

Radiological Terrorism

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ABSTRACT

We run the risk that terrorists will decide to detonate an explosive device laced with radioactive materials (a radiological dispersal device, or RDD). If such an attack occurs, it is unlikely that the affected population or emergency responders would be exposed to high levels of external radiation, although airborne radionuclides may present a health risk under some circumstances. However, the effects of radiation and radioactivity are not well known among the general population, emergency responders, or medical personnel. This could lead to unwarranted panic, refusal to respond to the incident, inappropriately delaying or denying treatment to injured victims, and other unfortunate reactions during the emergency phase of any response. During the recovery phase, current regulations may lead to costly and restrictive radiation safety requirements over very large areas, although there have been recent efforts to relax some of these regulations in the first year following a radiological attack. The wide spread of radioactive contamination can also lead to environmental contamination, particularly in low-flow areas and near storm sewer discharge points, but the total radiation dose to the environment should not be excessively high in most locations.

Key Words: RDD, dirty bomb, radiation, radiation health effects, terrorism, nuclear weapons, radiological weapons.

INTRODUCTION

Since June 2002 we have become aware of the arrest of a suspected radiological terrorist (*e.g.*, Warrington 2002), al Qaeda plans for constructing radiological weapons (El Baradei 2003), and the availability of large numbers (probably over 100,000) of “orphaned” radioactive sources in the world, thousands of which are sufficiently strong to cause harm (Gonzalez 2004). According to the International Atomic Energy Agency (IAEA), there have been nearly 300 attempted radioactive

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Table 1. Some important RDD-related events.

Date	Place	Event ^a
1997	Russia	Chechen terrorists set, but do not explode, bomb with Cs-137 in a Moscow park
June, 2002	US	Jose Padilla arrested for alleged “dirty bomb” plot
Dec, 2002	Ecuador	Theft and ransom of 5 industrial indium sources, 3 sources returned, 2 unaccounted for
Dec, 2002	Nigeria	Theft of well-logging Cs-137 source, found in Germany in Sept, 2003
May, 2003	Tbilisi, Georgia	Police stop attempt to smuggle radioactive sources into Turkey or Iran
June, 2003	Bangkok, Thailand	Police arrest man attempting to sell Cs-137 for over \$200,000

^aInformation in table taken from Warrick, 2003a.

materials smuggling incidents in the last decade. These recent events have been widely reported (Warrick 2003a, b, c), leading to the perception that the threat of a radiological attack is a new threat, and one that may lie in the near future.

In actuality, the idea of a dirty bomb goes back at least a half-century. During the Korean War, General Douglas MacArthur suggested sowing dangerous levels of radioactivity along the Korean–Chinese border to prevent further Chinese involvement in Korea following the presumed United Nation’s victory in Korea (Manchester 1978). Even earlier, in 1941, the National Academy of Sciences explored the idea of radiological warfare in the form of bombs that would distribute radioactivity in enemy territory (Ford 1998). In the 1980s, Saddam Hussein is thought to have experimented with Radiological Dispersal Devices (RDDs), eventually giving up on them for reasons to be outlined later (Muller 2004). In fact, the most recent incarnation of RDDs is not even a terrorist innovation; al Qaeda appears to have gotten this idea from watching U.S. news broadcasts in the late 1990s (Eng 2002). Some have called RDDs a “poor man’s nuclear weapon” whereas others have referred to them as “weapons of mass disruption.”

In recent years, the first potential radiological terror event was by suspected Chechen terrorists in Russia (NOVA 2003). It is also possible that al Qaeda produced an RDD (AP 2003). This, and other events, are summarized in Table 1. However, we have become increasingly aware that radiological materials remain available for misuse. This article discusses the expected effects of a successful RDD attack and suggests strategies for responding to such an attack. Finally, some suggestions are made as to how the risk of an RDD attack may be lessened and, if one is carried out, how the aftermath may be managed. First, however, it is necessary to define some basic terms and concepts.

Nuclear Weapons *vs.* Radiological

There is a tendency to confuse nuclear and radiological weapons when, in fact, the differences, as explained later, are profound.

Nuclear weapons

In a nuclear weapon, energy is produced via the fission of uranium or plutonium atoms, in particular, atoms of either U-235 or Pu-239. The process is similar to that which takes place in a nuclear reactor, but the characteristics of a nuclear weapon are such that the energy is released in a very brief period of time, causing an explosion rather than the controlled production of energy.¹ The nuclear explosion itself can be devastating, as was seen in Hiroshima and Nagasaki, but the nuclear (fission) bomb can also be used to initiate a thermonuclear (fusion) explosion, which is even more powerful.

Constructing a nuclear weapon is not an easy matter, but the theoretical details were worked out long ago. We must also remember that the United States constructed nuclear weapons with the technology available in the 1940s, and any nation with this level of technology is, in theory, capable of doing so today. Luckily, most nations lack the national desire and the resources necessary to develop nuclear weapons, and international safeguards have limited the abilities of rogue states to do so, although these safeguards have been ineffective in the cases of some nations. From a technical standpoint, the limiting factor in nuclear weapons development is the production of weapons-grade uranium or plutonium; producing these components is extremely difficult, time-consuming, and expensive and is difficult to accomplish undetected. It is also beyond the financial resources of most nations.

Nuclear and thermonuclear explosions are extraordinarily destructive. Consider: the bomb set off in Oklahoma City was equivalent to a few tons of TNT. The bomb detonated over Hiroshima was equivalent to 10,000 Oklahoma City-type bombs. In Oklahoma City, somewhat fewer than 200 people were killed and one building was destroyed, whereas the Hiroshima bomb killed nearly 100,000 people and destroyed virtually an entire city. Nuclear weapons detonation generates shock waves, heat, radiation, and large amounts of radioactive fallout, all of which can be extremely damaging. With nuclear weapons, we see extensive damage to structures, extensive casualties, and the loss of city utilities and services over a large area.

Discussion of nuclear attacks is beyond the scope of this article. There are, however, a great many references on this subject. Among the best are works by Glasstone and Dolan (1977) and the North Atlantic Treaty Organization (NATO 2004), both available on-line and in print.

Radiological weapons

Radiological weapons are in no way similar to nuclear weapons. In a radiological weapon, terrorists would presumably add radioactivity to a “conventional” terrorist bomb so that the bomb would spread radioactivity when it detonated. This means that the physical damage from any such “dirty bomb” is limited to the amount of

¹It bears mention that commercial nuclear reactors cannot explode with a nuclear yield; nuclear weapons contain much higher concentrations of the fissionable isotopes (U-235 or Pu-239) and the low enrichment of commercial reactors makes a nuclear explosion physically impossible.

damage that can be caused by the bomb itself. As we have seen in Oklahoma City, Indonesia, and the Middle East, even this level of explosion can be quite damaging, but nowhere near as catastrophic as a nuclear explosion. An RDD is simply a “normal” bomb that has been “dirtied up” with radioactive materials in order to spread panic and cause civic and financial disruption.

The health effects of an RDD, then, are similar to those of any terrorist bomb, plus the health effects of radioactive materials, and the radiological health effects depend strongly on the weapon’s radiological characteristics. The factors controlling these radiological health effects include the radioisotope used, the type of radiation emitted, the amount of radioactivity used in the weapon, and the route of exposure (*e.g.*, inhalation, ingestion, external radiation). Under most circumstances it is likely that a radiological attack, while disruptive, will probably not lead to widespread radiation sickness at the time of the attack or to cancer epidemics in later years. Accordingly, a city subjected to a radiological attack must be prepared to deal with a large number of “worried well,” many contaminated or potentially contaminated people, and large cleanup costs; but the physical damage will likely be limited to the area near the explosion itself. A “stealth” radiological attack² would be less physically damaging, but potentially more disruptive because of the potential for contamination to spread beyond the original attack site before detection.

Radiation terminology

Radiation is the transfer of energy from one place to another via some sort of particle or ray. Radioactive atoms contain excess energy in their nuclei, and they rid themselves of this energy by emitting alpha particles, beta particles, or gamma rays. If the radiation has enough energy, it can strip electrons from atoms, creating an ion pair. These ions can then go on to cause DNA damage as described further in this section. A short glossary of terms used in the radiological sciences can be found in the Appendix at the end of this article.

It is important to understand that the units of radioactivity, the Curie (Ci) and the Becquerel (Bq), are a measure of the rate at which radiation is emitted from a mass of radioactive materials. Long-lived isotopes decay slowly, so a relatively large amount is needed to give the same radiation dose found in smaller amounts of shorter-lived isotopes. For example, one gram of radium-226 (half-life = 1600 years) contains the same amount of radioactivity (and the same Curie content) as about 3 tons of depleted uranium (U-238 half-life = 4.38 billion years).

Radiation dose is a measure of the amount of energy deposited in an absorber (for example water, air, tissue) by ionizing radiation. This energy causes ionizations, which go on to damage the cell or its DNA. This is more precisely referred to as radiation absorbed dose as it measures only the amount of energy absorbed by an absorber, and that absorber need not be living. Radiation dose is measured in units of Gray (the SI unit) or rad (the US unit).

²It is possible that a terrorist organization may work to contaminate a city surreptitiously by spreading radioactivity in the airport, the subway, on city streets, and so forth. Such an attack would trade immediate panic for longer-term uncertainty and greater levels of civic disruption.

Some types of radiation are inherently more damaging to living cells. Alpha radiation, for example, interacts readily with matter, leaving very short (a few microns) and very densely ionized tracks. In living tissue, alpha particles cause double-strand DNA breaks and multiply damaged sites—damage that is far more difficult to repair than the single-strand DNA breaks typically caused by beta or gamma radiation. Accordingly, exposure to alpha radiation is more likely to cause changes that can lead to cancer than exposure to the same dose (*i.e.*, energy deposition) of beta or gamma radiation. Because of this, quality factors (also referred to as relative biological effectiveness factors) have been assigned to each of the major forms of ionizing radiation; these factors account for the higher level of biological damage caused by some kinds of radiation. Multiplying the absorbed dose (rad or Gy) by the quality factor gives one an effective dose in units of rem or Sievert (Sv). For example, the quality factor for alpha radiation is 20. If a person is exposed to sufficient levels of radon to deposit 100 ergs of alpha particle energy for each gram of lung tissue, they will receive an absorbed dose to the lung of 1 rad and an equivalent dose of 20 rem because of the high quality factor for alpha radiation. ***It is important to note that the quality factor (and, by extension, the units of rem or Sv) measure biological damage that may lead to cancer later in life. Accordingly, it is not appropriate to use these units except for living organisms. It is also not appropriate to use these units to refer to acute radiation exposure or to determine acute radiation effects because of the length of time required for carcinogenesis.***

Each radioisotope emits a particular type of radiation with a characteristic energy. For example, Co-60 emits two gamma rays with energies of about 1.1 and 1.3 MeV (million electron volts) whereas Cs-137 emits a single gamma ray with an energy of 0.662 MeV. This means that one curie of Co-60 emits nearly four times as much energy as one curie of Cs-137. Because of this, the radiation dose rate from 1 Ci of Co-60 is four times as great as from a comparable activity of Cs-137. This amount of Co-60 gives a radiation dose rate of 1.3 rad/hr at a distance of 1 meter, whereas 1 Ci of Cs-137 has a radiation dose rate of only 0.33 rad/hr at the same distance. This gamma constant (usually referred to as Γ) is also sometimes referred to as a dose conversion factor for external radiation exposure.

Exposure to internal radioactivity (from, *e.g.*, ingestion or inhalation) also produces radiation dose from the direct irradiation of tissues in which the isotopes are absorbed and (in the case of gamma-emitting isotopes) in nearby tissues. Radiation dose from internal radionuclides must account for the biokinetics of the particular radioactive materials; some isotopes (*e.g.*, H-3, C-14, Cs-137) distribute evenly throughout the body whereas others (*e.g.*, I-131) target specific organs. Biokinetics vary for different elements, for elements in different chemical forms, and even for the same element depending on the part of the body to which it travels. For example, when I-131 is introduced to the bloodstream, 30% is absorbed by the thyroid, where it remains with a biological half-life of about 80 days. The rest of the I-131 is excreted from the body with a biological half-life of about 1–2 days. This isotope emits a gamma ray (364 keV) and a beta particle (606 keV); the beta particle only deposits energy in the thyroid whereas the gamma rays can penetrate the entire body. Because of this, internal exposure to I-131 gives a much different radiation dose to the body than does internal exposure to H-3, which emits only a single beta particle (18 keV). All of these factors (target organ(s), type and energy of emitted radiation, biological half-life, *etc.*) go into determining the radiation dose a person

receives from ingested or inhaled radioactivity. These are used to calculate dose conversion factors—the amount of effective whole-body radiation dose per unit activity that enters the body—for various radionuclides.

BIOLOGICAL EFFECTS OF RADIATION EXPOSURE

When ionizing radiation interacts with organisms it can create ion pairs within living cells. These ion pairs can then go on to damage DNA, just as free radicals from metabolism can cause DNA damage. If the damage is repaired before the cell reproduces (a high probability) we see no effect from this irradiation; a mutation only occurs when DNA damage is unrepaired or is repaired incorrectly. Even mutations are not necessarily dangerous—the process of evolution is the accumulation of beneficial mutations, and most mutations seem to occur in non-coding parts of the genome, causing no damage.

Sometimes mutations will occur in important parts of the genome, perhaps damaging one of more of the DNA repair mechanisms. When this happens, the cell will likely die (in which case the mutations are not passed on to future generations), but if the damage is sublethal, the damage will be passed on to the next generations of cells. The right type of mutation can turn these cells cancerous. However, although radiation is a confirmed carcinogen, it is a weak carcinogen and even radiation levels significantly in excess of natural background levels do not significantly raise cancer risks. As radiation dose increases, the cancer risk increases in a fairly predictable manner. However, at low levels of exposure (less than about 10 rem, or about 30 years of natural background radiation exposure), the added risk is so low compared to the natural cancer rate that we cannot calculate a numerical risk estimate (HPS 1996).

At higher levels of radiation exposure, on the order of hundreds of rem, a variety of radiation syndromes begin to manifest themselves. These are summarized in Table 2. A radiation dose of 1000 rem is invariably fatal with our current medical technology. At higher levels of exposure, a variety of syndromes appear, but they are not relevant to this article and will not be further discussed. The effects of such extraordinarily levels of radiation exposure are described in, among other references, Hall (2002). The reader should note that, in most RDD scenarios, radiation exposure levels will

Table 2. The effects of acute radiation exposures.

Radiation dose (rem)	Effect
0.3	Natural background radiation exposure (average)—no expected effect
10	0.5% risk of radiation-induced cancer ^a
100	Mild radiation sickness in about 10% of the population
350	LD ₅₀ dose with no medical treatment
750	LD ₅₀ dose with adequate medical care (including immune system support)
1000	LD ₁₀₀ with current standards of medical treatment

^aBEIR V.

be far lower than those shown to cause medical effects (Veenema and Karam 2003). The effects of acute radiation exposure are summarized in Table 2.

MAKING A RADIOLOGICAL DISPERSAL DEVICE (RDD)

To successfully launch a radiological attack, a terrorist organization must be able to find a way to obtain and disseminate radioactive materials. These issues are discussed in the following sections, and the problems they pose may give some insights into methods by which the risk of radiological attack may be mitigated. Various methods of obtaining radioactive materials and assembling them into an RDD have been the subject of much recent work (Barnaby 2004; Allison 2004; Ferguson and Potter 2004).

What Makes a “Good” RDD Isotope?

A great deal of attention has been given to the question of what sort of radioactive materials are at the highest risk of being used in an RDD attack. To some extent, the selection of materials will reflect the terrorists’ aims (*e.g.*, widespread contamination versus radiation injury), but a more important consideration may be simply which radioactive materials are available in large quantities. In general, it is thought that the selection of radioactive materials will depend on a combination of factors:

1. *Availability of a particular isotope.* One must be able to obtain an isotope in order to use it. Even an “ideal” isotope, if unavailable, cannot be made into an RDD.
2. *Availability of an isotope in large quantities.* Unless an isotope can be found in large quantities, an RDD attack will be forced to take place on a small scale.
3. *Ease of use.* An organization must be able to work with an isotope to put it into a form that can be used for the intended purpose. Soluble cesium chloride powder, for example, is easier to fashion into a dispersal device than is insoluble cobalt alloy.
4. *Ability to shield.* An isotope with very penetrating radiation is more difficult to shield and, hence, more difficult to work with safely and to hide, although such isotopes yield a higher radiation dose for the same amount of material.
5. *High activity level.* More highly radioactive materials (those with a shorter half-life) produce more radiation for a given mass and volume of isotope.
6. *Sufficiently long half-life.* A very short-lived isotope (*e.g.*, Tc-99m with a half-life of 6 hours) can be intensely radioactive, but decays to stability in the space of only a few days, making for only a short-lived contamination problem. However, even some short-lived isotopes can cause problems; I-131 has a half-life of only 8 days, but is still capable of causing contamination problems for a few months after an incident. Some of these properties are provided in Tables 3, 4, and 5 for some of the most commonly used medical, research, and industrial isotopes.

The availability of a particular radioactive isotope depends on many factors also, including the prevalence of the isotope in the quantity desired, the security surrounding sources of the activity desired, the safety, and so forth.

Table 3. Properties of various medical therapy sources.

Isotope	Half-life	Photon energy (MeV)	Specific activity (Bq gm ⁻¹)	Gamma constant (mSv hr ⁻¹ MBq ⁻¹ at 1 m)	Source activity (MBq-typical)	Source size (mm)
⁶⁰ Co ^{a,b}	5.27 yrs	1.17 1.33	4.1854×10^{13}	3.703×10^{-4}	A few tens to several thousand MBq	A few mm to a few cm in length
¹⁰³ Pd	17 days	0.0202	2.7593×10^{15}	6.219×10^{-5}	55.5–74	0.5×5
¹²⁵ I	60 days	0.027	6.4207×10^{14}	7.432×10^{-5}	18.5	0.5×5
¹³⁷ Cs	30.2 yrs	0.662	3.2207×10^{12}	1.032×10^{-4}	185–740	A few mm to a few cm in length
¹⁹² Ir	74 days	0.317	3.3914×10^{14}	1.599×10^{-4}	18.5 (LDR seeds) 37,000 (HDR src)	Seeds about 0.5×3
¹⁹⁸ Au ¹	2.7 days	0.412	9.0478×10^{15}	7.882×10^{-5}	18.5–74	0.8×2.5
²²⁶ Ra ¹	1600 yrs	0.186	6.3539×10^{10}	3.274×10^{-6}	185–925	1×10

^aNo longer used extensively in many nations.^bA gamma knife may contain about 200 sources of ³⁰Co (1.1 TBq) each.

Obtaining Radioactive Materials

In recent years the attention of those involved in RDD prevention has focused on two major possibilities: the risk that terrorists will steal radioactive sources from a domestic licensee and the risk that the radioactive materials will be brought in

Table 4. Properties of various nuclear medicine isotopes.

Isotope	Half-life	Primary Emission	Energy (MeV)	Specific activity (Bq gm ⁻¹)	FGR 11 ALI Ingestion/ Inhalation (MBq) ^a	Typical administered dose (MBq)
¹⁸ F	1.8 hrs	Positron Photon	0.634 max 0.511 (×2)	3.5272×10^{18}	2000/3000	555
⁶⁷ Ga	3.3 days	Photon	0.093	2.2217×10^{16}	300/500	370
⁸⁹ Sr	50.6 days	Beta	1.49 max	5.6303×10^{12}	20/30	148
⁹⁰ Y	64 hrs	Beta	2.28 max	2.0137×10^{16}	20/30	1480
⁹⁹ Mo	66 hrs	Beta	1.2 max	1.7561×10^{16}	40/50	18.5–111 GBq in new generator
^{99m} Tc	6.01 hrs	Photon	0.141	1.9444×10^{17}	3000/6000	74–1480
¹²³ I	13.1 hrs	Photon	0.159	7.0905×10^{15}	100/200	3.7–111
¹²⁵ I	60.1 days	Photon	0.027	6.4207×10^{14}	1/2	74–1850
¹³¹ I	8.04 days	Beta Photon	0.606 max 0.364	4.5817×10^{15}	1/2	0.37–9250
²⁰¹ Tl	73.1 hrs	Photon	0.071	7.8045×10^{15}	600/800	74–185

^aEPA, Federal Guidance Report Number 11.

Table 5. Properties of various isotopes used in research.

Isotope	Half-life	Emission	Energy (MeV)	Specific activity (Bq gm ^{−1})	FGR 11 ALI Ingestion/ inhalation (MBq) ^a	Stock vial or source activity (MBq) ^b
Research isotopes—usually from stock vials						
³ H	12.3 yrs	Beta	0.019 max	3.5869 × 10 ¹⁴	3000/3000	10–40
¹⁴ C	5730 yrs	Beta	0.156 max	1.6513 × 10 ¹¹	90/90	10–40
³² P	14.3 day	Beta	1.71 max	1.0573 × 10 ¹⁶	20/30	10–1000
³⁵ S	87.4 day	Beta	0.167 max	1.5787 × 10 ¹⁵	200/80	10–40
⁴⁵ Ca	163 days	Beta	0.257 max	6.5072 × 10 ¹⁴	60/30	10–40
⁵¹ Cr	27.7 day	Photon	0.005	3.4078 × 10 ¹⁵	1000/700	10–40
		Electron	0.320			
¹²⁵ I	60.1 day	Photon	0.027	6.4207 × 10 ¹⁴	1/2	20–400
		Electron				
Isotopes used in neutron sources (e.g. PuBe or AmBe ^d sources)						
²³⁸ Pu	87.8 yrs	Alpha	5.499	6.4345 × 10 ¹¹	0.03/0.0003	4000–40,000 ^c
²⁴¹ Am	432 yrs	Alpha	5.486	1.2769 × 10 ¹¹	0.03/0.0002	4000–40,000 ^c
		Photon	0.060			
²⁵² Cf	2.64 yrs	Alpha	6.118	1.9848 × 10 ¹³	0.09/0.0007	4000–40,000 ^c

^aThe ALI (Allowable Limit for Intake) is the amount of an isotope that, when taken up, will give a whole-body radiation dose of 5 rem or a specific organ dose of 50 rem. The ALI will vary according to the route of uptake (inhalation or ingestion) and the chemical form of the isotope. In some cases there are multiple ALIs depending on the chemical form of the isotope; values presented here are the lowest ALIs noted for each isotope.

^bStock vial and source activity vary widely—the ranges given are approximations only.

^cSource activity depends on desired neutron flux and can vary widely depending on actual use.

^dPuBe and AmBe sources consist of mixture of plutonium (Pu) or americium (Am) with beryllium (Be). These sources are used to produce neutrons.

from overseas—and sources from overseas may be either or stolen or purchased—legally or on the black market. Accordingly, prevention efforts have largely focused on securing radioactive sources against theft and securing borders against the illicit importation of large amounts of radioactivity.

Perhaps the best single summary of the availability of commercial radioactive materials for illicit use is the one authored by Charles Ferguson of the Monterey Institute of International Studies (Ferguson *et al.* 2003). This report discusses in detail the manufacture and distribution of commercial radioactive sources and their properties.

Obtaining radioactive materials domestically

The U.S. government has been stating for over a year that universities and hospitals are considered “soft targets” due to their lack of security and, because of this, they are considered prime candidates for theft. Many hospitals maintain high-activity radioactive sources for therapy and sterilization purposes, and many research institutions maintain high-activity sources for purposes of research. One radiological terrorism scenario suggests that terrorists or professional thieves may attempt to

steal radioactive sources from research or medical institutions. Theft of such sources from industrial facilities is considered a somewhat lesser risk because such facilities often contain lesser amounts of radioactivity and because their security is often more stringent. Other possibilities have received lesser levels of attention, although they may be more likely. Some of these are discussed in greater detail in the following section.

It is also possible that terrorists may choose to attack a vehicle making deliveries of radioactive materials or that they would attack radiological facilities (*e.g.*, a hospital's nuclear pharmacy) with vehicle bombs to release the radioactive materials stored on-site. Yet another possibility is that a domestic or foreign terrorist organization could purchase a used irradiator (which are sometimes advertised for sale) from an existing licensee using falsified documents.

Finally, it is also possible, indeed likely, that terrorists may attempt to obtain radioactive materials overseas and import them into the United States in a cargo container. In fact, it seems likely that multiple attempts to do this have already occurred (Warrick 2003a,b,c,d) and the reported instances are doubtless only a fraction of total attempts. Some recent (since January 1, 2002) incidents involving the possible loss or illicit transportation of radioactive materials are summarized in Table 1. Sources of radioactive materials could include radio-isotopic thermal generators, such as those found in the nation of Georgia in early 2002, abandoned medical therapy sources such as those that caused the contamination incident in Goiania, Brazil (mentioned in more detail in the following sections), or theft of a large radioactive source as happened in Nigeria in 2002.

In summary, there are a number of ways a terrorist group can either "legally" or illegally obtain radioactive materials for use in a radiological weapon. Once obtained, however, the group will still need to fabricate a radiological weapon, move it into position undetected, and use it.

Constructing an RDD

At its most basic, assembling an RDD consists of constructing an explosive device and adding radioactive materials to it. Complications arise from the fact that radioactive materials are not necessarily easily dispersible, and a large radioactive source can emit life-endangering levels of radiation. Obviously, many terrorists are not deterred by sacrificing their lives, but a terrorist will need sufficient working time to accomplish something—it is hard to construct a device if workers receive an incapacitating radiation dose in only 15 minutes. In addition, large quantities of unshielded radioactive materials produce high levels of radiation, making an RDD "factory" easier to detect by law enforcement officials. Accordingly, working with a very high level of radioactivity will necessitate using lead shielding and/or remote manipulators, which are not necessarily easy to obtain.

Dispensability is another attribute of "good" RDD materials, and some sources are more easily dispersed than others. In the recent television show on RDDs (WGBH Television, NOVA 2003) it was mentioned that Cs-137 is often found as an easily dispersed powder. Cobalt, on the other hand, is usually used as a metal alloy and Sr-90 is often found in ceramic form. These latter forms must be processed somewhat in order to be made into an RDD; failure to process them would lead to a relatively

short-range dispersal of radioactive materials and would blunt the potential impact of the attack. Although radioactive materials come in many physical and chemical forms, large sources are more likely to be restricted to a few well-tested physical forms, primarily for manufacturing considerations, and these most likely physical forms will help to dictate the steps necessary to construct an RDD (Levi and Kelly 2002).

PREVENTING AN RDD ATTACK

To construct an RDD, a terrorist group must obtain radioactive materials, use those materials to fabricate a weapon, deliver the weapon to the attack site, and detonate the device. Each of these steps suggests intercessionary measures that can be used to help prevent an attack.

Obtaining radioactive materials requires access to the materials; radioactive sources must be either purchased or stolen. Legal purchase in the United States requires possession of a radioactive materials license, and vendors are not allowed to sell radioactive materials except to properly licensed customers. Terrorist groups could accomplish this via subterfuge (*e.g.*, copying or altering a legitimate radioactive materials license or applying for a license under false pretenses). A terrorist group can also take advantage of existing bulletin boards on which radioactive sources are advertised, often “free to a good home” by organizations that no longer use them. To transfer a radioactive source legally, it is sufficient to have a copy on-hand of the radioactive materials license of the recipient, which can be supplied by the receiving organization. This leaves open the possibility that a terrorist group could falsify these records to obtain an unwanted radioactive source. To preclude this possibility, regulatory bodies should consider requiring licensing documents be obtained only from a regulatory authority with licensing jurisdiction over the source recipient rather than counting on the integrity of the source recipient.

The most straightforward deterrent to stealing radioactive sources is to increase security via better locking systems, the presence of security guards, alarm systems to indicate a source’s theft, and so forth. It is also important to note that radioactive materials licenses are considered public documents and are available for scrutiny by the public. This means that a terrorist organization may be able to obtain copies of licensing documents and use these to identify likely targets for theft. Accordingly, we may wish to remove these documents from public scrutiny.

Radioactive materials obtained overseas must be moved into the United States in order to be used against us. This means that containers with large radioactive sources must either emit high levels of radiation or they must contain large amounts of lead. Developing suitable detection instruments may help address this problem. That being said, current radiation detectors are difficult for untrained personnel to use; it may be necessary to develop a new family of radiation detectors that will help avoid some of the errors that have occurred in the recent past.³

³A Customs officer’s radiation “pager” alarm led to a ship’s being ordered into international waters until subsequent inspection indicated the presence of natural radionuclides in a container of ceramic tiles. In other instances, police have stopped and questioned or searched

Finally, radioactive materials must be transported from the point of entry to the location of fabrication or use. Establishing a network of sensitive radiation sensors around likely target cities can help to detect any but the best-shielded radioactive sources, possibly permitting interdiction prior to use. Aerial surveys may help in this matter, too, depending on the number of available aircraft, detector sensitivity, and the size of the city.

Fabricating an RDD, as noted earlier, can lead to exposure to dangerously high levels of radiation. This, plus the need to avoid detection, may necessitate the use of remote manipulators and/or large amounts of lead shielding. Accordingly, it may be desirable to require lead vendors to report sales of large amounts of lead, remote manipulators, and other such paraphernalia. Although this will not prevent RDD construction, it may at least make it more difficult, more dangerous, or more amenable to detection.⁴

HUMAN EFFECTS OF AN RDD ATTACK

In spite of our best preventative efforts, it is entirely likely that an RDD may still be successfully detonated. If this comes to pass, we must be prepared to work to address and, if possible, minimize the effects of any such attack. To do this we must first understand what some of these effects may be so that actions can be prioritized. In general, we are concerned about the physical effects of the explosion itself and the radiation levels at the site of the attack, the health effects of this radiation exposure on victims and emergency response personnel, and later effects on the city and on society. Please note, however, that radioactive materials do not need to be spread by an explosive device—radioactive powders can be blown from the top of a tall building with a fan (or a good wind), for example.

Effects of the Explosion

There is ample evidence that explosions are deadly, even in the absence of radioactive materials. Oklahoma City, Beirut, Baghdad, and too many other sites have shown us the destructive power of a vehicle full of explosives. In the aftermath of any such attack, we may expect to see fires, damaged or collapsing structures, and victims of the blast. Even without the presence of radioactive materials, we can expect to see these effects plus accompanying injuries.

Radiological Health Effects

Radiological health effects are more difficult to describe because of the potentially great variability in exposure due to actual exposure pathway (*e.g.*, inhalation or ingestion) and the dose to which people are exposed. External exposure to minor amounts of Sr-90 contamination, for example, may lead to no noticeable health effects whereas inhalation of small amounts of Am-241 may prove fatal. Some of

nuclear medicine patients because of similar radiation pager alarms. These could have been avoided with proper instrumentation.

⁴Similarly, training physicians to recognize radiation illness or injury may help identify potential RDD plots by noting unusual patterns in radiation-related injury.

Table 6. Factors influencing the biological impact of a radiological attack.

Factor	Influence
The kind of radiation emitted by the isotope	Alpha and beta radiation are not external radiation hazards, but alpha radiation gives a very high internal dose
The energy of emitted radiation	High-energy radiation causes more harm than low-energy radiation because it's more penetrating. High-energy gamma radiation penetrates more deeply into tissues and travels further through air than low-energy radiation
Chemical form of ingested or inhaled isotopes	Soluble radioactive materials are more easily absorbed by the intestines and lungs.
Biokinetics of a particular element	Some elements (e.g. carbon and hydrogen) are distributed evenly through the body while others (e.g. plutonium) concentrate in particular organs. Some elements are rapidly cleared from the body (e.g. I) while others remain for years or decades (e.g. U).

these scenarios will be explored and summarized in the following section and its accompanying tables. Table 6 summarizes some of the factors that affect the biological severity of a radiological attack.

In the event of an RDD explosion, it is reasonable to expect that those persons closest to the explosion will be both most badly injured and most heavily contaminated with radioactivity. This poses an obvious dilemma to emergency and medical responders, who will be concerned about their own exposure to radioactivity. Although the general consensus is that radioactively contaminated victims and patients pose little or no risk to those caring for them (NATO 2004), this is not common knowledge, and unwarranted fears of radiation and radioactivity have caused caregivers to delay or deny needed care in the past.⁵

Inhalation pathway

In general, inhalation is the most damaging exposure pathway, and inhalation of alpha radiation is the most dangerous because alpha radiation deposits a large amount of energy in a relatively short ionization path. One study has suggested that a single alpha particle can cause oncogenic transformations in cells (Wu *et al.* 1999; Grosovsky 1999) whereas others have shown that inhalation exposure to large levels of alpha-emitting isotopes can cause other significant health problems, including death (NAS 1988, 1998; Alvarez 2003).

Inhaled alpha-emitting radioactivity can be a significant health hazard under certain circumstances (Zimmerman and Loeb 2004). If evenly distributed in air and inhaled, one gram of Am-241 (which contains nearly 3.5 Ci) can produce over

⁵Although this has not been widely documented in the literature, the author has spoken with emergency responders and medical caregivers from New York City, Orlando, Cleveland, Rochester, New York, Los Angeles, and other cities who have stated their reluctance to provide medical care to radiological patients for the reasons stated.

Table 7. The Allowable Limit for Intake (ALI), specific activity (Curies per gram of isotope), and the mass of 1 Ci of activity for some likely RDD isotopes

Isotope	half-life (yrs)	atomic mass (amu)	ALI ^a (μ Ci)	specific activity (Ci/gm)	grams per Curie
Cs-137	30.17	137	200	86.91	0.01151
Co-60	5.27	60	30	1136.01	0.00088
Am-241	432.7	241.06	0.0008	3.44	0.29038
Pu-238	87.7	238.05	0.0007	17.21	0.05812

^aALI is the Allowable Limit for Intake. Ingesting or inhaling 1 ALI will give a person a radiation dose of 5 rem in a year to the whole body, or 50 rem in one year to the most-exposed organ.

one million doses of 500 rem or more to the whole body over the course of a year. Although this dose, if accumulated in a very short period of time, would be lethal to 50% of those receiving it, when protracted over the course of a year, it is not as damaging. Nevertheless, it is reasonable to assume that many of those exposed will develop fibrosis of the lungs, radiation pneumonitis, or other pulmonary diseases in the short term, some fatally so; others may die of radiation-induced cancers over the longer term. Although this may not lead to an immediate influx of patients, over the course of a year and longer, we can expect to see a large number of patients with these pulmonary diseases in the first year post-exposure and many added cases of lung cancer in the years or even decades following the attack. Luckily, it may not be plausible to assume that one million people can be exposed in this manner because of the difficulty of producing such an even distribution of Pu,⁶ but it may be possible to introduce radioactivity into the ventilation system of a large building, theater, sports arena, or other enclosed space.

Radiation dose via the inhalation pathway is determined by the radioactivity concentration in air, particle size, the isotope present, and the type of radiation emitted. Lung (and whole-body) radiation dose increases as airborne radioactivity concentrations increase as particle size decreases until the particles are so small that they behave like a gas. A dense spray of any isotope is more dangerous than a light spray, an isotope with a high dose conversion factor per unit activity inhaled is more dangerous than one with a low dose conversion factor, and alpha-emitting isotopes are more dangerous than others. This is demonstrated in Table 7, which shows the amount of inhaled radioactivity needed to produce a radiation dose of 5 rem to the whole body (the Allowable Limit for Intake, or ALI). This clearly shows that inhaling alpha-emitting radioactive materials is far more dangerous than inhaling an equivalent amount of gamma-emitting radioactivity.

It is likely that a “dirty bomb” attack will produce large quantities of relatively large particles that will settle out near the site of the explosion (Alvarez 2003). This could lead to relatively high exposure levels to persons near the attack site and lesser exposure to others. Persons upwind of the attack will, of course, receive little or

⁶Although it is easy to imagine scenarios such as crop-dusting, aerosol sprays, dissemination into ventilation ducts, and so on that can produce relatively uniform, large-scale distribution of radioactive powders.

no inhalation dose. It is also possible, however, to disperse radioactive materials by blowing powder from a tall building, from an aircraft, or from a vehicle. In this case, particle size is likely to be more uniform and, indeed, the material may be processed to achieve a predetermined optimal particle size.⁷ In such cases, it is entirely possible that a large number of persons may receive enough radioactivity to produce a high radiation dose. For example, inhaling 1 μg (1.13 mCi) of Co-60 powder in soluble form will produce a whole-body dose of about 170 rem. This radiation dose can cause radiation sickness, although it is not likely to be fatal to the exposed individual.

Respiratory protection can be effective in reducing the risk of inhaled radioactive particles provided the protection can effectively filter the particle sizes represented in the event. In the case of a “dirty bomb,” most particles will likely be relatively large, but micron- and submicron-sized particles may be generated by burning radioactive materials or by blowing fine radioactive dusts and powders into the air.

Ingestion pathway

A large cloud of radioactive particles may be ingested as well as inhaled. People breathing through their mouths because of hard work or excitement can have particles settle in their mouths that are subsequently swallowed. Larger particles settling in the lungs or respiratory passages may be entrained in mucus, swept into the throat, and swallowed. Nervous individuals who bite their fingernails may swallow particles beneath (or on) the nails. Finally, radioactive particles may settle onto gardens or prepared foods.

For insoluble radioactive materials (*e.g.*, cobalt oxide), the ingestion pathway is considered less harmful than inhalation because the ingested materials pass through the digestive system relatively rapidly and are excreted. Soluble radioactive materials may be absorbed by the body and retained with whatever biological half-life is typical for that element; these can range from days to decades, depending on the biokinetics of the particular element. For example, insoluble uranium has an uptake factor of about 0.002 (*i.e.*, 0.2% of ingested insoluble uranium is absorbed into the body) and soluble uranium has an uptake factor of 0.05. Of the uranium that enters the body, 20% enters the mineral bone and is retained with a biological half-life of 20 days, 2.3% enters the mineral bone and is retained with a biological half-life of 5000 days, and the remainder is distributed to other tissues (primarily the kidneys) and is retained with biological half-lives ranging from 6 to 1500 days (Hodge *et al.* 1973).

In general, the ingestion pathway is not considered as serious as the inhalation pathway because of the relatively short biological half-life for materials that are not absorbed into the body. However, both pathways are important for radioactive materials in soluble form, such as CsCl, that can easily enter the body.

⁷Large particles will not penetrate far into the lungs and are relatively easily cleared from the body. Particles that are very small tend to be entrained in the air and may not be deposited in the lungs but, rather, are simply exhaled. “Ideal” particles are those that are sufficiently small to be drawn deeply into the lungs, but large enough to remain during an exhalation—these particles are typically around one micron in size.

External exposure pathway

Finally, it is necessary to consider the external exposure pathway, which will be a concern under most circumstances involving gamma-emitting radionuclides. Alpha- and beta-emitting nuclides are not an external radiation concern because of the short range of alpha and beta particles in tissue (about 5 microns and 1 cm maximum range, respectively). The extremes for gamma radiation exposure would occur from the widespread distribution of radioactive contamination (lowest dose) and the placement of an intact irradiator source in a public area (highest dose). This section will also consider an intermediate case in which large amounts of radioactive materials are spread over a relatively small area of one acre.

Radioactive materials regulations restrict access to any areas in which loose surface contamination is present at levels higher than 1000 dpm/100 cm² (or about 0.16 Bq/cm²). Contaminating a large area to these levels can result in access restrictions and contamination controls. If a terrorist group desires to deny use of the greatest area possible and to cause the highest cleanup costs, they may decide to distribute radioactive materials at this level of contamination.

Consider: a 1 Ci (37 GBq) radioactive source decays at a rate of 37 billion disintegrations per second (dps), which is 2.22 trillion dpm. With a maximum allowable contamination level of 10 dpm/cm², this level of activity is sufficient to contaminate about 200 billion cm² to levels requiring remediation and entry controls. One square meter contains 10,000 cm² and there are one million m² in a km², so a single Ci of activity can contaminate 22 km² (5485 acres). With the specific activity of Cs-137 (87 Ci/g), such a source would contain only 11.5 mg of Cs (less than 20 mg of CsCl), and the dose conversion factor of Cs-137 would produce a radiation dose of about 1.5 μ r/hr to a person living on this surface.⁸ Such a radiation dose rate is trivial in that living continuously in such a radiation field will give occupants an added 13 mr (0.13 mSv) per year, about equal to 2 weeks of exposure to natural background radiation. Obviously, the widespread distribution of radioactivity is a regulatory, financial, and social problem, not a health risk.

On the other extreme, terrorists may want to place an intact radioactive source in a public place, attempting to make people ill from radiation sickness. To again use Cs-137 as an example isotope, an unshielded 1000 Ci (37 TBq) radioactive source produces a radiation dose of about 1.032×10^{-4} mSv/hr for each MBq at a distance of one meter. This source, then, would give a radiation dose of about 3.3 Gy/hr (330 r/hr) at a distance of 1 meter. At this exposure rate, a person standing at arm's length from the source would receive a lethal dose of radiation in 2–3 hours and would receive sufficient radiation to cause radiation sickness in about 15–20 minutes. This may seem an alarmingly short time, but we must also consider that it is unusual for a large number of people to spend even 20 minutes at a distance of 1 meter from anything. For example, perhaps 15 people can fit into an elevator (albeit uncomfortably), but elevator rides are relatively short. A larger number of people can fit into a bus or train car, but the dimensions of the car are such that very few people would be within 1 meter of any given spot.

⁸These calculations were performed using the MicroShield program, an industry-standard software package. MicroShield was written by Grove Engineering.

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A source placed in a building lobby or on a street corner would face similar limitations in that few people would spend an appreciable amount of time in close proximity to any given location. Only in specific settings, such as sporting events, concerts, movies, or theatre productions can a relatively large number of people be in close proximity for a sufficiently long period of time to experience ill effects from a radioactive source. However, even in such settings, seats are more than a half meter in width, so only a dozen or so people in these settings could receive a lethal radiation dose and fewer than 100 would fall ill from radiation sickness. Although these numbers are not trivial (they are higher than the number of people who became ill or died from the 2001 anthrax attacks), they are far fewer than those who have perished in many other terrorist attacks. In addition, radiation safety professionals have a great deal of experience with locating, isolating, and recovering even high-activity radioactive sources; recovering from such an incident would not be a simple matter, but it would be an exercise for which there is ample precedent and for which there exists much expertise.

An intermediate case would occur if terrorists disperse large amounts of radioactivity in a relatively limited space. For example, spreading 1000 Ci of Cs-137 in a space of only one acre would produce radiation levels of about 8 r/hr (using calculations such as those performed above). At this level of exposure, victims and emergency responders would exceed regulatory dose limits for radiation workers in about 40 minutes, but would require over 12 hours of exposure to begin to develop radiation sickness, and over 50 hours to reach the LD₅₀ dose (without medical care) of 400 rem. Clearly, although this exposure level is a concern, it is not a health risk for any reasonable work and exposure times.

ENVIRONMENTAL EFFECTS OF RADIOLOGICAL TERRORISM

In addition to the effects on humans, it is necessary to consider the environmental effects of a radiological attack. Whether distributed through an RDD explosion, sprayed onto food or introduced into the water supply, sprayed onto a crowd, or disseminated in other modes, it is probable that the radioactive material released will end up in the environment at some point. Even radioactivity surreptitiously introduced into a building is likely to be, at some point, introduced into the sanitary or storm sewer system or to escape the building on the clothes or shoes of unsuspecting workers. In these cases, concerns include soil and surface water contamination and the contamination of food or drinking water.

Soil and Water Contamination

Consider the explosion of an RDD. The explosion scatters radioactive materials into the surrounding area, and some radioactivity is lofted into the air by the force of the explosion or by subsequent fires. As this radioactivity settles to the ground, it will likely (in an urban environment) settle onto streets, sidewalks, buildings, parking lots, and other manmade surfaces. Some contamination may drift into parks. Unless all of the contamination is cleaned up before the first rainfall or snow melt, water will carry contamination into storm sewers and into nearby bodies of water. Contamination that settles onto soil will be transported into the soil, either percolating

into the groundwater or attaching to clays in the soil. In each of these cases, the radioactive contamination will enter the environment and will migrate according to its environmental mobility.

In the absence of a concentrating mechanism, radiation dose from these isotopes is not likely to exceed that of the original site; this has already been shown to be fairly low. Accordingly, it is safe to say that radiation dose from environmental contamination may be mildly elevated, but it is not likely to be sufficiently high as to present a risk to plants, animals, or humans.

Soils

Soil column filtration was used to remove contaminants from water until the 1970s. This utilized the cation exchange capacity of clays in soils to attract dissolved ions, binding them to the surface of the clay minerals. Depending on the chemical properties of the exact isotope(s) used, this same phenomenon will cause much of the contamination from a radiological attack to remain in the soil as contamination. This, in turn, can lead to the need for decontamination via soil removal, soil washing, or other methodologies. The need for such decontamination will depend on the isotope(s) used, the concentration of isotope in soil, and the cleanup limit for the particular isotope(s) in question.

Water

Solubility depends on the chemical properties of a material. Some isotopes are either inherently soluble or are often found in soluble form (*e.g.*, H-3, C-14, Cs-137 as CsCl); these are more likely to become mobile as they dissolve into water (precipitation or surface water) and are transported from a contaminated site. Dissolved isotopes will be transported until they are removed from the water by ion exchange with rocks or soils, by precipitation, until the water leaves the region of interest, or until they are diluted beyond detectability. Insoluble isotopes (*e.g.*, Co-60) will be carried in water as particles until they are filtered out by soil or other materials or until they settle out in a low-flow area. Contaminant transport is a well-studied phenomenon (see, *e.g.*, the textbook by Domineco and Schartz (1997)), and the details are beyond the scope of this article.

Although there is a possibility that dissolved isotopes may enter the municipal water supply, water treatment will remove most of the activity, along with other contaminants to meet drinking water standards (USEPA 2003). The most likely areas to be attacked are urban, which have municipal water treatment, reducing the potential for radionuclide ingestion. Similarly, urban residents are not likely to obtain a large fraction of their food from home-grown vegetables or fruits, reducing radiation dose from this exposure pathway. In short, although there are exposure pathways that can lead to high levels of human radiation exposure, they are unlikely to be seen in the urbanized areas most likely to be attacked. Regarding radiation dose to organisms, it is similarly unlikely that any organisms will receive a high radiation dose with the exceptions noted later.

Some areas may tend to concentrate radionuclides. Low-flow regions of rivers or streams will let particles settle to the bottom, for example, cesium, which can bind to clays, may concentrate in the top-most soil layers, and iodine that is distributed

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widely across a pasture can concentrate in cow's milk (Eisenbud and Gesell 1997). Other areas in which chemical or mechanical processes may lead to radionuclide reconcentration are:

1. Sediments at the point a stream or storm sewer enters a river or lake.
2. Oxidation-reduction fronts where ground or surface water becomes anoxic.
3. Sediments or rough concrete at the bottom of storm sewer pipes.
4. Gutters, particularly in cracks and expansion joints.
5. Potholes and other depressions in paved and natural surfaces.
6. Soil horizons that mark changes in soil mineralogy or soil chemistry.

These concentrating mechanisms can lead to elevated radiation dose in limited areas or to small numbers of organisms that, in extreme cases, can be unhealthy. In such circumstances, it may be prudent to consider remediating these areas in which reconcentration occurs, even if it is prohibitively expensive to remediate the entire affected area.

MANAGING THE AFTERMATH OF AN RDD ATTACK

If a radiological attack occurs, society will be faced with medical, psychological, social, political, economic, organizational, and other challenges. Many of these challenges have been experienced in radiological and other settings in the past, and radiation safety professionals know what to expect to a large extent, although these issues have not been seen on a scale similar to what might be seen in the event of a successful radiological attack.

Although there have been no known successful radiological attacks, there have been several instances of widespread contamination. Of these, perhaps the most instructive is that in Goiania, Brazil, described in detail by the National Council on Radiation Protection and Measurements (NCRP 2001). In this incident, an "orphaned" Cs-137 radiation therapy source (1375 Ci, 50.9 TBq) was found by unsuspecting residents, who managed to open the source. Fascinated by the blue powder they found, residents played with it and spread it on their bodies, unaware of its radioactivity. By the time the nature of the source was known, nearly 250 people had been exposed to elevated radiation levels; 103 had evidence of ingestion, and 4 died of radiation sickness.

During the course of the incident and recovery, more than 3000 cubic meters of contaminated materials were removed for disposal and over 100,000 persons were surveyed for contamination at the city's soccer stadium (of whom only a few hundred were actually contaminated). The recovery process was time-consuming and expensive. However, the social impact was far greater and, even a decade later, Goiania residents were stigmatized by their association with the region. This stigmatization included an economic impact because sales of agricultural products from Goiania experienced a significant decline. Similarly, NCRP (2001) suggests that a successful RDD attack may also produce significant social and economic impacts on the city attacked.

In the immediate aftermath of a radiological attack, it will be necessary to manage the scene and the city so that the scene is stabilized, victims are cared for, and

essential city services (including access to uncontaminated medical facilities) are maintained. At the same time, some foresight may help with later recovery efforts. Many organizations and authors have developed materials describing actions to take in the event of a radiological attack (Karam 2004a, b; CDC 2004; REAC/TS 2004; AFRRI 2003; NCRP 1980), and summarizing them here is beyond the scope of this article.

SUMMARY

Some terrorists have made no secret of their desire to attack our allies or us with radiological weapons. In the event of a successful radiological attack, we will be faced with a bevy of problems. These include the “normal” disruption associated with any terrorist attack plus the added complications associated with radiological patients and “hot” work. In spite of the fact that any radiological attack is unlikely to lead to mass radiological casualties (indeed, there may be no radiological casualties at all), radiation safety measures and radiological regulations are likely to complicate our efforts.

If we are faced with tens or hundreds of thousands of contaminated (or potentially contaminated) persons, we will need to develop rapid and reasonably accurate field screening techniques to help us concentrate attention on only those persons who require this attention. We may wish to revisit regulatory guidance so that our regulations are based on risk rather than on our ability to detect ever-lower levels of contamination, and it may be necessary to change our medical treatment paradigm from patient-centered to community-centered for the duration of the emergency. In all of this, it will be important to remind emergency response and medical personnel that contaminated patients do not pose a risk to those caring for them (and that universal precautions are usually sufficiently protective), and that it is essential to care for life-threatening injuries first, regardless of a patient’s contamination status.

Having said all this, it is safe to assume that no actual incident will meet our expectations and any plans we develop will have to be altered to address the reality with which we will be faced. However, by developing a good set of plans, training to these plans and reasonable variations on them, and by setting in place actions and precautions based on risk instead of technology, we should be able to successfully manage the scene in the aftermath of a radiological attack, manage the city so that essential services are retained, and manage the longer term consequences so that the city and our society recover as rapidly as possible.

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APPENDIX: GLOSSARY OF RADIATION SAFETY UNITS AND TERMINOLOGY

Becquerel (Bq)—unit used to measure radioactivity. One Becquerel is the amount of a radioactive material that will undergo one transformation in one second. Often radioactivity is expressed in larger units like: thousands (kBq), or millions (MBq) of becquerels.

There are 3.7×10^{10} (37 billion) Bq in one curie.

Curie —a measure of radioactivity based on the observed decay rate of approximately one gram of radium. One curie of radioactive material will have 37 billion atomic transformations (disintegrations) in one second.

dose (radiation)—denotes the quantity of radiation or energy absorbed. Dose may refer to the following:

- absorbed dose, the amount of energy deposited per unit mass;
- equivalent dose, the absorbed dose adjusted for the relative biological effect of the type of radiation being measured;

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- committed dose, a dose that accounts for continuing exposures over long periods of time (such as 30, 50, or 70 years).

gray (Gy)—a unit of measurement for radiation absorbed dose. It relates to the amount of energy actually absorbed in a material, and is used for any type of radiation and any material. One gray is equal to one joule of energy deposited in one kg of a material. The unit gray can be used for any type of radiation, but it does not describe the biological effects of the different radiations. Absorbed dose is often expressed in terms of hundredths of a gray, or centi-grays. One gray is equivalent to 100 rads.

half-life—the time in which one half of the atoms of a radioactive isotope disintegrates into another nuclear form. Half-lives vary from billionths of a billionth of a second to billions of years. Also called physical or radiological half-life.

- **biological half-life**—the time an organism takes to eliminate one half the amount of a compound or chemical on a strictly biological basis
- **effective half life**—incorporates both the radioactive and biological half-lives. It is used in calculating the dose received from an internal radiation source.

radioactivity—the process of undergoing spontaneous transformation of the nucleus, generally with the emission of alpha or beta particles often accompanied by gamma rays.

Roentgen (R)—a unit of exposure to ionizing radiation. It is an indication of the strength of the ionizing radiation. One Roentgen is the amount of gamma or x-rays needed to produce ions carrying 1 electrostatic unit of electrical charge in 1 cubic centimeter of dry air under standard conditions.

Roentgen absorbed dose (rad)—a basic unit of absorbed radiation dose. It is being replaced by the “gray,” which is equivalent to 100 rad. One rad equals the dose delivered to an object of 100 ergs of energy, per gram of material.

Roentgen Equivalent Man (rem)—a unit of equivalent dose. Rem relates the absorbed dose in human tissue to the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. For example, alpha particles are likely to cause double-strand DNA breaks, which are more damaging to a cell than the single-strand breaks most commonly caused by gamma radiation.

Sievert (Sv)—unit used to derive a quantity called equivalent dose. This relates the absorbed dose in human tissue to the effective biological damage of the radiation. Not all radiation has the same biological effect, even for the same amount of absorbed dose. Equivalent dose is often expressed in terms of millionths of a Sv, or μSv . One Sv is equivalent to 100 rem.