# A Risk and Economic Analysis of Dirty Bomb Attacks on the Ports of Los Angeles and Long Beach

## H. Rosoff[*] and D. von Winterfeldt[1],[*]

This article analyzes possible terrorist attacks on the ports of Los Angeles and Long Beach using a radiological dispersal device (RDD, also known as a "dirty bomb") to shut down port operations and cause substantial economic and psychological impacts. The analysis is an exploratory investigation of a combination of several risk analysis tools, including scenario generation and pruning, project risk analysis, direct consequence modeling, and indirect economic impact assessment. We examined 36 attack scenarios and reduced them to two plausible or likely scenarios using qualitative judgments. For these two scenarios, we conducted a project risk analysis to understand the tasks terrorists need to perform to carry out the attacks and to determine the likelihood of the project's success. The consequences of a successful attack are described in terms of a radiological plume model and resulting human health and economic impacts. Initial findings suggest that the chances of a successful dirty bomb attack are about 10–40% and that high radiological doses are confined to a relatively small area, limiting health effects to tens or at most hundreds of latent cancers, even with a major release. However, the economic consequences from a shutdown of the harbors due to the contamination could result in significant losses in the tens of billions of dollars, including the decontamination costs and the indirect economic impacts due to the port shutdown. The implications for countering a dirty bomb attack, including the protection of the radiological sources and intercepting an ongoing dirty bomb attack are discussed.

**KEY WORDS:** Dirty bomb; economic impact analysis; project risk analysis; terrorism

## 1. INTRODUCTION

### 1.1. The Dirty Bomb Threat

Since the events on September 11, 2001, the prospect of a terrorist attack using a radiological dispersal device (dirty bomb) is cited as among one the most serious terrorist threats.[1] Several recently reported incidents confirm the concerns of security officials. In June 2002, the United States arrested Jose Padilla for his involvement with Al Qaeda in planning a dirty bomb attack on the United States,[2] and

in January 2003, British officials found documents in the Afghan city of Herat indicating Al Qaeda successfully built a small dirty bomb as well as possessed training manuals on using the explosive device.[3]

There are several reasons why terrorists may consider dirty bombs to be an attractive weapon. Radioactive materials are relatively easy to obtain and building a dirty bomb is a fairly simple process, requiring little more than the skills required for assembling a conventional bomb.[4] Furthermore, dirty bombs can create large radioactive plumes, cause health and psychological effects, and have major economic impacts due to the need for decontaminating large areas.

The primary challenge faced by terrorists is procuring the radioactive material. The International Atomic Energy Agency (IAEA) states that nearly

every country has devices containing radioactive material useful for the creation of dirty bombs and questions whether security in many of these locations is adequate.[5] Significant quantities of radioactive material have been lost, stolen, or abandoned—referred to as "orphan sources"—from U.S. and international facilities. According to an August 2003 General Accounting Office report, since 1998 more than 1,300 radioactive sources have become orphaned in the United States.[6] A primary concern of U.S. and international security experts is the number of orphan sources scattered throughout the former states of the Soviet Union and the security of nuclear facilities in Pakistan, India, and other developing countries.

A dirty bomb consists of radioactive material packaged in conventional explosives. When detonated, the radioactive material scatters into the environment, some forming a radioactive plume, and the remaining quantity falling in clumps or large particulate matter near the location of the explosion. No nuclear-fission and/or fusion reaction takes places as in a nuclear weapon. However, a dirty bomb can result in both death and injuries from the initial blast of the conventional explosives as well as radiation sickness and cancer from exposure to the radioactive material. Furthermore, the dirty bomb is widely recognized as having psychological and long-term economic impacts that could outweigh its health consequences. More specifically, depending on the amount of radioactive material released and dispersed, the contaminated area could require complete evacuation, followed by decontamination efforts that could take months or even years. Locally, evacuations and decontamination efforts impact the economy and instill public fear about returning to the contaminated area. Nationally, this could result in dirty bomb scares, both real and hoaxes, and instigate residual repercussions throughout the economy.

This article presents a risk and economic analysis of a dirty bomb attack on the ports of Los Angeles and Long Beach. We attempt to answer the following three questions:

1. What are the threats and vulnerabilities of a dirty bomb attack upon the ports?
2. If a dirty bomb attack was successfully carried out at the ports, what might be the health and economic impacts?
3. Given our risk and economic analysis, what are potential policy recommendations for more effective countermeasures?

The next section of this article describes the sources of radioactive material in the United States and abroad that could be used to construct a dirty bomb. Section 3 summarizes an analysis of 36 attack scenarios and describes a methodology and some preliminary findings for estimating the relative likelihood of a successful attack. Section 4 presents an analysis of the consequences of the most likely attack scenarios in terms of the health effects and economic impact of a port shutdown. Section 5 examines possible countermeasures and their cost effectiveness.

## 2. SOURCES OF RADIOACTIVE MATERIAL

Millions of radioactive sources are distributed worldwide, with hundreds of thousands in varying quantities and sizes currently being used, stored, and produced. In the United States alone, approximately 2 million licensed sealed sources are in use.[6] Among the 15 member states of the European Union, the European Commission reported that about 500,000 sealed sources have been located.[6] As seen in Table I, there are multiple sources of radioactive material that pose different levels of security risk given the amount of curies (unit of measurement of radioactivity) they could generate. Spent fuel rods from nuclear reactors and waste facilities, industrial and blood irradiators, and radiography equipment are among some of the primary sources that contain radioactive material. For a terrorist to build a dirty bomb, any of the radioactive material necessary for these applications could be employed. Most reports of trafficking incidents or unauthorized movement of radioactive material involve sealed sources, with a few incidents involving unsealed sources such as contaminated scrap metal.

### 2.1. Nuclear Reactor and Waste Facilities

In the United States, nuclear power and waste facilities contain millions of curies of radioactive material that is the mostly deadly in nature, but also extremely difficult to obtain and handle. Special licenses are issued by the U.S. Nuclear Regulatory Commission (NRC) to ensure the facilities are designed, constructed, and operated in accordance with safety standards. In addition, security surrounding nuclear power and waste sites is extremely high. While the large inventories of radioactive material may be appealing to terrorists, such precautions present a formidable challenge to acquiring the material. However, material from the nuclear fuel cycle are less

**Table I.** Sources of Radioactive Material

| Source | Radioisotope | Radioactivity Level (Curies) |
|---|---|---|
| Spent fuel assembly | Multiple sources | 300,000–2,000000 |
| Industrial irradiator (sterilization and food preservation) | Cobalt 60 (Co 60) | Up to 4,000,000 |
| | Cesium 137 (Cs 137) | Up to 3,000,000 |
| Blood irradiator | Co 60 | 2,400–25,000 |
| | Cs 137 | 50–15,000 |
| Radiotherapy (single and multibeam) | Co 60 | 4,000–27,000 |
| | Cs 137 | 500–13,500 |
| Medical radiography | Co 60 | 1,000 |
| | Iridium 19 (Ir 192) | 1–200 |
| Industrial radiography | Co 60 | 3–250 |
| | Ir 192 | 3–250 |
| Calibration | Co 60 | 20 |
| | Cs 137 | 60 |
| | Americium 241 | 10 |

*Sources*: Modified (1) Center for Nonproliferation Studies (CNS), *The Four Faces of Nuclear Terrorism*, 2005; (2) CNS, *Commercial Radioactive Sources: Surveying the Security Risks*, 2003; (3) IAEA, *Categorization of Radioactive Sources*, 2003; (4) personal communication with nuclear safety expert, Pacific Northwest National Laboratory, August 2004.

protected in some countries and may be available from "rogue" countries that are developing a nuclear power capability (see below).

### 2.2. Medical, Research, and Industrial Facilities

The NRC also issues licenses for medical, research, and industrial applications requiring radioactive material. Medical and research institutions use radioactive material in medical diagnosis, sterilization of medical equipment, radiotherapy (both internal and external), and for research in nuclear medicine. Radiotherapy, the treatment of disease with radiation, employs radioisotopes that are susceptible to security risk.[7] In contrast, the material used for sterilizing equipment and medical diagnosis present a smaller security concern, since they require relatively low amounts of radioactive material with short half-lives.

Industrial facilities use radioactive material to operate machinery such as food irradiators, gauging devices, well-logging devices, and industrial radiography systems. Irradiators pose the greatest security risk because they typically contain thousands to millions of curies.[7] Industrial radiography contains lower quantities of radioactive material, but they are placed in portable devices that present a security risk.[7] Gauging and well-logging devices typically contain inconsequential amounts of radioactive material.[7] While the NRC is responsible for issuing licenses and monitor-

ing such facilities, security requirements are less stringent than those found at nuclear reactor and waste facilities.

### 2.3. Foreign Sources of Radioactive Material

Internationally, experts are concerned about the security risk associated with spent fuel assemblies and reprocessed material abandoned, lost, or poorly guarded in the former states of the Soviet Union. There are also approximately 1,000 radioisotope thermoelectric generators (RTGs) that have exhausted their design life and are in need of dismantlement. The amount of radioactivity generated by these sources can be in the millions of curies. Surplus radioactive material coupled with a large number of sites with inadequate protection present opportunities for illegal stealing, selling, and trafficking. Compared to the United States, acquiring material of this quantity in some foreign countries may be less challenging mostly because of less stringent accountability and security standards.

The former Soviet Union also houses weapons-grade plutonium and highly enriched uranium produced in excess during the Cold War. If a terrorist were to acquire plutonium or highly enriched uranium, he or she would most likely save these materials for the construction of a nuclear weapon. However, experts have noted that of all known cases

of attempted trafficking of weapons-grade nuclear materials, the total acquired material is not enough to build a single nuclear bomb.[8]

## 3. SCENARIOS AND PROBABILITIES

Ports are attractive terrorist targets because of the potential for a successful attack to result in lives lost and economic damage to local businesses, harbor operations, and the flow of trade worldwide. Overall, ports are major trade nodes, have complex business infrastructures, and are difficult to secure due to their extensive size and accessibility by water and land. Most ports are located near major metropolitan regions that rely heavily on the resources and jobs provided by the businesses within the harbors. Also, ports are connected through several transportation modes (e.g., road, ship, and rail), and often industries, businesses, and tourist attractions are close by, presenting terrorists with several options for deception and attack scenarios.

In this analysis, we examined possible dirty bomb attacks on the Los Angeles and Long Beach harbors as an example. Combined, they are the third busiest port in the world, which handles 14.2 million 20-foot unit equivalent containers annually with a value of about $295 billion.[9,10] In addition, 44% of U.S. imports enter into the country through these two ports.[9,10] Dispersed across the harbors are oil refineries, business offices, storage facilities for hazardous materials and cargo, container terminals, and more. Cargo is transported to the ports via land, ship, or rail, increasing the challenge of securing the region. And whether coming to the ports for work or to make a delivery, many people enter the Los Angeles and Long Beach harbors daily.

Immediately surrounding the ports are parks and various roads leading to fishing wharfs and tourist attractions such as the Queen Mary and cruise line terminals. Also in the proximity are downtown Long Beach and San Pedro. Major highways, roads, and bridges pass through or alongside the ports. The activity in the nearby metropolis and recreational areas makes a terrorist attack on the ports of significant consequence both to the local livelihood as well as to the regional and national economy.

To analyze the dirty bomb threat to the ports of Los Angeles and Long Beach, we explored the danger of varying sources and quantities of radioactive material (measured in curies—Ci), as well as the differences in such attacks when the material originates from domestic versus international locations. We con-

sidered three scenarios, each depicting either a small, medium, or large-scale attack:

1. Low radioactivity scenario: Theft of radioactive material from a radiotherapy device in a U.S. hospital.
2. Medium radioactivity scenario: Theft of radioactive material from an industrial irradiator in a U.S. facility.
3. High radioactivity scenario: Purchase of a spent fuel assembly from a former Soviet Union nuclear power or reprocessing plant.

In collaboration with a counterintelligence expert, we examined these three scenarios in more detail. In particular, we studied the motivations and capabilities of terrorists to engage in any of the three scenarios to attack the ports of Los Angeles and Long Beach and conducted a qualitative "red teaming" exercise for each. In a red teaming exercise, the scenario is played out from the perspective of the terrorists to better understand the opponents' thinking and plans. For each source scenario, we considered four transportation modes (truck, ship, train, and plane or helicopter) and three locations (bridge, harbor-elevated, harbor-ground). We examined a total of 36 possible terrorist attack scenarios.

For illustrative purposes, this article will focus primarily on the medium radioactivity scenario and its transportation and location subscenarios. We assumed that a moderate quantity of radioactive material (100,000 curies) is stolen from a U.S. blood or industrial irradiator. Once the radioactive material is acquired, we assumed it would be transported to a warehouse near the port for dirty bomb construction. A separate terrorist cell, equipped with technical expertise, would be accountable for building the dirty bomb during this phase of preparation for the attack. Finally, upon construction completion, a third cell would drive the dirty bomb to the selected site and remote detonate the device at a safe distance from the explosion.

### 3.1. Type of Bomb Constructed

The type of dirty bomb constructed can vary in sophistication depending on the quantity and type of radioactive material used and the amount of time provided to assemble the device. Furthermore, the level of the terrorist's expertise in balancing the use of explosives with the nature and quantity of radioactive material determine the severity of the blast effect and plume formation. A successfully built dirty bomb

might result in very minor consequences (dispersing a few clumps of radioactive material over a fairly small area) or significant consequences (dispersing a large fraction of radioactive material as aerosols or fine particulates into the air).

Also, the time allocated for bomb construction is sensitive to the possibility of detection following material theft or black market purchase. If detected, only limited time may be provided for building the bomb. Under time constraints, the terrorists might simply use the vehicle carrying the radioactive material as the detonation device.

### 3.2. Delivery Modes

Terrorists are likely to select a delivery mode that has a low probability of detection by port security, yet maximizes the potential for damage to the ports. As such, the vehicle of choice is based upon what is the ideal means of dirty bomb transport to the detonation site. The ports of Los Angeles and Long Beach are accessible by land, air, and sea. A truck, car, or train might be the best mode of transport if entering the port by one of the surrounding access roads or as a package on a cargo train. With respect to arriving through the ports' waterways, a cargo ship or recreational boat most likely provide the most flexibility. Nearby helicopter landing pads and airports make planes and helicopters alternative modes of transport, although less likely because of additional security barriers associated with gaining access to their launch sites.

In addition, the vehicle selected depends on the size and weight of the dirty bomb. A bomb's dimensions vary based on the amount of conventional explosive and radioactive material used in construction. Typically, radioactive material tends to be easily packaged because it comes in either a powder or pellet form. However, the shielding material can be bulky and heavy. The bomb's surface area is altered most significantly when explosives are packaged around the radioactive material. Ultimately, the bomb can be designed to fit into something as small as a suitcase or as large as a van.

### 3.3. Detonation Site

To increase the effects of the dirty bomb, the detonation site is carefully selected based upon factors such as the ease with which it can be accessed, and its compatibility with the weather conditions surrounding the ports. Detonation site access is evalu-

ated based on variables such as population density, location within or outside of the ports, and the selected mode of transport for executing the attack. Finally, weather conditions as well as wind direction and velocity are considered as they affect the size and directional flow of the radioactive plume. Overall, to a terrorist, the optimal detonation site causes damage resulting in lives lost and economic consequences. A location that is less visible and susceptible to suspicious behavior is critical to enhancing the probability of attack success. However, too few people in the surrounding vicinity, winds blowing out to sea, and a detonation site located miles from the harbors might deem the attack insignificant.

### 3.4. Pruning Scenarios and Assessing Relative Likelihoods

An important step was to determine which combinations of radioactive source × transportation mode × delivery location were implausible, not likely, or likely, given the intent to attack the ports of Los Angeles and Long Beach. We worked with a counterintelligence expert to help make these qualitative judgments. Plausibility was judged simply by considering the logical combination of the scenario factor (amount and type of bomb, delivery mode, location of detonation). For example, we considered it implausible that a terrorist group would use a small amount of radioactive material to attack the ports. If terrorists were to obtain a small quantity of radioactive materials, they probably would plan for its release within an enclosed facility or building where the dispersal effects would have a greater impact. Another example is the combination of a truck as a delivery mode and an elevated harbor location. This would require getting the truck into the harbor, waiting for the container to be placed on a ship, and exploding it in mid air. This all seems very complicated compared to simply detonating the truck either within or close to the perimeter of the harbor.

Table II shows the four transportation scenarios and the three detonations site scenarios considered for the medium radioactivity source scenario. Using qualitative judgments, we were able to narrow the 12 scenarios down to two likely ones. These two transportation/location scenarios were not significantly different in judged probability or consequences, so only one was analyzed for this scenario (a similar process was conducted for the high radioactivity scenario, though different cells were judged to be likely). Because of the sensitivity of information, the plausibility

**Table II.** Transportation and Location Scenarios

| | | Transportation | | | |
|---|---|---|---|---|---|
| | | Truck | Ship | Train | Plane/Heli |
| Location | Bridge<br>Harbor – ground<br>Harbor – elevated | | | | |

and qualitative likelihood judgments of this portion of the project are not included in Table II.

### 3.5. Probabilities of Success

We used Microsoft Project© to lay out the details for the selected scenarios. This software originally was created to provide businesses with a computer tool that tracks a project's progress by task, timeline, and resources. A terrorist attack operates much like any other complex business project, starting with an attack planning phase, followed by the actual preparations for the attack, and culminating with the attack execution. Microsoft Project was used to outline planning, preparing, and execution tasks, and defined each in terms of task duration and number of resources (people) required. For example, in the medium radioactivity scenario, the project starts with tasks such as planning how and where the attack will take place, determining who will be involved in the attack scenario, and establishing a means of communication among the operatives. Next, preparations begin, which include tasks such as traveling into the United States and purchasing explosives for the dirty bomb. Ultimately, the planning and preparation tasks come together with the execution of the dirty bomb attack on the ports of Los Angeles and Long Beach.

Each task was entered into Microsoft Project© through a table format known as a Gantt chart. Tasks were inserted chronologically and described by relevant details, such as predecessor information, task duration, and resources needed. Once the Gantt chart was completed, the tasks were grouped together to form what is termed a network diagram, also known as a PERT chart. The network diagram is a graphic layout of the entire attack scenario from start to finish. Figs. 1 and 2 are snapshots taken from the medium radioactivity scenario network diagram. They illustrate the steps involved for two separate tasks, building the dirty bomb and transporting the dirty bomb into the harbors. For example, Fig. 1 shows how building the dirty bomb involves obtaining the explosive and radioactive material prior to assembling the device.

Fig. 2 shows how detonating the dirty bomb involves transporting and dropping off the bomb at the selected site and then using a remote detonation device to generate the explosion. Fig. 3 depicts how all the individual tasks come together to form the network diagram. For security reasons, we do not provide the details of each of the boxes, but only show the overall schematic. The upper-left parallelogram represents the start of the initial planning for the dirty bomb attack. The box on the far right signifies project completion with dirty bomb detonation.

Each of the planning, preparing, and execution tasks was associated with a probability of detection and disruption of the project. To determine how the probability of detection affects overall attack success, we collaborated with a counterintelligence analyst with whom we identified the most vulnerable tasks and assigned a probability of success to each. Table III lists some of these tasks for the medium radioactivity scenario. For example, the theft of radioactive material is clearly a very vulnerable task from the perspective of the terrorists.

The probability of success for each of these tasks depends upon the complexity of the task, the number of people involved, and the time required to perform the task. Preliminary assessments of success probabilities were made for a given estimate of the number of people involved and task duration. A logit model was used to estimate variations in these probabilities as a function of changes in the number of people and time to task completion. We then developed probability distributions over the number of people and time for each task and used a probabilistic simulation model (@Risk by Palisades, Inc.) to simulate the uncertainty around the overall success probability of each task.

The research team, with the help of a counterintelligence analyst, used only publicly available, open-source data to make all assessments. The data represent very preliminary estimates and are largely illustrative of the methodology used. Refinements of these probability estimates would require access to classified data as well as the use of established procedures for formal elicitation of probabilities from personnel currently working in counterintelligence and counterterrorism operations.

An example of the results from the medium radioactivity scenario probabilistic simulation is shown in Fig. 4. Interestingly, the probabilities of success are relatively small (less than 20–40%). This is because for the overall project to be successful, all individual tasks must be successful. As the uncertainty and risk affecting the success of the vulnerable tasks listed in
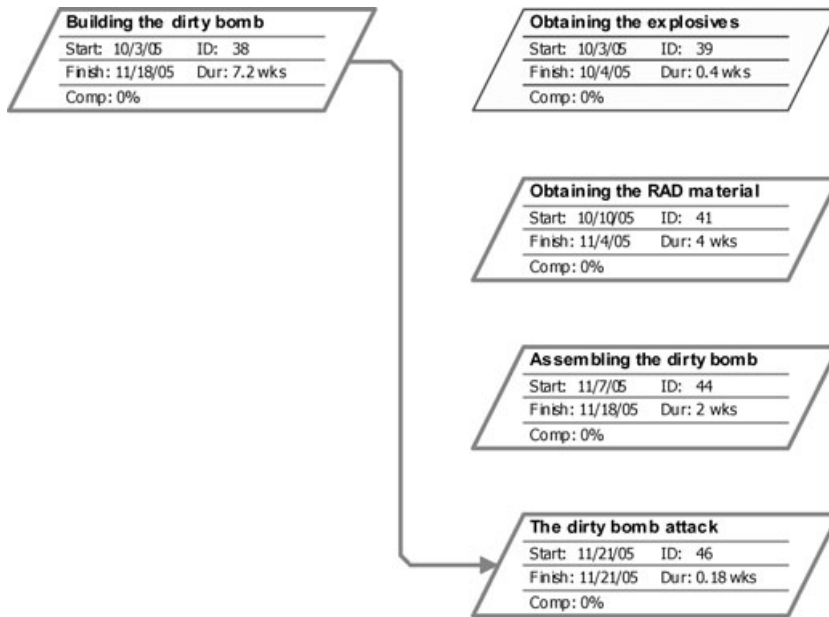
**Fig. 1.** Microsoft Project tasks—building the dirty bomb.

Table III varies, this in turn affects the overall probability of project success. Of course, terrorists may engage in multiple, independent projects, thus increasing the probability that at least one of them succeeds.

## 4. CONSEQUENCES

The consequences of a dirty bomb attack fall into three categories: (1) immediate fatalities and injuries due to blast effects and acute radiation exposure, (2) medium- and long-term health effects caused by airborne dispersal of radioactive material, and (3) economic impacts resulting from shutting down port operations—including evacuations, business losses, property losses, and decontamination costs. In the medium radioactivity scenario, we assumed that

5–30% of the material contained in the bomb was released into the air as aerosols or fine particulates. This results in a plume carrying roughly 500–3,000 Ci. The ranges of various damage estimates are shown in Table IV. Explanations for these ranges are provided below. We tried to be conservative on the upper end of the ranges, using information, model assumptions, and existing estimates that are at the high end. The low end of these ranges is usually self-explanatory, resulting from a failure of a successful dispersal of radioactive materials into the air.

### 4.1. Blast Effects and Acute Radiation

The immediate fatalities and injuries following the explosion of the dirty bomb depend on the amount of explosives used and the population density in the
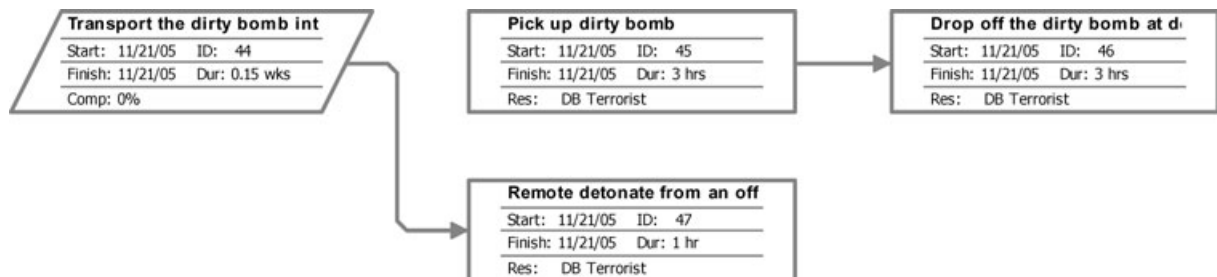


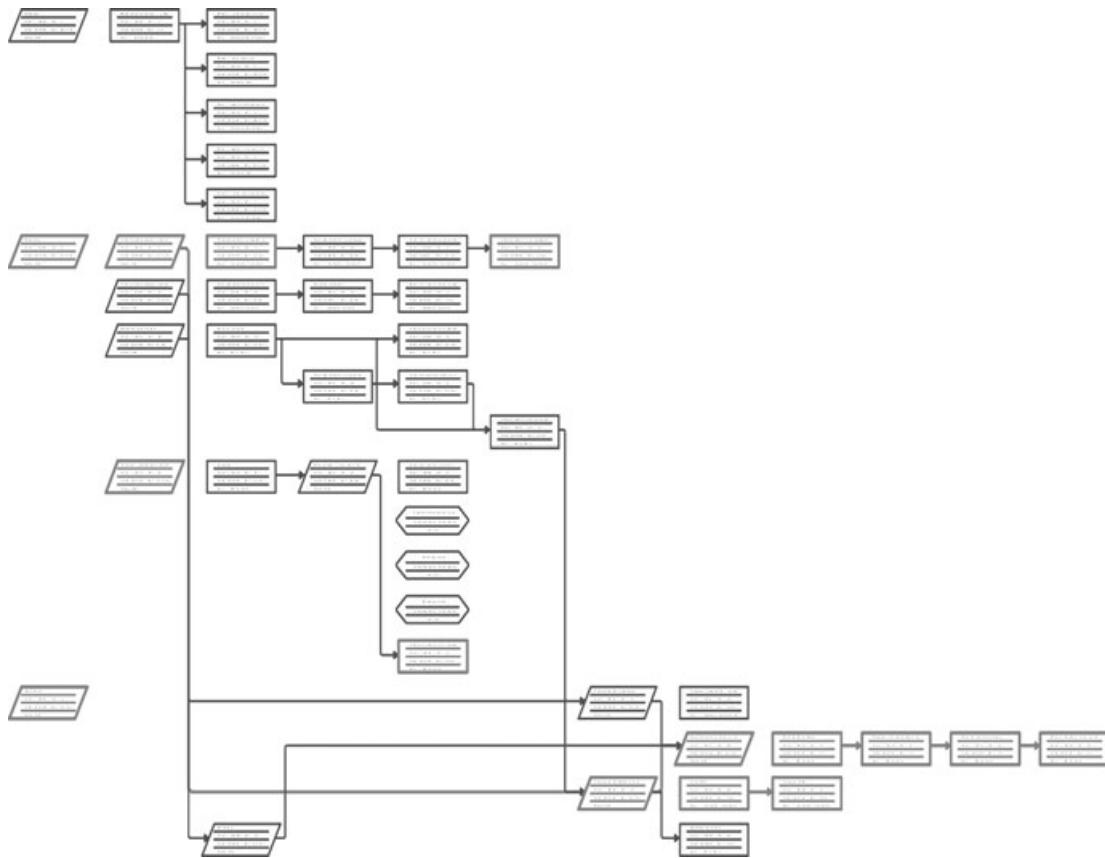**Fig. 2.** Microsoft Project tasks—transporting the dirty bomb.

**Fig. 3.** Schematic view of the complete project.

area near the detonation site. To explode a dirty bomb, only a limited amount of explosive material is needed and, therefore, the blast effects are limited to an area within 100 feet of the detonation point.[11] Unless the bomb is set off in a very densely populated area, the effects are likely to cause only a few fatalities and several injuries. Acute radiation sickness might occur if bystanders or emergency workers who rush to assist blast victims suffer from prolonged exposure to highly radioactive material. For example, during a 2004 dirty bomb exercise held in Long Beach, emergency workers rushed to the blast site, unaware of the radioactive material and without protective clothing. Had this been a real attack, they probably would have suffered from some level of radiation exposure, though most likely not in a range that produced acute radiation effects. Overall, the severity of radiation sickness depends on the dose and duration of exposure. For example, total body exposure of about 100 rem can result in radiation sickness, where 400 rem causes radiation sickness and death in half of the exposed individuals.[12]

**Table III.** Vulnerable Tasks of the Medium Scenario

| Tasks |
| --- |
| Travel into the U.S. - the coordinator |
| Obtain a job at the selected facility (for stealing the radioactive material) |
| Steal radioactive material from research hospital |
| Transport radioactive material from research hospital |
| Casing of the Los Angeles Port |
| Travel into the U.S. - attack executioners |
| Assemble the dirty bomb |
| Transport the dirty bomb into the LA Port |
| Dirty bomb detonation - first explosion |
| Second explosion |

### 4.2. Health Effects Due to Airborne Releases

The incidence of health effects following the detonation of a dirty bomb depend largely on the source and amount of radioactive material used, and the
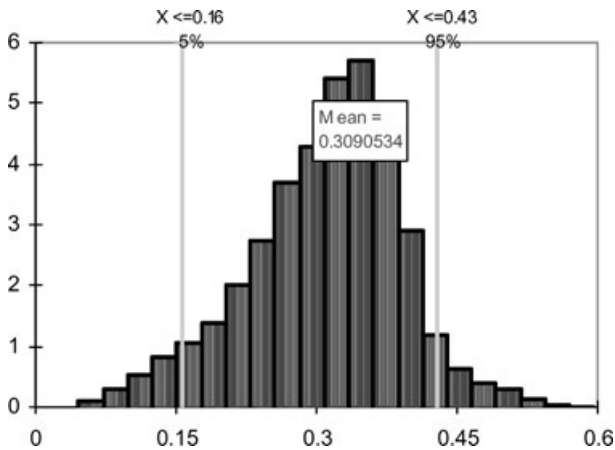
**Fig. 4.** Distribution over the probability of a successful attack (medium radioactivity scenario).

sophistication of the detonation device. If successfully detonated, a respirable fraction of the material will be released into the air that varies from about 1% to 80% of the original source.[18] The remaining material will fall in clumps or larger particles within hundreds of feet of the detonation site. In addition, weather

**Table IV.** Ranges of Consequence Estimates

| Consequences | Medium Scenario | High Scenario | Measure |
|---|---|---|---|
| Blast and acute radiation effects | 0–10 | 0–50 | Fatalities |
| Latent cancers | 0–20 | 0–1,000 | Fatalities |
| Port shutdown and related business losses | 0–200 million | 30–100 billion | Dollars |
| Evacuation cost (plume) | Negligible | 10–100 million | Dollars |
| Business loss (plume) | Negligible | 1–3 billion | Dollars |
| Property values (plume) | Negligible | 100–200 million | Dollars |
| Decontamination costs (plume) | 10–100 million | 10–100 billion | Dollars |

*Note:* The lower end of the health effect ranges include cases in our simulation where one or more of the following might occur: (1) unsuccessful airborne releases due to faulty construction of the dirty bomb; (2) wind direction toward populated areas; and (3) low radioactive doses (10 mrem or less) that produce no health effects. The higher end of the health effects were based on (1) 20% release of the source term; (2) wind direction flowing toward populated areas; and (3) NARAC estimates of doses (up to 100 mrem) and a linear dose–response function. The ranges in Table IV should be considered preliminary for the purpose of an illustration of the analysis' capabilities.

conditions, wind direction, and wind velocity exacerbate the situation as they predicate the formation of the radioactive plume.

Fig. 5 shows the medium radioactivity scenario Gaussian plume. This plume is hypothetical and not based on specific models. However, we have obtained similar plumes from the National Atmospheric Release Advisory Center (NARAC) to verify that these examples are realistic. While the following calculations were conducted with the NARAC plumes (not included), the results would be very similar when applied to the plumes shown (see Reference 23 for a summary of the plume and dose modeling capabilities of NARC).

The plume in Fig. 5 defines an inner ellipse with more than 1 mrem exposure per hour and an outer ellipse covering an area exposed to more than 0.1 mrem/hour. NARAC model calculations for a similar plume suggest that the total four-day effective dose equivalent exceeds 1,000 mrem or 1 rem in the inner ellipse and 100 mrem in the outer ellipse. To put these numbers into perspective:

- Public background radiation exposure is about 300 mrem/year
- A single CAT scan (for medical diagnostic purposes) creates an exposure of 1.3 rem
- Worker radiation standards are set at 5 rem/ year
- Radiation effects occur around 400 rem or higher.

While these numbers may not be comforting to those exposed to 100 mrem or more, it is clear that the health impacts will be relatively small.

Initial exposure to radioactivity occurs through inhalation of contaminated material as the plume passes over an area. Typical calculations assess the amount of exposure during the first four days following the event. To get a rough first-order approximation of the four-day exposure, the analysis assumed median exposure values (500 mrem) in the outer ellipse of the plume and higher exposures in the inner ellipse (2 rem) to calculate and integrate population doses. All persons located in the area covered by the radioactive plume are susceptible to radiation exposure and contamination (both internal and external). Using this crude approximation and a linear dose-response function for the population estimates provided by NARC, results indicated there would be no more than 10 latent cancers for the medium scenario and no more than 500 latent cancers for the high scenario. All assumptions made

**Fig. 5.** Hypothetical plume due to a release in a medium radioactivity scenario.

in these calculations were conservative, so the actual latent cancers are likely to be much lower.

While Fig. 5 identifies the area in which short- and medium-term exposure to radioactive material could occur, there also might be a significant level of ground deposition resulting in long-term exposure consequences. Radiation from deposition is usually referred to as "ground shine." The process by which deposed material is resuspended, inhaled, or gets into the food chain is complicated. Only a fraction of this radioactive material eventually is absorbed by people, thus creating the same effect as the inhalation of material transported through the plume. This process will occur continually until decontamination procedures are effective.

According to the NARAC models, the ground shine contours are similar to those shown in Fig. 5 with the outer ellipse defining areas above 100 mrem/ year and the inner ellipse defining areas exceeding 1 rem/year. To get a first-order approximation of the health effects, we assumed all the ground shine would be absorbed by people living in the plume area during the first year following the attack. This assumption is clearly conservative, since only a fraction of the ground contamination would be resuspended or get into the food chain during this time. Furthermore, we assumed that workers and the public would return to the contaminated areas and not take any particular precautions. Next, we assumed decontamination

would be successful within a year following the attack and that no additional ground shine occurs thereafter. Together, these assumptions imply that the health effects due to ground shine are approximately the same as those due to the first four days of plume exposure. Both estimates are included in the health effect ranges shown in Table IV.

### 4.3. Economic Consequences

One of the major concerns about the dirty bomb threat to the ports of Los Angeles and Long Beach is the potential for an extended shutdown of the region's operations. While it is very hard to predict how long the ports would be inoperable following the medium radioactivity scenario, it is understood that large areas of the ports would be subjected to short-, medium-, or even long-term closures because of:

- Concerns of dock workers about returning to work
- Concerns of shippers about delivering goods to the harbors
- Extensive procedures related to decontamination activities.

Several shut-down scenarios were analyzed, ranging from short (15 days) to medium (120 days) to long (one year). To assess the economic impacts, the Southern California Planning Model (SCPM) was

used. This is a highly disaggregated regional input-output model of the southern California economy that was previously used to estimate the impacts of earthquakes and other disasters in southern California.[14]

The results are shown in Table IV. The 15-day shutdown has a small impact (about $300 million) because most ships would simply wait out the port closures and businesses would be supplied through other ports. The 120-day and one-year shutdowns, in contrast, have significant impacts ($63 and $252 billion, respectively) because they account for the economic impacts of a delay of delivering goods as well as all ripple effects throughout the nation's economy that such long-term delays involve. This includes costs ranging from the loss of local dock worker jobs to the reduced income and possible forced closure of nationwide businesses not receiving necessary parts or retail products.

Additional analysis focused on the costs associated with the evacuation of the plume area, reductions of property values, and business losses resulting from stigmatization of businesses in the contaminated region. We assumed that all residents and businesses would evacuate for one week from a plume with higher than 100 mrem activity (Fig. 5). In addition, property values in the plume area were estimated to drop by 25% during the first year following the attack and then recover to previous levels.[15] Finally, we assumed business activity would be reduced by 10% for the first year following the attack and then return to former levels.[15]

The results in Table IV show that the economic impacts of the evacuation are small. This occurs because the evacuees would likely continue their business as usual, albeit from shelters, homes of family or friends, or hotels. The cost of the (temporary) reduction in property values can be in the hundreds of millions, but not nearly of the same magnitude as the cost of shutting down the ports. The costs of business disruptions could be fairly large, certainly in the billions of dollars, but only if one assumes the majority of businesses relocate outside of the region or cease to exist.

In addition to the social costs inflicted upon the contaminated region, there are extensive costs associated with decontaminating surfaces with depositions of radioactive material. More specifically, the cost of decontamination depends on the required clean-up level and the cost of disposing low-level radioactive material. One study estimated extremely large costs (in the trillion dollars) even for the high radioactivity scenario plume.[16] This was based on the assumption

that the clean-up standards would be those promulgated by the Environmental Protection Agency (15 mrem/year) and the cost of disposal would be similar to that imposed by the current low-level radioactive waste sites at Barnwell in North Carolina or at Envirocare in Utah. Using less stringent clean-up standards (e.g., 100 mrem/year) and disposal costs closer to those of a landfill, these cost estimates can be reduced by a factor of 1,000. Nevertheless, the clean-up costs are still in the billions (Table IV).

## 5. COUNTERMEASURES

Current efforts to counter the threat of a dirty bomb attack involve plans to check all cargo for radiological materials—both dirty bombs and actual nuclear devices.[17] For example, on June 4, 2005, Secretary Chertoff announced that the Los Angeles and Long Beach ports will be equipped with sensitive radiological detection devices in the form of portals to screen all international cargo entering the harbor.[18] This is certainly a step in the right direction, as radiation portals are very effective and relatively unobtrusive measures to detect even very low levels of radiation.[19] However, the following discussion shows that significant threats remain, even within the specific set of scenarios analyzed in this article.

In addition to radiation portals at the entry and exit points of the harbor, it would also be useful to install radiation detection devices in the outer perimeter of the harbor, especially in areas where an RDD device could do damage. Furthermore, one of the complicated aspects of countering terrorism is that terrorists shift their attack modes in response to our defensive actions. In the case of radiological detection devices, it seems likely that terrorists would attempt to develop attack scenarios that avoid any newly installed radiation detection devices. Thus, trucks or cars having to go through screening checkpoints would be a less likely method of attack. Instead, terrorists might opt for delivery vehicles that completely bypass detection measures.

Another problem with radiological detection devices is the anticipated rate of false alarms. These devices can detect very low radioactivity levels. They have the potential to pick up radiation from many sources other than weapons-grade material or radioactive material used in dirty bombs. For example, some naturally occurring material, such as granite, give off low levels of radioactivity that might be detected. People who recently received medical procedures involving radiography also are likely to set off

alarms. It is very important to define the optimal sensitivity level of the detection devices (balancing the costs of missing a threatening device against the cost of too many false alarms). Significant research exists in this area, known as "signal detection theory," that can guide the operators of these systems on how to set the optimal level of sensitivity (see Reference 20 for a general introduction and Reference 21 for a specific example).

When optimizing the sensitivity of the detection devices, the costs and benefits of false alarms, hits, misses, and correct rejections (using the signal detection terminology) have to be considered carefully together with the probability that a piece of cargo might contain a radiological device. The initial inspection at the radiation portal is a relatively efficient process. However, if the alarm is set off, the truck or container must go into a special inspection cue. Such secondary inspections create shipment delays, require significant amounts of manpower, and incur large operational costs.[22]

In addition to highlighting ways of modifying current countermeasure efforts at the ports of Los Angeles and Long Beach, our research demonstrated how a terrorist attack can be interrupted at many stages. The project risk analysis identifies the attack tasks most susceptible (from the terrorists' point of view) to disruption and thus defines the terrorists' vulnerabilities (see Table II for an example). In the dirty bomb scenarios discussed in this article, the findings suggest that the most cost-effective solution is to prevent or interdict the purchase or theft of radiological material. Radioactive material in the United States is highly regulated by the NRC and thefts are difficult to carry out successfully. In our attack scenario involving theft from a research or industrial facility, we hypothesized that an employee would assist in attempting to bypass NRC barriers. As such, one implication of focusing on this phase of the attack would be the benefit associated with improving security of the facility, particularly management of employees with access to radioactive sources. Similarly, in the scenario involving theft or purchase of significant material in the former Soviet Union and other foreign countries, we recognize the importance of improving safeguards and security at these facilities.

## 6. CONCLUSIONS

A terrorist attack using a dirty bomb in the United State is possible, perhaps even moderately likely, but would not kill many people. Instead, such an attack primarily would result in economic and psychological consequences. Moreover, it would not be easy to carry out a dirty bomb attack. Considering the difficulties associated with obtaining and transporting radioactive material, building the dirty bomb, and detonating the device successfully, our preliminary analyses suggest that the chances of a successful attempt are no better than 15–40% for the medium radioactivity scenario, and less likely for the high radioactivity scenario. Of course, multiple independent attempts would increase these chances. While our probability estimates are mostly illustrative, the chances of terrorists succeeding with an attack that involves relatively low-level radioactive material from a U.S. facility are larger than their chances of succeeding with the import of a large quantity of foreign sources. This is because transporting foreign source material through a number of international ports increases susceptibility to detection.

If a dirty bomb attack is successful, the consequences depend primarily on the amount of radioactive material in the detonated source term, the amount released into the air, weather conditions, and the population density in the impacted region. The medium radioactivity scenario analyzed in detail suggests there would be some, but fairly limited, health effects and possibly significant economic impacts.

The most costly economic impact would result from a lengthy shutdown of the ports and decontamination efforts. The length of the harbor shutdown would in part depend on the decision to declare access to the ports as safe. In a national emergency, standards of safety different from those promulgated by the EPA may be appropriate. For example, worker safety standards may be more appropriate than public safety standards. The same also holds true for clean-up standards. Because we don't know how policymakers and harbor workers will react in such an emergency, we have parameterized the length of the harbor shutdown, from 15 days to one year, corresponding to roughly $130 million to $100 billion in costs.

The economic consequences of evacuations, property value impacts, and business losses due to stigmatization in the plume area are in the billions, but not in the tens or hundreds of billions. People and the economy are likely to respond in a resilient way. Many people would relocate for some time out of the areas with relatively high levels of radioactivity (100 mrem or more), but they would not stop working. Also, businesses may relocate and later return to their original location. Similarly, effects on property

values may be severe in the short term but, like in many other disasters, return back to normal in a year or so.

Regarding countermeasures, our analysis clearly supports ongoing programs to install radiation detection technology around the harbor. In addition, the analysis raises concerns regarding the security risks associated with cargo material as it is offloaded from ships but not yet transported through the portals, incoming containers from the U.S. mainland (by truck, small boat, or air), and harbor perimeter control. Finally, the analysis suggests preventing terrorism by interdicting vulnerable activities during the planning and preparing stages of an attack scenario. Such action might include being more proactive in controlling and protecting the original sources of radioactive material.

## ACKNOWLEDGMENTS

## REFERENCES

1. Blair, B. (2002). *What if Terrorists Go Nuclear?* Available at http://www.cdi.org/terrorism/nuclear-pr.cfm.
2. Johnson, K., & Locy, T. (2002). Threat of dirty bomb softened. *USA Today* on the web June 12, 2002. Available at http://www.usatoday.com/news/nation/2002/06/11/bush-others.htm.
3. Gardner, F. (2003). Al Qaeda "was making a dirty bomb." *BBC News Online* on the web January 31, 2003. Available at http://news.bbc.co.uk/2/hi/uk_news/2711645.stm.
4. King, G. (2004). *Dirty Bomb: Weapons of Mass Disruption* (p. 25). New York: Penguin Group.
5. International Atomic Energy Agency. (2002). *Inadequate Control of World's Radioactive Sources*. Available at www.iaea.org/search97cgi/s97_cgi?action=View&VdkVgwKey=http%3A%2F%2Fwww%2Eiaea%2Eorg%2FNewsCenter%2FPressReleases%2F2002%2Fprn0209%2Eshtml&QueryZip=dirty+bomb&&viewTemplate=cvw_smpl.hts&collection=PressR.
6. General Accounting Office. (2003). *Nuclear Security: Federal and State Action Needed to Improve Security of Sealed Radioactive Sources*. Available at http://www.gao.gov/new.items/d03804.pdf.
7. Ferguson, C. D., Kazi, T., & Perera, J. (2003). *Commercial Radioactive Sources: Surveying the Security Risks*. Monterey Institute of International Studies, Center for Nonproliferation Studies.
8. Council on Foreign Relations. (2004). *Terrorism Q&A: Making a Bomb*. Available at http://cfrterrorism.org/weapons/making_print.html.
9. The Port of Long Beach. *About the Port—Port Statistics Index*. Viewed on January, 2007. Available at http://www.polb.com/html/1_about/portStatsMain.html.
10. The Port of Los Angeles. *About the Port—FAQs*. Viewed on January, 2007. Available at http://www.portoflosangeles.org/about_faq.htm.
11. National Council on Radiation Protection and Measurements (NCRP). (2004). *Management of Terrorist Events Involving Radiological Material*. National Academy Report, NCRP Report No. 138, NCRP, Bethesda, MD, October 24, 2001.
12. Medline Plus. *Medical Encyclopedia Radiation Sickness*. Accessed February 19, 2005. Available at http://www.nlm.nih.gov/medlineplus/ency/article/000026.htm.
13. F. Harper. Presentation at the Department of Homeland Security Conference on Research and Development, Boston, April 26, 2005. Presentation at the Department of Homeland Security Conference "Working Together: R&D Partnerships in Homeland Security," Boston, April 27–28, 2005.
14. Gordon, P., Richardson, H., & Moore, J. (2004). The economic impacts of a terrorist attack on the twin ports of Los Angeles-Long Beach. Presentation at the CREATE Economics Symposium: Economic Costs and Consequences of a Terrorist Attack. Los Angeles, University of Southern California, August 2004.
15. Gordon, P., Moore, J.E., Pan, Q., & Richardson, H. (2005). Los Angeles–Long Beach seaports radioactive plume economic impact. Draft Report, Center for Risk and Economic Analysis of Terrorist Events, University of Southern California, 2005.
16. Reichmuth, B. (2005). Economic consequences of a rad/nuc attack: Cleanup standards significantly affect cost. Presentation at the Department of Homeland Security Conference "Working Together: R&D Partnerships in Homeland Security," Boston, April 27–28, 2005.
17. Martonosi, S. E., Ortiz, D. S., & Willis, H. (2005). *Evaluating the Viability of 100 Per cent Container Inspection at America's Ports*. RAND Corporation.
18. Krikorian, G. (2005). Port complex to get radiation detection devices to forestall terrorism. *Los Angeles Times*, June 4, 2005. Available at http://www.latimes.com/news/local/la-me-chertoff4jun04,1,7330940.story?ctrack=1&cset=tru.
19. Board on Energy and Environmental Systems, Division of Engineering and Physical Sciences, and National Research Council. (2002). *Committee on Alternatives for Controlling the Release of Solid Materials from Nuclear Regulatory Commissioned-Licensed Facilities*. Washington, DC, National Academy Press.

20. Green, D. M., & Swets, J. A. (1966). *Signal Detection Theory and Psychophysics*. New York: John Wiley and Sons Inc.
21. Heasler, P., & Woods, T. (2005). Game theoretic modeling of detection and deterrence. Presentation at the Department of Homeland Security Conference on Research and Development, April 26, 2005.
22. U.S. Government Accountability Office. (2006). *Combat Nuclear Smuggling: DHS Has Made Progress Deploying Radiation Detection Equipment at U.S. Ports-of-Entry, But Concerns Remain*. GAO Report No: GAO-06-389. Washington, DC.
23. Bradley, M. (2005). NARAC: *An Emergency Response Resource for Predicting the Atmospheric Dispersion and Assessing the Consequences of Airborne Radionuclides*. Available at www.llnl.gov/tid/idf/documents/pdf/324174.pdf.