or industry research reactors could be more attractive to terrorists than spent fuel from power reactors.

With spent fuel from any reactor, terrorists would need to know the radioactive dose rate of the material to ensure against radiation sickness effects while working with it. Assuming the theft of research reactor fuel that had not been irradiated for too long a time or that had been out of the reactor long enough for its radioactivity to have cooled significantly—both of which are more likely with small university research reactors than with power reactors—making a radiological weapon out of used research reactor fuel seems more likely than making one from used power reactor fuel.

Research reactors versus power reactors as terrorist attack targets. The typical power reactor is likely to have much more radioactive spent fuel in cooling ponds and to contain much more radioactivity within its core than the typical university research reactor or less-used large government or industry research reactor. A power reactor would likely be a more attractive target for a suicidal terrorist truck bomber or airplane pilot because the radioactive dispersal possibilities could be large—if the attack was successful in breaking through the reactor's containment building or into the spent fuel pool or in causing sufficient damage to other vital areas of the reactor. This dispersal seems far beyond what might be achieved in a successful terrorist attack involving a truck bomb or aircraft crash at a typical, less-well-protected research reactor. However, from the terrorists' point of view, a university reactor may appear much more vulnerable because its protection barriers against attack are likely to be much lower than those of power reactors or government or industry research reactors and it is more likely to be located within or near a populated area.

Protection barriers for nuclear fuel in research reactors versus those for power reactor fuel. Both irradiated and fresh nuclear fuel are likely to be less well protected from terrorist attacks at university research reactors than at power reactors for many reasons.

First, typical research reactor fuel elements are much smaller than those for power reactors. The large size (perhaps 10 ft long) and weight (up to 1 ton) of power reactor fuel mean that a crane or other heavy machinery is needed to move an assembly. Taking it apart is not easy. On the other hand, research reactor fuel elements may be 4 ft long and weigh a few 10s of pounds. They can be disassembled more easily and can typically be moved by one person, properly shielded.

Second, university research reactors tend to be located in or near cities—in places where there are many people going back and forth. Government and industry research reactors are more likely to be somewhat removed from populations and surrounded by stronger fences or walls than university research reactors. Power reactors tend to be both farther from cities and more likely to be surrounded by fences, open areas, and walls, which can delay attackers and provide opportunity to observe them before the attack if guards are on duty, as is typical at power reactors.

Third, power reactors are ordinarily in operation all the time except for maintenance or when the fuel needs to be changed. Operating personnel are likely to be present during the day even when the reactor is shut down and guards are likely to be present both day and night. Many university research reactors are shut down and left unused for significant periods with only skeleton staff nearby. Power reactors are typically guarded by professional guards hired and trained for the purpose. That may also be true of government and industry research reactors, which are often in operation most of the time. University reactors, with intermittent operation, may rely on the university campus police who are usually present elsewhere and not trained adequately in antiterrorist procedures. When the research reactor is not in operation, they are not likely to check it often.

Fourth, as we have seen, the irradiated fuel removed from university research reactors is likely to be less radioactive than that from power reactors. Moreover, many research reactors are not used as much as their suppliers or owners originally expected or are operated at a lower power level than originally anticipated.

Indeed, many university reactors are no longer operated. If the fuel has been removed, as is the practice in the United States, they are not likely to constitute a risk. But this is not a uniform practice. There is probably a great deal of irradiated research reactor fuel accumulated from many years of past operation that is stored in or near research reactors around the world, fuel that is easier to handle for terrorists than power reactor fuel would be.

Finally, research reactors, particularly those at universities, tend to have less effective security than power reactors and their fuel. Inadequate protection may result for several reasons.

1. There is no treaty requiring any level of protection for power or research reactors from terrorists. The relevant treaty, the Convention on Physical Protection of Nuclear Material, only provides protection standards to protect nuclear material from being stolen while it is in international transport. A consensus of most of the treaty's parties to amend it to cover material used or stored domestically, and prohibit sabotage as well as theft, was achieved in general terms in May 2001. However, except for some general principles, no specific standards for domestic protection were specified in this consensus agreement. Such standards exist in the treaty now for international transport and for storage while awaiting international transport. But the parties have been unable to agree to apply those or any other specific standards to regular domestic operations. Without such standards, the amendment has much less value (G. Bunn & Zaitseva, 2002; M. Bunn & Bunn, 2002; NRC, 2002).
2. In 1999, the IAEA issued revised recommendations for protecting nuclear material from sabotage. These are in IAEA Information Circular 225, Revision 4. This revision contains general provisions on sabotage, such as,

   > The objective of the physical protection system should be to prevent or delay access to or control over the nuclear facility or nuclear material through the use of a set of protective measures including physical barriers or other technical means [e.g., security alarms, closed-circuit TV cameras, electronic sensors, finger-print identification devices, etc.] or the use of guards and response forces so that the guards or response forces can respond in time to prevent the successful completion of sabotage.

   This lists detailed recommendations on how to guard against sabotage of *power* reactors, but it contains no specific recommendations for sabotage to *research* reactors. Moreover, unless it is brought into force by the bilateral agreement of the reactor supplier and the recipient country, it remains only general recommendations. Unless national legislation or regulations or bilateral supply agreements require these recommendations, research reactor operators may ignore them.
3. IAEA Information Circular 225, Revision 4, also contains recommendations for protection against *theft* of nuclear material by terrorists. These apply wherever the nuclear materials are located within a country, including storage at or within research reactors. They say that the level of protection should be based on what *the country perceives the threat to be*. This is called the "design basis threat." Unlike the U.S. regulations issued for reactors by the U.S. Nuclear Regulatory Commission, these recommendations do not specify any minimum threat to guard against. Circular 225 divides nuclear material into categories and specifies the strongest protection recommendations for the most sensitive categories, one of which is HEU of 5 kg or more. Irradiated reactor fuel is not in this category but in the next most strongly protected category. The circular then sets forth some useful standards of protection against "unauthorized removal of nuclear material in use and

storage." Again, however, these remain only recommendations except for countries subject to nuclear supply agreements where the supplier country has required adherence to them or where the country has otherwise adopted them through national regulations or legislation. In general, supply agreements suggest simply that the recipient country take these recommendations into account.

4. The Nuclear Suppliers' Guidelines (Nuclear Suppliers Group, 1996), negotiated among various nuclear suppliers to apply to what they supply to other countries, summarize what protection against unauthorized use should be provided by recipients. The guidelines say HEU and spent fuel rods should be used and stored within a *protected area*, "an area under constant surveillance by guards or electronic devices surrounded by a physical barrier with a limited number of points of entry under appropriate control, or any area with an equivalent level of physical protection." HEU of 5 kg or more should, in addition, be used and stored within a *highly protected area* inside the outer *protected area* with

   > access restricted to persons whose trustworthiness has been determined and which [area] is under surveillance by guards who are in communication with response forces. Specific measures taken in this context should have as their objective the detection and prevention of any assault, unauthorized access or unauthorized removal of material.

   The guidelines suggest that these standards "should be" the subject of negotiation between the suppliers and recipients of nuclear reactors and nuclear fuel (Nuclear Suppliers' Group, 1996). Provisions relating to them appear in many supply agreements, but they are not public knowledge and are not required to be submitted to IAEA inspectors so that the inspectors can check whether the recommended protections have in fact been provided. Moreover, they are not applicable to small university-type research reactors unless the total HEU present in or near the reactor is 5 kg or more. Because of provisions in federal legislation and U.S. practice, U.S. agreements with foreign recipients usually call for the possibility of occasional U.S. inspections of the facility to observe, among other things, the protection the recipient provides (Nuclear Nonproliferation Act, 1978; Atomic Energy Act of 1954). The Nuclear Suppliers' Guidelines themselves do not call for inspections, and other suppliers may not ask for them. Moreover, this requirement did not prevent the theft of U.S.-supplied research reactor fuel from a reactor in the Congo.
5. National statutes and regulations on physical protection of reactors vary a great deal around the world. A survey by the Nuclear Energy Agency of the international Organization for Economic Cooperation and Development (OECD) showed major differences from country to country (OECD, 2000). The 29 countries in the survey, mostly well-developed countries with significant nuclear programs, seemed to have a wide variety of security requirements set forth in reactor licenses, regulations, statutes, and royal decrees. The summary did not compare the requirements to the regulatory recommendations of the IAEA, and it is not possible to do that effectively from the information provided. The variations in regulatory requirements raise questions about such compliance. In most cases, the OECD nuclear programs began long before the current IAEA physical protection recommendations and Nuclear Suppliers' Guidelines were issued, and some of the OECD respondents to the survey were themselves nuclear suppliers (OECD, 2000).
6. In a survey conducted by Stanford University, similar country variations appeared in actual physical protection practices for HEU research reactors (with 5 kg or more). Six of the responses to a questionnaire, mostly from less-developed countries than those covered by the OECD survey, relate to government research

reactors. The countries were located in Latin America, Central and South Asia, and Eastern and Western Europe. Four of the five that answered questions on threat perception said their facilities faced major threats of armed violence from outsiders and that collusion by insiders (possibly involuntary collusion) with the outsiders was feared as well. However, despite considerable similarities in *threat perceptions*, there were great variations in the *level of protection* provided (barriers, sensors, etc.) for the protected area and the inner areas within the protected areas where the HEU was stored or used. For example, one respondent confirmed that the outer protected area could be accessed by climbing a wall or walking around the end of a fence or by crawling through a duct through a wall or something similar. Others described varying degrees of stronger protection. For the inner area where HEU should be kept, all said there were guards, at least during working hours. But two did not provide guns for the guards. Three said that during hours when the area was not in use for experiments or other purposes, there were "standard locks or better at critical access points" instead of guards. Another three, these with more nuclear experience and resources, said they used "ID actuated locks or better" when guards were not present. Contrast this with the Nuclear Suppliers Guidelines recommendation described above that recommend, for both spent fuel and HEU of more than 5 kg, "constant surveillance by guards or electronic sensors" (G. Bunn, Steinhausler, & Zaitseva, 2002).

7. The variation in *actual* practices for protection despite IAEA recommendations or Nuclear Suppliers' Guidelines was confirmed by experts who were participants in the first 10 missions of the IAEA's "International Physical Protection Advisory Services" to review security at nuclear facilities—mostly in Eastern Europe where particular countries had requested assistance. The experts reported that their visits to nuclear sites showed that physical protection practices "*will vary from State to State. Differences in culture, perceived threat, financial and technical resources, and national laws* are some of the reasons for variations" (Soo Hoo et al., 2000).
8. Given these differences in the way states respond to similar threat perceptions; given the lower level of financial resources and importance usually provided to university and some little-used government research reactors as compared with power reactors; given the lack of specific provisions for protection from sabotage of research reactors in, for example, the Convention on Physical Protection of Nuclear Material and the IAEA recommendations; and given the intermittent operation of university and some government research reactors as compared with power reactors, it should not be surprising that the actual practices for protection of research reactors tend to be much weaker than those for power reactors.

Conclusion. Research reactors and their fuel are more likely than power reactors to be the targets of well-informed terrorists seeking to make dirty bombs or nuclear weapons. On the other hand, the fuel from many of them is likely to be much less radioactive than that from power reactors. This means that their fuel will usually be easier for the terrorists to handle, and it is less likely to be adequately protected from theft or from external attacks by truck bombs and aircraft.

NOTE

1. For the purposes of its safeguards system to account for all the uranium and plutonium in reactors of non-nuclear-weapon countries, the International Atomic Energy Agency (IAEA) has designated 25 kg of Highly enriched uranium (HEU) as a "significant quantity." According to the IAEA, this means that it is "the approximate quantity of nuclear material in respect to which, taking into account any conversion process involved, the possibility of manufacturing a nuclear explosive device cannot be excluded" (http://www.iaea.org/worldatom/inforesource/other/safeguars/pia3810.html). U.S. experts believe that something like 15 kg of HEU enriched to 90% or more in uranium-235 is sufficient to make a nuclear weapon. This helps to explain the Department of Energy (DOE) quotation in the text that follows this note.

REFERENCES

Bridis, T. (2002, June 10). U.S. arrests alleged bomb terrorist. *Associated Press*.

Bunn, G. (1992). *Arms control by committee*. Stanford, CA: Stanford University Press.

Bunn, G., Steinhausler, F., & Zaitseva, L. (2002, June). *Could terrorists or thieves get weapons usable material from research reactors and facilities?* Proceedings of the 43rd annual meeting of Institute of Nuclear Materials Management, Northbrook, IL.

Bunn, G., & Zaitseva, L. (2002). Efforts to improve nuclear material and facility security. In *2002 SIPRI annual report* (App. 10D, pp. 11-14). Stockholm: Stockholm Institute of Peace Research.

Bunn, M., & Bunn, G. (2002, Spring). Strengthening nuclear security against post September 11 threats of theft and sabotage. *Journal of Nuclear Materials Management*, *30*(3), 48.

Bunn, M., Holdren, J. P., & Weir, A. (2002). *Securing nuclear weapons and materials: Seven steps for immediate action*. Cambridge, MA: Kennedy School of Government, Harvard University Press.

Civiak, R. L. (2002). *Closing the gaps: Securing high enriched uranium in the Former Soviet Union and Eastern Europe*. Washington, DC: Federation of American Scientists.

Department of Energy, U.S. (DOE). (1997). *Final nonproliferation and arms control assessment of weapons-usable fissile material storage and excess plutonium disposition alternatives* (DOE/NN-0007, p. vii). Washington, DC: Author.

Department of Energy, U.S. (DOE). (2002). *FY 2003 budget request: Detailed budget justification. Defense nuclear nonproliferation*. Washington, DC: Author. Retrieved from http://www.cfo.doe.gov/budget/03budget/content/defnn/nuclenonpl.pdf

Eisenhower, D. E. (1953). *Atoms for peace proposal: Address of President Eisenhower to the U.N. General Assembly. U.S. Department of State, Documents on disarmament, 1945-1959*. Washington, DC: General Printing Office.

International Atomic Energy Agency (IAEA). (2000). *Nuclear research reactors of the world*. (Ref. Data Series 3, pp. 59-69).

International Atomic Energy Agency (IAEA). (2002). *Research reactor data base*. Retrieved from http://www.iaea.org

National Council on Radiation Protection and Measurement (NCRP). (2002). *Management of terrorist events involving radioactive material*.

National Research Council (NRC), Committee on science and technology in countering terrorism, division of engineering and physical sciences. (2002). *Making the nation safer: The role of science and technology in countering terrorism*.

Nuclear Nonproliferation Act of 1978, PL 95-242, 1978.

Nuclear Suppliers' Group. (1996). *Guidelines for nuclear transfers, IAEA Information Circular 254, Rev. 4*. [Pamphlet, Add. 1, par. 3 and Annex C]

Organization for Economic Cooperation and Development (OECD), Nuclear Energy Agency (2000). *Nuclear legislation: Analytical study. Regulatory and institutional framework for nuclear activities*.

Ritchie, I. (1997). Technical and administrative preparations required for shipment of research reactor spent fuel to its country of origin. IAEA-Argonne National Laboratory Training Course, Lecture L.1.2, text at Figs. 8, 9, 10.

Smith, G. C. (1987). *Adviser to Dulles*. In J. A. Thompson (Ed.), *Gerard Smith on arms control* (p. 117). College Park: University of Maryland Press.

Soo Hoo, M., Ek, D., Hageman, A., Jenkins, T., & Weiss, B. (2000). *International physical protection advisory service: Observations and recommendations for improvement*. Proceedings of the 42nd annual meeting of the Institute of Nuclear Materials Management, Northbrook, IL.

Steinhausler, F., & Zaitseva, L. (2002). *Database on nuclear smuggling, theft and orphan radiation sources*. Stanford, CA: Center for International Security and Cooperation, Stanford University.

Travelli, A. (2000). *Status and progress in the RERTR program in the year 2000*. Proceedings of the 2000 international meeting on reduced enrichment for research and test reactors, Las Vegas, NV.

Travelli, A. (2002). *Progress of the RERTR program in 2001*. Proceedings of the International Conference on Research Reactor Fuel Management, Ghent, Belgium.

von Hippel, F. (2001, November/December). Recommendations for preventing terrorism: FAS Public Interest Report. *Journal of the Federation of American Scientists*, *54*(6).

Wald, M. L. (2002, June 11). Fear itself is the main threat of a dirty bomb, experts say. *New York Times*, pp. A-18.

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