Science and Global Security, 11:85–107, 2003
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ISSN: 0892-9882 print
DOI: 10.1080/08929880390246912

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Research Reactor Vulnerability to Sabotage by Terrorists

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The September 11 terrorist attacks demonstrated that the technical competence, available resources, level of preparation and suicidal determination of contemporary terrorist groups like al Qaeda have greatly increased over the last decade. This article will consider the likelihood that sophisticated terrorist groups could successfully launch sabotage attacks against nuclear research reactors and cause radiological releases that threaten nearby populated neighborhoods. While the theft by terrorists of highly enriched uranium (HEU) from research reactors to make relatively simple gun-type nuclear explosives has been a concern for some time, the sabotage threat to research reactors—a threat which is independent of fuel enrichment—has not been widely addressed. Nuclear regulators should reassess the level of physical protection that research reactor operators provide in light of the increased terrorist threat.

INTRODUCTION

Before September 11, most terrorist attacks typically involved the use of conventional weapons in conventional ways, usually causing relatively small numbers of casualties and localized property damage. In the aftermath of the September 11 attacks, intelligence agencies have repeatedly warned that terrorist groups like al Qaeda wish to increase the lethality and range of their

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Received 19 December 2002; accepted 21 July 2003.

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actions by acquiring the capability to launch chemical, biological, nuclear, and radiological attacks. One radiological scenario that is attracting considerable attention is the threat that a team of well-trained and equipped suicide attackers could commit an act of sabotage at a nuclear power plant, causing a meltdown and a large radiological release that could threaten downwind populations.[1] In contrast, the consequences of terrorists' sabotage attack on a research reactor that produced releases of radioactivity have been little discussed even though research reactors around the world, typically much smaller than power reactors, tend to be less well protected from such a sabotage attack.[2] Some reasons for this are:

- There is no international treaty requiring any protection of research reactors (or, for that matter, nuclear power plants).[3] The internationally-accepted but nonbinding Nuclear Suppliers' Guidelines for export of fissile material and nuclear equipment state that agreements between research reactor recipients and their supplier countries, most often the U.S. or Russia and its predecessor, should call for measures to protect nuclear material from theft. However, though these guidelines refer to general protection recommendations from the International Atomic Energy Agency (IAEA), they leave protection to the discretion of the supplier and recipient, and do not require inspections to verify the effectiveness of protective measures.[4]
- These IAEA recommendations focus on protecting five kilograms or more of highly-enriched uranium (HEU) or other weapon-usable fissile material at research reactors from theft by outsiders. They contain only a one-sentence, very general recommendation for protecting even large research reactors from sabotage attacks (though more detailed IAEA sabotage recommendations have been issued for nuclear power plants).[5]
- A survey for the international Organization of Economic Cooperation and Development (OECD) Nuclear Energy Agency of national regulations and statutes on physical protection of reactors in most developed countries shows considerable variation in requirements from country to country.[6] In questionnaire-based surveys of nuclear security practices in a few countries in Eastern and Western Europe, Central and South Asia, and Latin America conducted by researchers at Stanford University, considerable variation from country to country appeared in the actual practices for protecting research reactors.[7]
- The reasons for such variations in actual practices for protection given by nuclear experts who were members of IAEA reactor-security advisory teams to 10 countries—mostly in Eastern Europe—were "[d]ifferences in culture, perceived threat, financial and technical resources, and national laws."[8]

> Moreover, most of the national statutes and regulations contain considerably more detailed provisions for protecting nuclear power plants from theft and sabotage than they do for research reactors.[9]

The danger of diversion of HEU from research reactors to bombs has been recognized for a long time, and has been the primary focus of security practices instituted in the past at such research reactors. In 1981, Israeli aircraft attacked Iraq's French-supplied HEU-fueled research reactor then under construction because of fear that the HEU fuel would be used to make nuclear weapons or that the reactor would be used to breed plutonium for weapons. Later, just before the Gulf War of 1991, when Iraq had a crash nuclear-weapon-building program, its scientists planned to use some 36 kg. of fresh and irradiated fuel supplied by France and the Soviet Union for a research reactor supplied by France. In 1998, fresh and irradiated HEU fuel from a Soviet-built research reactor in Georgia was removed and airlifted to Britain for fear that it would be used by dissidents to make a bomb. In August of 2002, enough HEU for two or more bombs was removed from a shut-down Soviet-supplied research reactor in Serbia and returned to Russia for fear that it might be acquired by terrorists or a nonnuclear-weapon state seeking weapon-usable material.[10]

Because of the known dangers that HEU research reactor fuel could be converted to nuclear weapons, Argonne National Laboratory, acting for the U.S. Department of Energy, has for many years made major efforts to convert HEU-fueled research reactors supplied to other countries by the U.S. to low-enriched uranium (LEU), less than 20 per cent uranium-235. This is called the Reduced Enrichment for Research and Test Reactors (RERTR) program. LEU is not useful without enrichment (a major technical undertaking) for making nuclear weapons. The U.S. has taken back the HEU fuel from many reactors it supplied after they were converted to LEU. About half the research reactors supplied by the U.S. have been converted so far. This program has not moved faster in part because of funding limits and in part because considerable research has been required to develop LEU fuels that will enable conversion of all research reactors without any penalty in performance.[11]

Around 80 percent of the operating and shut-down research reactors around the world were supplied with their uranium fuel by the U.S. and Russia (or the Soviet Union).[12] During the 1980s, the Soviet Union also had a conversion program for the HEU research reactors it had supplied to Eastern European Warsaw Pact countries, to Iraq, to North Korea, and to Vietnam. The Soviet plan stopped for lack of funds.[13] With U.S. financial assistance, a new Russian program like the American RERTR program has been started to develop LEU fuels to convert Soviet and Russian-supplied HEU-fueled research reactors.[14]

These conversion efforts should eventually make the research reactors supplied by the Soviet Union or Russia and the U.S. less attractive to terrorists who want to steal HEU to make nuclear weapons. Almost all the small university research reactors in the U.S. have converted to LEU.[15] But there are about 200 HEU reactors around the world that have been shut down rather than being converted, and some still have HEU on site. There remain some 20 metric tons of civilian HEU in research reactors in 43 countries.[16] (Although much of this is contained in irradiated fuel, the radiation level is in many cases too low to provide adequate self-protection.) The continuing danger, despite the progress of the RERTR and related programs, is demonstrated by repeated reports of illicit trafficking in small amounts of uranium from research facilities in several countries.[17]

The RERTR and related programs just described are intended to deal with the threat that research reactor HEU will be used to make nuclear weapons, not to prevent sabotage that could spread radioactivity over a populated area. Even LEU research reactors at universities and elsewhere may present a risk of such dispersal by terrorists. These are the reactors that are, in general, least well protected from theft or sabotage.[18]

VULNERABILITY OF US RESEARCH REACTORS TO SABOTAGE

In this section, we focus on protection practices for U.S. research reactors, because we know more about U.S. practices, and because the many forms of security (or lack thereof) for specific research reactors around the world are not public knowledge. Since September 11, secrecy has increasingly become the practice in the U.S. for new security requirements. Because U.S. Nuclear Regulatory Commission (NRC) regulations for protection of research reactors are still in part public, and because much has been published in the past about U.S. security practices, we know much more about them than we do about practices for other research reactors in the world.

Research and Power Reactor Security Compared

In the U.S., while practices vary from research reactor to research reactor, many research reactors operated by universities and sometimes by industry are open to visitor specialists (if not to the general public) and have fewer protective security practices than typical nuclear power plants.

- A research reactor is often part of a larger research center or university where there are potentially many users representing various scientific disciplines. (Nuclear power reactors typically limit attendance to the reactor operators and guards who are on duty in shifts throughout the 24 hours of each day.)
- A research reactor is more likely to be located in or near a city for easy access by the users. (Nuclear power reactors are usually required to be located at some distance from population centers.)
- The perimeter protection of a research reactor, if there is such protection, is typically a wire fence without antivehicle barriers, and without motion sensors or electronic/computer-based detection and assessment systems. (Nuclear power reactors tend to have such antivehicle barriers and detection and assessment systems as well as fences much further removed from the reactor.)
- The daytime protection during operating hours (perhaps five days per week) typically relies on access control of the users and visitors by unarmed security guards. (Nuclear power plants operate 24 hours per day, seven days per week, and have security guards present at all times, usually armed.)
- The nighttime protection consists of locked doors and windows, a surrounding fence and patrol near the reactor by a guard, usually armed with a handgun. In some cases, the guard comes to the reactor periodically because he or she has other duties on a campus or in the research institute. (Nighttime protection at nuclear power plants is essentially the same as that during the day).

While research reactor protection levels tend to be lower than those of power reactors, research reactors pose lower radiological risks to the public from accidents than do power reactors. First, the core radionuclide inventories of research reactors are much lower than those of power reactors as a result of their lower power levels and often, shorter operating cycle lengths. Second, the lower decay heat in research reactor cores is associated with a lower risk of core melt and fission product release in the event of a loss-of-coolant accident (LOCA).

Nevertheless, the quantities of radioactive materials in research reactor cores and stored spent fuel can be substantial (on the order of millions of curies) and could present a significant radiological hazard if released into the environment. This risk is exacerbated by the fact that the regulatory regime governing the safety and security of research reactors is, as we have seen, considerably less stringent than that for power reactors. In fact, the NRC is inhibited from imposing strict regulations on research reactors by the U.S. Atomic Energy Act, which allows the NRC to impose "only such minimum amount of regulation . . . as will permit the Commission to fulfill its obligations under this Act . . . "[19]

Accordingly, compared to power reactors, U.S. research reactors generally lack thick-walled, leaktight and pressure-resistant containment structures. In addition, they have smaller population exclusion radii, less equipment redundancy and diversity, and less rigorous operator training programs, although specific requirements may vary widely.[20] Emergency planning requirements, including the size of emergency planning zones, if any, around the reactor are also decided on a case-by-case basis for research reactors, whereas all large power reactors must develop emergency plans for protecting the public within a zone of 10-mile radius.

The requirements of the NRC for physical protection of research reactors from sabotage thus provide a concrete example of requirements that are less stringent than those for power reactors. For power reactors, the NRC rules require that protection be provided against a sabotage threat thought to be realistically possible based on past experience, a threat termed the "design basis threat" (DBT) of radiological sabotage. This assumes "several" attackers with four-wheel drive vehicles, weapons, explosives, and assistance from an insider to the reactor.[21] Specific details of the DBT for each power reactor beyond this general threat—such as size, weaponry and tactics of the attacking force, or the size of the vehicle bomb—are "safeguards information" and not made public. To protect against their DBT, power reactor operators must have in place an NRC-approved security plan. These plans are site-specific, but in general require a nominal 10-member armed response force to deter an external attack, a background investigation program for employees to protect against the insider threat, and strict measures to control access of individuals and vehicles near "vital" areas of the reactor. Additional structural and sensor/alarm requirements have already been described.

In contrast to power reactors, U.S. research reactors are not generally required to protect against radiological sabotage, and do not have to provide an armed response to attack.[22] Research reactors are also specifically exempted from the requirement that they be protected from attacks by truck bombs. Exceptions are the class of research reactors operating at or greater than 2 MW for which the NRC has the authority to require additional measures to protect against radiological sabotage, depending on individual facility and site conditions.[23] However, these additional measures are likely to be secret.

Since research reactors that use HEU must provide security to protect this weapon-usable material from theft, they may also enjoy greater security protection against sabotage than LEU-fueled research reactors. However, given similar protection, power, and other characteristics, the radiological consequences of radioactive dispersal from a terrorist sabotage attack on an LEU research reactor would probably be about the same as a similar attack on an HEU research reactor. The total effective dose equivalent (TEDE) is dominated not by the actinides but by fission products (e.g., iodine and cesium), the inventories of which are very similar in HEU and LEU reactor cores.[24]

Research reactors in the U.S. receive authorization to operate by demonstrating that the risks to the public from "design-basis accidents" are below regulatory limits. Design-basis accidents are not, of course, worst-case accidents, but are judged to be of sufficiently high probability that they require regulatory consideration. Design-basis accidents typically give full credit to automatic scram systems, emergency core cooling systems (if present), operator intervention, and containment or confinement systems.[25] So-called "beyond-design-basis" or "severe" accidents involve multiple system failures and have the potential to result in greater damage and larger radiological releases than design-basis accidents, but do not have to be considered in NRC licensing (except, sometimes, in Environmental Impact Statements conducted under the U.S. National Environmental Policy Act).

When sabotage is considered, however, consideration of consequences similar to those of severe accidents becomes more important. While simultaneous multiple failures of safety systems are considered improbable if assumed to result from accidents, they could be induced by knowledgeable saboteurs intent on achieving a massive radiological release. Hence, a consequence analysis of a successful sabotage attack must consider scenarios more severe than the "design-basis" accident events analyzed in safety analysis reports, by relaxing some of the assumptions that limit the consequences of design-basis accidents.

This type of analysis is used in the U.S. to develop security plans for power reactors. Analysts draw on nuclear plant probabilistic risk assessments (PRAs) to identify "target sets"—minimum sets of systems that if simultaneously disabled would lead to "significant core damage" (meltdown). Security plans can then be devised to protect at least one element of any target set in the event of an attack, thereby preventing meltdown. In addition to core damage, terrorists could also damage containment or confinement systems, facilitating radiological releases to the environment.

For research reactors, core damage can result from several different classes of accidents, including reactivity excursions, blockage of primary coolant flow, and loss of primary coolant. The relative severity of these accident classes is dependent on reactor-specific issues, including design, power level, type of fuel, and the availability of additional on- and off-site safety systems. The lack of redundancy, diversity, and physical separation of safety functions at research reactors implies that target sets will be typically smaller than those for power reactors; hence saboteurs would need to attack fewer targets to achieve core damage.

Because research reactors in the U.S. are not required by the NRC to protect against the radiological sabotage DBT applicable to power reactors, there is no requirement that their operators carry out target-set analyses for their facilities. However, in the post-September 11 era, this type of analysis needs to be done on an urgent basis—it is an essential tool for identifying the vulnerabilities of research reactors and for developing plans to strengthen them.

CLASSIFICATION OF RESEARCH REACTORS

Based upon power level, we distinguish small, medium-sized, and large reactors in use today (Table 1). Research reactors with power levels below 100 kW are not considered in the remainder of this study because of their comparatively low fuel and radioactivity inventory.[26]

The radioactive inventory of a reactor core depends to a first approximation upon the total energy produced (i.e., fission events that have occurred) in the fuel of the reactor at the end of its life or equilibrium cycle. For more accurate estimates than those in Table 1, many additional reactor-specific data—such as fuel type, neutron flux and spectrum, or fuel management strategy and operating history of the reactor—have to be considered. To assess the potential impact of research reactor sabotage from the table, typical maximum fission product inventories are given.[28] Even under severe accident conditions, release fractions of the isotopes present in the fuel can vary from virtually 0% for some elements up to 100% for the noble gases. Off-site radiological consequences will

Table 1: Generic characteristics of today's research reactors by power level.[27]

	Small reactor	Medium-sized reactor	Large reactor
Power level	100 kW–1 MW	1 MW–10 MW	10 MW–250 MW
Designation (examples)	In particular: TRIGAs	MTR-type, some TRIGAs, IRTs	MTR-type, VVRs
Operational (world)	ca. 40 reactors	ca. 60 reactors	ca. 50 reactors
Reactor type	Pool-type	Pool or tank-type	Tank-type
Fissile inventory	Typically <5 kg U-235	Approx. 10 kg U-235	10 kg–40 kg U-235
Power density in core	<10 kW/liter	10–100 kW/liter	Up to 2,000 kW/liter
U-235 burnup	Typically <5%	20%–50%	20%–50%
Maximum fission product inventory of core	ca. 0.1 MCi (3.7×10^{15} Bq)	1–10 MCi ($37–370 \times 10^{15}$ Bq)	Up to 100 MCi (3700×10^{15} Bq)

be dominated by the cesium isotopes and the halogens, in particular the iodine isotopes. Together, these isotopes constitute 10–20% of the total fission product inventory, and both are expected to have high release fractions under severe accident or sabotage conditions.

There are many kinds of research reactors, and the next section will describe a few accidents at several reactors not among the major types as well as accidents in reactors that are among the major types. We discuss below some of the technical characteristics of the main research reactor types.[29]

Among the commonly used reactors with a thermal power of less than 1 MW, the TRIGA (Training, Research, Isotopes, General Atomics) reactors are predominant and, in fact, represent the most widely used research reactors in the world. Their fuel rods—one of the most distinctive characteristics of TRIGA's—consist of a uranium-zirconium-hydride (UZrH) alloy that moderates neutrons insitu, that is, in the fuel rather than in the water coolant. Fuel burnup is relatively low and very few fuel elements are exchanged over the life-time of the facility. While earlier TRIGA reactors were designed for HEU fuel, the more recently built reactors use LEU fuel.

The second "generic" reactor type is the Materials Testing Reactor (MTR) which is represented in all three size categories listed in Table 1. The original MTR was developed by Argonne National Laboratory and designed to irradiate and test materials to be used in other reactors. The reactor design, and especially that with aluminum-clad, plate-type fuel, was subsequently used as a "prototype" for numerous research reactors to be built in the U.S. and provided by the U.S. to other countries. Power levels reach from near zero-power (around 100 watts) to 250 MW for the largest research reactor of this type, the U.S. Advanced Test Reactor (ATR). MTRs, up to power levels in the low MW range, are open pool-type reactors, and cooling is either by natural convection or by pumping pool water through the core. In Table 1, medium to large-sized MTR-type reactors are usually tank-type in order to satisfy more demanding cooling requirements. Power densities of MTR-type reactors are as high as 2,000 kW per liter of core volume, significantly above those acceptable in TRIGAs. In contrast to TRIGA reactors, the larger MTR-type reactors do require a regular supply of fresh fuel. Most MTRs were, and some of them still are, HEU-fueled.

Most Soviet/Russian-designed research reactors are technically very similar to the MTR-type reactors of U.S. design and are equally based on aluminum-clad, plate-type fuel. The pool-type reactors of the so-called IRT-type are the main Soviet/Russian design of the medium-sized reactors in Table 1. Again, for cooling purposes, the Soviet/Russian reactors of higher power levels are tank-type. The main representatives of this class are the light-water-moderated reactors of the VVR class.

In Table 1, reactors operated at power levels above 10 MW are classed as large reactors. Among them are, in particular, the so-called high-flux reactors, which in some cases use a single fuel element to achieve a very compact core geometry. Also of the MTR-type (aluminum-clad fuel plates), due to the high power level and continuous operation, these reactors have a fuel demand on the order of 25–100 kg of uranium-235 per year and an elevated fuel and radioactive inventory in their cores. Technically, all these facilities are tank-type reactors with fully pressurized tanks due to the unusually high power densities and resulting cooling requirements.

CAUSES FOR RADIOLOGICAL RELEASES FROM RESEARCH REACTORS

The sabotage threat to research reactors can be characterized by identifying (a) sequences of events that could lead to core damage and radiological release, (b) the target sets corresponding to these sequences, and (c) the modes of attack that are capable of destroying or disabling these target sets. Several modes of sabotage attack are listed in more detail in the next section. They could include overt, armed commando-type assaults or attacks by stealth by outside groups—in either case with possible assistance from an insider. It is clear that the chances of success of an external attack would be greatly enhanced with the help of an insider who could supply design and security information, deactivate alarm systems and/or disable emergency safety systems. Damage to the reactor and reactor confinement system could also be caused by explosives delivered by hand, vehicle bombs or small aircraft. In addition, a knowledgeable insider may be able to use less violent but equally effective means to cause core damage.

One mode of sabotage that is not credible for power reactors but which may be possible for research reactors is the direct use of explosives next to the core to disperse the core. This is because, unlike a power reactor core, the mass of a typical research reactor core is comparable to the mass of explosives that could be easily transported to the site, and the core is likely to be much more accessible than the core of a power reactor. Also, the relatively low melting point of aluminum-matrix MTR fuel—on the order of 700°C—raises the possibility that use of an external explosive in tandem with pool draining could cause a core melt even if the decay heat of the fuel itself was insufficient to do so.

A recent survey of accident safety analysis reports for U.S. medium-sized and larger research reactors summarized a number of design-basis accident analyses.[30] The severity of these accidents is limited in most cases as a result of the assumption that engineered safety systems will work as designed. The potential for sabotage of research reactors to pose a significant public health threat depends on whether there are credible means for saboteurs to cause a beyond-design-basis radiological release. A review of some of the assumptions underlying the safety case for these reactors provides evidence that they are not immune from the risk of a core melt and dispersal resulting from carefully planned sabotage, even though the risk of such an outcome resulting from random accidents may be low. Some argue that the risk of core melt is much less than the risk of dispersal of large chunks of radioactive material close to the reactor. However, if the reactor has been operated, it will contain plutonium, and that could produce respirable airborne releases when vaporized by the detonation of high explosives in close proximity to the core.[31] The available energy density from such an explosion is on the order of 1300 calories per gram of explosive. The energy density needed to vaporize aluminum clad fuel in the rods of a research reactor is on the order of 200–300 calories per gram. With appropriate loading of the high explosive in proximity to the fuel rods, there should be enough energy from the explosion to melt and vaporize a significant part of the fuel—probably resulting in dispersal over a much wider area than would result from an explosion that produced only large chunks of radioactive material.

Reactivity Excursions

The potential for major reactivity excursions to cause large-scale melting and explosive disassembly of the cores of research reactors using aluminum-clad, aluminum-matrix fuel was demonstrated, both intentionally and unintentionally, several times early in the era of nuclear energy development.

- The 1.3 MW BORAX-I reactor was subjected to a large reactivity insertion in 1954 which caused most of the core to melt. Fuel-coolant interactions caused the tank to explode, scattering pieces of fuel plate as far as 200–300 feet away.[32]
- The 3 MW SL1-reactor experienced a serious reactivity excursion accident in 1961 due to rapid manual removal of a control rod by an operator. The core was destroyed and 10% of the fission products were ejected from the vessel.[33] Although sabotage has long been suspected as a possible reason for this event,[34] it has never been substantiated.
- The first Self-limiting Power Excursion Test (SPERT-I) in 1962 induced a large reactivity excursion that caused 35% of the core to melt and violently react with the primary coolant, resulting in a steam explosion and large pressure pulse that completely destroyed the core.[35] This test was used to establish design limits for maximum allowable reactivity insertions.

While lessons from these incidents have been incorporated into the design and operation of today's research reactors, prevention of such excursions is achieved by a reactor-specific combination of technical and administrative measures. A review of design-basis reactivity excursion events indicates that in most cases, credit for termination of the event is given to automatic reactor "trips" triggered by excessive power, excessive neutron flux, or a short reactor period. Thus if the scram mechanisms were disabled by tampering with their instrumentation and control systems, there would be no means to terminate a reactivity excursion induced by a saboteur beyond the negative reactivity coefficient inherent in the core design.

For rapid reactivity insertions, negative reactivity feedback may terminate the excursion even if automatic scram systems are disabled. However, saboteurs with some nuclear engineering knowledge would be able to avoid this setback by choosing the rate of reactivity insertion and the initial conditions appropriately. TRIGA reactors may be less susceptible to reactivity excursions, since they are designed for pulsed power operation.

Flow Blockage

Some reactors appear to be quite vulnerable to coolant inlet flow blockage resulting from intrusion of foreign material. For example, in 1961, the inadvertent failure to remove a plastic sight-glass from the reactor tank at the Engineering Test Reactor at Idaho National Engineering Laboratory led to the melting of 18 plates in six elements. At least three MTR-type research reactors have experienced accidents of this type.[36]

The operators of one important university research reactor, a 5-MW MTR-type, consider coolant flow blockage in the fuel element containing the hottest fuel plate to be the "maximum hypothetical accident" (MHA).[37] The blockage is assumed to result from a foreign object that falls into the core tank. The consequences of this event are limited because the reactor's "Safety Analysis Report" postulates that only an object small enough to pass through one of the fuel nozzle inlet openings would cause a problem, and boiling would occur only in the blocked channel, resulting in the melting of only four fuel plates (or approximately 1% of the core). Multiple systems exist to alert operators to the event and allow them to intervene. Finally, the operators' analysis credits the ventilation dampers in the containment building, which are automatically triggered by high radiation levels in the containment atmosphere.

This is clearly not the most severe event that could be caused by sabotage. A saboteur need not be limited to a single foreign object; a sack full of correctly sized objects thrown into the tank could cause much more widespread fuel melting. And in considering a sabotage scenario, credit should not be awarded to operator intervention or to automatic scram and ventilation damper systems that could be easily disabled by overt attack, prior covert tampering, or insider assistance in the control room. Thus the consequences of this event could be significantly greater than those presented in the Safety Analysis Report.

Estimates for similar accidents at similar research reactors suggest that significant consequences could result. For instance, an analysis of a partial flow blockage event at the 5 MW, open-pool type Greek Research Reactor (GRR) in Athens found that nearly 10% of the fuel would be damaged.[38]

Loss-of-Coolant Accidents (LOCAs)

Some research reactors have found that the most severe design-basis accident is a large-break loss-of-coolant accident (LOCA). For instance, at the GRR, it was calculated that a guillotine break of the largest pipe connected to the bottom of the reactor pool would lead to core uncovering in less than 30 minutes and core damage in about an hour, assuming that the reactor was tripped at the time of the rupture. About 20% of the core was predicted to melt as a result of this event.[39] If the reactor had not been tripped, the rate and extent of melting would have been more severe. Clearly, such a LOCA could be caused by a sabotage attack, utilizing explosives to damage the reactor piping or pool bottom. Thus, three classes of accident initiators at research reactors have been shown to lead to core damage, and all could be initiated by sabotage.

The consequences of severe core damage leading to large radiological releases must be considered to evaluate fairly the need for enhanced security and emergency planning measures at research reactors. A calculation of possible releases using the "MACCS2" consequence assessment code was performed for a generic 5MW MTR-type reactor. The calculation assumed an equilibrium core radionuclide inventory and an extensive core melt. No credit was provided for the containment system, since an attacking force could easily penetrate the containment building or open the dampers. Few research reactors have robust, leak-proof containment that could withstand a significant explosive load. Containments often have dampers or vents that can be opened. A huge hole is not necessary to vent a significant fraction of the radioactive nuclide inventory of the containment.

The core inventory was drawn from the safety analysis report used as an example in the flow blockage discussion above, and the radionuclide release fractions were drawn from the assumptions of safety analysis reports for the German pool-type reactor BER II.[40] These assumptions were: 100% for noble gases and halogens, 61% for cesium, 7% for tellurium and 1% for low-volatiles.

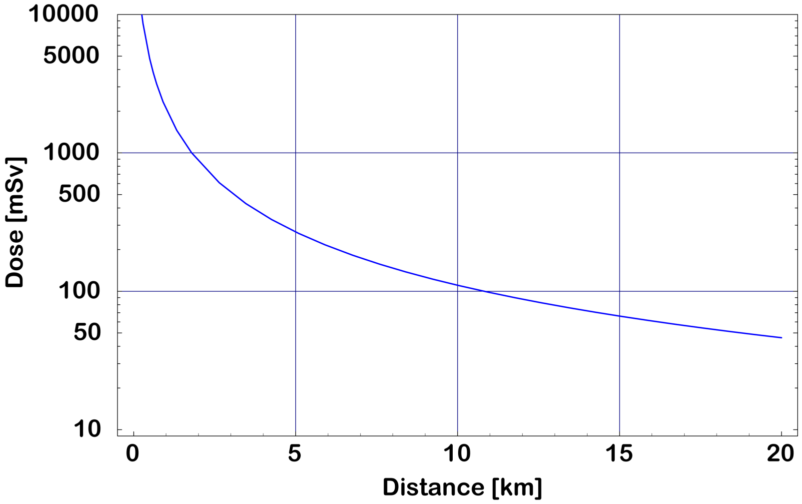

Figure 1: Thyroid dose, large release, 5 MW MTR.

The calculation estimated peak downwind doses to the thyroid and total effective whole-body dose equivalents for adults due to exposures incurred within a one-week period after the accident. (Figures 1 and 2). Peak doses at 0.035 km from the release point were 1.86 Sv whole-body and about 9 Sv thyroid. The

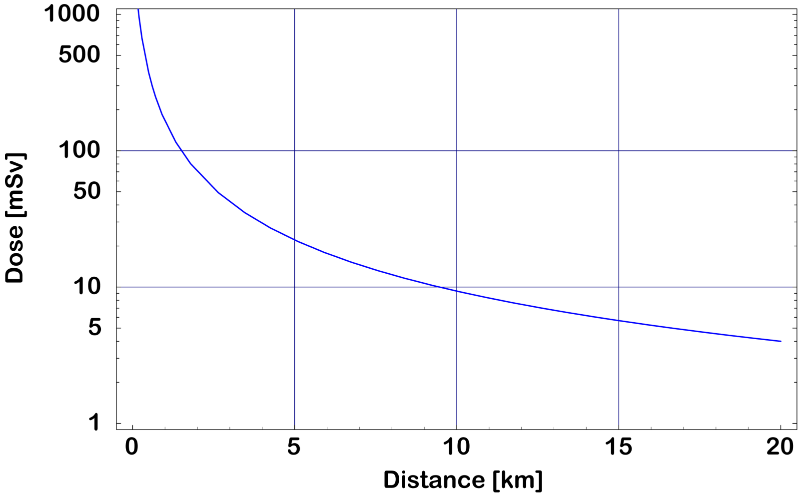

Figure 2: Whole-body dose, large release, 5 MW MTR.

peak whole-body doses exceeded 0.01 Sv (the Environmental Protection Agency trigger value for consideration of evacuation) as far as 14 km from the release site. Peak thyroid doses exceeded 0.1 Sv (the Food and Drug Aministration trigger value for administration of potassium iodide for adults under 40) at over 8 km from the release site.

These results are of concern because of the proximity of some high-power research reactors to populated areas. For example, for the exclusion zone for the university reactor used as an example in the preceding discussion of "flow blockage," the distance to the nearest point of public pedestrian or auto traffic is only eight meters and the distance to the nearest point of public occupancy is only 21 meters. Given that the consequences of a terrorist sabotage attack on a medium to large research reactor such as this could be significant for several kilometers downwind, serious consideration should be given to improving emergency planning in the proximity of such large research reactor sites, including evacuation planning and the distribution of potassium iodide, especially for children.

MODES OF SABOTAGE ATTACK

The preceding section describes potential threats to research reactors based largely on past experience with accidents and tests, not major sabotage attacks on research reactors—because none have yet occurred so far as we know, except for the 1981 Israeli military aircraft bombing on an Iraqi research reactor. Given the catastrophic damage clearly intended by the September 11 attacks, we list below potential future attack modes that might have severe consequences as great as those described in the preceding section. The following modes of attack might be used against a typical research reactor such as those included in Table 1. They are examples based upon past terrorist attacks on other facilities and upon the weapons known to be available to terrorists, or that could be available to terrorists.

Higher Probability Attack Modes

Raid

A group of terrorists covertly puts explosives next to the core or vital system support components of the research reactor and at the fresh and spent fuel storage site; later, by remote control the group detonates the explosives. This would require a detailed study of the onsite conditions and/or help of an insider, military-style training, automatic weapons, explosives, and remote triggering mechanisms. The feasibility of such an attack is possibly high in the U.S. (See the first three paragraphs of the preceding section).

Truck Bomb

Such an attack could be carried out in two ways.

(1) Truck bomb is detonated near the perimeter fence, aimed at vital system support components of the research reactor, or
(2) Suicide commandos, equipped with several four-wheel-drive vehicles, break through the barrier, drive towards vital system support components and detonate on-board explosives.

In case (1), insider support is crucial for supplying the information on blast-susceptible areas of the research reactor; furthermore, a four-wheel-drive vehicle capable of transporting about 1 ton of the explosive material close to the perimeter fence is needed. Case (2) would require a suitable truck loaded with explosives, capable of breaking through the fence(s) and/or concrete barrier(s), with other trucks following through the gap created by detonation of the first truck.

The feasibility of either truck bomb attack mode is considerable. Large truck bombs have been used successfully against nonreactor U.S. facilities by terrorists in the past (e.g., U.S. Embassy in Beirut, April 1983; U.S. Marine barracks and French military headquarters in Lebanon, 1983; World Trade Center in New York City, 1993; Oklahoma City Federal Building, 1995; Khobar Towers, U.S. military housing in Saudi Arabia, 1996; two U.S. embassies in East Africa, 1998).

Lower Probability Attack Modes

Anti-Tank Weapons

One or more vehicle-mounted rocket-propelled grenades are fired against vital system support components.[41] Insider support would be crucial for supplying the information on grenade-susceptible areas of the research reactor; also, direct line of sight to the reactor from the grenade launching site is essential. Rocket-propelled grenades are widely available at relatively low cost on the black market. They are the weapon of choice in the hands of terrorists whenever a concrete and/or steel layer is to be overcome in an attack (e.g., concrete building; armored vehicle).

Airplane or Helicopter

Two modes of attack are feasible.

(1) Suicide commandos crash several hired business jets (loaded with explosives and fully fuelled), or crash a hijacked large civilian aircraft (fully fuelled), into a research reactor.
(2) Terrorists fly several hired helicopters or a refurbished and rearmed surplus military attack aircraft in an attack on a research reactor with military weapons.

Case (1) requires suicide commandos, trained to crash civilian aircraft into a research reactor; case (2) requires training in flying a helicopter or military plane, as well as the acquisition of military weapons, such as rocket-propelled grenades. Both scenarios require adequate time to deviate from the cleared flight plan (despite many flight restrictions near nuclear establishments) in order for the plane(s) or weapons to hit the research reactor.

For both cases, feasibility is low to medium. Although it is relatively easy to lease business jets, considerable skills are needed to actually hit the small cross-section of the target area of a research reactor to cause an uncontrolled release. On the other hand, criminals have demonstrated successfully the use of chartered or hijacked helicopters to attack security facilities (e.g., for armed jail breaks). Furthermore, the high speed of a military plane would increase the surprise element in the attack, and its sophisticated arms are likely to inflict significant damage (e.g., the 1981 Israeli aircraft bombing and destruction of the Iraqi research reactor).

RESEARCH REACTORS AT RISK

Table 1 gives examples of the sizes and types of reactors that may be most at risk. The many small reactors that are operated at power levels lower than 100 kw have not been considered here because of their comparatively low radioactive inventory. They probably constitute a little more than half the total number of research reactors in the world.[42]

Of the classes described after Table 1, TRIGA type research reactors are less susceptible to sabotage than are other types of research reactors due to their inherent shutdown capability based on a high negative temperature coefficient of reactivity. Pool-type MTR reactors, whose power is usually below 2 MW, are probably more susceptible to sabotage than the TRIGAs. Smaller MTRs, not big enough to need a tank and also without a containment building, may present easier targets to attack, but their core inventories and therefore their radioactive releases will be lower. MTR type reactors with separate fuel storage pools are more amenable to damage (due to pool water loss and core uncovering) than are the MTR type reactors that have an interconnected fuel storage pool. High flux reactors (HFR), due to their generally larger inventory, and higher fissile volumetric density cores, could present more attractive targets to terrorist groups bent on sabotaging a nuclear facility. However, these reactors are generally located away from population centers and better-guarded than smaller reactors (at least in the U.S.). Additional factors that may help determine the susceptibility of a research reactor to a terrorist sabotage threat are the availability of a guard force on site, and the terrorist's knowledge of how to manipulate the reactor's control system so as to remove the control rods from the core.

ASSESSING RESEARCH REACTORS ACCORDING TO RISK

Within each broad class of research reactors, there exists a further assessment of reactors based on common factors. Here we will review some factors that might affect the priority assigned for remedial action. These ranking factors are equally applicable when conducting an actual assessment of the specific risk profile of each individual research reactor. Among the most salient factors we include:

Political Environment

This is the most sensitive and the least publicly discussed factor, yet it is highly relevant. Nuclear facilities in a country at war or with internal political instability may be more likely to be exposed to the possibility of an attack by a terrorist group than would similar facilities located in a country enjoying a more stable political situation or less likely to be attacked by terrorists for other reasons. Furthermore, a country in an unstable political situation may not have the financial or other resources to provide adequate protection for nuclear facilities within its territory.

Location

In general, research reactor sites include suburban locations on university campues, urban locations at university or industrial research centers, and remote locations in well-guarded national laboratories or research centers. For the terrorist bent on a sabotage attack, the reactor located in an urban environment would represent the best target, all other factors being equal, followed by the reactor located in a suburban campus, and then the reactor located in a remote national laboratory.

Security Culture at Reactor

The more stringent the security protection culture in a research reactor facility, the less tempting a target it is likely to present to a prospective terrorist group. In general, better physical protection measures are available at remote national laboratory sites that are guarded by a government-established force than would be expected in a reactor located in a suburban campus and guarded mostly by campus police. An urban reactor may fall in between these two extremes, depending, often, on what type of organization operates the reactor. We should stress here that we refer to all aspects of the security or physical protection culture, not just to the availability of guard forces. Other factors that contribute to this culture include: adequate (initial and routine) screening and training of the guard personnel; adequate physical barriers around the reactor facility to prevent truck bomb attack; adequate locks, intruder sensors and physical barriers to entry, the availability of a containment structure, and the implementation of communication systems and procedures with local and regional security forces.

Financial Resources Available

This is of course important because guards, barriers, sensors, and so forth can be expensive to support and maintain. Research center financial resources may diminish with age as the reactor is less used.

CONCLUSIONS

We conclude that terrorists could do considerable damage through a sabotage attack on a research reactor of medium or larger size, and that these reactors are generally not as well protected from outside attackers as nuclear power reactors. The consequences of a successful sabotage attack could be significant radioactive release and contamination of an area near the reactor site. Since many research reactors, unlike most power reactors, are located within or close to populated areas, they may present a greater threat of disruption to the public from a sabotage attack than do most power reactors.

Research reactors could be attractive targets for sabotage because terrorists' dispersal of reactor fuel could result in significant doses of radioactivity to local populations. The presently applied regulatory framework in many countries needs to be improved to meet the additional threats posed by the new terrorists. In addition, we recommend that operators of research reactors, at least those with power greater than 100 kw, consider what terrorist threats to their reactors may exist after September 11 and whether the physical security of their reactors is adequate to those risks. We also recommend that they consider enhanced emergency planning to deal with possible threats; that they institute background checks for all those regularly present at their reactors including of course employees but also student users and operators; and that they consider strengthening their guard forces to add stronger weaponry and new training on potential terrorist threats and how to deal with them.

NOTES AND REFERENCES

1. See, e.g., U.S. Nuclear Regulatory Commission (NRC), "NRC Will Order All Nuclear Power Plants and Key Facilities to Enhance Security," NRC News No. 02-018 (Sept. 27, 2002), available at ⟨www.nrc.gov⟩; G. Bunn and F. J. Steinhausler, "Guarding Nuclear Reactors and Material from Terrorists and Thieves," *Arms Control Today* (Oct. 2001), p. 8; M. Bunn and G. Bunn, "Nuclear Theft and Sabotage: Priorities for Reducing New Threats," *IAEA Bulletin* (v. 4, no. 2, 2001), p. 20; G. Bunn and L. Zaitseva, "Efforts to Improve Nuclear Material and Facility Security," *SIPRI Yearbook 2002*, App. D, p. 74; R. Alvarez, J. Beyea, K. Janberg, J. Kang, E. Lyman, A. MacFarlane, G. Thompson, F. N. von Hippel, "Reducing the Hazards from Stored Spent Power-Reactor Fuel in the US," *Science and Global Security* (v. 11, No. 1, 2003), p. 1.

2. See, e.g., O. Bukharin, C. Ficek and M. Roston, "U.S.-Russian Reduced Enrichment for Research and Test Reactors (RERTR) Cooperation (RANSAC, 2002), p. 6.

3. The Convention on the Physical Protection on Nuclear Materials presently provides protection standards only for nuclear material in international transport. Since 1999, experts have been meeting to agree upon an amendment that would make the treaty applicable to nuclear material within a country and not in international transport. The current drafts of possible amendments would provide some useful general principles but no numerical or other specific standards. Even if these are adopted by the treaty's parties, putting them into effect for all the countries with research reactors will take many years.

4. Nuclear Suppliers' Guidelines, IAEA Information Circular 254, Revision 4 (2000), Part 1, par. 3 and Annex C. This annex contains a few specific provisions that are recommended for agreement, such as placing weapon-usable nuclear material (e.g., 5 gm or more of HEU) under guard and limiting access to persons "whose trustworthiness has been determined."

5. IAEA Information Circular 225, Revision 4, 1999. See par. 6.1.1 and compare par. 6.2 with par. 7.3.

6. Nuclear Energy Agency, *Nuclear Legislation: Analytical Study: Regulatory and Institutional Framework for Nuclear Activities* (NEA: Organization for Economic Cooperation and Development, 2000 and 2001 supplement); see also International Nuclear and Radioactive Material Working Group, "Reducing the Threat from the Loss of Control over Nuclear and Other Radioactive Material," Report for European Forum, Institute for International Studies, Stanford University (2002), pp. 27–34, 49–53.

7. G. Bunn, F. Steinhausler, L. Zaitseva, "Could Terrorists or Thieves Get Weapons Usable Material from Research Reactors and Facilities?" Paper for the Institute of Nuclear Materials Management 43rd Annual Meeting, June 2002; see also International Nuclear and Radioactive Material Working Group, above.

8. M. H. Soo Hoo, D. Ek, A. Hageman, T. Jenkins, C. Price, and B. Weiss, "International Physical Protection Advisory Service: Observations and Recommendations for Improvement," Proceedings of the 42nd Annual Meeting of the Institute of Nuclear Materials Management (2000).

9. See, e.g., G. Bunn, C. Braun, and F. Steinhausler, "Terrorism Potential for Research Reactors Compared with Power Reactors: Nuclear Weapons, 'Dirty Bombs,' and Truck Bombs," International Conference on Physical Protection, Strengthening Global Practices for Protecting Nuclear Material," September 8–13, 2002, University of Salzburg, Austria.

10. Bukharin, Ficek, and Roston, above, p. 6.

11. See A. Travelli, "The Reduced Enrichment for Research and Test Reactors (RERTR) Program," Center for International Security and Cooperation Summer Study, Stanford University (2002).

12. See U.S. Department of Energy, *Final Environmental Impact Statement on a Proposed Nuclear Weapons Nonproliferation Policy Concerning Foreign Research Reactor Spent Nuclear Fuel,* App. B (DOE/EIS 0218F, 1996), v. 2.

13. Bukharin, Ficek and Roston, above, p. 5; International Atomic Energy Agency, *Nuclear Research Reactors of the World*, IAEA Reference Data Series No. 3 (Vienna, 2000), Tab. 9.

14. See T. P. Mustin, M. Clapper, and J. E. Reilly, "A Continuing Success: The U.S. Foreign Research Reactor Spent Nuclear Fuel Acceptance Program," International RERTR 2000 Meeting, Las Vegas, NV (2000).

15. The U.S. recently announced that five larger research reactors will be converted to LEU by 2012.

16. See M. and G. Bunn, "Strengthening Nuclear Security against Post-September 11 Threats of Theft and Sabotage," *Journal of the Institute of Nuclear Materials Management* (Spring 2002), pp. 48–49.

17. Stanford University Center for International Security and Cooperation, Illicit Trafficking Data Base: DSTO (2002).

18. Bukharin, Ficek and Roston, above, p. 6.

19. U.S. Atomic Energy Act of 1954, as amended, Sec. 104(b).

20. U.S. NRC, Division of Systems Analysis and Regulatory Effectiveness, *Survey of Research Reactors* (undated), ADAMS Accession Number ML003706367.

21. “Radiological sabotage” is defined by the NRC as “any deliberate act directed against a plant or transport . . . or against a component of such a plant or transport which could directly or indirectly endanger the public health and safety by exposure to radiation” (10 Code of Federal Regulations, Sec. 73.2).

22. U.S. research reactors that possess special nuclear material (SNM) must provide protection against unauthorized removal of that material. However, even if the amount of SNM exceeds a “formula quantity,” 5 kg for HEU, an armed response capability is still not required. See E. Lyman and A. Kuperman, “A Reevaluation of Physical Protection Standards for Irradiated HEU Fuel,” 24th International Meeting on Reduced Enrichment for Research and Test Reactors (RERTR-2002), Bariloche, Argentina, November, 2002.

23. 10 Code of Federal Regulations, Sec. 73.60(f).

24. I. G. Kollas, “Research Reactor Accidents: Analysis and Impacts,” Fourth International MACCS Users Group Meeting, Sept. 6, 2002, Monte Carlo, Monaco.

25. It is important not to confuse the terms “design-basis threat” and “design-basis accident.” The design-basis threat of sabotage could be capable of causing abnormal conditions that go well beyond a design-basis accident.

26. The IAEA lists 132 operational research reactors with less than 60 kW constituting roughly 50% of the total. International Atomic Energy Agency, *Nuclear Research Reactors in the World*, note 13 above, Figure 7.

27. Typical values derived from data collected in R. R. Burn, ed., *Research, Training, Test, and Production Reactor Directory. United States of America.* Second Edition (American Nuclear Society: La Grange Park, 1983). Number of operational reactors in the various categories from IAEA, note 13 above.

28. Actinides do not contribute significantly to the total radioactive inventory during operation or shortly after discharge of irradiated fuel.

29. There are many additional research reactor types that do not fit in any of the design characteristics described above. Among them are liquid and aqueous homogeneous reactors, in which the fuel is a uranium-compound in solution. In addition, there are graphite-moderated and organic-moderated reactors. Other research reactors were envisioned as prototypes for future commercially operated reactors. They include, in particular, prototypes of fast breeder reactors, which are often classified as research reactors. Finally, in some cases, research reactors have been used for military applications, such as producing plutonium for nuclear weapons, leading again to particular fuel and facility designs.

30. U.S. NRC, *Survey of Non-Power Reactors*, pp. 3–7.

31. See C. M. Steele, T. L. Wald and D. I. Chanin, “Plutonium Explosive Dispersal Modeling Using the MACCS2 Computer Code,” U. S. Dept. of Energy, Los Alamos Area Office Technical Report (April 1998), p. 2.

32. Argonne National Laboratory-West Reactor Homepage, www.anlw.anl.gov/anlw_history/reactors.

33. W. E. Nyer, G. O. Bright and R. J. McWhorter, “Reactor Excursion Behavior.”

34. D. Ford, *Cult of the Atom* (Simon and Schuster, New York: 1982), p. 204.

35. U.S. NRC, *Survey of Non-Power Reactors*, p. B-2.

36. I. G. Kollas, *Research Reactor Accidents*, p. 2.

37. *Safety Analysis Report for the MIT Research Reactor (MITR-III)*, Rev. 1 (Nuclear Reactor Laboratory, Massachusetts Institute of Technology, Cambridge, MA, February 2000), Sec. 13.1.1.

38. I. G. Kollas, *Research Reactor Accidents*, p. 3.

39. I. G. Kollas, *Research Reactor Accidents*, p. 4.

40. R. Boehert et al., "Differences in the Radiological Effects of a Major Accident Using HEU or LEU Fuel Elements at the BER II," JAERI-M 94-042, RERTR conference (1994).

41. Some such grenades are powerful enough to penetrate up to 1 meter of steel from a range of 2 km.

42. See note 26.