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Urban Operation Threat Assessment After a Multistage Radiological Dispersive Device Attack

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ABSTRACT

The urban environment may be a relevant setting for special military operations. Due to the options offered by urban infrastructure, this environment can be an essential catalyst for the proliferation of local asymmetric actions. These actions are triggered by extremist groups offering resistance to regular troops. Improvised weapons such as radiological dispersive devices (RDD) can be used to provoke even more threatening situations by increasing the risks of operations. This study is directed, via computer simulation using the Hot Spot Health Physics code, to a hypothetical context where a multistage RDD (RDD-M) is triggered in two non-simultaneous phases. This non-linear triggering causes overlapping contamination and impacts the coping strategy and the projections of variations in the size of the potentially affected population. In this study, the primary consideration is the contamination carried out at such a level that the association between human exposure and deterministic effects is feasible. The exposure to high doses of radiation at short distances about the triggering location of the device. The simulated data show that the threats are leveraged, and the environmental variables have a high value when assessing the criticality of the situation and establishing effective countermeasures.

Keywords: Radiation; Military operations; Computer simulation; Radiological dispersive device

1. INTRODUCTION

The urban operational environment may be subject to asymmetric actions or 4th generation warfare environment[1]. In this perspective, extremist groups are expected to make use of improvised artifacts to cause damage. These artifacts may be Radiological Dispersive Devices (RDD), such as simplified mechanical systems that couple radioactive material and conventional explosives[2]. The main goal of an RDD is not to cause casualties, although they may occur, but instead to negate inhabited areas by increasing the radiological risk[3,4]. This type of environment is studied from the perspective of Chemical, Biological, Radiological, and Nuclear defence actions (CBRN)[5].The work was conducted by computer simulation using the Hot Spot Health Physics version 3.1.2 code package[6] produced by the American Lawrence Livermore Laboratory (LLNL). The study's main objective was to verify possible relationships between environmental and technological variables generating threats that overlap the decision-making process in urban areas under combat.

In this study, was carried out an exercise in which an RDD is presented in two stages triggered by different modes of release of radioactive material. The first stage works by mechanical release of the material (without explosives), and a conventional explosion triggers the second. This innovative perspective brings some characteristics that may be of interest to developing leadership and decision-making processes.

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2. METHODOLOGY

2.1 Source-Term and Computer Simulation

A two-stage release RDD was computationally simulated considering the dispersion of 4.4400E+14 Bq (1.2E+3 Ci) of Cs-137 in an urban environment for each triggered stage (puff or explosion).The total effective dose equivalent (TEDE)[7] is the hypothetical radiation dose under consideration. Although the effects on the environment are cumulative, the results are presented irrespective of the release mode. The source-term is representative of those used for blood components irradiation[7]. The dispersion of Cs-137 was calculated by applying the code HotSpot Health Physics[6], which uses Gaussian modelling (Eqn.1).

HotSpot utilises Gaussian analytical modeling to assess the spread of a radioactive contaminant in a given area. The software provides a straightforward interface that allows users to select relevant variables for their analysis. However, the developers suggest that simulations focus on a 10 km range to minimise potential uncertainties[6]. The aforementioned statement highlights a significant limitation in Gaussian modeling simulations. Unlike the numerical approach, Gaussian modeling simulations encounter difficulties in resolving obstacle edges, which can lead to systematic errors that propagate over long distances, thus reducing the overall accuracy of results. The Gaussian propagation model applied by HotSpot is introduced by Eqn. (1). The simulations run under FGR-11 Dose Conversion Data for estimating the Total Effective Dose Equivalent (TEDE)[6]. Also, calculations considered the International Commission on Radiological Protection (ICRP 60/66) model[6]. Table 1 presents the primary input data applied to HotSpot.

$$C(x,y,z,H)=\left(\frac{Q}{2\pi\sigma_y\sigma_z u}\right)\exp\left[-0.5\left(\frac{y}{\sigma_y}\right)^2\right]$$
$$\left\{\exp\left[-0.5\left(\frac{z-H}{\sigma_z}\right)^2\right]+\exp\left[-0.5\left(\frac{z+H}{\sigma_z}\right)^2\right]\right\}\exp\left[-\frac{\lambda x}{u}\right]DF(x) \quad (1)$$

where, C, Q, H, and λ are the atmospheric concentration (Ci-s)/(m^3), the source-term (Ci), the effective release height (m), and the radioactive decay constant (s^{-1}) respectively. The coordinates x, y and z are the downwind, the crosswind, and the vertical axis distances (m), respectively. The standard deviation of the concentration distribution in the cross and vertical wind direction is represented by σ_y and σ_z respectively. The variable u is the mean wind velocity at a specific release height (m/s), and DF(x) is the plume depletion(dimensionless).

The HotSpot takes into account the wind speed and the local Pasquill-Gifford (PG) class, which is determined by the temperature difference between the air and its surroundings[6]. The standard deviation (σ_θ) for wind slope (in radians) is calculated in the plume's propagation direction. Pasquill-Gifford (PG) stability classes are considered from (A) extremely unstable to (F) moderately unstable[8-9].

Table 1. Main input data for simulation (puff or explosion) in HotSpot.

Input	Puff	Explosion
Source material	Cs-137	
Material-at-risk (MAR)	4.44E+14 Bq	
Damage ratio (DR), airborne fraction (ARF), and leak path factor (LPF)	1.0	
Respirable fraction (RF)	1.0	0.2
Wind speed (at h = 10 m)	3.0 m/s	
Effective release height	soil surface	
Atmospheric stability class (City)	A to F	
High explosive	10 pounds (≈4.54 kg) of TNT	none
Sample time	10 min	
Respirable deposition velocity	0.30 cm/s	
Non-respirable deposition velocity	8.0 cm/s	40.0 cm/s
Receptor height	1.5 m	
Inversion layer height	none	
Distance coordinates	the distances are on the plume centerline	
Breathing rate (conservative option)	3.33E-04 m^3/s	

2.2 Analytical Approach and the Release Framework

This (analytical) approach is interesting for studying events with little information available and in early stages of evaluation[3,5,10-11]. The study considers a timeframe of approximately 100 hrs (≈4 days). Analytical modeling can offer several benefits, including faster processing times in a typical computing environment and simplified calculation processes. The Gaussian approach, although it may yield unrealistic results, is a useful tool for the preliminary stages of assessing radioactive scenarios due to its conservative nature. Presenting results that allow for the overestimation of threats can provide sound guidance to decision-makers regarding reducing risks for field teams.

For this study, the dispersion was simulated in two stages, one by mechanical release of the radioactive material (puff) and the other induced by conventional explosion (explosion). The consequences of releases on the environment can also be referred to as waves of attack. Therefore, the release of the first stage would be the first wave, and the release of the second stage would be the second wave of attack. The sequence for the modes of material released by the RDD was carefully chosen due to the energies involved in the dispersion process. The puff mode (mechanical dispersion) delivers less power to the system, and the plume evolves smoothly under concentrated influence in PG classes. On the other hand, in explosion mode, energy delivery to the system produces turbulence effects that significantly change the deposition profiles in the soil and suspended particles. This leads to changes in the dose and size profiles of the plumes.

The releases do not co-occur. This choice was made to reduce the influence of one model on another. The difference between the activation times (puff, explosion) was defined as the time required for the first stage (puff) to contaminate the environment with a plume of 700 mSv of isodose. This level of TEDE is indicated as one in which some deterministic effect on humans is already expected from radiological exposure, and the initial phase of consequences, such as acute radiation syndrome (ARS), is also expected[12].

HotSpot calculates the plume travel time for each atmospheric stability condition and must be such that the first contamination plume is established immediately before the second departure. Under the conditions of this study, the time for the first 700 mSv plume to settle down was estimated at 11 min. by the HotSpot code. It is the longest time for the most stable atmospheric stability condition to reach the 700 mSv boundary. Thus, after 11 min past the mechanical release (puff) of the RDD, the explosion mode starts operating, hence defining a multistage RDD(RDD-M). As it is a conservative simulation, re-suspension effects are not considered. The cumulative impact generated by the interaction of the two events, other than the accumulation of the TEDE, was also neglected.

2.3 TEDE Limits and Expected Effects

This study examines the movement of a radioactive

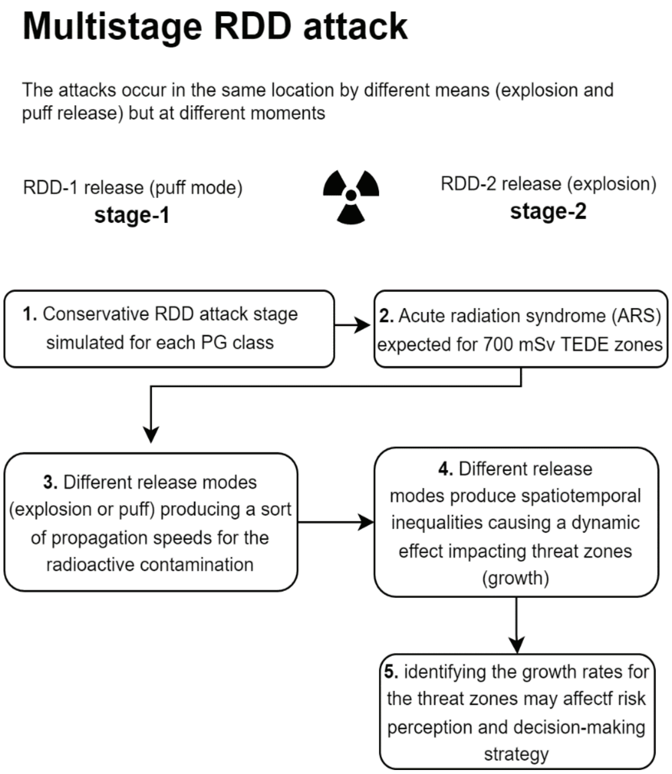

Figure 1. Schematic summary of threat assessment in a multistage RDD scenario.

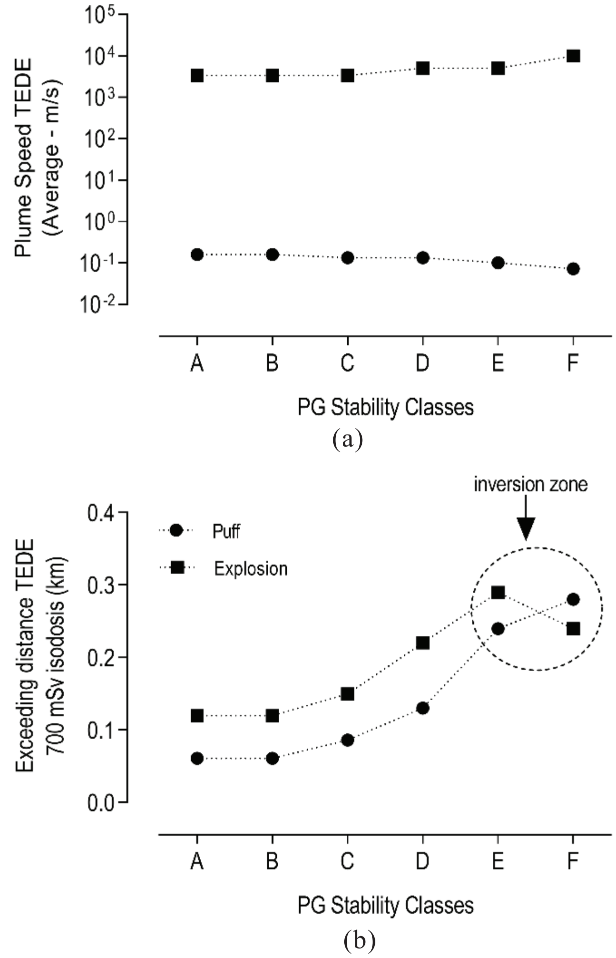

Figure 2. Characteristic velocities 2(a) and maximum contamination plume distances for 700 mSv TEDE boundary 2(b).

contamination plume through an urban area. The primary focus is on the TEDE (Total Effective Dose Equivalent) contour, specifically the 700 mSv isodose zone, which could result in deterministic effects in the early stages.

2.4 Combined Threat Over an Urban Zone

The study is limited to studying threats posed by the model of release of radioactive material. However, when associated with the expected effects, these threats can influence the consequences. The product between threat and potential consequences is what can be called risk in the context of this study. Thus, a quick assessment of the context and the ability to resist (resilience) is facilitated by evaluating the relationship between threats and consequences of the event. For this study, the main effect allows us to identify the growth rates for the potentially affected population in the threat zones and how their intervening variables may affect risk perception and decision-making strategy.

The ratio between the calculated values for the two release modes was used to present the results. This ratio was introduced to reduce the amount of data and simplify comparing the effects of the events (puff and explosion).A ratio equal to unity indicates equivalence of the results, while trends above and below this value allow us to discuss the predominance of one or another model on the effect under evaluation. Figure 1 presents a scheme summarizing the central ideas.

3. RESULTS

Figure 2 shows the characteristic velocities (Fig. 2(a)) and maximum distances from the point of release for the isodose curve for the 700 mSv TEDE (Fig. 2(b)) experienced by the radioactive contamination plumes. Effects are presented concerning Pasquill-Gifford (PG) classes.

In Figure 3(a), the TEDE ratio estimated in the puff and explosion models is presented for each Pasquill-Gifford (PG) class and location, along with the major axis of the elliptical plume derived from the simulation. Figure 3(b) displays the standard deviation (SD) for the ratios at each location, illustrating the impact of local atmospheric stability variations on the puff/explosion relationship.

Figure 4 compares the influence of local atmospheric activity on the extension of the areas of contamination plumes for the two release modes.

Table 2 shows the expected number of individuals potentially exposed to risk in the 700 mSv plumes at the end of the observation time. The anticipated growth of this potentially affected population due to triggering the second stage of the RDD is also shown. Data were tabulated as a function of local atmospheric stability conditions.

4. DISCUSSION

The work is dedicated to studying a simulated radioactive environment, where radioactive material is released through the action of an RDD in two stages, one mechanical and the other explosive. Under these conditions, TEDE at the 700 mSv level (expected deterministic effects) may be able to cause acute incapacitation of operating teams. Potential deterministic effects typical of ARS, such as emesis, fever, and disorientation, may occur. The degradation of operational capacity can reduce the missions' chances of success and increase the radiological risks.

Figure 2 presents results that indicate the dynamic differences between the two models of release of radioactive material by the artifact (RDD). Figure 2(a) shows the differences between plume velocities. This condition helps to clarify the need to avoid simultaneous release events. Assuming different speeds, it becomes necessary to temporally de-phase events. This makes it possible to study the phenomenon from an exclusively spatial perspective, reducing undesirable technical (mathematical) difficulties in the case of an *in-situ* evaluation. From the perspective that considers the PG classes, the results suggest no implication of changes in local atmospheric stability on the plumes' velocities in each release mode. However, a slight divergence can be seen in the transition from class PG E to F, regardless of the release mode. Figure 2(b) shows the behavior of the characteristic distances of the generated plumes at the release point. It is noticed that there is a tendency to increase these distances with variations of the PG classes in the direction of A to E. However, for variations of the PG class E to F, this tendency is inverted when considering the puff and explosion modes. Perhaps because the PG class F offers the most significant distances, the average energy of the particles released in explosion mode is not enough to reach these distances when compared to puff mode. This is because, in the explosion process, turbulence is generated with energy expenditure such that from the PG class E, the energy levels of particles suspended in the plume are lower than those presented in puff mode, causing the inversion of the ranges. This condition reverses the threat assessment for this PG class change. Considering that the positive difference between the sizes of the plumes produces an additive effect for the population at risk, it can be expected that no new individuals at risk are added.

The results presented in Fig. 3(a) indicate that the puff/explosion ratio for the TEDE assumes values greater than unity only for zones close to the release point. This suggests that for distances up to about 300 m from the release point, the PG classes E and F give less advantage to the explosion mode, thus assuming lower TEDE values. The PG class F maintains this behaviour for all simulated distances in burst mode. This dataset makes it possible to determine strategies that minimize exposure to the threat and, consequently, radiological risks for the teams. Figure 3(b) adds information indicating that the impact of possible variations of the PG classes on the puff/explosion ratios (TEDE) are more critical only for regions close to the release point (higher values of the standard deviation - SD).Even so, this finding is not enough to disregard the influence of the variations of the PG classes on risks. It can only be inferred that the impacts are equivalent, not negligible.

Figure 4 shows the evolution of the sizes of the radioactive contamination plume areas, regardless of the release modes. PG classes A and C have no variation in areas, although the dose levels are additive. However, from PG class C onwards,

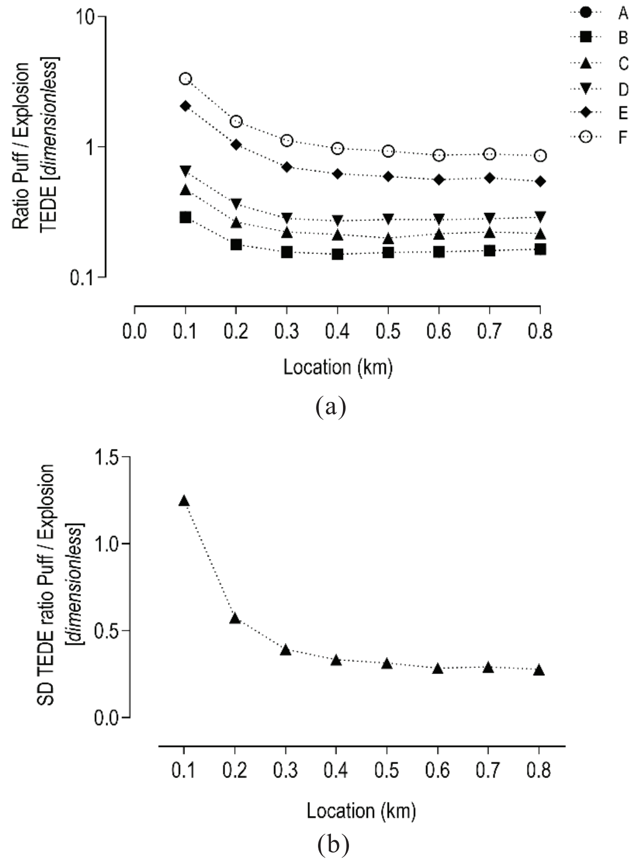

Figure 3. Ratios between TEDE; (a) and variability concerning PG classes (b).

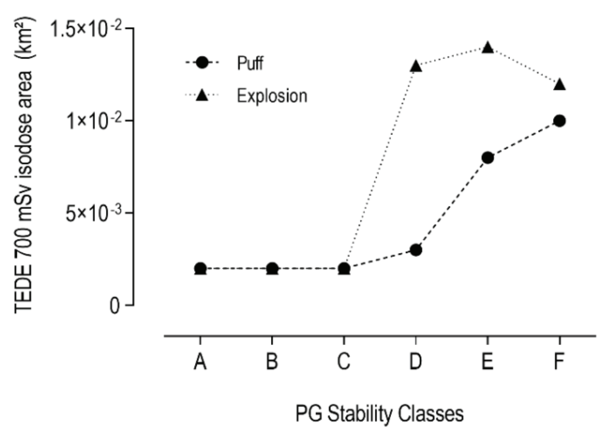

Figure 4. Influence of PG classes on the spatial evolution of radioactive plumes.

variations in the plumes' areas are significantly influenced by the PG classes. These variations in the areas of the contamination plumes have a direct impact on variations in the size of the potentially affected populations. As this study presents results from both a conservative and initial perspective of radiological risk assessment, the prognoses are pessimistic.

In addition to Fig. 4, Table 2 may also be used since it presents estimates of the growth of the potentially affected population in the regions where the contamination plume are growing. These changes in the number of affected individuals differently occur differently for each release mode considered (puff or explosion) and for each release mode considered (puff or explosion) and for each PG class. The case with the most significant positive variation is for the PG class D (neutral), which is not verified in any case as a reduction in areas but in its growth rate. Additionally, it is essential not to confuse the evolution of contaminated plume areas (Fig. 4) with variations in exceeding distances (Fig. 2(a)). Although the distances to the release points may vary, especially for the PG classes E and F (Fig. 2(a), (b)), these one-dimensional variations cannot be compared with those two-dimensional variations (areas)shown in Fig. 4.

The study's primary outcome was to assess the impact of both local atmospheric stability conditions (PG classes) and the overlap of different release modes (puff and explosion) on a single multistage RDD event. Together, these boundary conditions for the problem of potential threats in operations in a typical CBRN environment can enable effective decision-making. This study represents a conservative strategy for risk assessment. Therefore, the main goal, which is to conservatively verify the evolution of the threat scenario through the inclusion of new areas in the affected areas, was achieved. According to the calculations carried out in this study, these new areas result from an evolution of threats (increase in contaminated areas). Another stress factor is the dependence on atmospheric stability classes, the PG classes. This dependence may lead to gross errors in assessing threats, as the evolution of areas occurs under the influence of more stable PG classes (D to F).

The study developed in this work can be adapted and applied as a tabletop exercise promoting leadership development and decision-making preparation in innovative situations. This work did not aim to develop applications in case studies, which can be an interesting model for future communications. The study also has a dual character and may be applied to the development of military training strategies in CBRN defence and to support both initial decision-making and training of civilian response teams.

Table 2. Effect of PG classes on population growth potentially affected by the 700 mSv plume.

PG class	**Individuals** (700 mSv, puff)	**Individuals** (700 mSv, explosion)	**Growth** (%)
A, B, C	1.92E+01	1.92E+01	0.00
D	2.88E+01	1.25E+02	76.92
E	7.68E+01	1.34E+02	42.86
F	9.60E+01	1.15E+02	16.67

5. CONCLUSIONS

The study was developed to assess exposure to particular threats in an urban combat environment. The innovative application of a multistage radiological dispersion device (RDD - M) has produced findings that show both the dependence of environmental conditions and the mode of release, whether mechanical (puff) or explosion. The methodological approach also allows commanders to evaluate changes in the size of the potentially affected population from a temporal perspective. As a result, there is a strong dependence between the evolution of the size of the potentially affected population, both in terms of local atmospheric stability and the mode of release of the radioactive material (puff or explosion). An interesting application in continuation of this work would be to apply the results obtained concerning the threat (TEDE) in epidemiological equations of radiological risk to evaluate biological effects on members of special teams and troop fractions.

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