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The radiological threat: verification at the source

Klaas van der Meer

Soon after the discovery of radioactivity it became clear that it not only had beneficial properties but could also pose health risks caused by irradiation, from both external contamination of the skin and internal contamination by digestion or inhalation. Safety standards were progressively developed to protect radiological workers and the public against the hazards of ionizing radiation, for example, by ensuring safe work practices and adequate shielding. Such safety measures are intended to prevent accidental exposure to radioactive materials.

But since the dawning of the nuclear age there has also been a preoccupation with the possibility that fissionable nuclear material, such as plutonium and high enriched uranium (HEU), might be used for hostile purposes. In addition to the fact that such materials can be used in nuclear weapons, there has also been concern that they might be dispersed by conventional explosive to cause widespread death and injury. The multilateral disarmament negotiating body in Geneva, the Committee on Disarmament (subsequently the Conference on Disarmament (CD)) attempted for many years to negotiate a Radiological Weapons Convention which would have banned the use of conventionally-dispersed fissionable material for hostile purposes.[1] Such efforts were abandoned in 1993 as a result of the CD's preoccupation with negotiating a Comprehensive Nuclear Test Ban Treaty (CTBT). The negotiations have never been resumed.

By the beginning of the 1990s there was a growing realisation that non-fissionable radioactive sources might also be used for hostile purposes through dissemination by conventional explosives.[2] They could, at the very least, be used to create panic and thereby societal and economic chaos. These factors and the ease with which their component materials could be obtained could make them attractive to terrorists.

Such a device has come to be known as a radiological dispersion device (RDD) or by the general public as a 'dirty bomb'. The terrorist attacks on the United States on 11 September 2001 greatly increased fears that RDDs would be used sooner rather than later. However, despite the notable increase in awareness of the threat, only a few countries have adopted or adapted legislation to deal with it.

The International Atomic Energy Agency (IAEA) plays an important role in the security of nuclear and radioactive materials to prevent terrorist and other malevolent activities, such as the illegal possession, use and transfer of and trafficking in these materials. In September 1994 the General Conference of the IAEA adopted a resolution that called on its members to 'take all necessary measures to prevent illicit trafficking in nuclear material'.[3] In December 1994 the IAEA's then Director General, Dr Hans Blix, called for other radioactive sources to be dealt with in similar fashion.[4] The key role of the IAEA is shown by its management of the recently established Nuclear Security Fund, which aims to reduce the threat of terrorist use of nuclear and other radioactive material; the maintenance of an Illicit Trafficking Database, in which states can register illegal actions regarding nuclear and other radioactive material; and the recent revision of a Code of Conduct on the Safety and Security of Radioactive Sources.[5] The last General Conference of the IAEA in September 2003 asked the current Director General, Dr Mohamed ElBaradei, to continue his efforts to improve nuclear and radiological security and asked the member states to support these efforts.[6]

This chapter examines the nature of RDDs, the threat they pose, and how accounting, monitoring and verification might help deal with the threat. On the basis of the technology and materials needed to construct an RDD, the chapter discusses the relevance of the IAEA safeguards system to the establishment of national measures for preventing the misuse of radioactive sources. It concludes that elements of the IAEA safeguards system can be used as a model.

What is an RDD?

The aim of a radiological dispersion device is to contaminate a large area with radioactive material in order to cause maximum havoc and disruption. The most frequently cited scenario is the dispersal of the radioactive material using conventional explosives, although other means, such as aerial dissemination, could also be used.

The amount of explosive needed for the dispersion appears to be surprisingly low. Only 2.5–5 kilograms (kg) is sufficient if the radioactive material is highly dispersible. This is the case for caesium-137 (^{137}Cs).

The area that will be contaminated depends in part on the effectiveness of the dispersion, which will in turn be determined by factors such as the quantity of the explosive charge, the physical state of the radioactive material, the amount of radioactive material, weather conditions and the type of landscape (for example, a built-up area or open terrain).

Radioactive material

If a terrorist intends to cause maximum havoc and disruption, the radioactive material chosen should have a reasonably long half-life, in the order of a year or longer. The most obvious candidates from this perspective are the beta-gamma

Table 1 **Half-life and type of radiation emitted by isotopes that could be used in an RDD**

Isotope	Half-life	Radiation type
Manganese-54 (^{54}Mn)	312.1 days	γ
Cobalt-60 (^{60}Co)	5.3 years	β, γ
Strontium-90 (^{90}Sr)	28.78 years	β
Silver-110 (^{110}Ag)	249.8 days	β, γ
Cadmium-109 (^{109}Cd)	462.6 days	γ
Barium-133 (^{133}Ba)	10.53 years	γ
Caesium-137 (^{137}Cs)	30.07 years	β, γ
Europium-152 (^{152}Eu)	13.54 years	β, γ
Europium-154 (^{154}Eu)	8.59 years	
Iridium-192 (^{192}Ir)	73.8 days	β, γ
Plutonium-238 (^{238}Pu)	87.7 years	α
Americium-241 (^{241}Am)	432.7 years	α
Californium-252 (^{252}Cf)	2.65 years	α

Note The isotopes are ordered by the number of protons that the nucleus contains.
Source Josef R. Parrington *et al.*, *Nuclides and Isotopes,* 15th revised edn, Knolls Atomic Power Laboratory, San Jose, CA, 1996.

(β, γ)-emitters cobalt-60 and caesium-137, and to a lesser extent the beta (β)-emitter strontium-90 (^{90}Sr) and the beta-gamma (β, γ)-emitter iridium-192 (^{192}Ir). Some of the more 'exotic' radionuclides or mixtures cannot be excluded completely.[7] Table 1 gives some basic data on isotopes that could be used in an RDD. The amount of radioactive material needed to contaminate a large area is estimated to be about 1,000 Curies (Ci) or several grams, depending on the isotope that is used.[8]

Availability

Access to the material would have to be relatively easy and it should be available in sufficient quantities. In terms of availability, cobalt-60 and caesium-137 are the most common isotopes, while strontium-90, iridium-192 and the alpha (α)-emitters plutonium-238 (^{238}Pu), americium-241 (^{241}Am) and californium-252 (^{252}Cf) are also available in large quantities. All are frequently used in medical and industrial equipment. The other isotopes listed in table 1 are less likely to be used for an RDD since they are not produced on an industrial scale.

Physical/chemical state

The physical/chemical state of the radioactive material used is important for the dispersion of the material in an RDD. Cobalt-60 is normally produced in metallic pellets. During an explosion it will be dispersed in small metallic fragments. Cleaning of the contaminated area will be limited to the search for and collection of these particles with the help of Geiger-Müller counters, which are cheap and easy to use. Although time-consuming, the clean-up will be relatively straightforward. Caesium-137, however, takes the form of a powdery salt and is often highly dispersible, so that decontamination of an area would be very difficult and time-consuming. Strontium-90 also occurs in the form of a salt and, like caesium-137, is extremely dispersible. Iridium-192 is produced in the form of metallic pellets and has the same qualities as cobalt-60. The α-emitters plutonium-238, americium-241 and californium-252 are produced in the form of oxides. The oxide particles are not sintered (formed into a hard crust) and therefore have a small diameter (10–50 μm), which makes them highly dispersible.

Containment vessel

The safe transport of a strong radioactive β, γ source requires a shielding container, which would normally be made of lead and weigh several hundred kilograms (kg), even up to 1,000 kg. Such a container is not easy to handle and has a considerable volume (20–80 litres). Even suicidal terrorists will not be able to handle an unshielded radioactive source with a strength of 1,000 Ci for longer than one hour within a range of 1 metre from the source. Although α radiation requires hardly any shielding, most α-emitters also emit β, γ radiation and therefore require the same shielding as β, γ radiation. On top of that, californium-252 emits neutrons and requires shielding by light materials such as plastics or water. The thickness of this shielding should be about 40–50 centimetres (cm). This will considerably increase the volume of the shielding container and therefore the visual detectability.

Conventional explosive

The conventional explosive used in an RDD could be ordinary trinitrotoluene (TNT). This is readily available to terrorists and has sufficient propellant force for the radioactive material to be dispersed. The amount of explosive needed for an RDD is estimated to be between 2.5 and 5 kg of TNT. Other means of dispersion will not be discussed here, although one possibility is aerial spraying.

Consequences of the use of an RDD

The main consequences of use of an RDD will be loss of life through direct impact of the explosion and contamination. Direct casualties due to the impact of the explosion are likely to be limited and there will probably be no immediate casualties from radioactive contamination (the 'deterministic effects of radiation'). In the long run, however, contamination may cause casualties (through the 'statistical' effects, such as radiation-induced cancer and genetic defects in future generations), but probably fewer than commonly claimed in public discussions.[9]

The types of radiation emitted by the RDD isotopes that are most likely to be used have different effects. When inhaled or ingested, α radiation involves heavy particles that can cause great damage to the human body. It does not pose a health risk outside the human body, since the outer dead layer of the human skin absorbs all its energy. β, γ radiation involves light particles (β) or electromagnetic radiation (similar to light, ultra-violet (UV) light or X-rays) that are more penetrating and therefore harmful for human health, both as an internal and as an external source. They have a longer range and the damage they create in the human body is spread over a larger area than is the case for α radiation.

With respect to the number of likely casualties, an RDD is likely to have no greater impact than a conventional bomb. The real difference lies in the extent of radioactive contamination of a large area. Appreciative dispersion calculations performed to determine the spread of radioactive material after the explosion of an RDD have shown that a large area (0.28 square kilometre) can be contaminated by dispersing a source with a strength in the order of only 1,000 Ci.[10] This aspect of contamination is likely to cause widespread public panic, fear and uncertainty. Depending on the physical state of the radioactive material, the decontamination costs may be very high. Decontamination will be time-consuming and will need to take place immediately after the contamination occurs, since the radioactive particles will increasingly stick to buildings and other surfaces the longer they remain.

There are also likely to be economic effects, such as a loss of real estate value, however temporary, and disruption to economic activity, at least in the immediate area. The Goiania incident in Brazil in 1987, when a radioactive source used for medical applications was illegally dumped in a junk yard, caused a fall in economic activity of 20 percent in Goiana, which the town took five years to recover from. However, relatively large amounts of radioactive source material are needed to contaminate a large area—a fact which will make a monitoring and verification system for controlling radioactive sources likely to be more effective.

Local and national governments play a very important role in reducing public fear of RDDs. The general public needs to be convinced, as shown by the dispersion calculations, that the radiation effects, even in close proximity to the explosion of an RDD, are relatively low compared to those that would result from an accident at a nuclear facility, such as a nuclear power plant. A policy of providing quick, open and reliable information to the public will reduce the likelihood of widespread panic and thereby frustrate the aims of the terrorists.

The likelihood of RDD acquisition and use

The Illicit Trafficking Database of the IAEA, inaugurated in 1996, lists some 330 'incidents' involving illegal trafficking in radioactive material.[11] Half of them involved radioactive material other than fissionable nuclear material (uranium and plutonium). The database includes only incidents that have been officially confirmed; the actual number is probably much higher. On the other hand, the definition of 'illicit trafficking' used by the IAEA includes any unauthorised act, whether there was an apparent intention to misuse the radioactive material or not. German statistics show that in 13 percent of unauthorised cases the source was stolen with the intention of misusing it.[12] The IAEA database shows a pronounced peak in 1994 and a less pronounced one in 1999–2000. It is not clear whether the decline in the number of incident reports is due to fewer actual incidents or to reluctance to report them, for instance, because this would show weak points in a country's security system.[13]

So far there has been only one confirmed case of an attempt to use radioactive material for terrorist purposes. In 1996 Chechen rebels placed a container containing caesium-137 in a Moscow park, but no dispersion of radioactive material occurred. The action was probably intended as a warning and not a real attempt to disperse the material. In June 2002 one Jose Padilla was arrested in the US and charged with planning a 'dirty bomb' attack in that country.[14] In June 2003 a large quantity of 100 grams (g) of caesium-137 intended for sale to terrorists was intercepted in Thailand. These and other incidents have created growing concern regarding the use of RDDs by terrorists.[15]

Production and presence of radioactive sources

Thousands of radioactive source materials have been produced worldwide. One or a combination of these sources contains sufficient material for an effective RDD. The main producers of radioactive isotopes are Argentina, Belgium, Canada, the Netherlands, Russia and South Africa. Canada is clearly the largest exporter of radioactive isotopes, but it is not easy to determine a clear ranking of the other countries by scale of production, since this depends on which isotope is considered. Moreover, these data are often not revealed for commercial reasons.[16] France is a minor player, while the US has a substantial market share only for some isotopes of concern (notably californium-252). End-users of radioactive sources are spread all over the world and number in the tens of thousands. They include hospitals, oil companies, food irradiators, research institutes and gauging companies. The level of security at most of these facilities, even those with strong radioactive sources, like food irradiators and hospitals, is low, since the emphasis is on safety rather than security. Most of them use sources that are not of concern because of their low activity or short half-life. However, for non-state actors it is easier to obtain radioactive material for an RDD from such sources than to obtain safeguarded fissile material.

IAEA safeguards: a model for verifying radioactive sources

Elements of the IAEA safeguards system may serve as a verification model for radioactive sources. The goal of IAEA safeguards is to prevent further horizontal nuclear weapons proliferation. The first version of IAEA safeguards system for fissile material was established in 1961.[17] The system has developed gradually into full-scope safeguards for verifying state party compliance with the 1968 Nuclear Non-Proliferation Treaty (NPT).[18] As a consequence of the 1991 Gulf War and the discovery by the United Nations Special Commission (UNSCOM) of Iraq's secret programme to acquire nuclear weapons, which Iraq had managed to pursue even though it was subject to full-scope safeguards, the IAEA developed additional measures to detect similar secret programmes. These measures are in part contained in an Additional Protocol to comprehensive safeguards agreements.[19]

The basis of the IAEA safeguards system is material accountancy. The materials that are verified are plutonium (Pu), uranium (U) and thorium (Th). These materials can be used directly for a nuclear weapon or converted (in a reactor) into material suitable for a nuclear weapon. Several measures are used to support the material accountancy system. The most important are visual inspections, destructive and non-destructive analysis, and containment and surveillance. Recently open source information and environmental sampling have been added to the verification tools.

Similar measures can be envisaged for verifying the non-diversion of radioactive sources. Again, the basis should be a reliable accountancy system to account for all relevant radioactive sources. Non-destructive analysis of sources, for example, by gamma-spectrometry, is an adequate measure to verify that a source is still in its containment vessel. Other measures will not be necessary.

IAEA safeguards are based on the ability to detect diversion of what is called a significant quantity of fissionable material. This is the amount of material that is estimated to be needed for one nuclear weapon. For uranium-235 the significant quantity is 25 kg, for plutonium 8 kg and for thorium 20 tonnes. The latter is the amount of thorium that would need to be irradiated in a nuclear reactor to produce sufficient uranium-233 for a nuclear weapon.

In the case of RDDs, the verification of radioactive sources should be limited to those with sufficient strength to contaminate a large area. Based on dispersion calculations, an initial estimate of the source strength above which measures are needed is 1,000 Ci. Since this type of calculation still suffers from large uncertainties, a large safety margin has to be allowed for. We therefore assume that a source with a strength as low as 100 Ci can cause significant damage. Assuming further that terrorists could construct an RDD using several smaller sources, we arrive at a lower limit of 10 Ci for sources that need some kind of verification. Refinement of the calculations would be necessary to improve this estimate and to use it for safety and verification policy. The number of sources and the total amount of material that pose a high risk and thus need to be controlled are therefore limited.

The frequency of IAEA safeguards inspections is determined by the 'timeliness goal'. This is the time that is needed to convert nuclear material into a form suitable for use in a nuclear weapon. For example, plutonium in irradiated, highly radioactive nuclear fuel needs to be separated from the other radioactive isotopes before it can be processed for use. Another example is HEU in the form of oxide, which has to be converted into a metal before it can be used in a nuclear weapon. HEU and plutonium that are not mixed with other radioactive isotopes are considered 'direct-use material' and should be inspected every month. 'Indirect-use material' such as low enriched uranium is inspected only once a year.

The verification frequency of radioactive sources could depend on the physical/chemical state of the source material. Material that can be easily dispersed could be inspected with a higher frequency, since it is more likely that terrorists would try to obtain such material. It would also be possible to consider relaxing the inspection frequency for sources with intermediate strength, that is, between 10 and 100 Ci. One source would probably not contain sufficient material to contaminate a large area, although several sources would.

National controls on radioactive sources

From a historical point of view, the control of radioactive sources has been designed to prevent hazards to the health of radiological workers and the public arising from accidents. The main concern of legislation was, and in most countries still is, safety. This does not, however, mean that there has been no progress.[20]

In Europe, France, Germany and the UK have established satisfactory procedures for preventing the misuse of high-risk sources. Other countries, such as Belgium, also a major producer of isotopes, still lack a legislative framework and practical procedures for the security and physical protection of high-risk sources. Some East European countries, such as Poland, have also developed at least some practical procedures to detect illicit trafficking of radioactive sources. But a major problem is the cost of implementation. In Russia the legal framework for combatting illicit trafficking exists (including even a finely-tuned definition of fines and punishments), but patchy law enforcement—the result of a lack of financial resources, the size of the country and the extent and porous nature of its borders—is a major problem.

In the Americas, Argentina, one of the main producers of radioactive sources, is working on legislation and is already applying practical control measures. Sources for export are of special concern. The US is late in passing legislation, particularly concerning the export of highly radioactive sources under general licences. This is the case for many other countries.

In Africa the problems are of a different order of magnitude. In most cases a central organisation exists that is responsible for radiation protection, but many countries lack well-trained customs officers who are able to recognise and deal with illicit trafficking. Many African countries are aware of the problem and have requested the IAEA's assistance.

In Asia the situation varies. India, which has an extensive nuclear fuel cycle, implements controls only from a safety point of view and has not yet established measures to deal with illicit trafficking. China is in more or less the same position. It has admitted that even for safety purposes there are occasional problems because of the absence of a safety culture. Although there is little information available for Japan it can be assumed that safety procedures are well established, given that it has an extensive nuclear fuel cycle. However, recent incidents in Japan's nuclear industry raise some doubts with respect to implementation of its safety procedures and thus the monitoring of radioactive sources. The Central Asian states that were formerly part of the Soviet Union have problems that are similar to those of Russia itself.

In the Middle East, Israel has developed a control system for both safety and security reasons. Sources with a high risk are subject to the application of physical protection measures. Other countries in this region have a more limited approach to safety.

Possible preventive measures

Measures taken for the physical protection of fissile material against theft by terrorists are not an international obligation but a national responsibility. Similarly, measures to prevent the construction and use of a RDD also fall under national law. The IAEA has issued some guidelines about the physical protection of fissile material, but these are only binding during international nuclear transport.[21] No specific guidelines for preventing the use of RDDs have been issued so far, but the IAEA is making sustained efforts to increase the awareness of the danger, for instance, by organising conferences on the subject.

A conference in Dijon, France, in September 1998 concluded that regulatory bodies for the control of radioactive sources must be independent and supported by governments, and must have an overview of all radioactive sources in the particular country; that radioactive sources must not disappear from the control system (the 'cradle-to-grave' philosophy); that efforts must be made to regain control over lost, abandoned or stolen ('orphan') sources; that the capability to detect illegal transport of radioactive sources must be improved; that an effective national regulatory body operating with suitable means is the key to avoiding orphan sources; that governments should create such a body if one does not exist; that governments should provide such a body with sufficient resources; and finally that efforts should be made to improve international co-operation in the effective operation of national regulatory bodies.[22] The conference resulted in the IAEA General Conference in 1998 encouraging all governments to 'take steps to ensure the existence within their territories of effective national systems of control for ensuring the safety of radiation sources and the security of radioactive materials'.[23]

In December 2000 a conference in Buenos Aires, Argentina, concluded that an essential component of improving the safety and security of radioactive sources is knowledge.[24] Training and education are therefore essential for regulatory staff, and developed countries were requested to support developing countries in this respect. It was also recognised that many countries still lack adequate control systems for radioactive sources. The need to establish continuous control of such sources during their complete lifetime was reiterated. The establishment of storage facilities for disused sources was advocated if disposal facilities were not (yet) available. Like the Dijon conference, the Buenos Aires conference emphasised the danger of orphan sources and the importance of developing national strategies to detect and recover them. The criminal misuse of radioactive sources was already considered an important issue and closer co-operation at both a national and international level was recommended to prevent such activities.

A conference in Stockholm, Sweden, in May 2001 dealt with the illicit use of both nuclear material and radioactive sources.[25] It focused on measures to reduce the possibility of theft, sabotage and illicit trafficking of nuclear materials and other radioactive materials, and concluded that a comprehensive approach to the security of these materials was needed, using technical, administrative and regulatory measures. It emphasised the key role of the IAEA in this.

The most recent conference organised by the IAEA in this respect was the International Conference on Security of Radioactive Sources, held in March 2003 in Vienna, Austria. It produced two major findings. The first was that high-risk radioactive sources that are not under secure and regulated control, including so-called orphan sources, raise serious security and safety concerns. An international initiative to facilitate the location, recovery and securing of such radioactive sources throughout the world should therefore be launched under the IAEA's aegis. The second was that effective national regulatory bodies are essential for ensuring the long-term safety and security of high-risk radioactive sources, and that an international initiative to assist governments in establishing these bodies should be launched under the auspices of the IAEA.

Additional findings were that there is a need to locate and secure high-risk radioactive sources; that the long-term control of radioactive sources must be strengthened; that greater international effort is needed to detect and interdict illicit trafficking in high-risk radioactive sources; that the roles and responsibilities for safety on one hand and security on the other should be clearly defined for the competent national organisations; that radiological emergency plans dealing with illicit use of radioactive sources should be developed; and that the general public's understanding of the nature and consequences of radiological emergencies largely determines its reaction to such emergencies.

Preventive measures in relation to RDDs should focus on radioactive material, since explosives or other means of dispersion can be relatively easily obtained by terrorists, and many states are already trying to control access to such means as part of their general anti-terrorism measures. Keeping track of all potentially harmful radioactive sources requires a series of measures.

First, a national accountancy and verification system for radioactive sources should be established by every country. Like the IAEA safeguards system, such a system should account only for strong sources, since, as we have seen, an effective RDD contains in the order of 100–1,000 Ci. However, smaller sources with activity in the order of 10 Ci should not be excluded since several smaller sources can make up a 100-Ci source. A 'significant quantity' should therefore be defined as being of the order of 10 Ci. As mentioned above, at present only a few countries have such an accountancy and verification system, most of them are voluntary and they are based on safety rather than security considerations.

Verification of both the type and the strength of each source can be performed relatively easily by non-destructive analysis, as is done in the case of IAEA safeguards. As has been seen, the physical state of the radioactive material is important since it determines how dispersible the material is. Sources could be divided into several classes according to their physical state, indicating the risk they pose in terms of potential for being used in an RDD. A verification system would have to take such risk factors into account, for example, by adjusting the inspection frequency.

Second, an inventory of the present sources should be established and brought into the national verification system. Some international co-ordination could be useful, especially participation by the main producers of radioactive isotopes.

Third, a 'return' system for sources no longer being used should be established so that owners are encouraged to send them back. When a source is purchased, a deposit should be paid that will be returned when the source is given back. Unused sources pose a major risk of being stolen because they are probably no longer being closely supervised. This part of a preventive system against RDDs will probably raise most protest among the radioactive source producers, since it will increase the purchase costs of sources and make them less competitive with possible alternatives. Several countries (such as the US) have programmes that encourage the return of unused sources, but their success has so far been limited, probably because they are voluntary. So far little more than 1 Ci has been returned in the US case.

Fourth, abandoned (orphaned) sources, which are no longer under anyone's control, should be secured. This could be done in a dedicated repository—preferably the national regulatory authority. Such a repository exists, for example, in Belgium.

Conclusion

National accounting and monitoring systems for radioactive sources should be established, but limited to those that pose a significant risk for society if used in or as RDDs. Based on dispersion calculations, an initial estimate of the source strength above which measures are needed is 10–100 Ci (although refinement of the calculations would be necessary to improve this estimate before it could be used for safety and verification policy). The number of sources and the total quantities that pose a high risk and which need to be controlled are thus limited.

The structure of a national control system could be comparable to that long established for IAEA safeguards with respect to material accountancy and verification of the presence and state of radioactive sources. Sources should be categorised according to the risk they pose in terms of their utility in or for an RDD. Aspects that should be included in quantifying this risk include the isotope concerned, its physical/chemical state and the quantity of material.

Local and national governments play a very important role in reducing public fear of the possible use and effects of RDDs. As shown by dispersion calculations, the radiation threat to the public, even in close proximity to the explosion, is relatively low compared to the threat that would result from an accident at a nuclear facility. Making quick, open and reliable information available to the public will reduce the effect of widespread panic and help confound the purposes of terrorists attempting to use RDDs.

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Klaas van der Meer studied experimental physics at the University of Amsterdam and reactor physics at the Technical University of Delft, Netherlands. At present he is Head of the Department of Safeguards and Physical Measurements at the Belgian Nuclear Research Institute (SCK CEN) in Mol, Belgium.

Endnotes

[1] The preoccupation with fissile material in the Radiological Weapon Convention negotiations seems strange. First, there are other materials that are as hazardous as plutonium when used in an RDD, such as americium-241 and californium-252. The hazards of uranium isotopes are small compared to those of cobalt-60, strontium-90, caesium-137 and iridium-192. Second, the security measures in place for plutonium and uranium have always been much tighter than those for other radioactive materials. Third, the amount of plutonium and uranium needed for 1,000 Ci is well above the critical mass of these two elements, so that if a terrorist were to acquire a sufficient amount of plutonium or uranium it would be more attractive for him to make a nuclear weapon than an RDD (even if it is technically more complicated). The home-made character of a plutonium bomb especially will probably make it less effective, but the resulting damage will still be much greater than that from an RDD based on plutonium-239. A home-made nuclear weapon based on uranium-235 is relatively easy to make.

[2] Fissionable or fissile nuclear material such as plutonium or uranium can be used to provoke a nuclear fission reaction. This reaction is used in a controlled way in nuclear power plants and in an uncontrolled way in a nuclear weapon. In shorthand these elements are also called nuclear material. In this chapter the term 'radioactive sources' is used for all radioactive material.

[3] International Atomic Energy Agency (IAEA), 'Measures against illicit trafficking in nuclear material', GC(38)/RES/15, IAEA, Vienna, 15 September 1994.

[4] IAEA, 'Measures against illicit trafficking in nuclear materials and other radioactive sources', GC(41)/21, IAEA, Vienna, 18 September 1997.

[5] IAEA, 'Code of conduct on the safety and security of radioactive sources', IAEA/CODEOC/2001, IAEA, Vienna, 2001.

[6] IAEA, 'Nuclear and radiological security: progress on measures to protect against nuclear and radiological terrorism', GC(47)/RES/8, IAEA, Vienna, 19 September 2003.

[7] Charles D. Ferguson, Tahseen Kazi and Judith Perera, *Commercial Radioactive Sources: Surveying the Security Risks*, Occasional Paper no. 11, Monterey Institute of International Studies, January 2003.

[8] The amount of radioactive material needed for a 1,000-Ci source depends on the half-life of the isotope being considered. The shorter the half-life, the less the amount of material needed for a 1,000-Ci source. For americium-241, with a half-life of 433 years, the amount is about 300 grams. For iridium-192, with a half-life of 74 days, the amount is only 100 milligrams. These figures apply to pure material. If the radioactive isotope is mixed with other isotopes, the amount needed is greater.

[9] NKS Conference on Radioactive Contamination in Urban Areas, Risoe, Roskilde, Denmark, 7–9 May 2003.

[10] The calculations were performed by Alain Solier in November 2002 using the HOTSPOT 2.01 computer code developed by the Lawrence Livermore National Laboratory in California, US. See www.llnl.gov/nai/technologies/hotspot. The results of the calculations are discussed extensively in Alain Sohier and Frank Hardeman, 'Radiological dispersion devices: are we prepared?', NKS Conference on Radioactive Contamination in Urban Areas, Risoe, Roskilde, Denmark, 7–9 May 2003.

[11] Anita Nilsson, 'Security of material: preventing criminal activities involving nuclear and other radioactive materials', International Conference on Security of Radioactive Sources, IAEA-TECDOC-1045, Vienna, Austria, 10–13 March 2003.

[12] Ilona Barth and Renate Czarwinski, 'Unusual events regarding losses and finds of radioactive materials in Germany in the years 1991 to 1997', International Conference on Security of Radioactive Sources, IAEA-TECDOC-1045.

[13] George Bunn and Lyudmila Zaitseva, 'Efforts to improve nuclear material and facility security', *SIPRI Yearbook 2002: Armaments, Disarmament and International Security*, Oxford University Press for the Stockholm International Peace Research Institute, Oxford, 2002, appendix 10D, pp. 598–612.

[14] See 'Radiological weapons I: US authorities arrest alleged "dirty bomber"', Global Security Newswire, 10 June 2002, available at www.nti.org.

[15] See 'Radiological weapons: Thai police block cesium-137 sale', Global Security Newswire, 13 June 2003, www.nti.org.

[16] Ferguson, Kazi and Perera, *Commercial Radioactive Sources: Surveying the Security Risks*.

[17] IAEA, 'The Agency's safeguards', INFCIRC/26, IAEA, Vienna, 9 April 1964, available at www.iaea.org/publications/Documents/Infcircs.

[18] IAEA, 'The structure and content of agreements between the Agency and states required in connection with the Treaty on the Non-Proliferation of Nuclear Weapons', INFCIRC/153 (Corrected), IAEA, Vienna, June 1972, www.iaea.org/publications/Documents/Infcircs.

[19] IAEA, 'Model Protocol Additional to the Agreement(s) between State(s) and the International Atomic Energy Agency for the Application of Safeguards', INFCIRC/540 (Corrected), IAEA, Vienna, December 1998, www.iaea.org/publications/Documents/Infcircs. See also chapter 2 in this volume.

[20] This remark is based on reading several contributions to the International Conference on Security of Radioactive Sources, IAEA-TECDOC-1045, Vienna, Austria, 10–13 March 2003.

[21] IAEA, 'Convention on the Physical Protection of Nuclear Material', INFCIRC/274/Rev. 1, IAEA, Vienna, May 1980, www.iaea.org/publications/Documents/Infcircs. The convention was signed on 3 March 1980 and entered into force on 8 February 1997. It obliges states parties to ensure the protection of nuclear material during international transport, whether within their territory or on board their ships or aircraft. The treaty has 89 parties to date.

[22] International Conference on the Safety of Radiation Sources and the Security of Radioactive Materials, Dijon, France, 14–18 September 1998.

[23] IAEA, 'The safety of radiation sources and the security of radioactive materials', GC(42)/RES/12, IAEA, Vienna, 25 September 1998.

[24] International Conference of National Regulatory Authorities with Competence in the Safety of Radiation Sources and the Security of Radioactive Materials, Buenos Aires, Argentina, 11–15 December 2000.

[25] International Conference on Measures to Prevent, Intercept and Respond to Illicit Uses of Nuclear Material and Radioactive Sources, Stockholm, Sweden, 7–11 May 2001.