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Assessing Radiological Weapons: Attack Methods and Estimated Effects

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Abstract. In the decade since September 11, 2001, a terrorist attack using radiological materials—usually referred to as a "dirty bomb," but actually encompassing other means of dispersal—has sometimes seemed inevitable. But terrorists have not yet carried out such an attack. Not only do many groups lack the motivation to engage in radiological terrorism, but these types of attacks also require technical, logistical, and financial means beyond those needed for terrorism using conventional methods. This article seeks to address technical questions associated with radiological terrorism. It first presents a summary of the commercially available radioactive sources, dispersal methods, and exposure pathways that could be deployed in a radiological attack. It then critically assesses the simulation-driven, open source research that has been done in the past ten years in the United States. The article goes on to note the estimated effects of a radiological attack according to these studies, with an emphasis on the motivations for, lessons derived from, and misconceptions or shortcomings contained in the various attack scenarios. Finally, the article draws conclusions and implications for the prevention and mitigation of radiological terrorism based on these studies and their respective limits, which mainly consist of technical, scope, and design limits or omissions, and suggests areas for further inquiry.

Keywords. Radiological terrorism, radiological dispersal device, commercial radioactive sources, open source studies, terrorism deterrence and mitigation.

Introduction

If radiological attacks appear, at first glance, to be easy to carry out, then the question of why terrorists have not yet done so must follow. This question has cast a shadow over studies of

terrorist behavior during the past decade, especially given that at least some terrorist groups seem motivated to launch such attacks. After all, if a radiological attack requires simply the detonation of a stick of dynamite in order to disperse radioactive material, expose people to ionizing radiation, and contaminate valuable property, why would terrorists not conduct such apparently easy attacks?

A partial answer is that these so-called "simple" attacks in reality require more effort, and thus more resources, than most conventional attacks, especially improvised explosive devices. Specifically, the terrorists would need to acquire potent radioactive materials, to know how to handle those materials without killing themselves prior to the attack—a concern applicable even to suicidal terrorists—and to determine effective means of dispersing the material. These steps involve a multitude of technical considerations.

Although the focus in this article is the assessment of technological issues, the first hurdle to overcome is actually motivational. It is worth pointing out that most terrorists are not motivated to use radiological or nuclear methods in the first place. As Jerrold Post asserts, for most terrorist groups—especially ones operating on their national territory or those for which constituent support are a concern—nuclear or radiological terrorism would be highly counterproductive; those who study terrorist motivation and decision making are "underwhelmed by the probability of such an event."[1] According to his analysis, the threat of nuclear or radiological terrorism would emanate mainly from political-religious, apocalyptic, right wing, and national-separatist groups.

Some terrorist groups have expressed interest in radiological attacks, most notably al-Qaeda. With numerous statements on the issue, Osama bin Laden has made no secret of his desire to acquire nuclear and radiological materials. In June 2002, then U.S. attorney general John Ashcroft announced the arrest of U.S. citizen Jose Padilla, an alleged al-Qaeda operative who was then accused of plotting a radiological "dirty bomb" attack on the United States; however, no charges related to an RDD were mentioned in Padilla's indictment and he was later convicted of criminal conspiracy charges. In 2006, British citizen Dhiren Barot, also linked to al-Qaeda, was convicted for his plans to construct a dirty bomb using the small radioactive sources contained in smoke detectors. In addition, Chechen terrorists have a substantial history of making radiological threats and seeking out radiological and nuclear materials. To cite one example, in 1995, these terrorists buried in a Moscow park a canister containing a small amount of cesium-137 and then informed the news media. While nothing was dispersed, this incident demonstrates the potential use of radiological material to instill public fear.

A consensus in the policy and technical expert community has emerged that the main threats posed by a radiological terrorist attack are economic, social, and psychological. While some deaths and injuries would certainly result, a radiological device is primarily a weapon of "mass disruption," rather than destruction.[2] Radiological terrorism is thus appealing because it has the

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[1] Jerrold M. Post, "Differentiating the Threat of Radiological/Nuclear Terrorism: Motivations and Constraints," paper presented to the IAEA Symposium on International Safeguards, special session on combating nuclear terrorism, Vienna, Austria, November 2, 2001, p. 2.

[2] Among the first experts to use this term were Henry Kelly, Steven Koonin, and Michael Levi. Henry C. Kelly, Testimony before the U.S. Senate Foreign Relations Committee, March, 6, 2002; Steven E. Koonin, "Radiological Terrorism," *Physics and Society*, vol. 31, no. 2, 2002, pp. 12-13; and Michael A.

potential to cause such effects as mass panic and economic losses. A document on a prominent jihadist website states "the important thing is to disperse radioactive material in a large commercial area so the government is forced to shut down this area." It goes on to explain that the ensuing "massive economic disruption" would result from: the high costs of decontaminating radioactive areas, the high economic losses in a large commercial area due to closures, subsequent job loss and stoppage of general life in that area, and large compounded problems to follow. Finally, it suggests Las Vegas, New York, London, Sydney, Tokyo, Moscow, other large tourist cities, and the commercial capitals of "all infidel nations" as ideal targets.[3]

Scope of the Technological Assessment

In general, four types of nuclear and radiological terrorism exist:[4]

1. The acquisition and detonation of an intact nuclear weapon from a nation-state's arsenal;
2. The acquisition of weapons-usable fissile material such as highly enriched uranium or plutonium, in order to make and detonate an improvised nuclear device, which is a crude nuclear explosive;
3. An attack on or sabotage of nuclear facilities such as nuclear power plants, spent fuel pools, other radioactive waste storage or processing facilities, or research reactors in order to disperse radioactive material; and
4. The acquisition of radioactive materials from commercially available devices or other radioactive materials in order to build a radiological weapon that disperses radioactive material or emits ionizing radiation.

The scope here is confined to use of commercially available radioactive sources, such as those used in hospitals, universities, oil wells, shipyards, and other industrial applications. Because other publications have comprehensively examined the commercial radioactive source industry and the details of the radioisotopes and radioactive sources that may pose security concerns, this article gives just an overview of the subject for ease of reference. Such a survey is also needed as context for analyzing the openly available studies performed over the past decade in the United States, which is the main aim of this article.

First, a few basic definitions are in order. A chemical element has unique chemical properties that derive from the number of protons (positively charged particles) inside the nucleus, or core, of each atom of the element. Also inside the nucleus are neutrons, which are uncharged and help to hold together the nucleus through the strong nuclear force. The number of neutrons also helps determine the nuclear properties of the nucleus. Perhaps the most important property is whether

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Levi and Henry C. Kelly, "Weapons of Massive Disruption," *Scientific American*, November 2002, pp. 71-81.

[3] Abu al-Usood al-Faqir, "Instances of Radiation Pollution from 1945-1987," *al-Farouq* jihadi website, October 2005, as quoted and translated in Sammy Salama and David Wheeler, "Unraveling al-Qa'ida's Target Selection Calculus," Combating Terrorism Center, U.S. Military Academy, West Point, New York, USA, December 2006.

[4] Charles D. Ferguson, William C. Potter, et al., *The Four Faces of Nuclear Terrorism*, Center for Nonproliferation Studies, Monterey, California, USA, 2004, pp. 46-258.

the nucleus is energetically stable or unstable. An unstable nucleus will want to emit radiation, a form of energy, to become more energetically stable or more tightly bound. Each element has a family of different nuclear forms called isotopes. Thus, isotopes of an element have the same number of protons, but different numbers of neutrons. Most isotopes are unstable and thus will eventually experience radioactive decay. This decay involves the emission of ionizing radiation. Half-life measures the amount of time it takes for half the radioactive substance to decay. Thus, a short half-life means a rapid decay time, and a long half-life means a more lengthy decay time.

Ionizing radiation can ionize or knock electrons off of atoms through scattering or absorption. The different types of ionizing radiation include: alpha radiation, which consists of two protons and two neutrons bound together and thus has a plus two charge; beta radiation, which is either an electron or a positron and thus has a minus one or plus one charge; and gamma radiation, which is highly energetic light and thus is uncharged. Alpha radiation is the least penetrating of the three types and can be stopped by a piece of paper or the dead outer layer of skin, but it is also the most ionizing and thus poses an internal health hazard if alpha emitting sources are ingested or inhaled. Beta radiation is intermediate in penetrating ability and can be stopped usually by thin sheets of aluminum, for example. Its ionizing capability is assigned a relative value of one, in comparison to a value of twenty for alpha radiation; beta radiation is considered mainly an internal health hazard, although it could damage unprotected eyes. Gamma radiation is the most penetrating and can be stopped by sheets of lead or thick concrete, for example. Thus, it can pose both internal and external health hazard; however, the lethal dose for a gamma emitter is larger than that of an alpha emitter by approximately ten times, meaning that the latter is much more potent. Alpha sources are often among the least well-protected types of commercial radioactive sources.[5] In addition to these types of ionizing radiation, some unstable nuclei emit protons, neutrons, and deuterons (proton and neutron combined). Yet other nuclei become more stable by spontaneously undergoing fission, that is, splitting into two smaller mass pieces (fission products) and releasing neutrons. Because the commercial radioactive sources of security concern are all alpha, beta, or gamma emitters, only those types of radiation will be considered here.

To determine the radioactive sources of security concern, the following studies have been done by a number of analysts. First comes the assessment of the number of different radioisotopes in use. In principle, more than 3,000 radioisotopes are available, but most of these decay very rapidly, in less than one second. These can be excluded because they will decay too quickly to pose any threat during a radiological attack. The next, more detailed analysis excludes any radioisotopes with a half-life shorter than a few days or longer than several thousand years. As already noted, short half-life materials would not last long enough to pose a serious threat of contamination; very long half-life materials decay relatively slowly and thus would not emit as much radiation as an intermediate half-life material. To place this concept on the human scale, one can conceptualize radioisotopes of concern by imagining living next to certain types of radioisotopes. Those that would emit all or an appreciable portion of their radiation during a typical human lifetime of several decades could present a health concern. An examination of Table

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[5] James M. Acton, M. Brooke Rogers, and Peter D. Zimmerman, "Beyond the Dirty Bomb: Re-thinking Radiological Terror," *Survival*, vol. 49, no. 3, 2007, p. 155.

1 shows that the half-life of each radioisotope of concern is within the range of 8 days to 433 years.

The other factor that determines whether a radioisotope has made this list is whether it is used relatively prevalently in commercial applications. Table 2 lists commercial radioactive sources that have large enough amounts of radioactive material to pose a potential security concern if used in a radiological attack. Note that this table shows the radioactivity content in units of gigabecquerels (GBq) and Curies (Ci). The gigabecquerel is the international unit and the Curie is the traditional unit, which is still used in the United States. The Becquerel is defined as one disintegration or decay per second; consequently, a gigabecquerel equals one billion decays per second. A curie is defined as the amount of radioactivity in one gram of radium. This means that one Curie would equal 37 billion Becquerels. Table 2 also indicates the category level of each source. The International Atomic Energy Agency (IAEA) defines the category. Table 3 compiles the categorization definitions assessed by the IAEA; however, it should be noted that debate continues between the U.S. and other governments and the IAEA as to whether this categorization is ideal from the perspective of evaluating security threats. The discussion is particularly focused on how to quantify the contamination, social, and psychological effects of sources below category 2.[6]

[6] Charles D. Ferguson, "Radiological Weapons and Jihadist Terrorism," p. 179, in Gary Ackerman and Jeremy Tamsett, eds., *Jihadists and Weapons of Mass Destruction*, CRC Press, Boca Raton, Florida, USA, 2009.

Radioisotope	**Half-Life**	**Specific Activity GBq/g (Ci/g)**	**High-Energy Alpha Emissions**	**High-Energy Beta Emissions**	**High-Energy Gamma Emissions**
Americium-241 (Am-241)	433 years	125.8 (3.4)	Yes	No	Low Energy
Californium-252 (Cf-252)	2.7 years	19,832 (536)	Yes	No	Low Energy
Cesium-137 (Cs-137) [Barium-137m (Ba-137m)]	30 years [2.6 minutes]	3,256 [19,980 million] (88 [540 million])	N/A	Low Energy [Low Energy]	N/A [Yes]
Cobalt-60 (Co-60)	5.3 years	40,700 (1,100)	N/A	Low Energy [Low Energy]	Yes
Iodine-131 (I-131)	8.0 days	4.8 million (130,000)	N/A	Yes	Yes
Iridium-192 (Ir-192)	74 days	>16,650 (>450) std >37,000 (>1,000) high	N/A	Yes	Yes
Polonium-210 (Po-210)	140 days	166,500 (4,500)	Yes	Low Energy	Low Energy
Plutonium-238 (Pu-238)	88 years	636.4 (17.2)	Yes	No	Low Energy
Plutonium-239 (Pu-239)	24,000 years	2.33 (0.063)	Yes	Low Energy	Low Energy
Radium-226 (Ra-226)	1,600 years	37 (1)	Yes	No	Low Energy
Strontium-90 (Sr-90) [Yttrium-90 (Y-90)]	29 years [64 hours]	5,180 [20.35 million] (140 [550,000])	N/A	Yes [Yes]	N/A [Low Energy]

Table 1: Radioisotopes of Security Concern[7]

[7] Table based on Charles D. Ferguson, Tahseen Kazi, and Judith Perera, *Commercial Radioactive Sources: Surveying the Security Risks*, Occasional Paper 11, Center for Nonproliferation Studies, Monterey Institute of International Studies, California, USA, January 2003, p. 16; and the U.S Department of Energy/Nuclear Regulatory Commission Interagency Working Group on Radiological Dispersal Devices, "Radiological Dispersal Devices: An Initial Study to Identify Radioactive Material of Greatest Concern and Approaches to their Tracking, Tagging, and Disposition," Report to the Nuclear Regulatory Commission and the Secretary of Energy, May 2003.

Type of Source or Application	**Radioisotope**	**Typical Radioactivity Level GBq (Ci)**	**Source Categorization**
Sterilization and food irradiation	Cobalt-60	148 million (Up to 4 million)	1
	Cesium-137	111 million (Up to 3 million)	
Radioisotope thermoelectric generator (RTG)	Strontium-90	740,000 (20,000)	1
	Plutonium-238	10,360 (280)	
Research and blood irradiators	Cobalt-60	88,800-925,000 (2,400-25,000)	1
	Cesium-137	259,000-555,000 (7,000-15,000)	
Single-beam teletherapy	Cobalt-60	148,000 (4,000)	1
	Cesium-137	18,500 (500)	
Multi-beam teletherapy (gamma knife, e.g.)	Cobalt-60	259,000 (7,000)	1
Industrial radiography	Cobalt-60	2,220 (60)	2
	Iridium-192	3,700 (100)	
High- and medium-dose brachytherapy	Cobalt-60	370 (10)	2
	Cesium-137	111 (3)	
	Iridium-192	222 (6)	
Well logging	Cesium-137	0.74-74 (0.02-2)	3
	Americium-241/Beryllium	0.74-74 (0.02-2)	
	Californium-252 (rare use)	37 (1)	
Level and conveyor gauges	Cobalt-60	0.74-74 (0.02-2)	3
	Cesium-137	0.74-74 (0.02-2)	

Table 2: High-Risk Radioactive Sources[8]

[8] Adapted from International Atomic Energy Agency, "Categorization of Radioactive Sources," IAEA-TECDOC-1344, Vienna, Austria, 2003; and Ferguson and Potter, op. cit.

Categories of Radioactive Sources	**Definition and Types of Sources**
Category 1	These sources "if not safely managed or securely protected would be likely to cause permanent injury to a person who handled [them], or were otherwise in contact with [them] for more than a few minutes. It would probably be fatal to be close to this amount of unshielded material for a period of a few minutes to an hour." This category includes radioisotope thermoelectric generators, research and blood irradiators, and radiation teletherapy sources.
Category 2	These sources "if not safely managed or securely protected could cause permanent injury to a person who handled [them], or were otherwise in contact with [them], for a short time (minutes to hours). It could possible be fatal to be close to this amount of unshielded radioactive material for a period of hours to days." This category includes industrial radiography cameras, and high-dose-rate and medium-dose-rate brachytherapy sources.
Category 3	These sources "if not safely managed or securely protected could cause permanent injury to a person who handled [them], or were otherwise in contact with [them], for some hours. It could possibly be fatal to be close to this amount of unshielded radioactive material for a period of days to weeks." This category includes oil well logging sources and fixed industrial gauges using high activity sources such as level gauges, dredger gauges, conveyor gauges, and spinning pipe gauges.
Categories 4 and 5	The sources in these categories contain relatively low activity materials and thus are generally not considered dangerous in the context of most radiological weapons unless a large enough aggregate amount of these sources were collected and used. Examples of sources in these categories are smoke detectors and medical diagnostic sources.

Table 3: Categorization of Radioactive Sources[9]

[9] All quotes in this table were taken from International Atomic Energy Agency, "Categorization of Radioactive Sources," op. cit., pp. 27-29.

Radiological Attack Methods

The purpose of a radiological weapon is to disperse radioactive materials or emit ionizing radiation from a stationary or mobile radioactive source that has not been dispersed into many pieces. Radiological weapons can use crude explosives, advanced dispersal techniques, or simple emission from radioactive sources. While many members of the public associate the term "dirty bomb" with any type of radiological weapon, or even a nuclear detonation, it strictly should refer to the use of explosives to spread radioactive material. In the policy and technical literature, three terms are used: radiological dispersal device (RDD), radiation emission device (RED), and radiological incendiary device (RID). Of these, the RDD encompasses the largest variety of mechanisms, which could include explosive or non-explosive and passive or active means, to spread radioactive material. An RED refers particularly to a stationary or mobile radioactive source that emits radiation. Terrorists, criminals, or other malicious people could use an RED to expose many people, few people, or just one specific person to ionizing radiation. The former and possibly the intermediate acts are usually associated with terrorists because they would typically want to instill fear in many people. In contrast, a criminal would most likely try to harm or kill one or a few people; this was the case in the 2006 poisoning-murder of Russian dissident Alexander Litvinenko, who died after ingesting polonium-210. An RID refers to a device that couples fire with radioactive material. One reason a terrorist group may want to use an RID is to complicate firefighters' efforts to rescue people and protect property.[10] Emergency responders would have to contend not only with public panic in regard to the fire, but also with the radioactivity.

There exist several generalized human exposure pathways for the materials that would be dispersed in an act of radiological terrorism: external exposure, inhalation, ingestion, and immersion. External exposure is typically associated with gamma emitters, since alpha and beta particles have a low ability to penetrate human tissue, and with scenarios that include exposure to an intact radioactive source or contamination from a dirty bomb or other RDD. It is the most commonly considered pathway, especially in regard to environmental decontamination and the regulatory challenges that would be posed by the distribution of radiation. Inhalation requires that a terrorist convert the radioactive source into an aerosol form in order to create particles small enough to be suspended in air and drawn in through the nose. Common inhalation scenarios include dispersal through ventilation systems, sprays, powders, or the small (micron- and submicron-sized) particles that could result from an RID. Inhalation is overall the most damaging exposure pathway, especially with alpha emitters.[11] However, it is rather challenging and complex to effectively execute on a massive scale. The ingestion pathway is also fraught with difficulty since the primary scenarios—contamination of the water supply, agriculture, or food production and processing—encounter vexing but not intractable problems of scale (the radioactivity would be quickly diluted) and access. It should also be noted that particles small enough to be inhaled could also be ingested. Except in cases where soluble radioactive materials are dispersed, the

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[10] Joseph W. Pfeifer, *Improvised Incendiary Devices: Risk Assessment, Threats, Vulnerabilities, and Consequences*, Master's thesis, Naval Postgraduate School, Monterey, California, September 2006.

[11] Joseph Magill et al, "Consequences of a Radiological Dispersal Event with Nuclear and Radioactive Sources," *Science and Global Security*, vol. 15, 2007, pp. 112-116.

ingestion pathway is generally less serious than that of inhalation because digestive system would cycle the material out of the body with relative speed, limiting the amount of exposure to radiation. Finally, it is plausible that terrorists cover people with contaminated water. This immersion pathway could lead to external injury (radiation burns) and inhalation or ingestion of radioactive material.

In 2007, researchers at King's College London undertook a reassessment of the threat posed by radiological terrorism. They assert that because radioactive materials cause more harm in smaller quantities when inside the body, as opposed to in the external environment, and since more commercial radioisotopes become available for use in an attack that would aim for internal exposure, that the threat paradigm for radiological dispersal devices should reorient to further include the risks posed by inhalation, ingestion, and immersion attacks, which they dub "I-cubed" attacks.[12] While the authors offer policy solutions to prevent I-cubed attacks—especially eliminating or further securing the commercial radioisotopes most likely to be used by terrorists and better informing the public of these plans.

In summary, once dispersal and subsequent exposure have occurred, the factors influencing the biological impact of a radiological attack include the kind of radiation emitted by the isotope used in the attack and its energy levels, as previously discussed, and the chemical form of the isotopes, which takes into account the varying solubility of different radioactive materials. Finally, it is worthwhile to emphasize again that a radiological attack carried out in any method, even if it does not succeed in exposing or killing large numbers of people, will still foster fear, uncertainty, and other social and economic disruptions.

Review of Open-Source Studies and Estimated Effects

As Peter Zimmerman and Cheryl Loeb emphasize, since most radiological scenarios tend to focus on high explosive dispersal devices, "generalizations about the RDD threat can be misleading."[13] It is thus important to understand the various case studies carried out over the past decades, as well as their shortcomings and conclusions. While the following review is not exhaustive, it illustrates the various types of research done in recent years. For each of the following studies, the discussion includes a description of its scenario or scenarios, the motivations for carrying out the study, conclusions found by the researchers, and any misconceptions or gaps in the scenario design or execution.

Within about six months of the terrorist attacks of September 11, 2001, radiological terrorism studies were initiated by two Washington, DC-based think tanks, the Center for Strategic and International Studies (CSIS) and the Federation of American Scientists (FAS). The Center for Strategic and International Studies has strengths in political science and policy analysis, in addition to being well networked to government officials. While FAS also has connections to government officials, it can further bring to bear scientific expertise, especially in the physical

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[12] Acton, Rogers, and Zimmerman, op. cit.

[13] Peter D. Zimmerman with Cheryl Loeb, "Dirty Bombs: The Threat Revisited," *Defense Horizons*, no. 38, January 2004, pp. 4-5.

sciences. These somewhat overlapping strengths and diverging differences played out in the RDD scenarios each organization investigated.

The March 2002 CSIS study focused mainly on the issue of the response to a large explosion in Washington, DC, by many levels of government, private industries, the news media, and the general public. In the words of the lead planner Philip Anderson, the "overall purpose … was to help frame the planning requirement … [for the Metropolitan Washington Council of Governments] led crisis-planning effort, by identifying some of the key issues and friction points to be resolved."[14]

It is important to know that the Washington metropolitan area is a complex mix of jurisdictions; Washington, DC, is a city but also has roles of a state, although it does not enjoy this official designation. The district is surrounded by two states, Maryland and Virginia. In addition, because Washington is the seat of the U.S. federal government, federal officials and police officers would become immediately involved in any terrorist attack in the city. Consequently, the CSIS scenario took into consideration plenty of tough policy and jurisdictional issues, even without the introduction of radioactive material into the explosion.

The scenario opens on the morning of May 23, 2002, with the detonation of a powerful improvised explosive device laced with about 1,000 Ci of cesium-137 and embedded inside a school bus that contains no people. The bus is parked just outside the National Air and Space Museum, a location chosen because it is a major tourist attraction and the outer building wall is made of a large amount of glass. Hundreds of people would likely be in the museum or the immediate vicinity; the glass shattering would create a tremendous spectacle in the center of the city. Moreover, thousands of U.S. government workers are within a few city blocks of this detonation. In the scenario, the federal government closes, leading to transportation issues and self-evacuation. Because of the large numbers of people who self-evacuated from the contaminated area, radiation would eventually be detected in areas far from the blast site. As the scenario continues, the psychological and economic effects of a radiological attack become more apparent; people refuse to return to the city for work, school, and tourism due to fears of radiation, even though the danger of death is almost nonexistent. (The scenario implies that some people would die from the attack, but provides no figures.) The CSIS study concludes that although immediate responses operate fairly smoothly in the scenario, emergency response and recovery would be more difficult in Washington, DC, than in anywhere else in the United States because of the inherent complexities of combining federal, state, local, and private sector decisions into comprehensive and coordinated contingency plans. It also underscores the necessity of rapid, clear, and accurate communications to the public in order to avoid hysteria and attempt to minimize economic losses stemming from fears of radiation. While the scenario can prove useful as a general exercise in jurisdictional policy coordination, it is limited by its lack of specificity.

Like the CSIS study, that of FAS also took place in March 2002. The U.S. Senate Foreign Relations Committee tasked FAS to examine three scenarios, which were chosen to illustrate the effects of relatively small and large amounts of radioactive contamination, as well as to compare

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[14] Philip Anderson, "Greater Washington, DC, Crisis Planning," Center for Strategic and International Studies, Washington, DC, USA, March 21, 2002, p. 2.

alpha and gamma radiation emitters.[15] The FAS researchers used Hotspot, a readily available computer code that can simulate two-dimensional scenarios. Consequently, one of the limitations of this study is that it cannot capture the effects of buildings and other three-dimensional structures. Hotspot uses a Gaussian plume model and thus illustrates neat oval patterns of radioactive material dispersal. In actuality, the situation would be more complex with eddy effects and high concentrations of radioactivity close to lower concentrations depending on the chaotic effects of wind and rain, as well as manmade and natural structures. In addition, all three cases assume calm winds, dispersal in a major U.S. urban area using explosives and resulting in fine particles, which can lead to inhalation, ingestion, or external exposure. The FAS researchers therefore caution that "it is only possible to make crude estimates of impacts" and that their results "might be off by an order of magnitude."

Each case presented in the FAS study makes use of radioisotopes of the type and corresponding quantity that would actually be found in common commercial applications. The first scenario involves cesium-137 from a medical gauge source similar to the one that was found abandoned in North Carolina in 2002; the detonation of 10 pounds of TNT would disperse the two curies of cesium over the area of approximately 40 city blocks in Washington, DC.[16] Because of the relatively small amount of material in the dispersal cloud, people would not be immediately harmed. But if they remained in the most contaminated area of about 5 city blocks, their cancer risk from associated radiation exposure could be one acquisition of cancer per 1,000 people. The second scenario describes the dispersal in lower Manhattan of 10,000 Ci of cobalt-60 from a food irradiation rod. The study predicts that such an attack would contaminate the entire borough of Manhattan to the extent that living in the approximate 300-city block area would carry a one-in-one hundred chance of dying from cancer caused by the residual radiation. The third scenario depicts 1 pound of TNT distributing in Manhattan 10 Ci of americium-241, an alpha emitter used to survey oil wells. Because of the risk posed by inhaling these particles, an area covering 20 city blocks would need to be immediately evacuated and subsequent cancer probability in a 10-block contaminated area could be one death per 1,000 people.

The FAS researchers concluded that radiological attacks pose a credible threat due to the availability of radioactive materials, the ability for some of these materials to be dispersed by explosive or other means. An act of radiological terrorism would not cause the same degree of fatalities as the detonation of a crude nuclear device, despite the much-criticized 2002 statement of then-attorney general Ashcroft, who said a dirty bomb "not only kills victims in the immediate vicinity, but…can cause mass death and injury."[17] Nonetheless, a radiological attack could contaminate many city blocks, prompting evacuation, panic, eventual demolition, and heavy economic losses. The study primarily recommends prevention through reducing access to the commercial radioactive sources that could be used in terrorist applications.

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[15] Henry Kelly, "Dirty Bombs: Response to a Threat," *FAS Public Interest Report*, vol. 55, no. 2, 2002; this article is based on testimony given by Dr. Kelly to the Senate Foreign Relations Committee. The analysis was done by Michael Levi, Robert Nelson, and Jaime Yassif.

[16] Michael Levi and Henry Kelly, "Dirty Bombs Continued," *FAS Public Interest Report*, vol. 55, no. 3, 2002.

[17] "Ashcroft Statement on 'Dirty Bomb' Suspect," transcript, CNN.com, June 10, 2002.

The Top Officials (TOPOFF) simulations are a series of Congressionally-mandated, high-level U.S. exercises, some with an international component, designed to strengthen domestic capacity to prevent, protect against, respond to, and recover from large-scale terrorist attacks involving weapons of mass destruction. TOPOFF 2 was the second in the series, but the first such event following the attacks of September 11, 2001, and the creation of the U.S. Department of Homeland Security (DHS). The exercise sought to identify vulnerabilities in U.S. domestic incident management capabilities by applying the plans, policies, procedures, systems, and facilities of federal, state, and local response organizations against a series of integrated terrorist threats and acts in separate regions of the country. For nearly a week in May 2003, TOPOFF 2 engaged 8,500 people from the United States and Canada in a fictional scenario in which an RDD is detonated in the city of Seattle, along with biological attacks in Chicago and threats against other locations.[18]

Compared to the previously described CSIS and FAS studies, TOPOFF 2 was an enormous set of events that simultaneously included actors, staged catastrophes, and computer simulations (no information was disclosed on the types of models used). In the end, TOPOFF 2 provided some important lessons for emergency responders, above all that interagency communication is of the utmost importance after a radiological attack.[19] Some of the main criticisms of TOPOFF 2 stem from its highly scripted, costly, and massive nature. For example, according to various press reports, officials in Seattle knew for weeks in advance the exact time and location of the "dirty bomb," allowing them ample time to practice for the scenario and potentially undermining its value as a measure of U.S. preparedness for such an attack. Yet most of the findings of TOPOFF 2 have not been made available to the public, a criticism this exercise shares with the original TOPOFF events, undertaken in 2000. As a matter of its design, the exercise is also weighed heavily in favor of addressing the immediate challenges posed by a radiological attack. But the limited time span of TOPOFF 2 misses what would be some of the most difficult aspects of mitigating a radiological attack, processes that would certainly require the same types of interagency coordination that the exercise seeks to bolster, albeit toward very different tasks.[20]

Finally, it should be noted that the stated purpose of the TOPOFF series is to simulate "worst case scenario" terrorism using weapons of mass destruction. This calls into question the choice of an RDD attack. A need exists to better inform policymakers and the public by dispelling myths propagated by a few government officials and some members of the news media. An RDD is an economic weapon and is capable of inflicting devastating damage, but as Zimmerman and Loeb strongly demonstrate, most radiological dispersals would result in few, if any, near term deaths or serious radiation health effects. They point out "some forms of radiological attack could kill tens or hundreds of people and sicken hundreds or thousands."[21]

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[18] "National Exercise Program," U.S. Department of Homeland Security, DHS.gov, last accessed January 2, 2010.

[19] Jaime Yassif, "How Well Did TOPOFF 2 Prepare Us for Mitigating the Effects of a Dirty Bomb Attack?," *FAS Public Interest Report*, vol. 56, no. 2, 2003.

[20] *Ibid.*

[21] Zimmerman and Loeb, op. cit.

In 2006, a senior scientist at Sandia National Laboratories and a health physicist at Brookhaven National Laboratory published an article providing specific guidance to first responders, planners, and other senior decision makers for protective actions that should be undertaken in the first 48 hours after the outdoor detonation of an RDD. The study bases its recommendations on over twenty years of experiments conducted at Sandia—these include more than 500 explosive experiments using upwards of 20 materials and 85 device geometries—to determine what might actually occur after a radiological blast. This data was then incorporated into the Explosive Release Atmospheric Dispersion (ERAD) effects model, which combines methods to simulate the buoyant rise after an explosion and the particulate plume, which in turn can predict the dispersal of actual radioactive sources based on the design of the RDD. Further analysis of the data gives correspondence between the radiological source, its physical form, the nuclide, and the RDD design, and potential health effects, providing extremely valuable and practical information for first responders. The recommendations include how to establish a high zone boundary at 500 meters in all directions from the site of the explosion, confirm and adjust the outer boundary of the high zone based on absorbed radiation dosage, most effectively ration medical triage based on the type of radionuclide used in the attack, interpret radiation levels and make operational decisions based on them.[22]

The limited scope of the project, as well as the depth of the hard data and the complexity of the models behind it, set it apart from the other scenario studies previously analyzed in this article. The authors also specify the need for planners to take different approaches for an RDD attack than they would for chemical or biological terrorism. Another distinctive quality of the Sandia paper is its focus on most probable scenarios, rather than worst case scenarios, in order to make its guidance as applicable as possible and to reduce unnecessary conservatism and inefficiency in RDD emergency response planning.[23]

While most simulation-based studies of radiological terrorism note that the long-term economic costs of such an attack will overshadow the casualties—most of which would occur immediately or very far in the future—very few employ any economic analysis beyond general cost estimates for decontamination or abandonment of an affected area.[24] H. Rosoff and Detlof von Winterfelt employ risk and economic analysis to study potential dirty bomb attacks on the ports of Los Angeles and Long Beach with an eye to identifying port vulnerabilities to radiological terrorism, assessing the potential health and economic impacts of such an attack, and formulating potential policy recommendations and countermeasures. The authors put forth three scenarios in their study: a low radioactivity case using material stolen from a radiotherapy device in a U.S. hospital, a medium radioactivity case using material stolen from a U.S. industrial irradiator, and a high radioactivity case using a spent fuel assembly from the former Soviet Union. They then multiply these three scenarios with four possible modes of transport for the material and three locations for the attack—for a total of 36 attack scenarios—before using qualitative judgments to

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[22] Stephen V. Musolino and Frederick T. Harper, "Emergency Response and Guidance for the First 48 Hours after the Outdoor Detonation of an Explosive Radiological Dispersal Device," *Health Physics*, vol. 90, no. 4, 2006, pp. 381-384.

[23] *Ibid*., p. 384.

[24] Henry Kelly, "Dirty Bombs: Response to a Threat" op. cit.

narrow probable scenarios.[25] The economic and risk models are finally applied to a medium radioactivity case.

The authors identify the main consequences of a dirty bomb attack as the immediate fatalities and injuries from the blast and acute radiation exposure, medium- and long-term health effects from airborne radioactive material, and the economic impacts that would result from closure of the port, which take account of evacuations, business and property losses, and decontamination costs. By combining a variety of means to analyze the data—including risk models to discover which steps in a potential attack are most subject to intercept—it is concluded that the most cost effective means to counter such a potentially economically damaging act of radiological terrorism are anticipatory. According to such logic, the prevention or interdiction of theft or purchase of the material is ideal, combined with optimally calibrated radiation detection at the ports.[26] As with the Sandia report, the scope of this study is highly limited; however, its specific recommendations are bolstered by the sophistication of the data and analysis backing them.

In contrast to the works analyzed thus far, a 2003 RAND report led by Lynn Davis takes a decisively different approach to preparatory response simulations. Motivated by the new public awareness and concern regarding terrorist attacks that followed September 11, 2001, this study aims specifically to enhance the role of the individual citizen as a supplement and complement to the parts played by federal, state, and local government agencies. The authors assert that identifying individual preparedness and response actions that enhance the safety and security of people in a large terrorist incident not only contributes to educating and empowering the very targets of such an attack, but could also serve to deter terrorist strikes in the United States.[27] In addition to radiological incidents, the report contains scenarios for chemical, nuclear, and biological attacks.

The report presents two RDD scenarios with similar timelines and control factors. In both, a car containing a radioactive source and 100 pounds of TNT explodes on a highway in a major metropolitan area at 10 am on a day with calm wind. Within fifteen minutes, the media releases the news of a "dirty bomb" explosion and within an hour, this is officially confirmed. The main difference is that one scenario images the dispersal of 10,000 Ci of cesium-137, while the other consists of 50 Ci of americium-241.

In either type of attack, the authors recommend individuals devise a strategy that above all else avoids inhaling dust that could be radioactive, while rightly noting that external radiation exposure from a contaminated environment is of secondary concern. They go on to advise people to seek indoor shelter in the case of an outdoor dispersion (or outdoor shelter in the case of an indoor dispersion), to decontaminate through bathing, and to evacuate and seek medical treatment only when directed by authorities. These instructions are sound and if followed by large numbers of people, would contribute to diminishing some of the disruption associated with radiological

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[25] H. Rosoff and D. von Winterfeldt, "A Risk and Economic Analysis of Dirty Bomb Attacks on the Ports of Los Angeles and Long Beach," Risk Analysis, vol. 27, no. 3, 2007, pp.

[26] *Ibid*., pp. 543-544.

[27] Lynn E. Davis et al, *Individual Preparedness and Response to Chemical, Radiological, Nuclear, and Biological Terrorist Attacks*, RAND, Arlington, Virginia, USA, 2003, pp. 1-3.

terrorism. However, the primary shortcoming of the radiological scenarios in the RAND report—and the subsequent advice it offers to the public—is the singular focus on "dirty bomb" dispersal. At no point in the radiological sections of the report is there any specific mention of immersion or ingestion pathways, not to mention non-explosive types of RDD.[28]

Implications and Conclusions

Scenario-based approaches have been used effectively to design mitigation strategies for non-terrorist hazards, such as earthquakes and floods. This article does not seek to call into question the utility of scenario- and simulation-based studies in the development of emergency response efforts against terrorism; however, those who undertake such research must properly balance benefits and risks. The gains from open source simulation studies of radiological attacks must be carefully weighed against the potential risk of providing instructions to potential terrorists. For this reason, most of the reports analyzed in this article openly omit portions of methodology or data, especially technical details related to delivery device design, quantities of TNT, and Curies of radioisotopes. This fact alone demonstrates the need to tread carefully in open source work in order to avoid compiling for potential terrorists a "recipe" for a maximally destructive radiological attack that exploits weaknesses in detection methods and vulnerabilities in first response plans.

As a whole, the studies analyzed here address both questions of preventing and mitigating an act of radiological terrorism, although the recommendations derived from these U.S. case studies tend to focus more heavily, or at least in more detail, on response. The most recurrent themes in terms of preventive policy options include limiting or further regulating access to commercial radioactive sources of security concern, increasing the security of existing sources, altering the physical qualities of sources of security concern in order to render them less able to be dispersed—especially forming cesium-137 into a ceramic or non-dispersible forms rather than as a powder, and substituting non-radioactive source alternative technologies, for example, accelerator-based treatment of cancer instead of using teletherapy sources and x-ray. In terms of mitigation, the recommendations generally focus on optimizing operational, communication, and logistical response strategies in the immediate- to intermediate-term after the detonation of an RDD. The review sample selected for this article purposefully includes studies that vary in their scope; the limited scope studies, such as the one undertaken by scientists from Sandia and Brookhaven, offer the most specific response guidelines. With the exception of the RAND report, which presents individual strategies, the other studies here are tilted toward informing first responders and senior decision makers. Another bias identified in the studies is their almost singular focus on "dirty bombs." As noted by Acton, Rogers, and Zimmerman, other plausible scenarios exist that would employ inhalation, ingestion, or immersion attacks.[29] Finally, among some of the more general reports, there emerges a need to be clearer on metrics and findings. To cite one example, the FAS

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[28] The "specific action" items highlighted in the radiological sections of the report, as well as its abridged versions, repeatedly use the phrases "if an explosion occurs outdoors or you an informed of an outside release of radiation" and "if an explosion occurs indoors or you are informed of a release of radiation." *Ibid*.

[29] Acton, Rogers, and Zimmerman, op. cit., pp.152-153.

study mentions both the risks of both cancer acquisition and cancer deaths, seemingly interchangeably at times.

In conclusion, it is not feasible to imagine a single open-source study or methodological approach to address the totality of technical, policy, security, logistical, communication, psychological, health, economic, and regulatory questions that must be considered in preventing, dissuading, and mitigating an array of potential acts of radiological terrorism in the immediate-, intermediate-, and long-terms. Nor would it be desirable to take such a fully comprehensive approach in an unclassified fashion, based on the potential risks it would pose. Many advances have been made in studying the specific challenges associated with potential acts of radiological terrorism, and differentiating planning for and responses to such attacks from actions that would follow a chemical, biological, or nuclear terrorism. Between the many studies of radiological terrorism already undertaken—those with broad and narrow scopes, focusing on broad policy recommendations and specific action items for first responders, as well as the many U.S. and international case studies not assessed in this article—areas for additional study continue to emerge. Examples include how governmental communication of defense-in-depth security measures can help dissuade terrorists from launching radiological attacks and whether there are other means of deterring terrorists from even planning these attacks.

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