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Analysis of a dirty bomb attack in a large metropolitan area: simulate the dispersion of radioactive materials

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Abstract: The potential for a radiological or nuclear attack has been widely acknowledged in the last two decades. The use of a dirty bomb by terrorist organizations is considered to be a credible threat for which policymakers and relevant security agencies must prepare. Radioactive materials are stored in thousands of facilities around the world and may not be adequately protected against theft. This article analyzes a hypothetical dirty bomb attack in a large metropolitan area, evaluating the radiation dose to the involved population. The dispersion of radioactive materials is simulated using HOTSPOT code, considering a number of possible radionuclides (alpha, beta and gamma emitters) and scenarios.

The findings of the present study corroborate and extend previous research demonstrating that it is unlikely that the atmospheric dispersion of radioactive material contained in a dirty bomb would produce deterministic effects in the exposed population. The radioactive material would be dispersed into the air resulting in relatively low doses. However, depending on the situation, the explosion of a dirty bomb is likely to contaminate properties (rendering them temporarily uninhabitable), thereby requiring potentially costly cleanup. Furthermore, due to the general fear of radiation, pervasive psychological effects are expected.

Keywords: Models and simulations; Simulation methods and programs; Radiation calculations

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1 Introduction

According to the University of Maryland's Global Terrorism Database [1], from 1970 to 2014 CBRN weapons have been extensively used across the world, for a total of 143 attacks (of which 35 biological, 95 chemicals, and 13 radiological). In particular, the recent surge of international terrorism suggests the potential for a malevolent use of radiological or nuclear material. In fact, it is postulated that terrorists could make use of devices intended to spread radioactivity, i.e. Radiological Dispersal Devices (RDD), generating contamination and panic. Even if many devices are possible, it is conceivable that a radiation source could be easily attached to a conventional bomb (as those already used during recent attacks all over the world) and then dispersed by detonation in crowded places or symbolic locations [2]. Other than the immediate consequences of the blast, extended areas can be affected for a long time, so that this device is popularly known as "Dirty Bomb". In addition to the environmental contamination, the economic impact can be very large because of the disruption of local activities and the clean-up effort [3–5]. Moreover, it is important to underline that the psychological effect already seen for past terrorist attacks can be greatly enhanced by the psychological effect due to the radioactive contamination [6, 7]. On the contrary, the radiological consequences during the preparation of such a device are not a concern for the terrorist, when the aim of the attack is suicidal. Differently from the atomic bomb, the making of a dirty bomb is a relatively simple process and does not require special-purpose components or difficult assembly.

The radiological part can be a high activity source as those used in industry or medicine throughout the world: for example, small local hospitals store (in their radiotherapy department) high activity sources, usually protected and difficult to steal or transport, but their malevolent use cannot be dismissed. The list of radionuclides that can be used — single or in combination — in a RDD is very large and the choice is dependent, among other things, on the availability or easiness to obtain [8].

The present study assesses the radiological consequences of a dirty bomb detonation in an urban area, evaluating the Total Effective Dose (TED) received by the exposed population performing simulations with the HOTSPOT code. HOTSPOT results can be considered conservative (in this work the dose to exposed individuals is estimated considering unprotected people freely moving in an open space of an urban environment. In a real situation sheltering and decontamination procedures reduce significantly the dose received by exposed people). In this study with HOTSPOT, the effect of building downwash and wake flow on plume dispersion cannot be considered, the authors use a simplified urban dispersion model.

It is a hypothetical event and our aim is to provide a large spectrum of results under different and *a priori* unpredictable conditions (related to the weather or to the device itself). A comparative assessment of several radionuclides is added, not knowing which radiation source could be available to terrorists.

2 Materials and methods

In order to evaluate the TED, several simulations are performed using HOTSPOT Version 3.0.3 [9], Health Physics software designed for short-term release durations and useful in predicting the consequences of radionuclide dispersal [10–13]. HOTSPOT is a hybrid of the well-established Gaussian Plume Model, widely used for initial emergency assessment or safety analysis planning. Virtual source terms are used to model the initial atmospheric distribution of source material following explosion, fire, resuspension, or user-input geometry. In the present study the *general explosion* module is used to study the atmospheric dispersion of radionuclides following an explosion involving radioactive material. HOTSPOT uses an empirically-based expression to describe the time-dependent height of the cloud top (H) as a function of the quantity of the explosive (w) and the time since detonation (t) for unstable and stable/neutral atmospheres (as explained in the HOTSPOT User's Guide, H is in meter, w in pounds and t in seconds). In the code, the expression for the time after detonation (t_m) at which the maximum cloud rise is attained (e.g. the time at which the cloud becomes thermally neutral) is:

$$t_m = 21.6w^{0.33}$$

The expressions for the stabilized cloud top (H) as a function of high explosive for unstable (stability class A, B and C) and stable/neutral (stability class D, E, F, and G) atmospheres are:

$$H_{A,B,C}\,(w) = 27.4w^{0.48}$$
$$H_{D,E,F,G}\,(w) = 23.3w^{0.44}$$

When the software is launched, the user is allowed to select either SI or U.S. units.

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The present analysis is divided in three steps. Firstly, three radionuclides (commonly used in medicine or industry) are considered, covering the three main emission types: ^{223}Ra (α emitter), ^{131}I (β^- emitter) and ^{60}Co (γ emitter). For each radionuclide a "Reference" scenario is considered and the TED is evaluated keeping all HOTSPOT parameters constant: source activity, explosive weight, atmospheric conditions (wind speed and stability class), radionuclide solubility and Respirable Fraction in the plume. The source activity is equal to 5.00×10^{10} Bq for ^{223}Ra, 2.00×10^{14} Bq for ^{131}I and 2.22×10^{14} Bq for ^{60}Co. In the second step, it is evaluated the influence of every parameter listed above on TED (i.e. parameters are modified one at a time, while all others are kept constant). Finally, the analysis is extended to several other radioactive nuclides, grouped according to their main emission (α, β^- or γ). All HOTSPOT parameters are those of the Reference scenarios, including the total activity: 5.00×10^{10} Bq for alpha emitters, 2.00×10^{14} Bq for beta emitters and 2.22×10^{14} Bq for gamma emitters.

Several assumptions are common in all simulations: the mass of the radionuclide is totally dispersed directly into the atmosphere and — in the evaluation of the TED — ground shine and re-suspension are also included; Dose Conversion Coefficients in HOTSPOT are derived from the U.S. Federal Guidance Report 13 (FGR-13), so that the lung model for internal contamination is taken from the International Commission on Radiological Protection (ICRP) Publication 66 [14].

In the present study, results are reported in terms of TED received by affected persons in the short time following the detonation (no specific exposure assumptions are considered, therefore HOTSPOT's default settings are used, including exposure time and breathing rate). As a consequence, the TED might not be representative of the dose received by emergency personnel or rescue workers, who are likely to arrive on site some time after the blast, possibly with protective equipment [15]. Results are presented according to three levels of TED, namely:

- 1 mSv. Public effective dose limit recommended by ICRP;
- 20 mSv. ICRP recommends a dose limit for workers of 20 mSv per year, averaged over defined 5 year periods (100 mSv in 5 years), with the further provision that the effective dose should not exceed 50 mSv in any single year;
- 100 mSv. For first responders undertaking urgent rescue actions, ICRP recommends that all reasonable effort should be made to keep doses below this limit [16].

3 Dirty bomb reference scenarios

Possible RDD material could come from the millions of radioactive sources used worldwide in industrial practices and in hospitals (nuclear medicine and radiotherapy departments). Therefore the Reference scenarios here considered simulate the explosion with radionuclides typically found and stored in these facilities.

In particular, ^{223}Ra is an alpha-emitting radionuclide used in medicine for the treatment of bone metastases and it is usually delivered in form of liquid $^{223}RaCl_2$, ready to be injected (standard therapy consists of six 3.5×10^6 Bq injections for a 70 kg patient) [17]. The maximum detained activity in a medium/large nuclear medicine department is likely to be as large as 5.00×10^8 Bq, assuming that 8 patients are undergoing therapy on the same day. In the present study, we consider

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an activity 100 times higher (i.e. 5.00×10^{10} Bq), believed to be a plausible radiation source for a dirty bomb attack.

Given its massive use in the medical practice, radioactive iodine is considered to be representative of beta-emitting radionuclides. In fact, ^{131}I is largely used for the treatment of thyroid cancer (typical quantities are up to 8.00×10^9 Bq) and thyrotoxicosis where it is generally administered by capsule or in liquid form [18]. Nuclear medicine departments are likely to detain large amounts of ^{131}I, ranging from hundreds of GBq [19] up to hundreds of TBq [20]. For the Reference scenario in the present study, we consider an activity equal to 2.00×10^{14} Bq (the corresponding mass is only 4.3×10^{-2} g), which we judge to be a plausible estimate of the ^{131}I used in a dirty bomb attack. Other than its potential malicious use, ^{131}I is an important radiological contaminant following nuclear accidents, according to the epidemiological evidence of several thousand thyroid tumors attributed to this radionuclide following the Chernobyl catastrophe [21]. The short half-lives of ^{223}Ra (11.43 d) and ^{131}I (8.03 d) limit the time allowed to assemble and detonate the device, but their large availability in medical facilities is believed to be attractive for a radiological attack.

Ultimately, ^{60}Co is a synthetic radioactive isotope of cobalt with a half-life of 5.27 years, produced artificially in nuclear reactors. It is a beta minus emitter, however, the decay is followed by the emission of two high-energy photons (1.332 and 1.173 MeV) that make this radionuclide an attractive gamma-emitting source [22]. an ^{60}Co is the most widely used radionuclide source for external beam radiotherapy (teletherapy machines) and for stereotactic radiosurgery (Gamma units), other than having several industrial applications. The total activity in the considered Reference scenario (2.22×10^{14} Bq, or 6000 Ci) is typical of a ^{60}Co source contained in a clinical Gamma unit.

It is worth noting that in the present study we deliberately consider Reference scenarios involving a large amount of radioactive material. This is especially true for ^{131}I. Despite being unlikely that such an amount of radioactive material is instantaneously handled or stored, the assumption is made that terrorists aiming to carry out a malevolent attack may collect huge amounts of radioactive material over time (from a single facility) or simultaneously (trough an illegal network operating in several facilities, overcoming the rapid decay of short-lived radionuclides), ultimately leading to the considered reference activity values.

The quantity of High Explosive considered in the Reference scenario is 10 kg, a realistic quantity for a conventional bomb, easy to transport and locate. The wind speed and direction are set to 3 m/s and 270° (respectively), while the considered Pasquill atmospheric stability class is "C" (slightly unstable conditions); these atmospheric conditions, possibly with a different wind direction, are considered to be representative of many locations all over the world and then representative of the dirty bomb effect in urban areas.

The solubility of the nuclide depends on the chemical form and class "M" (medium) is chosen. The Respirable Fraction is assumed equal to 1, so that the dose due to inhalation is maximized (it is considered that whatever its initial form, the source can be reduced to powder with easily available mechanical or chemical methods, and then dispersed in highly breathable form by the explosion) [23]. All listed parameters (table 1) influence the extent of the contamination and, in turn, the effective dose to affected persons [24].

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Table 1. Reference scenarios for ^{223}Ra, ^{131}I, ^{60}Co.

	^{223}Ra	^{131}I	^{60}C
Activity	5.00×10^{10} Bq	2.00×10^{14} Bq	2.22×10^{14} Bq
High Explosive weight	10 kg (TNT)		
Wind speed	3 m/s		
Wind direction	270° (wind from West)		
Atmospheric stability class	C (slightly unstable)		
Solubility class	M (medium)		
Respirable Fraction	1.0		

4 Reference scenario results

Our study hypothesizes the explosion of a dirty bomb in the city of Turin (Italy). Results obtained in Reference scenarios are described separately for the three different radionuclides considered in the study. Thresholds are represented in terms of isodose lines, shown in figure 1. Figures 2 and 3 compare the three radionuclides in terms of relative contribution due to inhalation, ground shine, submersion and resuspension.

4.1 A dirty bomb containing ^{223}Ra

In the considered scenario, it is found that for a ^{223}Ra device, the 100 mSv value is not exceeded and the maximum TED is 39 mSv, at only 10 m of distance from the explosion, within the incapacitating radius of the blast. The 20 mSv limit is exceeded in a small area (0.002 km^2), at a maximum distance (downwind) of 0.027 km from the explosion point, while the 1 mSv isodose is exceeded in an area equal to 0.052 km^2, at a maximum distance of 0.43 km from the point of detonation. More than 99 % of the total dose is determined by inhalation of the radioactive cloud during the plume passage. Consequently, the largest absorbed dose is received by the lung. In contrast, despite the chemical element Ra being a well-known bone seeker [25] the dose received by the bone surface is negligible. It is worth noting that the TED is influenced by the high biological effect of the emitted alpha particles, whose radiation weighting factor w_R is equal to 20, while w_R is unity for beta and gamma radiations. Spatial distribution calculations of ^{223}Ra deposited onto the ground indicate that a small area (0.008 km^2) is involved by a deposition density of 3.70×10^3 Bq/m^2.

4.2 Dirty bomb containing ^{131}I

Regarding the diffusion of ^{131}I following the detonation, the 100 mSv threshold is never reached, and a maximum TED of 67 mSv is obtained at 10 m distance from the point of explosion. The simulation indicates that the 20 mSv threshold is exceeded within a distance of 0.048 km downwind (covering an area of 0.003 km^2) and the 1 mSv limit is reached within a distance of 0.62 km (in 0.10 km^2). Inhalation accounts for about 75 % of the total dose and, as expected, the most exposed organ is the thyroid, followed by the lungs. Contamination can be important, with an area of 0.84 km^2 exceeding an activity per unit surface of 3.70×10^5 Bq/m^2. Most importantly, an area of 97 km^2 is likely to be involved by ground deposition levels exceeding 3.70×10^3 Bq/m^2.

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Figure 1. Reference scenarios. 1 mSv (left) and 20 mSv (right) isodose.

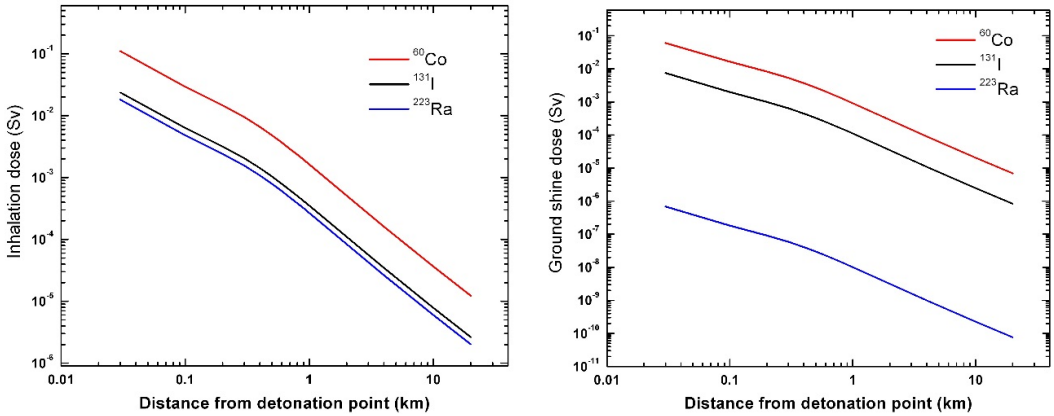

Figure 2. Reference scenarios. Dose contribution from inhalation and ground shine.

Significantly, because of the short half-lives of ^{223}Ra (11.43 d) and ^{131}I (8.03 d), their contamination is rapidly disappearing and a quarantine period could be sufficient for the return to normality. However, an extensive clean-up effort could be required, mostly to allay public concern and stigma [26].

4.3 A dirty bomb containing ^{60}Co

In the case of a ^{60}Co dirty bomb explosion, the 100 mSv value is exceeded within a distance of 0.053 km downwind (the area is equal to 0.003 km^2) and the maximum TED is 373 mSv (at 10 m). The 20 mSv limit is reached within a downwind distance of 0.23 km (in an area of 0.021 km^2), while the 1 mSv limit is reached within a maximum distance of 1.8 km (in an area of 0.73 km^2). The total dose is dominated by inhalation (about 63%) and ground shine (about 35%). Lungs receive more than 40% of the TED, while the remaining dose is almost equally distributed among the other organs. The ground contamination is higher than in the previous scenarios. A ground deposition of 3.70×10^7 Bq/m^2 is exceeded in a minor area of 0.005 km^2 around the point of explosion. However, the most striking result to emerge from our study is that a huge area (108 km^2) is likely to result in density deposition values exceeding 3.70×10^3 Bq/m^2. Given the relatively long half-life of ^{60}Co, clean-up and remediation actions need to be undertaken.

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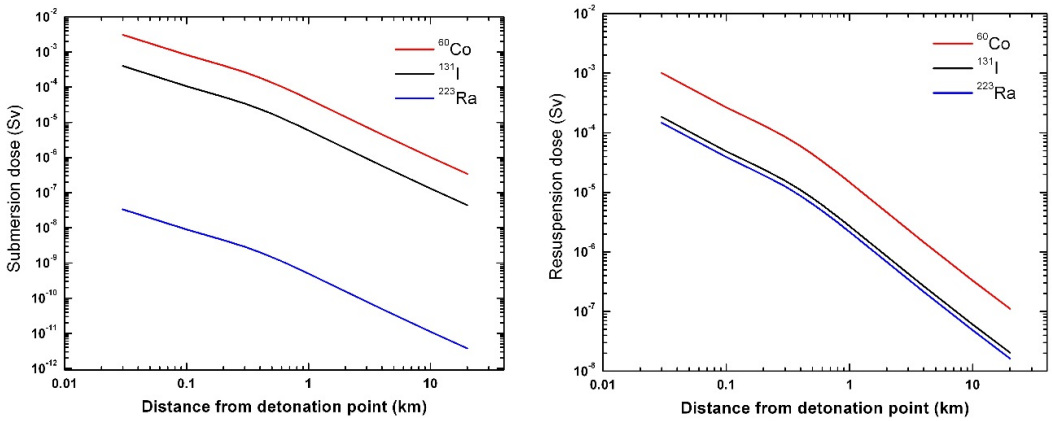

Figure 3. Reference scenarios. Dose contribution from submersion and resuspension.

Table 2. Maximum distance (km) for selected TED values according to the ^{223}Ra activity.

Activity (Bq)	100 mSv	20 mSv	1 mSv
5.00×10^{11}	0.054	0.24	1.8
5.00×10^{10} (Reference)	ne	0.027	0.43
5.00×10^{9}	ne	ne	0.054
5.00×10^{8}	ne	ne	ne

4.4 Impact of input parameters on the Total Effective Dose

Starting from the Reference scenario developed for each radionuclide, in the present section we analyze to which extent device-related or meteorological parameters are likely to influence the TED. Every relevant HOTSPOT variable is changed separately, keeping the remaining parameters constant and equal to the Reference scenario.

The first evaluation concerns the source activity and its impact on the final TED. To this purpose, with regard to the Reference scenario, activity values 10 times higher, 10 times lower or 100 times lower are considered. As expected, the TED increases if the source activity increases (so that, at the lowest activities analyzed, only ^{60}Co exceeds the 1 mSv limit). As for the Reference scenario, it is assumed that the source mass is totally dispersed. This is a highly conservative assumption, as complete pulverization of a solid source is highly unlikely. However, reducing the airborne fraction has the same effect on TED of a proportional increase in the source activity. Tables 2, 3 and 4 summarize the maximum distance (downwind) at which the Total Effective Dose limits are reached (in all tables, "ne" stands for "not exceeded").

Broadly speaking, an almost-linear relation exists between the source activity and the distance at which a given TED value is delivered (i.e. an increase of the source activity by a factor ten produces an increase in the distance by the same factor, approximately). This is particularly true for the case of ^{60}Co, when the dose is delivered over long distances.

Dirty bomb combines radioactive material with High Explosive (HE), such as trinitrotoluene (TNT). HE is any extremely powerful chemical explosive (e.g. TNT or gelignite) with the potential to inflict damage with rapidly expanding, very hot gas. Therefore we investigate the effect of variation in the weight of HE, considered to be TNT in all Reference scenarios. The HE weight influences

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Table 3. Maximum distance (km) for selected TED values according to the ^{131}I activity.

Activity (Bq)	100 mSv	20 mSv	1 mSv
2.00×10^{15}	0.088	0.39	2.5
2.00×10^{14} (Reference)	ne	0.048	0.62
2.00×10^{13}	ne	ne	0.088
2.00×10^{12}	ne	ne	ne

Table 4. Maximum distance (km) for selected TED values according to the ^{60}Co activity.

Activity (Bq)	100 mSv	20 mSv	1 mSv
2.22×10^{15}	0.41	1.2	7.1
2.22×10^{14} (Reference)	0.053	0.23	1.8
2.22×10^{13}	ne	0.026	0.41
2.22×10^{12}	ne	ne	0.053

the spread of the contamination, but it may play a key role in the transportability and location of the device. As a general rule, a relatively small quantity of explosives can be easily hand-carried. For the sake of completeness, in the present analysis, it is also considered the explosion of a very high quantity of HE (500 kg, for example, loaded in a heavy truck). Despite being unlikely, such an event cannot be ruled out *a priori*. HOTSPOT simulations show that an increase in the HE weight is associated with a reduction of the distance at which the considered limit is reached (table 5). This result is not unexpected. In fact, the higher the explosive power, the higher the dispersion of the radionuclide and consequently the lower the TED and the ground deposition. However, the International Association of Bomb Technicians and Investigators (IABTI) safe distance increases from 274 m (1 kg of HE) to 920 m (500 kg of HE). In case such an event should take place, the general consensus is that the blast effect of the device can cause the largest number of causalities, by far larger than radiation alone.

Another parameter that is likely to play a key role in the diffusion of radioactive material dispersed by a dirty bomb is the wind speed. Wind speed of 1, 5 and 10 m/s are analyzed in the present section (a value of 3 m/s is considered in the Reference scenario). Wind direction is fixed at 270 degrees, as it does not influence the extent of the contamination, but only its direction. The radioactive plume generated by the explosion is transported by the wind. The underlying assumption is that radioactivity travels longer distances and its concentration decreases as the wind speed increases. As a net result, the higher the wind speed, the shorter the distance at which the TED limits are reached (table 6). The 1 mSv distance increases by a factor of 4, approximately, if the wind speed decreases from 10 to 1 m/s.

Another factor that may greatly influence TED values and the extent of the ground deposition is the atmospheric stability class. Meteorological conditions may differ significantly between night and day and may even evolve quickly in a very short time. The present study analyses a short-term release scenario, therefore the atmospheric stability class is assumed to be constant during the entire transport. Past research indicated that this approach is likely to provide conservative results [27].

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Stability class "C" (slightly unstable) of the Reference scenario is compared with stability class "A" (very unstable) and "F" (moderately stable). Increasing the instability, the radionuclide concentration is diluted, and the distance at which TED thresholds are reached decreases (table 7). In particular, the radionuclide activity concentration tends to be higher for moderately stable atmospheric conditions (stability class F) due to minor dispersion effects. As a consequence, the dose contribution increases during the plume passage. The present analysis shows that no matter what radionuclide is taken into account, there is approximately a fourfold increase in the dose when switching from stability class A to F. More specifically, at a blast distance of 500 m, the inhalation dose increases from 0.476 mSv (class A) to 2.19 mSv (class F) for ^{223}Ra, from 0.625 mSv (class A) to 2.88 mSv (class F) for ^{131}I, from 2.90 mSv (class A) to 13.4 mSv (class F) for ^{60}Co. When explosion occurs, weather/atmospheric conditions are key parameters in the diffusion process of radionuclides; after some minutes, the radioactivity is in large part settled and the influence of wind speed or atmospheric stability are less important, while subsequent rain (not considered in the present study) can play a major role in washing off the contamination.

The impact of solubility of the dispersed material is also considered in the present analysis. Solubility depends on the chemical form and oxidation of the material, as well as on the temperature reached during the blast. In the Reference scenario, a medium "M" solubility is considered. Now we consider the effect of both classes "S" (slow) and "F" (fast). As a general rule, the impact of solubility depends on the biokinetics of the radionuclide. In fact, solubility influences the biodistribution and the dose to organs, with mixed effects on the TED.

For ^{223}Ra a decrease in the solubility produces a higher dose to the most exposed organ (i.e. lungs, with $w_T = 0.12$). As a consequence, TED increases. On the contrary, if the solubility increases, the radionuclide is distributed over several organs, mainly to the bone surface ($w_T = 0.01$) and the net effect is a decrease of the TED. For ^{131}I a decrease in the solubility leads to a reduction of the dose contribution to the most exposed organ, i.e. the thyroid ($w_T = 0.04$) so that the TED decreases. Finally, for ^{60}Co a reduction in the solubility is associated with a higher dose to the lungs, the most exposed organ. When the solubility increases, the radionuclide is distributed over different organs (with lower w_T) and the net effect is a reduction of the TED. These results are summarized in table 8. To sum up, the lower the solubility, the higher the TED for ^{223}Ra and ^{60}Co, while the opposite behavior is expected for ^{131}I.

Finally, this study analyzes the impact of the Respirable Fraction (RF, i.e. the fraction of aerosolized material that is respirable, AMAD = 1 micron), in the range 0.2 to 1.0 (the latter considered in the Reference scenario). As expected, when the RF value decreases, the dose due to inhalation during the passage of the plume decreases as well. Contrarily, a reduction of the RF value is followed by a net increase in the ground shine dose contribution, due to the higher ground deposition. This is because the HOTSPOT non-respirable source term, finally contributing to ground deposition, is proportional to (1 − RF) [9]. Such an increase is particularly important for highly penetrating γ radiation, and to a lesser extent for β radiation. At a blast distance of 500 m, the ^{60}Co dose due to inhalation decreases from 4.83 mSv (RF = 1.0) to 0.965 mSv (RF = 0.2), while the ground shine dose increases from 2.70 mSv (RF = 1.0) to 190 mSv (RF = 0.2). At the same distance, the ^{131}I inhalation dose decreases from 1.04 mSv (RF = 1.0) to 0.208 mSv (RF = 0.2), while the ground shine dose increases from 0.327 mSv (RF = 1.0) to 23 mSv (RF = 0.2). As expected, the impact of RF variations on the ground shine dose contribution is negligible for α emitters. In fact α radiation is easily stopped in a few centimeters of air thereby giving a negligible

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Table 5. Maximum distance (km) for selected TED values according to the High Explosive weight.

	^{223}Ra			^{131}I			^{60}Co		
High Explosive weight (kg)	100 mSv	20 mSv	1 mSv	100 mSv	20 mSv	1 mSv	100 mSv	20 mSv	1 mSv
500	ne	ne	0.078	ne	ne	0.13	ne	0.031	1.1
50	ne	ne	0.18	ne	ne	0.35	ne	0.098	1.5
10 (Reference)	ne	0.027	0.43	ne	0.048	0.62	0.053	0.23	1.8
1	0.022	0.084	0.58	0.035	0.13	0.79	0.14	0.38	2.1

Table 6. Maximum distance (km) for selected TED values according to the wind speed.

	^{223}Ra			^{131}I			^{60}Co		
Wind speed (m/s)	100 mSv	20 mSv	1 mSv	100 mSv	20 mSv	1 mSv	100 mSv	20 mSv	1 mSv
10	ne	ne	0.20	ne	0.017	0.28	0.021	0.12	0.86
5	ne	0.017	0.28	ne	0.036	0.44	0.040	0.16	1.3
3 (Reference)	ne	0.027	0.43	ne	0.048	0.62	0.053	0.23	1.8
1	ne	0.040	0.87	0.014	0.11	1.2	0.13	0.55	3.4

Table 7. Maximum distance (km) for selected TED values according to the atmospheric stability class.

	^{223}Ra			^{131}I			^{60}Co		
Atmospheric stability class	100 mSv	20 mSv	1 mSv	100 mSv	20 mSv	1 mSv	100 mSv	20 mSv	1 mSv
A	ne	0.027	0.32	ne	0.044	0.45	0.048	0.18	1.1
C (Reference)	ne	0.027	0.43	ne	0.048	0.62	0.053	0.23	1.8
F	ne	0.030	1.1	ne	0.055	1.7	0.061	0.54	7.7

Table 8. Maximum distance (km) for selected TED values according to the solubility class.

	^{223}Ra			^{131}I			^{60}Co		
Solubility class	100 mSv	20 mSv	1 mSv	100 mSv	20 mSv	1 mSv	100 mSv	20 mSv	1 mSv
F	ne	ne	Ne	0.023	0.10	1.1	0.037	0.16	1.4
M (Reference)	ne	0.027	0.43	ne	0.048	0.62	0.053	0.23	1.8
S	ne	0.032	0.47	ne	0.036	0.51	0.10	0.45	2.9

Table 9. Maximum distance (km) for selected TED values according to the Respirable Fraction (RF).

	^{223}Ra			^{131}I			^{60}Co		
Respirable Fraction (RF)	100 mSv	20 mSv	1 mSv	100 mSv	20 mSv	1 mSv	100 mSv	20 mSv	1 mSv
1.0 (Reference)	ne	0.027	0.43	ne	0.048	0.62	0.053	0.23	1.8
0.8	ne	0.029	0.41	0.063	0.24	1.4	0.34	0.87	4.0
0.6	ne	0.030	0.39	0.097	0.37	1.9	0.50	1.2	5.3
0.4	ne	0.032	0.38	0.13	0.47	2.2	0.62	1.4	6.4
0.2	ne	0.033	0.36	0.17	0.55	2.5	0.72	1.6	7.3

contribution to external exposure. The results obtained for ^{223}Ra show that at a distance of 500 m from the explosion site, the inhalation dose decreases from 0.792 mSv (RF = 1.0) to 0.158 mSv (RF = 0.2), while the ground shine dose never exceeds 0.01 mSv in both cases; however, a reduction of the RF value leads up to an increase of the resuspension dose (less than 0.01 mSv for RF = 1.0; 0.449 mSv for RF = 0.2).

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Table 10. Maximum distance (km) for selected TED values: α-emitters.

Nuclide	100 mSv	20 mSv	1 mSv
^{239}Pu	0.038	0.16	1.4
^{238}Pu	0.034	0.14	1.4
^{241}Am	0.031	0.13	1.3
^{252}Cf	0.011	0.070	0.81
^{233}Ra (Reference)	ne	0.027	0.43
^{226}Ra	ne	ne	0.23
^{210}Po	ne	ne	0.21
NU	ne	ne	0.21
^{235}U	ne	ne	0.20
DU	ne	ne	0.19
^{238}U	ne	ne	0.18
^{211}At	ne	ne	ne

5 Extension to other radionuclides

The aim of the present study is to analyze the realistic range of TEDs following the explosion of a dirty bomb in urban areas. Given the high level of uncertainty regarding the radionuclides that can be used in a dirty bomb, several simulations are performed with different sources, grouped according to their main emission (alpha, beta or gamma) and compared with the Reference scenario previously analyzed.

5.1 Alpha emitters

The following radionuclides are analyzed considering the same activity (5.00×10^{10} Bq) implemented in the Reference scenario for ^{223}Ra: ^{210}Po, ^{211}At, ^{226}Ra, ^{235}U, ^{238}U, ^{238}Pu, ^{239}Pu, ^{241}Am and ^{252}Cf. Amongst them, ^{210}Po received particular attention in recent years as it was the radionuclide used in the murder of the ex-KGB spy Litvinenko [28]; ^{226}Ra, ^{241}Am and ^{252}Cf are of concern due to existing high activity sources in medical or industrial settings [29]; plutonium isotopes are suitable for a RDD, because of elevated radiation toxicity by inhalation and high specific activity (6.34×10^{11} Bq/g for ^{238}Pu, 2.30×10^{9} Bq/g for ^{239}Pu) [30]; ^{211}At is considered given its importance in Targeted Alpha-Particle Therapy (TAT) [31]; the fissile radionuclide ^{235}U is included for comparative purposes, even if the mass (about 625 kg) is high enough to produce a nuclear detonation. In addition, two mixtures of uranium isotopes are evaluated: natural uranium (NU, 99.27% ^{238}U, 0.72% ^{235}U and 0.0054% ^{234}U by mass), present in nearly all rocks and soils, and depleted uranium (DU, about 99.8% ^{238}U, 0.2% ^{235}U and 0.0006% ^{234}U by mass) [32], recently claimed as causing cancer in Italian soldiers deployed in territories where DU ammunition were used [33]. The TED values of 1, 20 and 100 mSv are exceeded at the maximum distances summarized in table 10 and the boundaries at 1 and at 20 mSv are shown in the aerial view of figure 4.

Some radionuclides or mixtures are omitted from the figure, to avoid lines superimposition: ^{210}Po is not shown because the covered area is slightly smaller than that of ^{226}Ra, while NU, ^{235}U, DU and ^{238}U yield approximately the same isodose lines so that only ^{235}U is represented. The

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Figure 4. Alpha emitters. 1 mSv (left) and 20 mSv (right) isodose.

highest doses result from the dispersion of ^{241}Am, ^{238}Pu and ^{239}Pu, with a maximum TED of 217, 240 and 261 mSv, respectively. On the contrary, uranium isotopes and mixtures like DU are proved to be of low radiological impact, in agreement with the epidemiological evidence [34, 35] (It is worth noticing that activity of 5.00×10^{10} Bq of ^{238}U corresponds to a mass of about 4000 kg). With the exception of short-lived ^{211}At and ^{223}Ra, all radionuclides considered have half-lives ranging from 138.38 d (^{210}Po) to 4.47×10^{9} y (^{238}U), long enough to require remedial actions and clean-up before return to normality.

5.2 Beta emitters

In this section, several beta-emitting radionuclides are compared with the ^{131}I Reference scenario (at the fixed activity of 2.00×10^{14} Bq): ^{3}H, ^{14}C, ^{18}F, ^{32}P, ^{40}K, ^{59}Fe, ^{75}Se, ^{89}Sr, ^{90}Sr, ^{90}Y, ^{113}Cd, ^{133}Xe, ^{153}Sm, ^{165}Dy, ^{166}Ho, ^{169}Er, ^{177}Lu, ^{186}Re and ^{198}Au. Most of them are under study because of their use (or potential application) in nuclear medicine [36–39], where full safety against intrusion and theft is difficult to achieve. ^{90}Sr is one of the most largely used non-fissile radionuclides and hundreds of high activity orphan sources are reported in the former Soviet Union [40]. For comparison purposes, in the present analysis naturally occurring ^{40}K, the fission product ^{133}Cd and the radioactive tracer ^{3}H are also included. Furthermore, two additional radionuclides are analyzed in this group: ^{18}F, very extensively used in PET diagnostic (it decays through positron emission) and ^{75}Se, commercially available as a sealed source for industrial radiography (its main decay mode is electronic capture, EC). The TED values of 1, 20 and 100 mSv are exceeded at the maximum distances summarized in table 11. Isodose curves are shown in the aerial view of figure 5 (1 and 20 mSv), where only a selection of radionuclides is reported, to avoid lines superimposition (the area covered by the hidden ^{89}Sr is very similar to that of the shown ^{59}Fe; the area covered by ^{32}P is only slightly larger than the shown ^{131}I; areas of hidden ^{75}Se, ^{90}Y, ^{198}Au, ^{177}Lu, ^{186}Re, ^{169}Er, ^{166}Ho, ^{153}Sm, ^{18}F and ^{165}Dy are progressively one inside of each other and between ^{14}C and ^{3}H, which are shown where the limit is exceeded). Some radionuclides have the potential to deliver a moderate dose (> 100 mSv), mainly due to inhalation during the plume passage. The maximum dose values at 10 m from the explosion are: 1.2 Sv for ^{113}Cd, 746 mSv for ^{90}Sr, 300 mSv for ^{40}K, 134 mSv for ^{59}Fe and 131 mSv for ^{89}Sr. The range of half-lives is quite broad: of the order of hours or days for radionuclides typically used in the field of nuclear medicine, higher for ^{3}H (12.32 y), ^{90}Sr (28.79 y) or ^{14}C (5700 y) and very long for the fission product ^{113}Cd (8.04×10^{15} y). It is worth noticing

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Table 11. Maximum distance (km) for selected TED values: β-emitters.

Nuclide	100 mSv	20 mSv	1 mSv
^{113}Cd	0.13	0.56	3.5
^{90}Sr	0.095	0.41	2.7
^{40}K	0.043	0.19	1.6
^{59}Fe	0.017	0.088	0.96
^{89}Sr	0.016	0.085	0.94
^{32}P	Ne	0.053	0.66
^{131}I (Reference)	Ne	0.048	0.62
^{14}C	Ne	0.030	0.45
^{75}Se	Ne	0.029	0.44
^{90}Y	Ne	0.022	0.37
^{198}Au	Ne	0.019	0.35
^{177}Lu	Ne	0.014	0.29
^{186}Re	Ne	0.013	0.28
^{169}Er	ne	0.011	0.26
^{166}Ho	ne	ne	0.20
^{153}Sm	ne	ne	0.19
^{18}F	ne	ne	0.048
^{165}Dy	ne	ne	0.018
^{3}H	ne	ne	0.018
^{133}Xe	ne	ne	ne

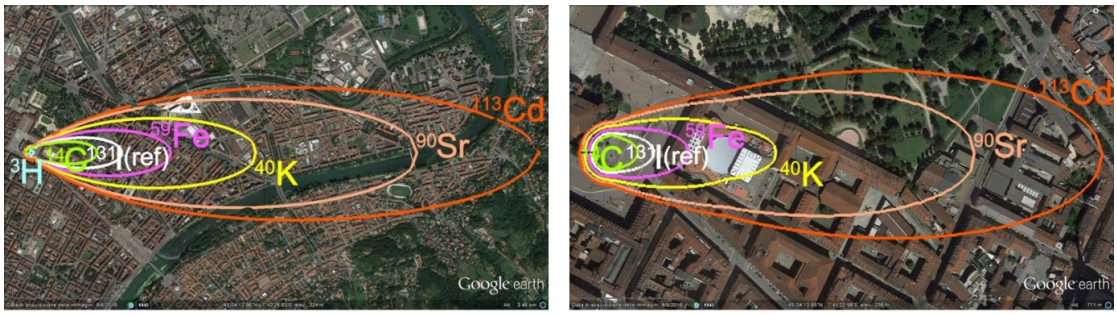

Figure 5. Beta emitters. 1 mSv (left) and 20 mSv (right) isodose.

that when considering a dirty bomb explosion in a large metropolitan area the radionuclide half-life may significantly affect the extent of remediation and site clean-up procedures.

5.3 Gamma emitters

In the present section, the atmospheric release of three additional gamma-emitting radionuclides (^{99m}Tc, ^{137}Cs and ^{192}Ir) is compared to the Reference scenario, i.e. the diffusion of ^{60}Co (the released activity is the same, 2.22×10^{14} Bq). The metastable ^{99m}Tc is the most commonly used medical radionuclide [41], thanks to its 141 keV gamma emission which is considered ideal for scintigraphic imaging. Despite both ^{137}Cs and ^{192}Ir decaying by beta emission, they are analyzed

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Table 12. Maximum distance (km) for selected TED values: γ-emitters.

Nuclide	100 mSv	20 mSv	1 mSv
^{60}Co (Reference)	0.053	0.23	1.8
^{137}Cs	0.037	0.16	1.4
^{192}Ir	0.022	0.10	1.1
^{99m}Tc	ne	ne	0.016

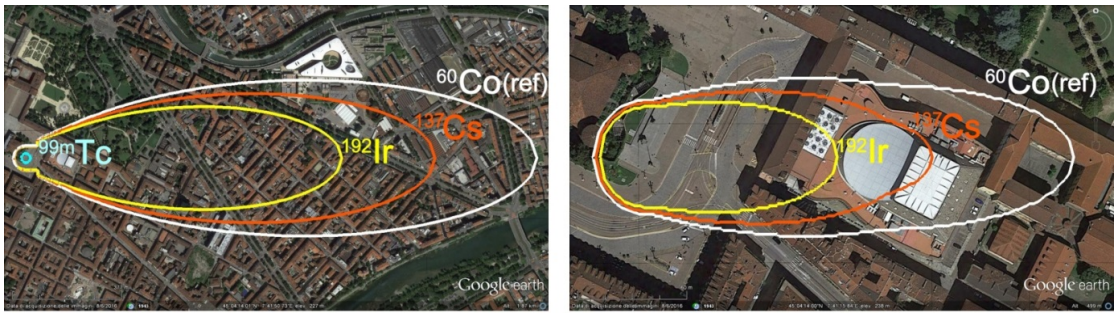

Figure 6. Gamma emitters. 1 mSv (left) and 20 mSv (right) isodose.

in this section because the associated gamma emission is often exploited in medical or industrial applications. At the same time, their radiological properties make them attractive for a radiological dispersal device [42–44]. In terms of TED (and ground deposition), the effect of both ^{137}Cs and ^{192}Ir is of the same order of magnitude as, but lower than, ^{60}Co (table 12). The maximum TED at 10 m is equal to 256 mSv for ^{137}Cs and 166 mSv for ^{192}Ir (compared to 373 mSv associated with ^{60}Co). On the contrary, a ^{99m}Tc bomb is likely to have a very limited effect: the 1 mSv value is only exceeded in a minor area. Furthermore its short half-life (6.01 h), in addition to limiting the time allowed to assembly the bomb, greatly reduces the environmental impact and remediation that could be unnecessary. On the contrary, remediation of contaminated areas in the aftermath of an accident using ^{137}Cs is likely to be challenging: with its 30.08 y half-life, it requires an extensive decontamination effort, as observed in the territories impacted by the Chernobyl NPP catastrophe [45] or by the Goiânia radiological accident [46]. An intermediate situation is predicted for ^{192}Ir, due to its half-life equal to 73.83 d. The aerial view shows the isodose contours for 1 and 20 mSv of the four nuclides (figure 6).

6 Summary and conclusions

Due to the international risk of terrorist attacks with new and panic-inducing techniques, the present study aims to assess the radiological impact of a “Dirty Bomb” explosion, a specific example of Radiological Dispersal Device (RDD) in which a conventional explosive and a radiation source are bound together. The device is intended to spread radioactivity through the detonation of the conventional part, causing exposure of people and contamination of the territory. Our results confirm that the event is likely to have a small biological effect on local populations and that the main concern is the explosion itself, which can cause serious injuries and property damage. The radioactive materials used in a dirty bomb would probably not create enough radiation exposure to cause

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immediate serious illness or future detectable increases in cancer rates. Dose and contamination depend on several atmospheric and device-related variables, but the worst-case scenario provides an effective dose of the order of 100 mSv in a small area for high activity alpha, beta or gamma sources, like ^{239}Pu, ^{90}Sr or ^{60}Co.

It is plausible that a number of limitations may have influenced the results obtained. Firstly, the effect of building downwash and wake flow on plume dispersion is not considered in HOTSPOT. Furthermore, the Gaussian dispersion model is based on a number of theoretical assumptions than might not be met in a realistic scenario. As an example, HOTSPOT makes use of a simplified urban dispersion model and debris or radioactive hotspots are not considered. A ground-level explosion is assumed, while an aerial detonation cannot be ruled out, for example, if the device is carried by a drone [47]. In addition, during the release, constant weather conditions are used. Ultimately, in the present study, the dose to exposed individuals is estimated considering unprotected people freely moving in an open space of an urban environment, disregarding individual behaviors. It is worth noticing that in a realistic scenario, relocation, sheltering and decontamination procedures are likely to reduce significantly the dose received by exposed people. Casualties would be washed to get rid of exterior radioactive contamination and treated in hospitals supplied with decontamination equipment, protective clothing and specialist monitoring devices.

The advantage of this study is the large spectrum of evaluated weather or device-related conditions and emphasis is given to organs at risk for deterministic or stochastic effects; also, an extended list of possible sources is taken into account.

In the case of a RDD explosion, it would be necessary to evacuate people from the contaminated area. However, evacuating contaminated areas, removing impacted materials and housing, feeding, and caring for displaced persons could have a huge financial impact. In particular, materials in the form of fine powder are much easier to disperse and therefore harder to clean up than blocks of solid material. Remediation could prove to be time-consuming and very expensive, particularly if public anxiety is pushing for irrational measures. In fact, the true danger of RDDs lies in the ability to induce panic and act as a disruption agent, especially if used in urban areas, near government buildings or in symbolic locations. Due to public fears of radiation, an intentional radiological release associated with a terrorist attack would certainly have a psychological effect much greater than the actual physical threat [48, 49], forcing mass evacuations, disrupting commercial activities, creating economic chaos, drop in property values and distress to those affected. To allay public concern and stigma, a clear, honest and coherent communication by trusted authorities is needed.

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