DIRTY BOMB RISK AND IMPACT

A Systems Analysis Overview

ABSTRACT

Over the last two decades, systems analysts from the NNSA labs (principally, Sandia) have developed the nomenclature and framework for the study of radiological terrorism and dirty bombs. This paper presents an overview of the risk-based systems approach. It compares the risk and impact of a dirty bomb employing the two most common high activity radionuclides, Co-60 and Cs-137.

Leonard W. Connell, PhD, Senior Scientist (Retired), Sandia National Laboratories

Introduction:

The risk of a dirty bomb has been studied in detail over the last two decades. Many nuclear terrorism experts wondered if the dirty bomb problem was really something warranting national level attention or if it was just a distraction away from what they consider to be the greatest danger of a terrorist group gaining access to a nuclear weapon or weapons usable nuclear material and building an improvised nuclear explosive device. The notional risk chart in Figure 1 below was used to help analysts and decision makers understand the dirty bomb problem [1].
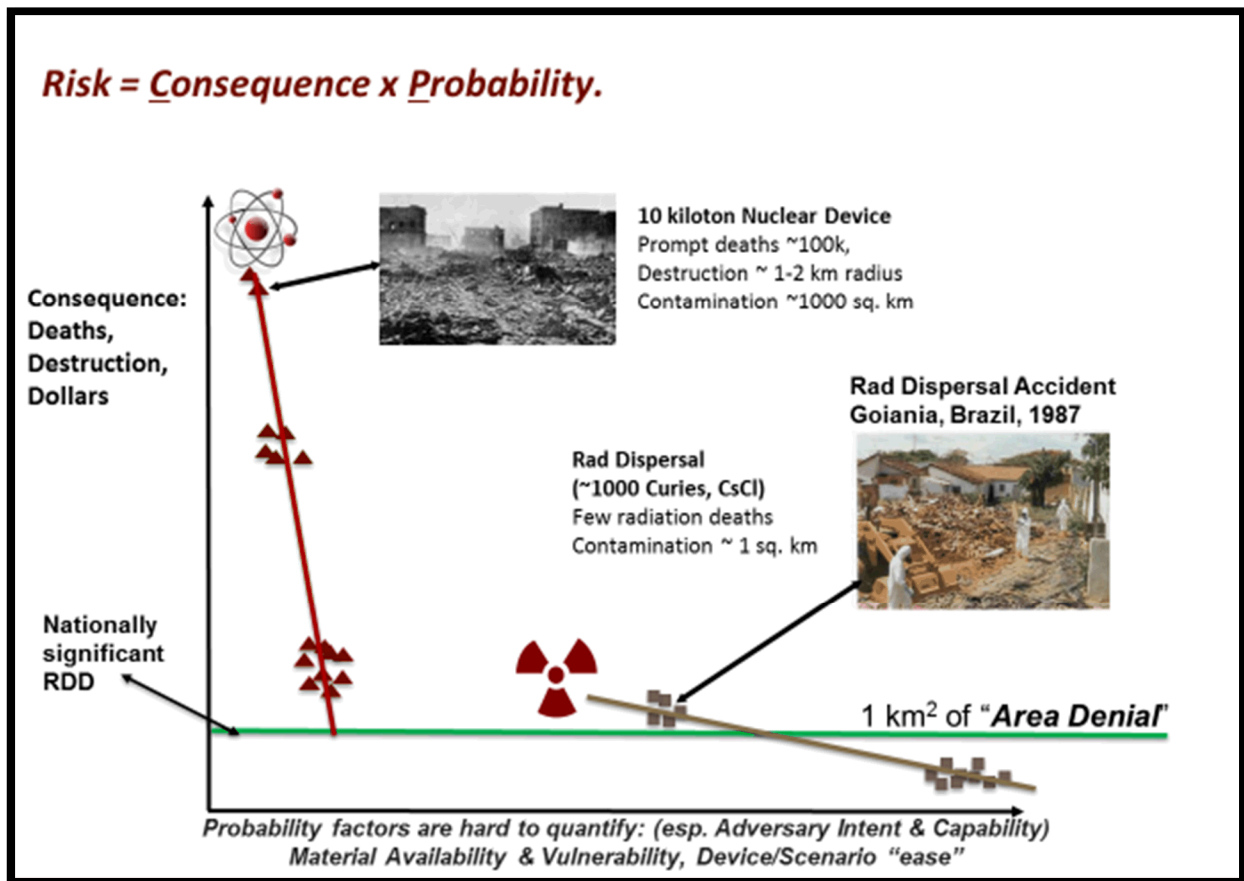
Figure 1. Notional comparison of radiological and nuclear terrorism risk.

There is a wide spectrum of scenarios for both nuclear and radiological terrorism and the chart above is meant to focus on a few key groupings. The main point is that the low end of the nuclear terrorism consequence (other than a complete dud) is that of a plutonium dispersal. This consequence is roughly aligned with the high-end of the radiological terrorism consequence. The U.S. learned in the 1960's (e.g., the Palomares incident in 1966 and others) that the consequences of a nuclear weapon accident where plutonium is explosively dispersed can be quite significant. These consequences include cleanup and disposal, population relocation, compensation, and medical surveillance, as well as the overall psychosocial, societal effects. Past radiological accidents, such as the 1987 Goiania event involving roughly 1000 Ci of Cs-137, created

comparable results but the consequences were more devastating since they occurred in a major city.

We have coined the term "area denial" to refer to those dirty bomb scenarios that can achieve such results. It is generally recognized in the USG that a national level dirty bomb event would be an area denial of roughly 1 km^2 of an urban area. Using the DHS/EPA protective action guide for relocation, this translates to the level of contamination that would trigger area quarantine, population relocation and cleanup, 20 mSv/yr.

However, the area denial dirty bomb __*risk*__ (consequence x probability) is greater than risk of a plutonium dispersal nuclear terrorism event because the availability and vulnerability of 1000 Ci of Cs-137 is much greater than that of a significant quantity of plutonium.

Of course, many dirty bomb scenarios will not produce the area denial consequence, i.e., those using low activity radionuclide sources and those using rad-materials that are not readily dispersible. Those scenarios are considered more likely (again using availability, vulnerability arguments) and while they cannot be ignored, the USG strategy for addressing them needs to be different than the strategy to proactively protect against the high consequence, area denial dirty bomb.

## 1. Characteristics of an Area Denial Dirty Bomb

A typical area denial dirty bomb scenario is depicted below in Figure 2 [2].
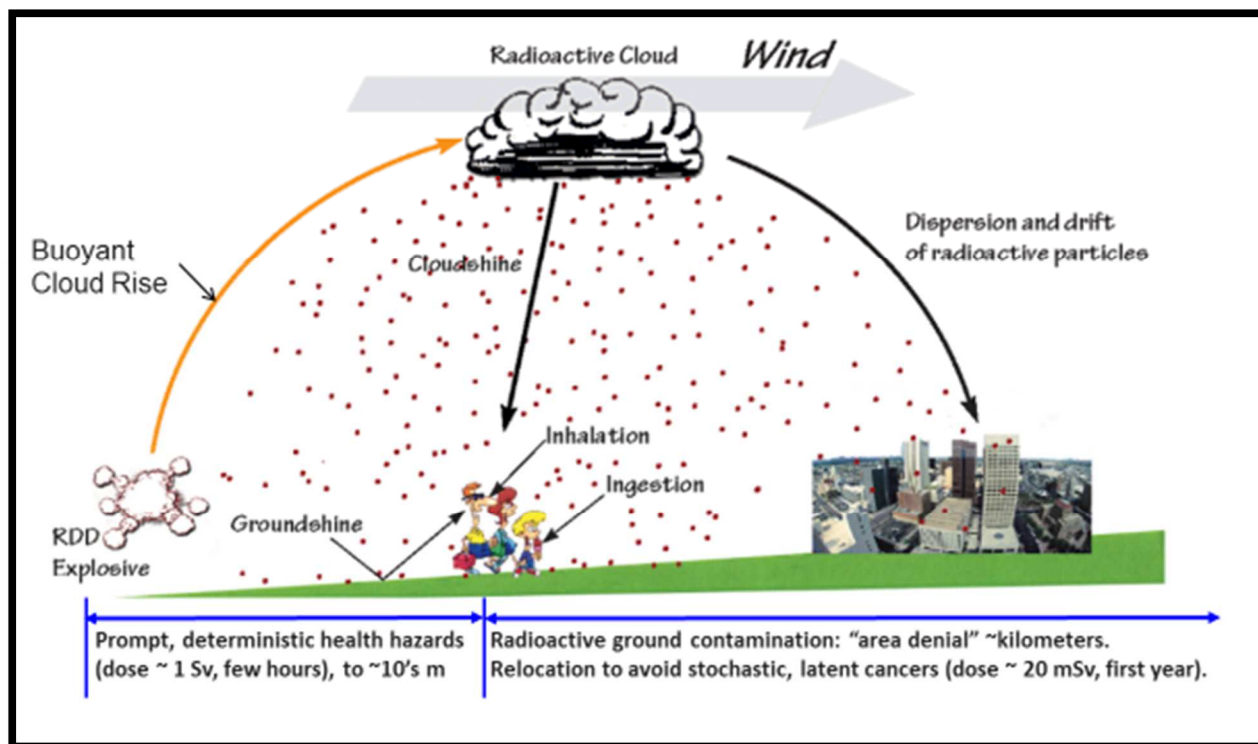
Figure 2. A typical area denial dirty bomb.

To produce the area denial effect, the high explosive must have sufficient shattering power (brisance) to pulverize the rad-material into a fine dust. The dust will become entrained in the explosive fireball and buoyant forces will then lift the cloud up, allowing atmospheric flow forces to disperse it over a wide area. Under the right explosive and atmospheric conditions of wind speed and turbulence, the amount of area could exceed the 1 km^2 criteria described previously for a nationally significant area denial dirty bomb.

Various terms have been used to describe the inherent area denial capability of a radionuclide material. The more correct term is the "Derived Deposition Level" for relocation but the popular term, used by the GAO is the Power to Contaminate (PTC). This is defined as the amount of radioactive material needed to be spread uniformly over 1 km^2 so that an inhabitant spending a year on the contaminated surface would receive a dose of 20 mSv, thus triggering the DHS/EPA relocation criterion. The PTC concept is described in Figure 3 and values for Co-60 and Cs-137 are given [2].
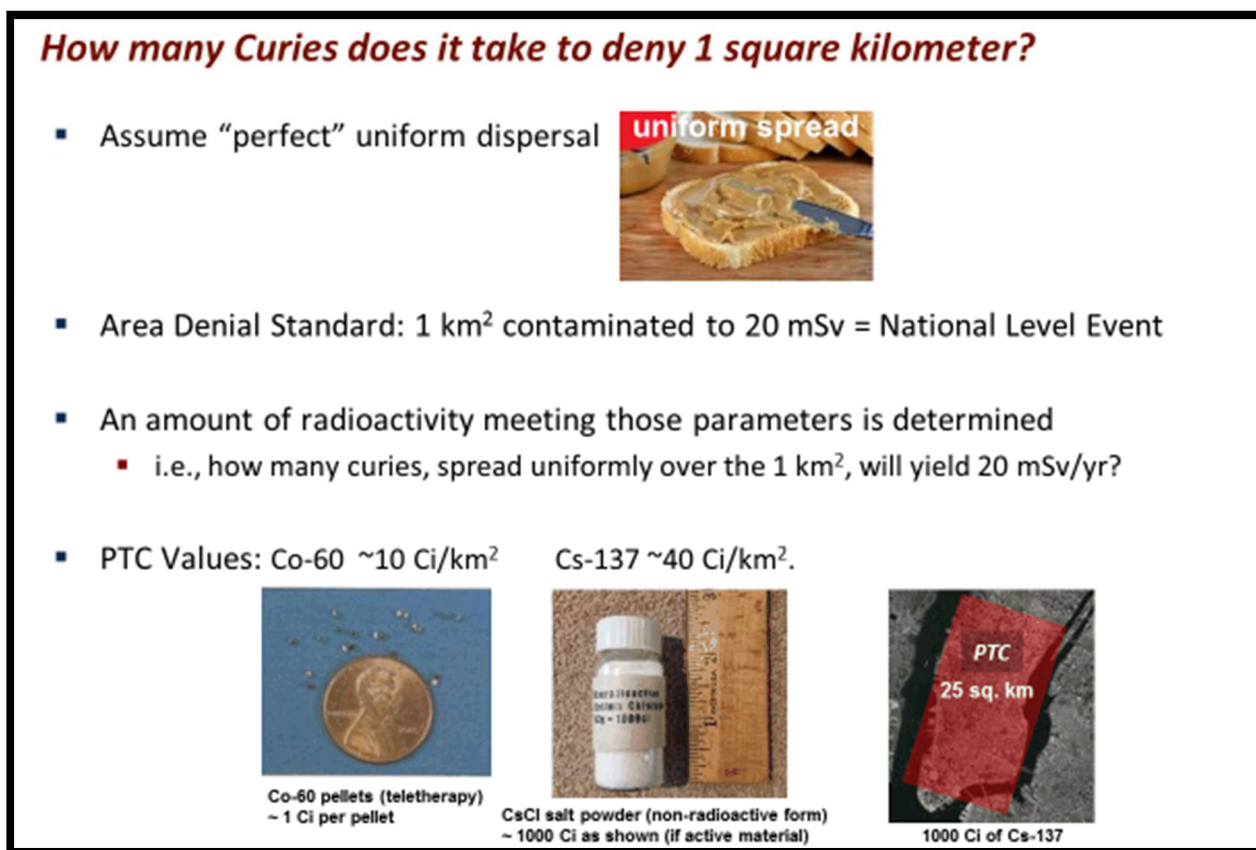
Figure 3. The Power to Contaminate (PTC) for Co-60 and Cs-137.

The typical form for Co-60, as used in cancer therapy machines, is shown in Figure 3. They are small metal pellets, roughly 1 mm in diameter, each having an activity of approximately 1 Ci. Thus, only 10 pellets of Co-60 would be needed to contaminate 1 km^2 of area to the DHS/EPA relocation protective action guideline while several thousand pellets would typically be contained

within a cancer treating teletherapy machine. For Cs-137 the PTC value is 40 Ci/km^2 and 1000 Ci or more of Cs-137 in the powdered salt form (CsCl) would typically be found in a blood irradiator. If 1000 Ci of CsCl were spread uniformly it would cover most of lower Manhattan, 25 km^2.

Co-60 and Cs-137 are the only two radionuclides that are used in commercial, civilian applications at activity levels that far exceed their respective PTC values, by factors of 10 to 100 or more. A Co-60 teletherapy machine, found in many hospitals and cancer therapy clinics worldwide would typically contain several thousand Ci. Similarly, Cs-137 (CsCl) blood and research irradiators, found in hospitals and universities, will contain a few thousand Ci.

This idealized analysis using the inherent power of a radionuclide to contaminate area leaves out the real-world issue of explosive dispersibility. Using the idealized PTC would lead one to believe that Co-60 poses a greater dirty bomb risk. However, the risk equation is more complex since one must also factor in the difficulty of pulverizing a hard, tough metal like Co-60 compared to the soft, salt powder of CsCl. Ultimately the true risk depends on adversary capabilities--knowledge, motivation, and ingenuity.

2. Dirty Bomb Scenarios for CsCl and Co-60

Figure 4 presents a modeling scenario of a dirty bomb over London using the CsCl source pencils of a blood irradiator [3]. This scenario employed a standard atmospheric dispersal code which models the buoyant rise and subsequent dispersal including the effects of random turbulent fluctuations in the mean wind speed, particle size distribution and gravitational drift. Atmospheric turbulence (stability) changes during the day and will influence the ground footprints, as shown in Figure 4 and will be discussed later.

Two contour footprints are shown in Figure 4, one for the 20 mSv/yr contamination level (1.5 – 1.8 km^2) and one for 5 mSv/yr (5 – 7 km^2). Not shown is the contour for 1 mSv/yr, which is approximately 30 km^2 for this example and off the scale of the map. All three dose contours are generally of interest, with the 20 mSv/yr contour representing relocation in the first year. If the dose is less than 20 mSv in the first year then relocation may not be performed, but if after the first year the dose is still above 5 mSv/yr (due to insufficient cleanup capability along with half-life decay and weathering reductions) then relocation would again be recommended. The 1 mSv/yr contour is important because it represents the total area in which at least some type of cleanup may be needed. This is because the ICRP recommends that the long-term goal for people living in a contamination zone should be to reduce the contamination to a level at or below 1 mSv/yr, an additional dose over and above the background terrestrial dose but also within the range of a typical background annual dose.
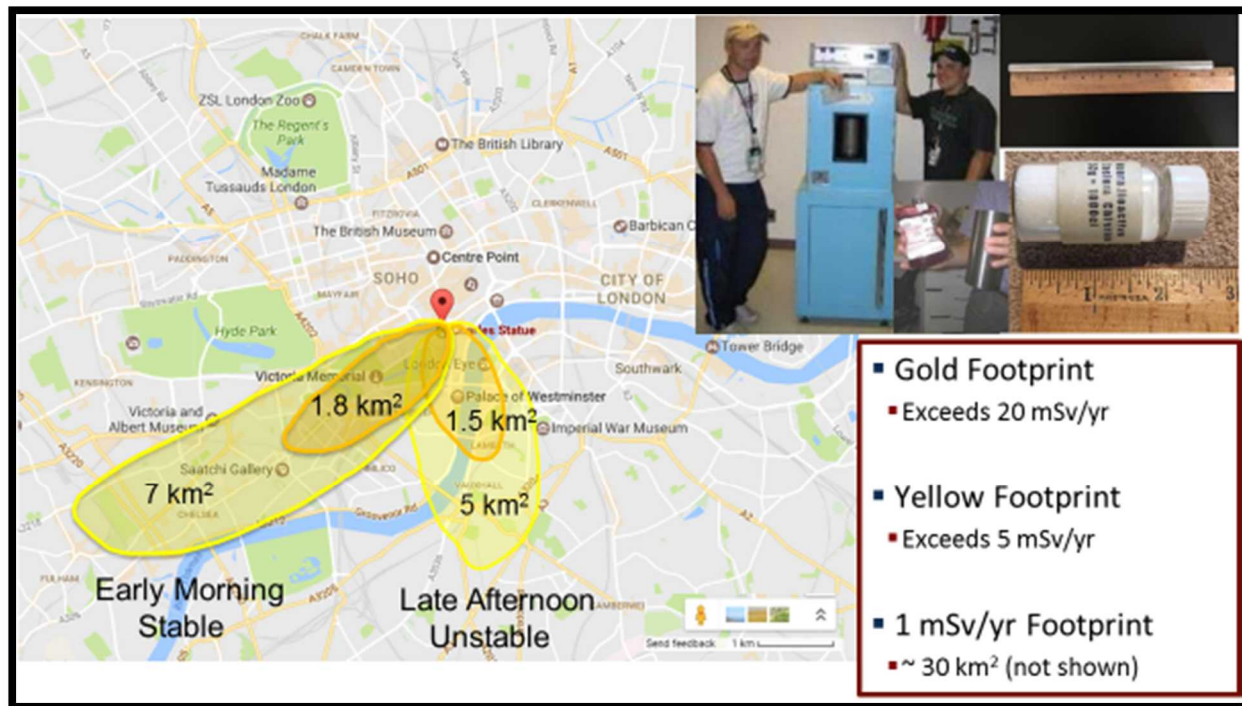
**Figure 4. Atmospheric dispersal modeling of CsCl blood irradiator sources.**

During a morning dispersal when the atmosphere is relatively stable, there will be less turbulent diffusion and the footprints tend to be longer and narrower than for the afternoon when ground heating results in more turbulence. These effects as well as the mean wind speed can change the amount of area contaminated to the various dose thresholds.

It should be emphasized that this is just one scenario representing one point-design and set of weather conditions. In general, one could expect a factor of 2 to 3 variation in area with atmospheric conditions, not to mention the large variations and uncertainties that can result from dirty bomb design. For planning purposes, it would be prudent to expect at least 1 km^2 of contamination to the 20 mSv/yr level if CsCl blood irradiator sources were to be acquired by terrorists and used in a dirty bomb.

Figure 5 [3] shows a model of an explosive dispersal of Co-60 pellets from a cancer treatment teletherapy machine, using the same location in London as in Figure 4. This is an important exception to the notion that "area denial" scenarios are the only ones that can create a national level dirty bomb event. Note the scale change from 1 km to 50 m. The small cobalt pellets will fly-out of the explosion in ballistic fashion with a maximum range from the ground zero of approximately 100 m. Thus, no significant pulverization of the cobalt pellets, they are too tough to disperse explosively. They will be ejected as ballistic buck-shot, posing a significant health hazard if embedded into exposed people but they will not create the large area denial consequence

which requires small dust sized particles. Nevertheless, this scenario, while not presenting a large area denial consequence, will still have a national level impact, given the lack of medical capabilities for treating patients with embedded Co-60 shrapnel. In addition, even though the Co-60 pellets will not be pulverized and can readily be found with radiation meters, the high dose rates within the 100-m zone will make cleanup more difficult as workers will quickly "burn-out" since the allowed annual dose limit of a rad-worker is 10 mSv.
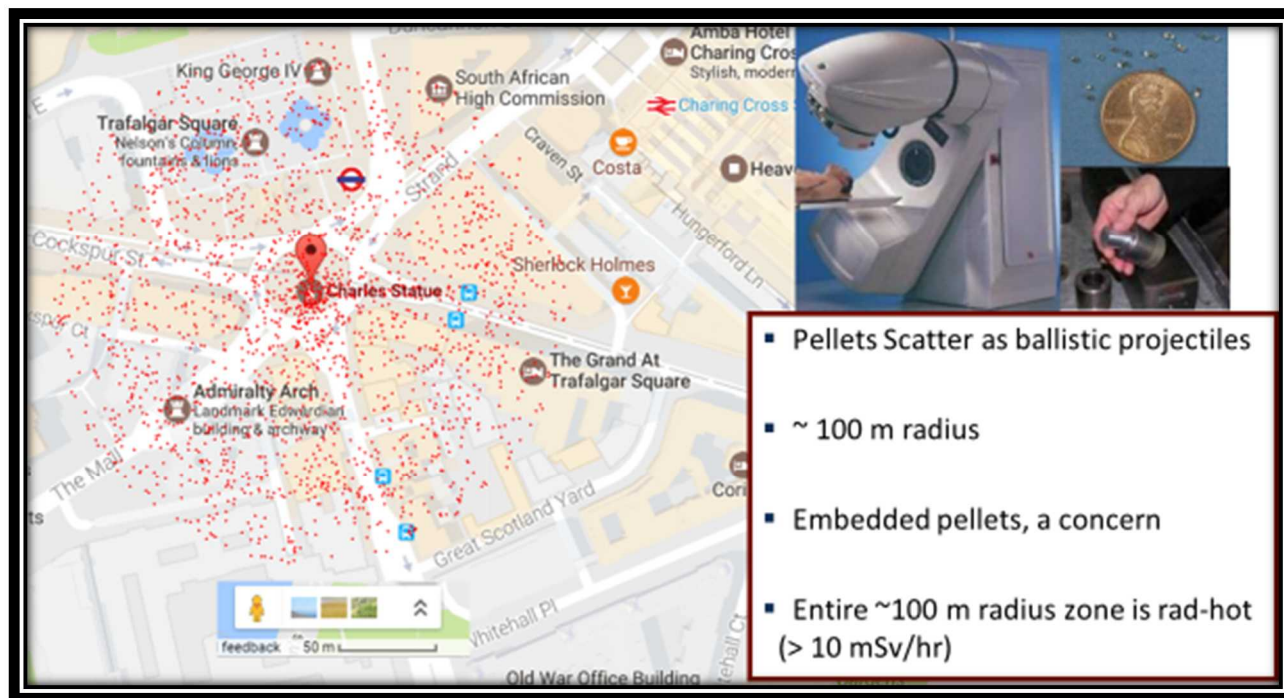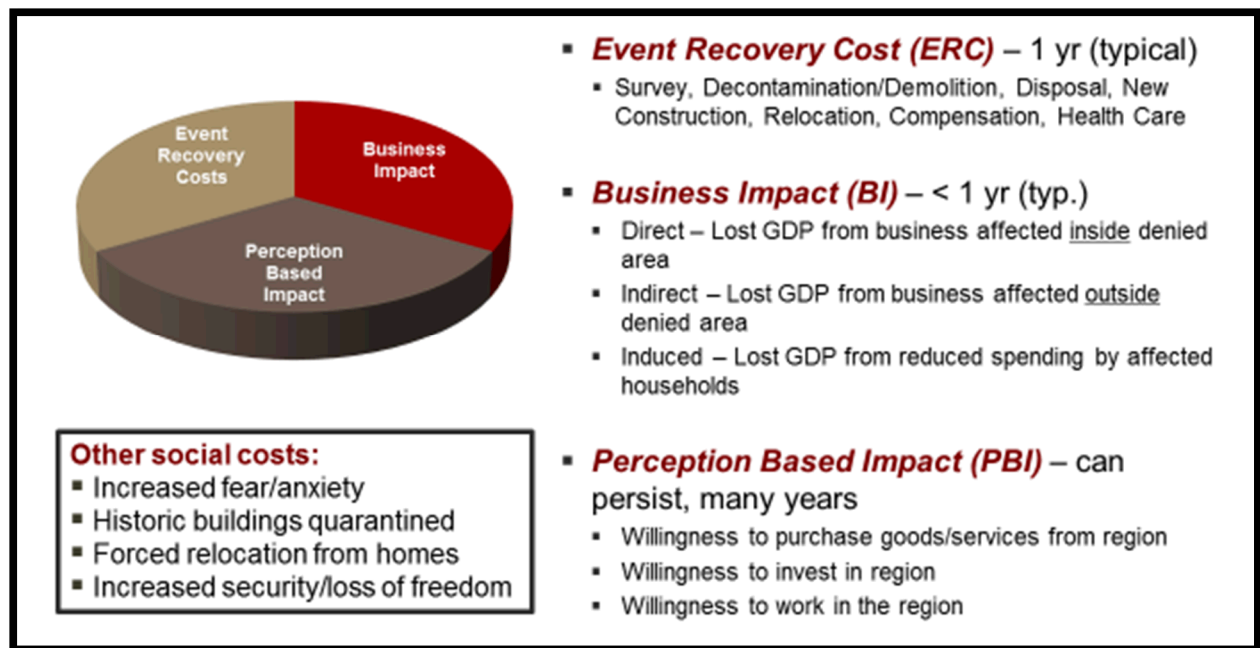

Figure 5. Dirty Bomb dispersal of Co-60 teletherapy pellets.

3. Economic Impacts of an Area Denial Dirty Bomb

From the examples in the previous section it is clear that the amount of area contaminated by a dirty bomb depends on the radionuclide used, weather conditions, and dirty bomb design. We saw that for CsCl blood irradiator sources, prudent practice would be to assume a 1 km^2 contaminated zone, while for Co-60 teletherapy sources the area denial problem is lessoned but the health hazard impacts are much greater due to the embedded fragment issue.   In this section, we will examine the factors to consider when estimating the economic impact of an area denial dirty bomb, such as that expected from CsCl, and will scale the impacts to the 1 km^2 national level event standard with contamination at or exceeding 20 mSv/yr.

Figure 6 presents the three main economic costs and impacts associated with an area denial dirty bomb [3]. These same three costs/impacts apply to other large area disasters, natural or otherwise, and the economic modeling has already been developed for hurricanes, earth quakes, etc., where people are relocated and recovery must occur before the public is allowed back into

the disaster zone. Other societal costs as listed above are not calculable but could be dominant in a dirty bomb attack.

- **Event Recovery Cost (ERC)** – 1 yr (typical)
  - Survey, Decontamination/Demolition, Disposal, New Construction, Relocation, Compensation, Health Care

- **Business Impact (BI)** – < 1 yr (typ.)
  - Direct – Lost GDP from business affected <u>inside</u> denied area
  - Indirect – Lost GDP from business affected <u>outside</u> denied area
  - Induced – Lost GDP from reduced spending by affected households

- **Perception Based Impact (PBI)** – can persist, many years
  - Willingness to purchase goods/services from region
  - Willingness to invest in region
  - Willingness to work in the region

Other social costs:
- Increased fear/anxiety
- Historic buildings quarantined
- Forced relocation from homes
- Increased security/loss of freedom

Event Recovery Costs — Business Impact — Perception Based Impact

Figure 6. Area Denial economic costs and impacts.

Economists make a distinction between a "cost" and an "impact". The recovery from a dirty bomb or other area disaster is a cost, the Event Recovery Cost (ERC) and includes spending by government, insurance companies and others to restore an area to its pre-disaster state. For a dirty bomb, the ERC would include the following costs (1) site surveys to map, track, contain and isolate the contamination, (2) population relocation, temporary housing and subsistence, (3) compensation for property losses, businesses, buildings and homes that are condemned, (4) radioactive decontamination and disposal of the rad-waste, (5) demolition and new construction, and (6) short and long-term health care to the affected population. ERC is what we normally consider to be the cost of a disaster. Most of the dirty bomb economic analysis in the open literature leave out the ERC because the economic modelers writing the papers do not have the rad-background to make such estimates.

Business impact (BI) is not a cost, per se, in that it is not money spent trying to recover from a disaster. Instead, it is a decline in the economic production, gross domestic product (GDP) because of the contaminated area being quarantined and effectively shut-down for economic output. There are three sub-categories for the BI as shown above. Standard economic software packages are available (e.g., IMPLAN, Impact Analysis for Planning) for estimating the impact on the economic inputs and outputs of the affected region. An area of uncertainty for the dirty bomb BI is the time to recover and thus the time for which the BI will persist. The economic modeler must make assumptions as to how many businesses in the affected area will
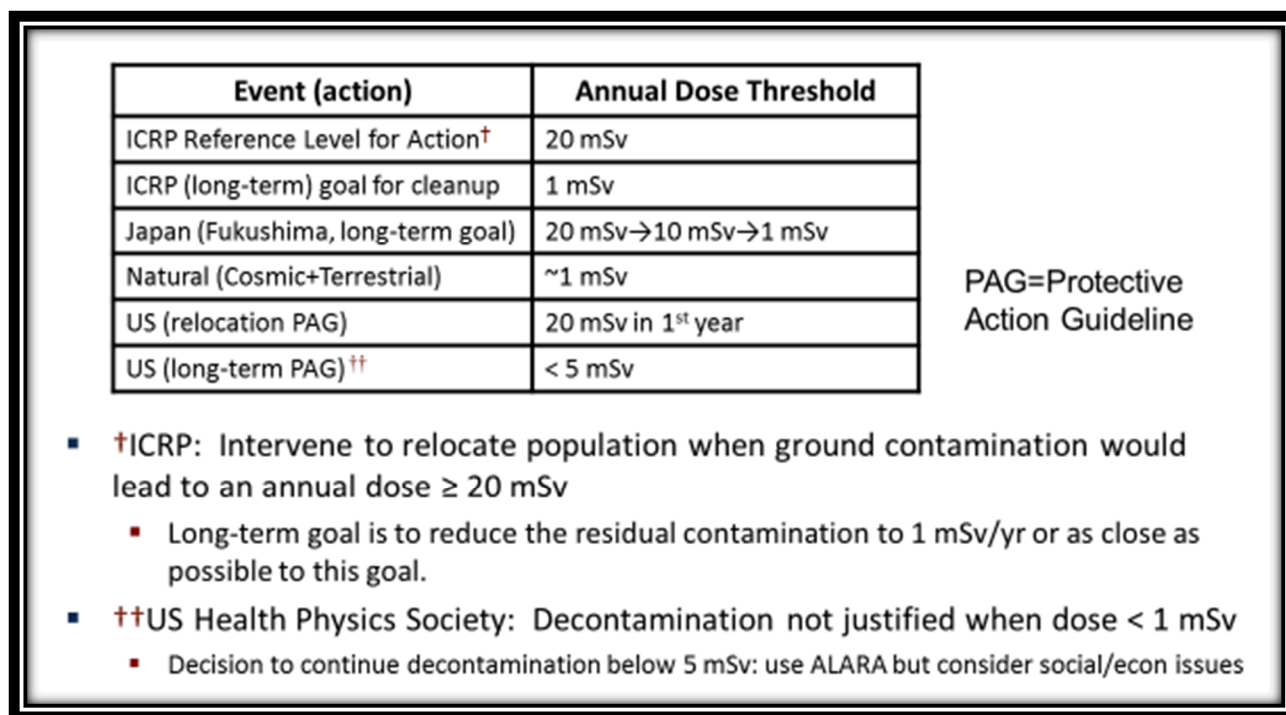
permanently shut down and how many will relocate and begin production again, and the time frame in which these decisions will be made. These are key short-run inputs to the economic BI model. The modeler will try to estimate the time frame and fraction of businesses that relocate (vs. permanent shut-down) based on past disasters. The 9-11 World Trade Center attack is a common data point used in dirty bomb BI with a time frame for business relocation being a few months. Some economic models also attempt to compute the **_net_** BI by including the increase in GDP in other economic sectors and regions that can offset the decline in the affected area. For example, a dirty bomb attack will be an economic boon to the decontamination industry. These type of GDP offsets are controversial in that they fail to account for the lost opportunity.

The Perception Based Impact (PBI) is more difficult to model but it also is an impact and not a cost in that it represents a decline in the GDP resulting from a decline in demand for goods and services within the affected area due to fear of the residual radioactive contamination or due to fear of another attack. The PBI is a long-term economic impact in that it can persist for many years.

Event Recovery Costs (ERC)

We will spend some effort discussing the ERC because it has not been covered as well in past open source articles on the economic consequences of a dirty bomb. Key drivers of the ERC will be (1) the total area to be decontaminated, (2) the acceptable, post-cleanup residual contamination, (3) and the actual decontamination factors that are achievable with existing cleanup technologies. All will be covered in this section.

Figure 7 presents some often-quoted annual dose thresholds for the public for dirty bomb protective action [3]. As discussed previously, the U.S. guideline for relocating the public from a radioactive contamination zone is 20 mSv/yr. This is a guideline, not a regulation with the force of law. In the U.S., it is called the DHS/EPA Protective Action Guideline (PAG) for relocation. This is also not the same as a cleanup standard, which instead would specify how much residual radioactive contamination will be allowed to remain on the urban surfaces after the cleanup has occurred. Some analysts have treated it as a de facto cleanup standard in that if the contamination could be reduced to just below this level then it would be acceptable to not relocate the public. Similarly, the 5 mSv annual dose-threshold for second year relocation has also been considered by some to be an acceptable post-cleanup standard. This is not how these criteria should be interpreted since cleanup is often performed even when the public is not relocated.

Event (action)	Annual Dose Threshold
ICRP Reference Level for Action[†]	20 mSv
ICRP (long-term) goal for cleanup	1 mSv
Japan (Fukushima, long-term goal)	20 mSv→10 mSv→1 mSv
Natural (Cosmic+Terrestrial)	~1 mSv
US (relocation PAG)	20 mSv in 1st year
US (long-term PAG)[††]	< 5 mSv

PAG=Protective Action Guideline

- [†]ICRP: Intervene to relocate population when ground contamination would lead to an annual dose ≥ 20 mSv
  - Long-term goal is to reduce the residual contamination to 1 mSv/yr or as close as possible to this goal.
- [††]US Health Physics Society: Decontamination not justified when dose < 1 mSv
  - Decision to continue decontamination below 5 mSv: use ALARA but consider social/econ issues

Figure 7. Annual dose action levels.

While there is also no set international standard for cleanup, the International Commission on Radiological Protection (ICRP) has stated that the long-term goal should be to achieve levels of residual contamination approaching that which is considered "normal," i.e., 1-mSv/yr [4]. The 1-mSv/yr level is the approximate amount of radiation dose that the public receives from the normal terrestrial background. This international guideline for cleanup has been used at Fukushima and many other past radiological accidents.

Therefore, when assessing the ERC, the prudent choice for a cleanup standard, i.e., a post-cleanup residual contamination, is the 1-mSv/yr guideline of the ICRP and not the EPA Relocation thresholds. The total area impacted by a dirty bomb is then all the area contained within the 1-mSv/yr contour, which for the scenario in Figure 4 was approximately 30 km^2, very much larger than the ~ 1-2 km^2 area covered in Figure 4 by the 20-mSv/yr relocation PAG.

Of course, the level of cleanup effort will increase significantly as one moves from the 1-mSv/yr contour to the 5-mSv/yr and then the 20-mSv/yr contours because the decontamination factor, DF, the ratio of the before to after level of contamination, will be that much higher. Figure 8 provides some background on decontamination technology and the DF's that were achieved at Fukushima with the cleanup of Cs-137.
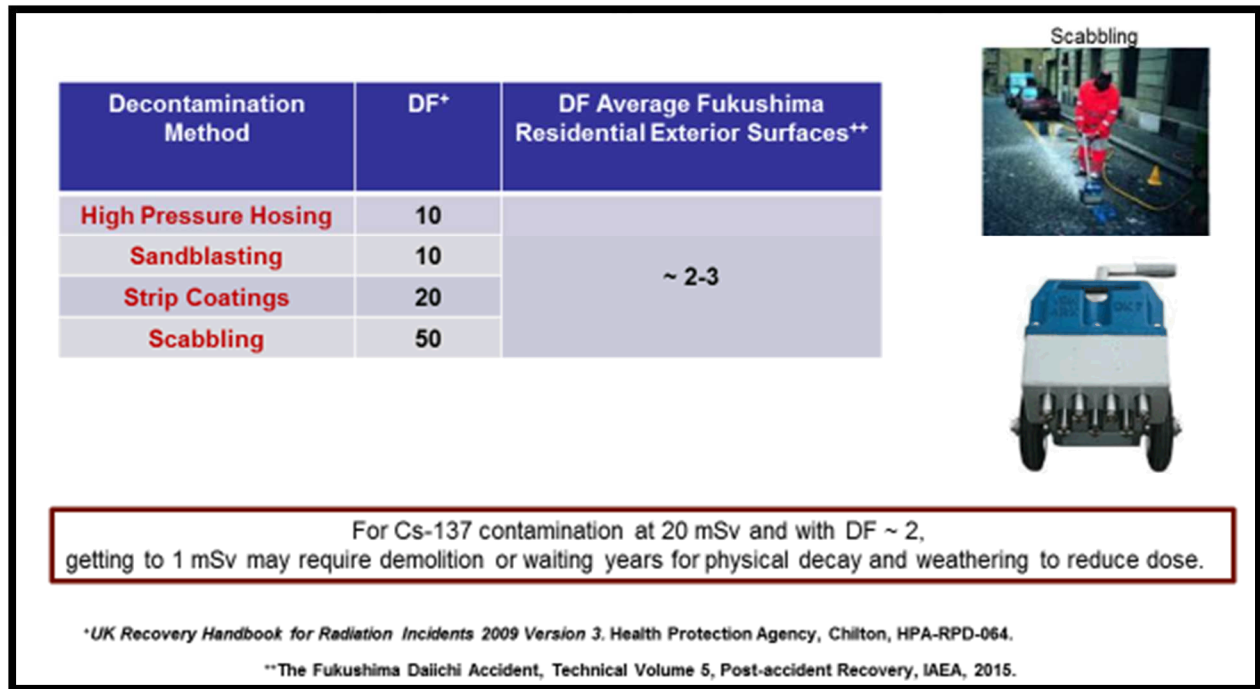
Figure 8. Decontamination of exterior urban surfaces. Theory and practice.

The amount of effort required to cleanup radioactive contamination will be a function of how much contamination exists relative to the allowed residual contamination, which we will assume is the 1-mSv/yr level discussed previously. This was described above as the Decontamination Factor:

$$DF = \frac{Initial\ Contamination\ Level}{Final\ Contamination\ Level} = \frac{Starting\ level\ in\ mSv/yr}{1\ mSv/yr}.$$

For example, if the starting level of contamination yields an annual dose of 20 mSv/yr and the cleanup goal is to achieve the "normal" level of 1-mSv/yr, then the DF = 20.

The table above presents some data on DF that can theoretically be achieved using distinct types of cleanup technologies [5]. However, based on past radiological accidents, particularly those involving Cs-137, (e.g., Chernobyl, Goiania, and most recently, Fukushima [6]) the actual DF's achieved are much lower than the values obtained in lab testing or on conditions that do not reflect realistic conditions for a dirty bomb.

Cs-137 is particularly difficult to decontaminate because of its chemistry. It is a group 1 alkali metal on the Periodic Table, meaning it is a shiny, soft and highly reactive metal and will chemically bond to many common building materials. Once on the surface it will also diffuse down into the material so that even surface removing technologies such as scabbling will not be completely effective. The data from Fukushima indicate that even the surface removing technologies when applied to residential areas were only able to achieve a DF of around 2 – 3.

This relatively low DF will have a significant impact on the Event Recovery Cost because, if a DF of 2-3 is the best that can be obtained, then it may not be possible to satisfactorily cleanup those areas where the initial contamination exceeds 3 mSv/yr. Those contaminated zones within the 5 mSv/yr and certainly 20 mSv/yr contours may need to be quarantined long-term or the buildings demolished and removed as contaminated waste, i.e., destructive decontamination, a very expensive proposition.

The data presented in Figure 9 represents a detailed analysis of the event recovery costs for a plutonium dispersal accident.
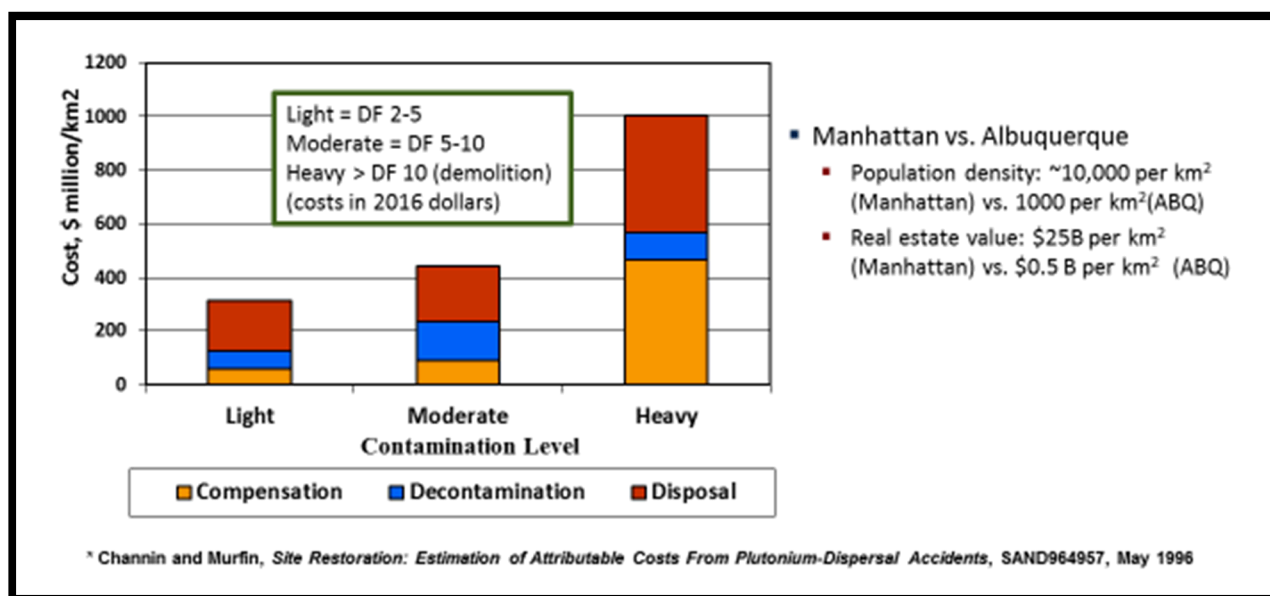
Figure 9. Event Recovery Costs for a Pu dispersal in a mixed-urban area, like Albuquerque, NM.

This chart is derived from the report by Chanin and Murfin [7] which studied the event recovery costs for plutonium dispersal accidents. The study is relevant to the dirty bomb problem in that plutonium is a soft metal that readily disperses into small particles under explosive loading. The Chanin-Murfin report reviews cleanup experiences from past accidents involving plutonium dispersal as well as other radionuclides. They found that the DF's obtained in the field are often much lower than those reported from laboratory or field simulations, particularly when there is a delay of 30 days or more before cleanup commences. This is likely to be the case, given that current planning calls for local, state, and federal authorities to work out a cleanup plan ad hoc, with public and media participation.

For Pu dispersals Chanin-Murfin estimated that if the DF required to achieve acceptable cleanup were to exceed 10, it could only be reached by destructive means, i.e., demolition of the affected structures and rebuilding. Under those conditions they estimated (in 2016 dollars) that the per
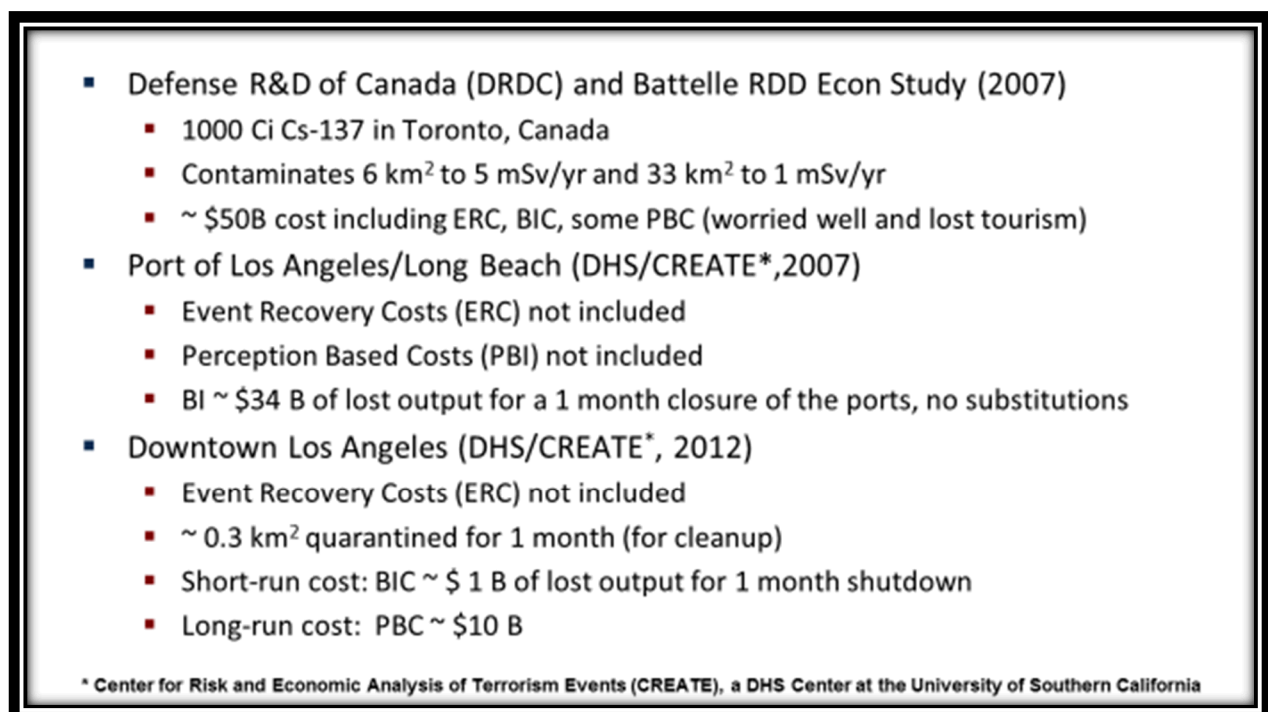
square kilometer costs for a mixed urban area (like Albuquerque, NM) would be approximately $1 B. However, if we use the lessons from Fukushima with Cs-137, a DF exceeding 3 should place us into the heavy contamination, demolition cleanup category (i.e. DF>3 instead of DF>10 causes destructive cleanup). To be conservative, we could assume that for Cs-137 a DF>5 places us in the "Heavy" contamination criterion where destructive cleanup is required.

Assuming the event recovery costs will scale linearly with population density and real estate values we can make a rough estimate for recovery of 1 km^2 of Manhattan, assuming destructive cleanup. A conservative estimate, using a factor of 10 increase over Albuquerque gives an "order of magnitude" ERC for Manhattan in the range of $10 B/km^2. As stated above, for a Cs-137 dispersal, this category of ERC would likely occur when the DF required exceeds 5.

A joint US-Canadian study on dirty bomb economic impacts [8] arrived at a similar ERC estimate. This is discussed further in the next section.

Business Impact and Perception Based Impacts from an Area Denial Dirty Bomb

Figure 10 presents results from three often cited open source studies on the economic impacts of a dirty bomb attack. Two of the studies were performed by the DHS Center of Excellence at the University of Southern California, the Center for Risk and Economic Analysis of Terrorism Events (CREATE). Each takes a different focus on the three cost/impact components.

- Defense R&D of Canada (DRDC) and Battelle RDD Econ Study (2007)
  - 1000 Ci Cs-137 in Toronto, Canada
  - Contaminates 6 km^2 to 5 mSv/yr and 33 km^2 to 1 mSv/yr
  - ~ $50B cost including ERC, BIC, some PBC (worried well and lost tourism)
- Port of Los Angeles/Long Beach (DHS/CREATE*,2007)
  - Event Recovery Costs (ERC) not included
  - Perception Based Costs (PBI) not included
  - BI ~ $34 B of lost output for a 1 month closure of the ports, no substitutions
- Downtown Los Angeles (DHS/CREATE*, 2012)
  - Event Recovery Costs (ERC) not included
  - ~ 0.3 km^2 quarantined for 1 month (for cleanup)
  - Short-run cost: BIC ~ $ 1 B of lost output for 1 month shutdown
  - Long-run cost: PBC ~ $10 B

* Center for Risk and Economic Analysis of Terrorism Events (CREATE), a DHS Center at the University of Southern California

Figure 10. Summary of past open source dirty bomb economic impact studies.

The 2007 study by R&D of Canada and Battelle [8] (a.k.a. the Reichmuth study) looked at several dirty bomb scenarios. The one most relevant here was an external dirty bomb attack using 1000 Ci of Cs-137 on Toronto, Canada near the CN Tower. The Reichmuth study considered all economic cost/impacts (ERC, BI, and PBI) to some degree with better focus on the ERC than most economic impact studies. It used the Chanin-Murfin report previously cited above and the Sandia RADTRAN code, an internationally accepted code for computing the ERC of a radiation dispersal accident, typically during transport. The Reichmuth study treated the cleanup standard as a sensitivity parameter and when the cleanup standard was set at 1-mSv/yr (the ICRP long-term goal for cleanup) they obtained an ERC of $30 B (2007 dollars). They also referenced a 9-11 cleanup cost for the lower Manhattan region around the World Trade Center of approximately $30 B. The areas contaminated to the 20 mSv/yr, 5 mSv/yr and 1 mSv/yr were quite like those obtained in the scenario in Figure 4, the Cs-137 blood irradiator scenario over London. In addition to the $30 B ERC, Reichmuth reported a BI of approximately $10B and PBC of approximately $10B for a total impact of $50B.

The DHS study in 2007 [9] examined the economic impact of a dirty bomb attack on the port of LA/Long Beach. It did not consider the ERC component, nor did it examine the Perception Based Impacts (PBI). It only examined the Business Impact, of a 1-month shutdown of the LA/LB port and came up with an estimate of $34 B. It did not examine substitutions or GDP offsets, just the declines in national GDP caused by the port shutdown. This study served to highlight the over-sized economic impact that a dirty bomb could have when the area denied is a high value strategic seaport, even when the down-time is just 30 days.

The DHS/CREATE Study from 2012 [10] examined a dirty bomb attack in downtown LA which covered a quarantined area of roughly 0.3 km^2. Although ERC was not examined, this was the first study to do a more detailed examination of Perception Based Impacts, which can last for many years past the event. They estimated a BI of a few billion dollars for a 1-month shutdown (scaling to 1 km^2), which is probably on the short end of a true area denial dirty bomb shutdown time for BI. The long-term PBI was calculated for about 5 years after the event and resulted in a PBI of approximately $10B.

4. Summary

We examined the relative risk and impact of a dirty bomb employing Co-60 and Cs-137, the two most common high activity source materials. We found that the risk of an area denial dirty bomb attack is greater for Cs-137 due to the form and chemistry of CsCl, the soft, powdery salt form currently in use for high activity Cs-137 sources, found in blood and research irradiators. Based on past accidents involving CsCl, a dirty bomb attack using CsCl blood irradiator sources will probably cause a quarantine and cleanup of an area equal to or exceeding the 1 km^2 reference area that is used to define a national level dirty bomb event.

The costs and impacts of such an attack were broken into 3 distinct types, (1) Event Recover Cost (ERC), (2) Business Impact (BI), and (3) Perception Based Impact (PBI). ERC is an actual cost and represents the expenses incurred (assumed to be funded by the Federal Government) to restore the area back to its original state or as close to original as possible.

The key uncertainty here is how clean is clean? What level of residual ground contamination will the public accept? We have assumed that the public will accept the ICRP's long term level of radioactive contamination dose of 1 mSv/yr, which is close to dose levels received from the naturally occurring background radiation, albeit this would be in addition to the background, so a doubling of the background dose. At that level of residual contamination and assuming an initial, post-event contamination level over the 1 km^2 of 20 mSv/yr, it is likely that destructive cleanup methods would be needed, i.e. buildings would have to be demolished and rebuilt to get to this level. Under those conditions the ERC could approach the \$10 B/km^2 level for the high contamination zone (20 mSv/yr). Additional, perhaps non-destructive cleanup will be needed in the other zones (defined here as the 5 mSv/yr and 1 mSv/yr zones), which for the CsCl blood irradiator example here (Figure 4) resulted in a 1 mSv/yr zone of approximately 30 km^2.

There are indeed other cleanup standards in use by the EPA and NRC for cleanup of superfund sites or for decommissioning a nuclear power plant site. Those levels are much lower, approximately an order of magnitude lower, at 0.15 mSv/yr (EPA). At those levels, a Cs-137 blood irradiator source used in a dirty bomb would likely cover an area denial zone 100 times larger than 1 km^2. As the residual contamination level goes down (i.e., the cleanup standard or threshold for how clean is clean), the amount of area needing some form or cleanup increases, the DF needed to achieve cleanup in the more contaminated areas increases, and the amount of area that gets classified as "destructive cleanup" goes up. These factors effect cost in a very non-linear fashion, causing the ERC to increase dramatically as the cleanup standard drops below the 1-mSv/yr level.

Studies performed by economists that examine the BI and PBI have similarly obtained impacts in the \$10 B range for each. Taken altogether then, the total impact of an area denial dirty bomb with at least 1 km^2 contaminated to the 20 mSv/yr level could be in the \$10's of billions.

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