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ORIGINAL PAPER

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Estimates of radiological risk from a terrorist attack using plutonium

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Abstract The possible use of radioactivity dispersal devices by terrorist groups has been recently reported in the news. In this paper, we discuss the threat of terrorist attacks by plutonium, with particular attention to the dispersal of plutonium by explosion or fire. Doses resulting from inhalation of radioactive aerosol induced by a plutonium explosion or fire are simulated using a Gaussian plume model (the HOTSPOT code) for different meteorological conditions. Ground contamination and resuspension of dust are also considered in the simulations. Our simulations suggest that acute effects from a plutonium dispersal attack are very unlikely. For late stochastic effects, the explosion poses a greater hazard than fire. However, even in the worst-case scenario, the dispersed plutonium would cause relatively few excess cancers (around 80 in a city of 2 million inhabitants) after many years from the explosion, and these excess cancers would remain undetected against the background of cancer fatalities.

Introduction

The recent tragic terrorist attacks in New York and Washington on September 11, 2001 have caused an increased concern for the possible use of non-conventional weapons (nuclear, biological, and chemical warfare) in future attacks on metropolitan areas. Warnings about the use of nuclear weapons by terrorists have been given for many years [1, 2], but the potential for such use is currently the cause of particular anxiety.

Although smuggled weapons-grade radioactive material might be used to make nuclear bombs, engineering a radioactive release is easier. There is substantial evidence that terrorist groups have access to nuclear material that could be used for nuclear detonations. However, large amounts of ^{235}U or ^{239}Pu are necessary to prepare a nuclear bomb. On the other hand, a limited amount of ^{239}Pu could be sufficient for an attack on a large city, by three possible actions:

a. Water contamination by introducing plutonium into the municipal water supply
b. Use of a radioactivity dispersal device (RDD) or “dirty bomb”, where conventional explosive is wrapped in a shroud of plutonium that creates fallout when the bomb explodes
c. Ignition of plutonium thereby causing a plume of radioactive material.

Plutonium would be the preferred choice for terrorist attacks, because of its high activity (about 3 kBq/µg) and its well known radiological toxicity by inhalation [3, 4]. In addition, public perception of the plutonium risk is grossly exaggerated, which would certainly lead to widespread panic in the event of an attack.

Dispersal of plutonium into the water supply of a large city would probably cause very limited damage. As a matter of fact, plutonium is much less of a hazard in water than in air, because only about 0.001% of the material released in water would be dissolved and suspended [5], the rest being immobilized in sediments. Plutonium in solution would be greatly diluted by the large volume of the water reservoir of a large city, and uptake by the gastrointestinal tract is minimal. The committed effective dose from ingestion of plutonium (239 plus 240 isotopes) is around 0.04 mSv/µg, to be compared to 250 mSv/µg by inhalation [6]. Based on these calculations, Sutcliffe et al. [7] excluded any serious health consequences of plutonium contamination in municipal water supplies.

However, explosions and fires pose a greater threat. Particles smaller than about 3 µm in activity median aerodynamic diameter (AMAD) will become airborne and can be inhaled. Such an aerosol will deposit in the lungs, and migrate via the blood stream to selectively concentrate in the bones and the liver. Acute effects such as pulmonary edema are possible at high doses, whereas

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cancer may be induced after a latency time of many years by considerably smaller inhaled amounts [3].

A number of simple models have been used to predict the risk from plutonium explosions or fire [7, 8]. In this paper, we elected to use a Gaussian plume model for plutonium dispersion, as implemented in the HOTSPOT code [9]. This code has been widely used to provide risk estimates following dispersal of radioactive material such as ^{140}La [10] or depleted uranium [11]. HOTSPOT takes into account wind speed and atmospheric stability classes, and provides 50-year committed effective dose (CED) values, acute doses to target organs, and ground contamination. Doses resulting from resuspension are also evaluated. Our simulations were performed for weapons-grade plutonium having a specific activity of 3 kBq/µg, assuming that 1 kg of plutonium is available to a terrorist group. It is unlikely that larger amounts can be smuggled, and in that case terrorists might rather consider making a bomb.

Methods

All calculations were performed using HOTSPOT 98 version 1.06 running on a PC computer. We used the large metropolitan area terrain type, to take into account the increased plume dispersion that results from crowded structures and the heat retention characteristics of urban surfaces, such as asphalt and concrete. The deposition velocity of the particles with AMAD of 3 µm was assumed to be 0.3 cm/s, whereas a value of 8 cm/s was used for the irrespirable fraction (AMAD=40 µm). A standard breathing rate of 1.2 m^3/h was assumed in all simulations. HOTSPOT uses ICRP publication 30 [12] to evaluate the dose conversion factors and publication 66 [13] for all inhalation calculations. A RBE of 7 for α-particles is assumed for acute dose conversion factors. Doses or ground contamination were plotted as a function of the downwind distance from the site of radioactive release. Details of the source code and meteorological conditions for the different simulations are given below.

Explosion

We assumed that the RDD is composed of 0.45 kg high explosive and 1 kg weapons-grade plutonium. Explosion tests involving plutonium have demonstrated that approximately 20% of the plutonium dispersed in the explosion can be inhaled [14]. Following these data and the HOTSPOT default, the value of 20% for the respirable fraction has been used in all explosion simulations. A number of meteorological conditions have been simulated. For calm conditions (wind speed 1 m/s), we simulated the following Pasquill categories: extremely unstable (A), moderately unstable (B), and moderately stable (F), corresponding to sun high in the sky (A), sun low in the sky or cloudy (B), and night time (F), respectively. For breeze (wind speed 7 m/s) and moderate gale (wind speed 14 m/s), we used classes C (slightly unstable, sun high in the sky) or D (neutral, cloudy or night time). In class F simulations, an inversion layer at a height of 300 m is assumed in all cases. We also considered the wet deposition in class D, assuming a rainfall rate of 5 mm/h, corresponding to a rainout coefficient of 6×10^{-4} s^{-1}.

Fire

The fraction of oxidised plutonium that becomes respirable after a fire is substantially lower than after an explosion. The fraction of respirable aerosol could be increased if plutonium dust is dispersed throughout the flammable material. However, it is likely that the fire will produce a lower fraction of respirable aerosol than an explosion, even if carefully engineered. To provide an example, we assumed a fuel volume of 37 l, a burn duration of 30 min, a heat of combustion of 50 kJ/g and the air temperature was set to 20°C. A respirable fraction released of 0.05% was assumed, which is a sound value for ignition of the bulk plutonium metal [15].

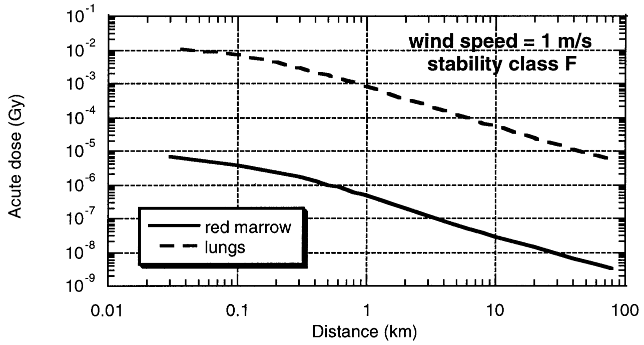

Fig. 1 Acute doses to lung and bone marrow as a function of the downwind distance from a Pu explosion. Wind speed is 1 m/s and stability class F

Resuspension

For plutonium resuspension, we used the results of the ground deposition from the explosion case as the source (see results). Based on those results, a worst-case scenario of 10^4 kBq/m^2 in a release radius (defined as the effective radius of the circle containing 95% of the contamination) of 300 m was simulated. A resuspension factor of 8.6×10^{-5} m^{-1} is the HOTSPOT default used, which is based on data from the Nevada test site. This high value is conservative, and might apply to a dry deposit in arid conditions.

Results

Explosion

A large amount of inhaled plutonium could cause acute radiation burden, and eventually death by pulmonary syndrome. Acute doses to the bone marrow and lungs are shown in Fig. 1 for a wind speed of 1 m/s and stability class F. Simulations performed using different meteorological conditions provided consistently lower values. Doses to the lungs do not exceed 10 mGy, which is far below the doses required to produce fibrosis or pulmonary edema.

For the stochastic effects of plutonium inhalation, we plotted in Fig. 2 the 50-year committed effective dose as a function of the downwind distance from the explosion site for different atmospheric conditions. For a wind speed of 1 m/s, stability class B gave the same results as for stability class A (not shown). The present simulations suggest that the worst-case scenario occurs for calm wind in Pasquill stability class F (moderately stable). Individuals at less than 100 m from the explosion will receive doses exceeding 1 Sv in 50 years for calm wind, in both F and A classes. Such high doses are unlikely for

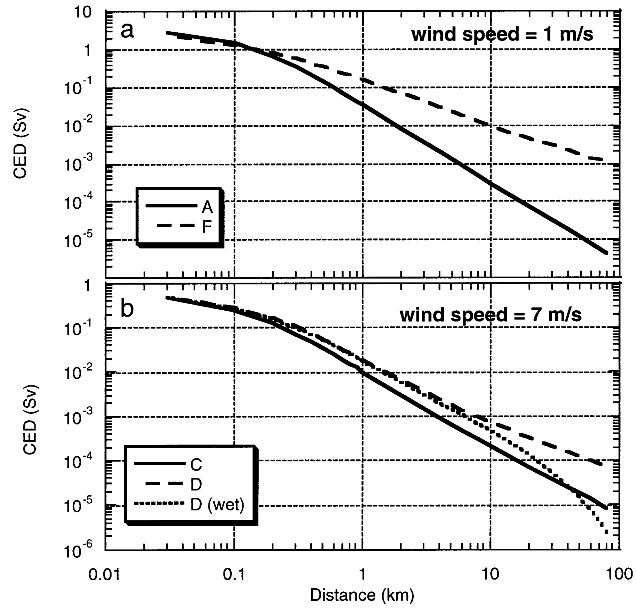

Fig. 2a, b Committed effective dose (CED) as a function of downwind distance from a Pu explosion. **a** Wind speed=1 m/s, stability classes A or F, **b** wind speed=7 m/s, stability classes C or D, and wet deposition (rain rate 5 mm/h) in class D

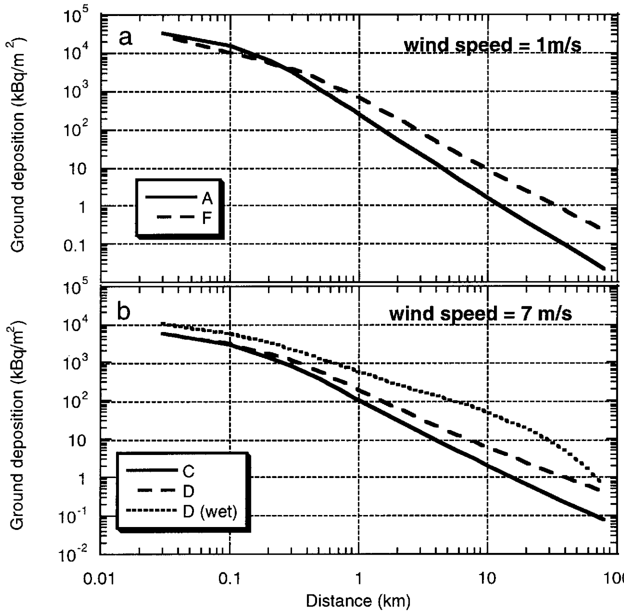

Fig. 4a,b Ground deposition of Pu as a function of downwind distance from the explosion site. **a** Wind speed=1 m/s, **b** wind speed=7 m/s, atmospheric stability classes as in Fig. 2

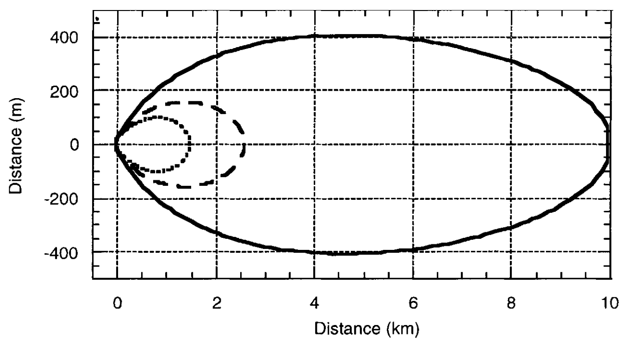

Fig. 3 Contour plot of committed effective doses (CED) at various distances from a Pu explosion. The detonation point has coordinates (0, 0). A calm wind (speed=1 m/s) is assumed along the x-axis. Pasquill stability class is F. (*Solid line* contains committed effective doses higher than 10 mSv, *dashed line* contains committed effective doses higher than 50 mSv, *dotted line* contains committed effective doses higher than 100 mSv)

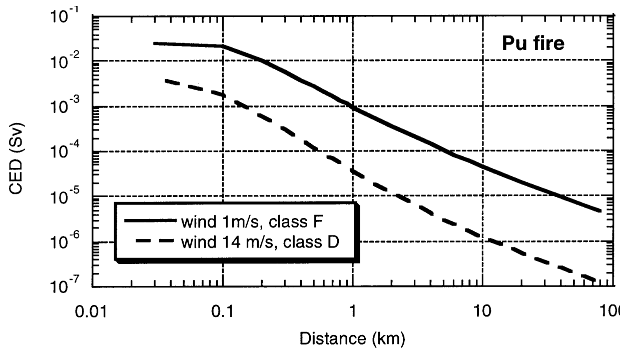

Fig. 5 Committed effective dose (CED) as a function of downwind distance from a Pu fire. Two meteorological conditions are simulated: calm wind (speed=1 m/s) in class F, and strong wind (speed=14 m/s) in class D

stronger winds: results for the breeze in stability classes C and D (including the case of rain) are provided in Fig. 2b, and lower values are estimated for a moderate gale (not shown). A contour plot of CED in the worst-case scenario (wind speed 1 m/s, Pasquill class F) is shown in Fig. 3.

The fallout of plutonium from the explosion results in spatially extensive ground contamination. As seen in Fig. 4, the worst-case scenario corresponds to calm wind and stability class F, although in class A we found slightly higher values at short distances. Stronger winds will reduce the overall ground deposition (Fig. 4b), even considering wet deposition.

Fire

We assumed that the fraction of radioactive material that can be inhaled is much lower after a fire than after an explosion. It is, therefore, expected that the hazard associated with a plutonium fire would also be much lower, as shown in Fig. 5. By comparing this plot with the one in Fig. 2, it is clear that expected committed effective doses are about two orders of magnitude lower after a fire than after an explosion.

Resuspension

Plutonium deposited on the ground can be resuspended by wind and pedestrian traffic, and can again be inhaled.

Table 1 Estimates of the collective effective dose (CED) commitment and excess fatal cancers in a city with 4,500 inhabitants/km² after a plutonium explosion in calm conditions (wind speed 1 m/s) and moderately stable (class F) atmospheric conditions

Downwind distance from explosion (km)	Contaminated area (km^2)	Average committed effective dose (mSv)	Number of citizens exposed	Collective effective dose commitment (person-Sv)	Estimated excess fatal cancers
<0.2	0.017	1040	76	80	4
<1.5	0.21	310	945	293	15
<2.2	0.39	76	1,755	133	7
<10	5.68	28	25,560	716	36
<18	10.7	7.3	48,150	351	18
Total	17		76,486	1,573	80

Committed effective doses for this worst-case scenario are shown in Fig. 3, and details of the calculations are given in the text. The number of citizens exposed and the number of fatal cancers expected are rounded to the closest integer value.

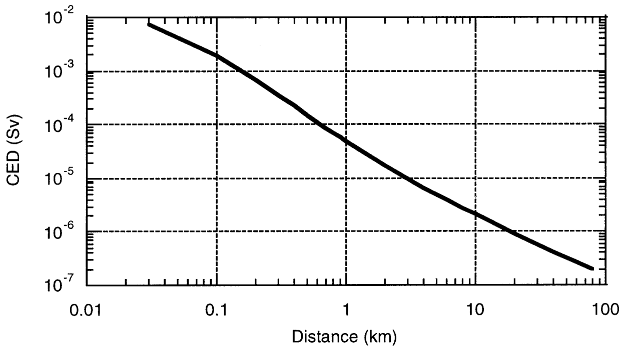

Fig. 6 Dose commitment (CED) per hour of downwind exposure caused by Pu resuspension as a function of downwind distance from the explosion site. The source term for resuspension is derived from the worst-case scenario for the committed effective dose shown in Fig. 3. Ground deposition in this scenario is given in Fig. 4a. The effective radius of the contaminated area is 300 m

Based on the results shown in Fig. 4, we assumed a worst-case scenario of 10^4 kBq/m² in a release radius of 300 m. Slightly higher concentrations of ground deposits might be achieved in wet deposition, but in this case resuspension would be very limited. According to this scenario, the committed effective dose caused by resuspension is provided in Fig. 6, assuming a 1 -h exposure in a given position downwind. It is clear that resuspension only provides a small contribution to the committed effective dose compared with direct inhalation of the plume (Fig. 2), even using a conservative resuspension coefficient.

Excess cancer deaths

Based on the results shown above, we observed that the worst-case scenario corresponds to the explosion in calm conditions (wind speed about 1 m/s) and atmospheric stability class F (Figs. 2a and 3). For this scenario, we estimated the expected number of cancer deaths in a metropolitan area. In our exercise, we assumed the attack being directed against an average city of about 2×10^6 inhabitants homogeneously distributed over an area of 25 km diameter, corresponding to a density of 4,500 people per km². The average committed effective dose in various areas was calculated for several contour lines such as those shown in Fig. 3. Doses due to resuspension were then added. Collective effective dose commitment was estimated by multiplying the committed effective dose by the number of exposed individuals in that particular area. Finally, the ICRP recommended risk coefficient for fatal cancer of 5×10^{-2} Sv^{-1} [16] was used to estimate the excess cancer deaths.

Results for this worst-case scenario are shown in Table 1. We estimate a collective effective dose commitment of around 1,600 persons-Sv, corresponding to 80 excess cancer deaths in the exposed population. This number is to be compared with approximately 15,000 naturally occurring cancer deaths in the exposed population of about 76,000 individuals, assuming a 20% cancer death rate.

Discussion

Terrorist groups are allegedly accumulating nuclear material to carry out attacks on large urban areas. It is, therefore, important to understand the risks associated with the dispersal of radioactive material, in order to ensure proper countermeasures. The issue of countermeasures against radiological terrorism has been excellently addressed by NCRP in its recent report no. 138 [17]. Medical management of radiation casualties, psychosocial effects and public communication etc. can be found in this recent NCRP publication. In the present paper, we provide an estimate of the expected casualties based on a Gaussian-plume model. We are aware of the limitations of this approach, especially in an urban area, where the wind field is not uniform. More sophisticated models may be used to take into account urban-specific effects, such as flow channelling in streets. However, the great number of unknown variables and parameters involved in modelling an attack is such that even very sophisticated mathematical models will probably fail to provide accurate estimates. The results of our calculations should be simply regarded as an exercise aimed at providing rough estimates and, possibly, the order of magnitude of the risk.

We have simulated an attack employing 1 kg weapons-grade plutonium, dispersed by either explosion or fire. We find that such an attack is very unlikely to lead to casualties due to acute radiation effects (Fig. 1). However, inhalation of plutonium aerosol will occur and an increased morbidity in the exposed population is expected due to radiation late effects. Results of the HOTSPOT code simulations suggest that the highest stochastic risk is associated with an explosion in meteorological conditions of calm wind (speed about 1 m/s) and atmospheric stability class F (see Figs. 2 and 3). Most of the committed effective dose is due to direct inhalation of the plume, with a minor contribution from plutonium resuspension (Fig. 6) derived from radioactive fallout (Fig. 4). However, even in this worst-case scenario, we estimated that in an average size city (25 km in diameter, 2 million inhabitants), about 80 excess cancer deaths would occur over the first 30 years after the explosion (Table 1). We argue that this number will remain undetected against the large background (approximately 15,000) of expected cancer deaths. However, a statistically significant increase in specific cancers might be observed, particularly osteosarcomas.

Sutcliffe et al. [7] using a simple wedge model, estimated 960 casualties in a terrorist attack on Munich using a RDD loaded with 1 kg of plutonium. However, the authors themselves contend that "our simple estimate (...) is so pessimistic to the point of not being credible" [7], because meteorological conditions were neglected. We believe that our calculations may provide a more realistic estimate of the potential casualties, still being rather pessimistic. As a matter of fact, simple countermeasures can easily reduce the number of victims of the attack [17]: people in the area of the detonation can reduce their exposure by taking shelter in their homes or other buildings, radioactive dust can be washed off, etcetera.

Estimates from our simulations should be compared with the casualties that could occur due to possible biological and chemical terrorist attacks. The most likely candidates for biological weapons are anthrax and smallpox, as these can be put into stable aerosol form in particles with a mass median aerodynamic diameter of 5 µm [18]. In the 1979 accident in a Soviet chemical manufacturing site in Sverdlovsk, approximately 10 kg of anthrax spores were released and spread 2 km downwind, probably causing around 1,000 casualties [19]. A well-planned attack using smallpox would cause many more casualties, but fortunately *Variola* virus is hard to grow and aerosolise.

As to chemical weapons, there exists the precedent of the Aum Shinri Kyo sect, which launched a large-scale sarin gas attack in the Tokyo subway in 1995. The attack resulted in 11 persons killed and about 5,500 injured, some of whom carry serious permanent disabilities. However, the terrorists used a low-quality gas (only 30% pure), and a poor dispersal method. It has been calculated that an attack with pure sarin gas and an efficient dispersal device would have caused about 10,000 casualties in the Tokyo subway [20]. Interestingly, Aum Shinri Kyo's leader Shoko Asahara collected and tested nuclear, biological, and chemical weapons, but eventually resorted to sarin for his criminal attacks. Chemical weapons are both easy to produce and disperse. In addition, poisonous gases are lethal even when produced and dispersed by sub-optimal methods.

In conclusion, within the limits of the mathematical model used, it seems that a terrorist attack based on dispersal of plutonium would be far less efficient than most attacks using biological or chemical weapons, let alone conventional explosives and airplane hijacking. We note, however, than one of the main goals of the terrorists is to create fear and panic in the population. Terrorists might profitably use the unsound myth that "plutonium is the most toxic substance known to mankind", and the widespread radiophobia to generate a catastrophic panic by a plutonium attack. Perhaps correct scientific information may help to mitigate this event.

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