ESTIMATING CONTAMINANT CONCENTRATION LEVELS ASSOCIATED WITH ^{137}Cs AND ^{90}Sr RADIOLOGICAL DISPERSION DEVICES

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ABSTRACT

Radiological dispersion devices (RDDs), commonly called 'dirty bombs', utilize a conventional explosive to deliberately disperse non-fissile material as an aerosol. Gaussian semi-empirical modeling is used to estimate the spatial extent (km^2) and radioactivity (Bq) of contamination subsequent to terrorists detonating a ^{137}Cs or ^{90}Sr RDD. Comparable source terms equaling 37,000 x 10^9 Bq, 11.5 grams of ^{137}Cs versus 7 grams of ^{90}Sr, with effective release heights for the radioactive plume of 50m and 100m above street level under varying local-scale atmospheric conditions, are assumed in order to evaluate contamination densities (Bq/km^2). The results can inform response strategies for emergency radiological situations involving intentional releases of non-fissile materials and underscore the need for an effective international regime to prevent illicit use of non-fissile material by terrorists.

INTRODUCTION

The possibility that terrorist groups, especially non-state organizations such as Al Qaeda, might combine non-fissile material with conventional explosives to manufacture a radiological dispersion device (RDD), commonly called a 'dirty bomb', has lead to increased awareness of the need to evaluate the potential consequences of such a terrorist event. Non-fissile material is stored in medical centers to diagnose and treat illnesses, research laboratories, processing plants to irradiate food to eliminate microbes, radiothermal generators, and oil well surveying instruments. Although unsuitable for producing nuclear weapons, radioactive isotopes such as ^{137}Cs, ^{60}Co, ^{90}Sr, and ^{192}Ir may be attractive for terrorists to use in an attack on urban areas [1-2]. As much as 370,000 x 10^9 Bq can be purchased legally from commercial sources depending on the isotope and the recovery of illicit nuclear materials in Europe demonstrates the potential for terrorists to obtain illegally radioactive materials [3-5]. As a result, the potential terrorist use of an RDD has transformed concerns about illicit trafficking in radioactive materials from a relatively obscure topic into a major international security concern [6-12].

Unlike a nuclear device, a dirty bomb does not involve either fission or fusion. Instead, a RDD disperses radioactive materials as aerosols by detonating a conventional explosive, such as TNT, PETN, HMX, or RDX. Dirty bombs are much easier for a non-state terrorist organization to produce than a nuclear device because the manufacturing infrastructure (i.e., U or Pu processing facilities) and linkage to a delivery system (i.e., missile technology) required to create a nuclear weapon are not needed. A RDD would not produce the mass casualties due to the blast and significant radiation exposure associated with a nuclear event. And relatively few, if any, people would die immediately after exposure to the ionizing radiation from a typical RDD using non-fissile material [13]. However, the potential for economic and societal disruption as well as the costs to remediate contaminated and structures has transformed concerns about terrorists using a dirty bomb into a major international security concern. This paper evaluates the potential risk consequences of radiological terrorism and identifies policy responses to limit illicit access to non-fissile nuclear materials.

Methods

As a first step in estimating concentrations of radioactive particles in an urban area, a semi-empirical Gaussian model is used to simulate dispersion for different wind velocities, meteorological conditions,

and release height. This analysis uses Gaussian modeling to because more detailed numerical or Lagrangian probabilistic model, including an urban canyon model, similarly fail to incorporate accurately all of the parameters necessary to evaluate a micro-scale scenario. Moreover, the output of simple Gaussian models is easy to interpret [14-15]. The releases of two isotopes with a source term equaling 37,000 x 10^9 Bq are evaluated:

(1) 11.5 grams of ^{137}Cs, a beta and gamma emitter with 30.2 year half-life, and

(2) 7 grams of ^{90}Sr, a beta emitter, with 29.1 year half-life.

The mass associated with either release can be calculated using Equation [1]:

$$M = \frac{Q \mu T_{1/2}}{N_A \ln 2} \qquad [1]$$

where μ is a molecular mass, N_A is Avogadro constant, Q is activity in Bq, and M is mass in kg. These amounts of ^{137}Cs and ^{90}Sr were chosen because they are comparable to the amounts typically available in commercial sources. It is worth noting that the total mass of the radiological source available for dispersion in a dirty bomb will exceed the mass of ^{137}Cs or ^{90}Sr because other Cs or Sr isotopes will be contained in the source.[a] The increase in total mass, however, does not fundamentally alter the underlying calculations or conclusions for this paper.

The momentum and buoyancy associated with the release of kinetic and thermal energy when a dirty bomb explodes causes the initial dispersion. Equation [2] represents the movement of the radioactive isotopes with power-like dependences of height of the thermal based on the time interval elapsed subsequent to the explosion [16]:

$$H(t) \approx \zeta \Theta^{1/4} t^{1/2} \qquad [2]$$

where Θ is TNT equivalent in kg and t is the time interval in sec. The automodel regime of movement forms in about 0.1−1.0 sec after the explosion. Taking into account that the constant ζ varies in the range of 30-50 m/(kg$^{1/4}$sec$^{1/2}$), the time interval for the thermal's rise is approximately 5−10 sec and TNT equivalent equal to 3−10 kg, the effective height of a release can be assessed in the range of 50 −150 m depending on the power of the explosion (i.e., 1 kg of TNT generates 4.2MJ of heat).

The relatively fast rise of the thermal makes it possible to consider dispersion rates and buoyancy separately. Dispersion rates depend on ensemble properties of the surface obstacles [17]. Buoyant rise is represented by effective release height. Because the contaminated area's spatial scale is substantially larger then the initial size of a plume, the source term is treated as a point source and handled parametrically so the initial concentration distribution of ^{137}Cs or ^{90}Sr particles is not essential for assessing the extent of contamination. A simple source depletion method is used to account for washout because measuring and modeling rainout is very complex requiring the inclusion of heterogeneous condensation and the nonlinear dynamics of condensation [18-19].

In this case, parametric dependences of the standard deviations of the Gauss distribution from *x*, *y* and *z* are used to describe aerosol dispersion. Equation [3] depicts the parametric dependences of the concentration dispersions in the x, y, and z directions (σ_x, σ_y, σ_z) over distance was used to estimate atmospheric diffusion for different classes of atmospheric stability [20]:

$$\sigma_y(x) = q\,x^{\eta}, \sigma_z(x) = s\,x^{\gamma} \qquad [3]$$

In general, the more unstable the atmosphere, the greater the diffusion of radioactive aerosols which reduces contaminant concentrations deposited at a given location. The σ's (plume spread parameters) represent functions of the downwind distance x for each Pasquill atmospheric stability class based on wind speed at 10 m with either incoming solar radiation during day or cloud cover at night [21].[b] The parameters are derived from the distribution of the ^{137}Cs or ^{90}Sr concentration averaged over time. While the radiological source is in the plume, the instantaneous concentration fluctuates due to changes in plume location and wind direction. Determining the plume spread parameters $\sigma_y(x)$ and $\sigma_z(x)$ is a two-step process of selecting an atmosphere stability class and specifying values for $\sigma_y(x)$ and $\sigma_z(x)$. Discrete stability classification introduces some undefined error in the concentration estimates, but any error is likely to be stochastic. Because the true dispersion rate may lie anywhere on the stability scale, this does not produce biased estimates. The dispersion model for plume size takes into account the influence of roughness length on plume growth. Urban complexes are considered in terms of uniform roughness.

Initial aerosol dispersion and deposition are affected by release height with the radioactive plume expanding spatially over time. As distance increases from the initial point of detonation increases and the plume spreads, the maximum concentration of radioactive substances distributed downwind reduces based on the isotopes' deposition velocity and wind velocity. The maximum ground level concentration is expressed by Equation [4]:

$$C_{max} \sim \frac{4Q\sigma_z}{(2\pi)^{3/2} e \sigma_y^2 h^2} \qquad [4]$$

where σ_y and σ_z are to be taken for a distance x_{max} where the maximum occurs.[c] Because maximum contamination density is limited by the rate at which plume size increases relative to the deposition rate, the following values were used for assessments: Q = 37,000 x10^9 Bq, U = 2.0 m/s, q = 1.46, s = 0.01, η = 0.71, γ =1.54, U_g = 0.01m/sec. The distance x_{max} where the maximum ground level concentration achieves can be obtained by solving $\frac{dC(x_{max})}{dx} = 0$:

$$x_{max} = \left[\frac{\gamma h^2}{s^2(2\eta+\gamma)}\right]^{1/2\gamma} \approx 320\text{m} \qquad [5]$$

This analysis assumes effective release heights of 50m and 100m above street level as the value for the release height parameter.

Precipitation can result in the removal of radioactive material from a plume. Two separate processes, washout and rainout, may be considered. Washout removes material by raindrops falling through a plume (i.e. below cloud removal) while rainout removes material incorporated into raindrops within the cloud. Because precipitation affects the entire plume, the deposition rate is dependent on the total amount of activity contained in the plume instead of the ground-level air concentration. Deposition rates are calculated using the washout coefficient, defined as the fraction of the dispersing material removed in unit time. For this analysis, to calculate washout intensity, it is assumed that in the control volume the part of the mass is deposited for the time interval dt:

$$dQ_w = Q_w V_w P\, dt \quad [6]$$

where Q_w is the mass in the control volume with the height equal a height of the cloud; dQ_w is a mass deposited due to the washout; V_w is the washout constant [hr/s/mm]; P is the rainfall rate [mm/hr]. The time history of the precipitation for only that part of the plume passing through the precipitation is depleted. Deposition rates are calculated using the washout coefficient, defined as the fraction of the dispersing ^{137}Cs or ^{90}Sr removed in unit time.

Results

Table I provides estimates of the spatial extent of the contaminated area with a minimum threshold of 1,000 x 10^9 Bq per square kilometer (km^2), total activity within the contaminated area (Bq), and contamination density (Bq/ km^2) for a ^{137}Cs or ^{90}Sr RDD based on different states of the atmosphere, surface wind speed, and deposition velocities. For example, with a 37,000 x 10^9 Bq release of either ^{137}Cs or ^{90}Sr at 50 m and no rainfall, the spatial extent of the area contaminated measured in km^2 with a minimum threshold of 1,000 x 10^9 Bq/km^2 is given in the first row of the 'H=50m' column for the 'no rainfall' category for each isotope. The total activity of this area is indicated in the second row of the 'H=50m' column. Density of contamination (Bq/km^2) is provided in the third row of the 'H=50m' column for the 'no rainfall' category. The entries under the 'with rainfall' category can be interpreted similarly.

Table I. Estimates of area contaminated and radioactivity by a ^{137}Cs or ^{90}Sr RDD with a minimum threshold of 1,000 x 10^9 Bq/km^2 (Q=37,000 x10^9 Bq, U=2 m/s, Ug=0.01 m/s)[1]

	^{137}Cs		^{90}Sr	
	H=50m	**H=100m**	**H=50m**	**H=100m**
Without Rainfall				
Area (km^2)	0.56	0.68	0.18	0.22
Activity (Bq)	1,676 x 10^9	1,092 x 10^9	995 x 10^9	617 x 10^9
Density (Bq/km^2)	3,000 x 10^9	1,612 x 10^9	5,528 x 10^9	2,805 x 10^9
With Rainfall				
Area (km^2)	12.20	14.50	2.50	2.53
Activity (Bq)	13,542 x 10^9	22,120 x 10^9	6,508 x 10^9	6,370 x 10^9
Density (Bq/km^2)	1,110 x 10^9	1,526 x 10^9	2,603 x 10^9	2,518 x 10^9

[1] Rainfall starts 10 min after release and lasts 1 hour; rainfall rate is 20 mm/hour. Source term = 37,000 x 10^9 Bq

The results reveal that the extent of the contaminated area with a minimum threshold of 1,000 x 10^9 Bq/km^2 tends to increase as a function of release height for ^{137}Cs or ^{90}Sr for most scenarios analyzed. For example, changing the release height from 50m to 100m causes the contaminated area to increase from 0.56 km^2 to 0.68 km^2 without rainfall (21%) or 12.20 km^2 to 14.50 km^2 with rainfall (19%) for ^{137}Cs. A similar impact due to changing from the 50m and 100m release heights was estimated in terms of the increase in size of the contaminated area for a ^{90}Sr release without accompanying rainfall. The area increases from 0.18 km^2 to 0.22 km^2 (22%). On the other hand, an extremely small increase from 2.50 km^2 to 2.53 km^2 (1%) is estimated to occur for a ^{90}Sr release followed by a rainfall event. The varying results potentially stem from differentials in atomic properties such as the density (g/cm^3) and activity of Cs relative to Sr.

This simulation also indicates that that the level of activity within the contaminated area varies by isotope and depends on release height and whether rainfall occurs. If the initial detonation of the RDD occurs when there is no precipitation, then the level of activity is relatively low. The analysis indicates, however, that a rainfall event increases both the spatial extent of the contaminated area and activity within the contaminated area due to washout which enhances localized deposition. For example, if the RDD releases ^{137}Cs, the size of the contaminated area increases by approximately two orders of magnitude from 0.56 km^2 to 12.20 km^2 (2,079%) and from 0.68 km^2 to 14.50 km^2 (2,032%) at heights of 50m and 100m respectively. The level of radioactivity increases almost one order of magnitude from 1,676 x 10^9 Bq to 13,542 x 10^9 Bq (710%) with rainfall at a 50m release and almost two orders of magnitude from 1,092 x 10^9 Bq to 22,120 x 10^9 Bq (1,926%) at a 100m release.

A similar pattern occurs for ^{90}Sr. When rainfall occurs, the contaminated area increases approximately one order of magnitude from 0.18 km^2 to 2.50 km^2 (1,288%) while activity increases approximately one-half order of magnitude from 995 x 10^9 Bq to 6,508 x 10^9 Bq (554%) with rainfall at a 50m release height. The size of the contaminated area increases by approximately one order of magnitude from 0.22 km^2 to 2.53 km^2 (1,050%) and activity by almost one order of magnitude from 617 x 10^9 Bq to 6,370 x 10^9 Bq (932%) with rainfall for a 100m release.

As a result, if rainfall occurs after some time elapses, the shift in atmospheric conditions can result in a RDD producing more extensive contamination of a larger area combined with elevated activity within the area. The rainfall effect on the RDD's impact is enhanced further when the release height is 100m. And, if significant runoff occurs due to a large rainfall volume, widespread re-distribution of the radioactive particles can occur subsequent to their initial deposition from the atmosphere.

The measure of density in Table 1 provides an indication of the level of activity by spatial unit (Bq/km^2). Because release height and atmospheric conditions affect both the level of activity and the size of the area contaminated, density is sensitive to specific scenario conditions such as the release height, time interval for a dry atmosphere, the rainfall rate, and rainfall duration on a localized basis with rainfall events.

CONCLUSIONS

These modeling results reveal that dispersion of radioactive material by a dirty bomb could result in extensive contamination of a limited area under some conditions. In addition to the influence of precipitation, if deposition velocity is low, the plume increases in size without significant deposition occurring so that non-fissile material is scattered over a relatively large area with a relatively low contamination density. On the other hand, if atmospheric conditions are stable and deposition velocities are ~ 1 cm/sec, the contaminated area can reach several km^2 with correspondingly higher ^{137}Cs or ^{90}Sr contamination density. The results indicate that a terrorist incident involving a RDD might have the greatest likelihood for causing adverse impacts if the wind velocity is low prior to a rainfall event, the atmosphere is stable enhancing the residence time of ^{137}Cs or ^{90}Sr particles in the air, and particle size and geometry for radioactive aerosols (i.e., density and area) maximizes the chances for dispersion.

This analysis reveals that, if terrorists detonate a RDD containing a relatively small amount of non-fissile material under favorable atmospheric conditions, the resulting dispersion can result in elevated concentrations of radioactivity within a limited large area. Initial news of such an event might create temporary economic and social disruption but has extremely limited potential to produce adverse health effects among the civilian population. Moreover, the potential consequences of a dirty bomb incident are minimized by developing countermeasures including enhanced public understanding of plausible risks, effective emergency response, decontamination capabilities, and active shielding by remaining indoors. After any initial panic subsides and the public understands the minimal health hazard posed even without

remedial action, the vertical migration of Cs or Sr isotopes deposited to surface soils into the soil column to a depth of several mm will provide shielding and attenuate naturally external radiation doses over time.

In addition, the results generated by semi-empirical modeling indicate that it is essential to establish an effective international regime for preventing terrorists from obtaining non-fissile materials. For example, because it is not a gamma-emitter, a ^{90}Sr dirty bomb might be difficult to detect prior to detonation creating serious problems for counter-terrorism efforts aimed at preempting an event.[d] As a result, investments in active measures to create accurate inventories of sources, maintain materials controls, secure orphan sources of non-fissile materials, and interdict illicit materials are likely to reduce significantly the threat posed terrorists attempting to use a dirty bomb to release radioisotopes in an urban area. Such a regime inevitably requires the active cooperation of multiple parties to ensure successful compliance.

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FOOTNOTES

[a] When ^{137}Cs is produced by a nuclear reactor, it usually is contaminated with an equal amount of ^{133}Cs and removal of the ^{133}Cs using isotope separation is cost-prohibitive for typical commercial products. Due to differential decay rates, the ^{133}Cs to ^{137}Cs ratio for a dirty bomb is likely to exceed 1:1 in a commercially marketed ^{137}Cs source. For commercial products, the Cs normally is located in a ceramic matrix, glass compound, as CsCl or in some other form so, in addition to the mass of the ^{137}Cs, the total mass of the radiological source will contain that material. This means the total mass of an actual source could be more than 10 times the values for the ^{137}Cs component. Similarly, nuclear reactor operations produce ^{89}Sr and ^{90}Sr as fission by-products when ^{235}U is split into smaller atomic mass fragments so the ratio of ^{90}Sr to ^{89}Sr or other Sr isotopes will be greater than 1:1 given its longer half-life (i.e., 29.1 years for ^{90}Sr versus 64.85 days for ^{85}Sr and 50.52 days for ^{89}Sr). Overtime, the total mass of a Sr dirty bomb will approximate the mass for ^{90}Sr.

[b] It is reasonable to ask whether the modeling approach used for assessing contamination levels attributable to terrorists deliberately releasing ^{137}Cs or ^{90}Sr in an urban setting is adequate. Although the Pasquill-Gifford stability classification is based on rural experiments such as the Prairie Grass studies, is it reasonable to use such coefficients in an urban scenario because Pasquill-Gifford coefficients obtained experimentally have been used for modeling both rural and urban dispersion [15, 17, 20]. And, using wind tunnel experimentation to simulate an urban setting, Hall *et al* demonstrated that the lateral and longitudinal distribution is Gaussian with dispersion rates dependent on the surface obstacles' ensemble properties rather than their individual characteristics [14].

[c] This equation is valid only if σ_y / σ_z is constant.

[d] Fortunately, some physical factors constrain terrorists using a RDD. First, the radioactivity of the source is a limiting factor, with very high activity levels necessary to cause extensive radioactive contamination. Second, shielding the radioactive source would increase weight potentially making the device more difficult to transport and reduce dispersion efficiency because the shielding could limit the amount of particles released.

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