# 4.19 MODELING $^{137}$CS DISPERSION FROM A RADIOLOGICAL DISPERSION DEVICE

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## INTRODUCTION

Significant amounts of non-fissile radioactive materials are 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 those facilities lack the types or volumes of materials suitable for producing nuclear weapons, they contain large amounts of radioactive material such as $^{137}$Cs, $^{60}$Co, $^{90}$Sr, and $^{192}$Ir which may be attractive for terrorists to use in an attack on urban areas. Moreover, the possibility of such material being used in a terrorist incident is plausible (*Stern J.,* 1999; *Schmidt A.P.,* 1999). Recent reports have documented the recovery of nuclear materials in Europe demonstrating the willingness to deal in radioisotopes as well as the potential for terrorists to obtain such materials (*Williams P and P.N. Woessner,* 1996).

If terrorists succeed in acquiring non-weapons grade nuclear materials, those radioactive sources might be dispersed deliberately in an urban area. Although a radiological attack would not produce the mass casualties due to the blast and significant radiation exposure associated with a nuclear event, it nonetheless could result in radiation concentrations exceeding International Commission on Radiation Protection (ICRP) guidelines for limiting exposures to gamma radiation (National Research Council 1990). Such an incident could create a variety of impacts ranging from extensive contamination requiring remediation, panic and economic disruption, to long-term exposure of civilian populations to low levels of radiation exceeding natural background levels. For example, information that a large urban area such as Moscow, New York, or Washington, DC was contaminated with several tens of Ci/km$^2$ might create extensive panic and paralyze the life of the city. Such a situation could occur because the general public may believe that the gamma-radiation dose rate has become several times higher than the background value. If the public perceives that radioactive contamination will endanger its health, assuaging those fears may be virtually impossible.

## METHODS AND RESULTS

### Modeling the initial release and subsequent atmospheric dispersion

Simple, semi-empirical modeling is employed to evaluate the initial release and subsequent dispersion of $^{137}$Cs. Such a straight forward approach makes it possible derive preliminary approximations of levels of contamination for varying source terms. After an RDD detonates, what commonly is referred to as a 'thermal' containing radioactive isotopes of $^{137}$Cs forms and moves upwards in the atmosphere. The momentum and buoyancy associated with the release of kinetic and thermal energy cause the initial rise of the thermal whose movement can be described by power-like dependences of height of the thermal based on the time interval elapsed subsequent to the explosion (*Gostintsev, Yu. A., L.A. Sukhanov and A.F. Solodovnik,* 1980):

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

where $\Theta$ 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 $\zeta$ varies in the range of 30-50 m/(kg$^{1/4}$sec$^{1/2}$), the time interval for the thermal's rise is aprroximately 5–10 sec (*Gostintsev et al,* 1980) and TNT equivalent of RDD is equal to

5–10 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).
To facilitate interpretation of the results, dispersion is estimated using a Gaussian model. Buoyant rise is represented in terms of an effective height of a release. The relatively fast rise of the thermal makes it possible to consider separately the processes of buoyancy and dispersion instead of coupling them. When the spatial scale of the contaminated area is substantially larger then the initial size of a puff, the source of $^{137}$Cs can be described as a point source and handled parametrically so the initial concentration distribution of $^{137}$Cs particles is not essential for assessing the extent of contamination expressed in terms of integral characteristics such as area and activity above some threshold levels.
As a first step in modeling the spread radioactive particles in an urban area, a simplified conceptual model is used to simulate dispersion for different wind velocities, meteorological conditions, and heights of release. To this end, semi-empirical models with parametric dependences of standard deviations of the Gauss distribution from *x*, *y* and *z* can be used to describe the spread of radioactive aerosols. Such models make it possible to assess spatial distribution of the contamination over an area after the explosion of a dirty bomb. If the release of $^{137}$Cs occurs in a short time interval, the point source Q(x,y,z,t) can be represented as a product of $Q \cdot \delta(t) \cdot \delta(\vec{r} - \vec{r}_0)$. For a source located at point (0,0,h), the concentration distribution C in the atmosphere at time t can be computed using the following equation:

$$C(x,y,z,t) = \frac{Q}{(2\pi)^{3/2}\sigma_x \sigma_y \sigma_z} \exp\left[-\frac{(x-Ut)^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right]\left\{\exp\left[-\frac{(z-h)^2}{2\sigma_z^2}\right] + \exp\left[-\frac{(z+h)^2}{2\sigma_z^2}\right]\right\} \quad (2)$$

where $\sigma_x$, $\sigma_y$, $\sigma_z$ are concentration dispersions in the x, y, and z directions (i.e., vectors) and h is the height of the release, U is wind velocity. The second term within the {} brackets is the term due to reflection at the ground.
The expression below representing the parametric dependences of the $^{137}$Cs contamination's horizontal transport (parameters $\sigma_x$ and $\sigma_y$) and vertical transport ($\sigma_z$) over time and distance can be used to estimate atmospheric diffusion for different classes of atmospheric stability (*Doury A.,* 1980, 1976; *McElroy J.L.,* 1969):

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

The σ's (or puff spread parameters) represent functions of the downwind distance x for each of the group of atmosphere stability classes and are derived from the distribution of the contaminant concentration averaged over some sampling time as it resides in the cloud. While the radiological source is in the cloud, the instantaneous concentration will fluctuate due to changes in cloud position and wind direction. Determining the puff spread parameters $\sigma_y(x)$ and $\sigma_z(x)$ involves a two step process of identifying the atmosphere stability and specifying values for $\sigma_y(x)$ and $\sigma_z(x)$ appropriate to the selected stability. We recognize that discrete stability classification introduces some undefined error in the concentration estimates since it is reasonable to expect that the true dispersion rate may lie anywhere on the stability scale. Nonetheless, such approach seems to be reasonable, especially when empirical data are used for modeling. The dispersion model for puff size takes into account the influence of roughness length on puff growth. Urban complexes are considered in terms of uniform roughness.
Initial dispersion and deposition of aerosols are affected by release height. For this analysis, aerosol dispersion and deposition are estimated for effective release heights of 50m and 100m above street level.

**$^{137}$Cs contamination after a dirty bomb explosion**

The diffusion and deposition of the $^{137}$Cs puff can be illustrated by considering the influence of effective release height on the dissemination of contamination. At an effective release height of 50 meters (h=50m) the radioactive puff grows in size with distance due to the convective diffusion and reaches ground level in the time interval $t_1$ defined by the expression:

$$\sigma_z(x) \approx h, \Rightarrow x \sim (h/s)^{1/\gamma} \sim 500\,\mathrm{m} \Rightarrow t_1 \sim U^{-1} \cdot (h/s)^{1/\gamma} \sim 2 \cdot 10^2\,\mathrm{sec} \quad (4)$$

where $s = 0.09$, $\gamma \approx 0.95$, $U \approx 3\,\mathrm{m/sec}$ and $h = 50\mathrm{m}$.

As the cloud spreads, the maximum concentration of radioactive substances reduces with x in accordance with the law ( $h << \sigma_z$ )

$$C \approx \frac{2Q}{(2\pi)^{3/2}\sigma_x(x) \cdot \sigma_y(x) \cdot \sigma_z(x)} \quad (5)$$

at the same time the contamination density in the downwind direction does not exceed a value of

$$A \approx \frac{2Q}{(2\pi)^{3/2}\sigma_x^2 \cdot \sigma_z} \cdot \frac{\sigma_x}{U} \cdot U_g \quad (6)$$

where it's taken into account that $\sigma_x = \sigma_y$ and Ug is the deposition velocity of radionuclides and U is the wind velocity. Applying expression (5) for horizontal and vertical transport makes it possible to derive an upper bound estimate of the distance moving away from the location for the $^{137}$Cs to the location at which the contamination density will be smaller than some threshold value $A_{th}$.

$$L_0 \approx \cdot \left( \frac{2Q \cdot U_g}{(2\pi)^{3/2} q \cdot s \cdot A_{th} \cdot U} \right)^{1/(\eta+\gamma)} \approx 2 \cdot 10^3\,\mathrm{m} \approx 2\,\mathrm{km} \quad (7)$$

The following values were used for assessments:

$U \approx 3$m/s, $q \approx 1.36$, $s \approx 0.09$, $\eta \approx 0.67$, $\gamma \approx 0.95$, $Q \approx 3$kCi, $A_{th} \approx$ 10 Ci/km$^2$, $U_g \approx$ 3 mm/sec.

The maximum ground level concentration is expressed by the following:

$$C_{max} \sim \frac{4Q\sigma_z}{(2\pi)^{3/2} e \sigma_y^2 h^2} \quad (8)$$

where $\sigma_y$ and $\sigma_z$ are to be taken for a distance $x_{max}$ where the maximum occurs. This equation is valid only if $\sigma_y / \sigma_z$ is constant. The distance $x_{max}$ is such that

$$h^2 \approx 2\sigma_z^2(x_{max}) \quad (9)$$

Maximum contamination density can be expressed by the expression:

$$A_{max} \sim \frac{4Q}{(2\pi)^{3/2} e h^2} \frac{\sigma_z}{\sigma_y} \frac{U_g}{U} \sim \frac{4Q}{(2\pi)^{3/2} e h^2} \frac{s}{q} \frac{U_g}{U} \sim 10\ \mathrm{Ci/km^2} \quad (10)$$

where $Q = 3\,\mathrm{kCi}, U = 3\,\mathrm{m/sec}, U_s = 3\mathrm{mm/sec}, s = 0.09, q = 1.36, \eta = 0.67, \gamma = 0.95, h = 50\,\mathrm{m}$, e is a base of ln(x). It is interesting to note that these computations suggest, if the radioactive puff rapidly increases in size, then the $^{137}$Cs deposition rate insufficient to create contamination exceeding the threshold level ($A_{th}$).

The process of puff depletion and the resulting spatial distribution of $^{137}$Cs can be modeled by calculating radioactive fallout for the time interval $\Delta t$ and subsequent subtraction of the activity from the source. To illustrate this, we conducted numerical investigations to estimate the radioactive contamination associated with the detonation of a $^{137}$Cs dirty bomb by terrorists. The computations assume the instantaneous release of radioactive materials with a total activity of 1,000 Ci and 3,000 Ci at heights of h=50m and 100m.

The results of the numerical calculations show that the spatial extent of the area with a high level of contamination strongly depends on the deposition velocity (i.e., the particle size) and local meteorological conditions including atmospheric stability and wind velocity. If the deposition velocity is low, the plume increases in size over a time interval during which substantial $^{137}$Cs deposition does not occur. In this case, $^{137}$Cs 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 contamination density. These modeling results reveal that $^{137}$Cs dispersion from a RDD could result in extensive contamination under some conditions.

In addition, it is worth considering the impact of washout during a rainfall event on the distribution of $^{137}$Cs were terrorists to detonate a dirty bomb. The analysis indicates, if the initial formation of the puff occurs when there is no precipitation and rainfall occurs after some time elapses, the shift in atmospheric conditions can result in extensive contamination of a relatively large area. Washout of $^{137}$Cs results in more extensive contamination within a city, with both the size of the contaminated area and the contamination density being dependent on the time interval for a dry atmosphere, the rainfall rate, and rainfall duration. Moreover, 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.

## CONCLUSIONS

This analysis reveals that, if terrorists detonate a RDD containing a relatively small amount of $^{137}$Cs (approximately 12-35g), the resulting dispersion can contaminate a relatively large area. The actual magnitude of a terrorist incident involving the release of radioactive material by a dirty bomb depends on the dimensions of the contaminated area and the accompanying contamination density (i.e., radioactivity) distributed within that area. Applying a semi-empirical model indicates that the spatial extent of the contaminated area and the level of activity within that area are dependent primarily on local scale meteorological conditions, especially whether rainfall occurs, as well particle size and effective release height. As a result, the magnitude of the consequences of terrorists acquiring non-weapons grade nuclear materials and releasing those materials with a dirty bomb is contingent on a number of factors beyond the scope of active countermeasures, especially the RDD's design elements and local-scale meteorological conditions. Modeling the dispersion of radioactive aerosols throughout an urban landscape, especially with accurate 3-D representation of its complex geometry and meteorology, is indispensable for assessing the potential consequences of a terrorist incident and implementing effective emergency response, health services, and decontamination decisions.

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