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Radiological Consequences Modelling for a Land-based Operation Environment

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ABSTRACT

Radiological Dispersive Devices (RDD) are often portrayed as weapons used by radical (asymmetric) forces, however they can also be used in a regular war. In this study, a hypothetical scenario where an asymmetric force contaminates the battlefield, by detonating an RDD prior to the soldier's arrival without being detected, is simulated. The software HotSpot was used due to its speed and conservative results which can help inform the decisions made by the commanding officers. HotSpot performs a Gaussian simulation of the radioactive dispersion in the environment. The plumes that arise from the explosion are considered to be affected by the atmospheric conditions. In this study, those conditions are represented by the Pasquill-Gifford stability classes. The results of the simulation show that remaining stationary, if the contaminated area size is not affected by the PG class variation, may increase the radiological risk. It is better to move the soldiers around in order to avoid additional exposure, however that may also be a challenge for various reasons including changes in the shape of the contaminated area. Nevertheless, the variations in local PG classes gain importance as the distance from the release point increases.

Keywords: Simulation; Radiation; Land-based operations; Atmospheric stability

1. INTRODUCTION

Scenarios involving radioactive contamination have been gaining attention in the scientific media during recent years[1-4]. In the field of military operations, radiological and nuclear events are not limited by technological accidents. Threats can be deliberate and intentionality becomes a context variable. Technological threats in combat scenarios are not expected to be unique or limited to contamination by radioactive elements. Actions involving chemical and biological agents can be expected, thus setting up a scenario for chemical, biological, radiological and nuclear (CBRN) defence actions.

By performing computer simulations this study presents the possibility of facing a non-conventional combat situation, or fourth generation warfare[5]. The fourth-generation warfare is marked by the presence of non-conventional forces that can use improvised mechanisms like a radiological dispersive device (RDD), also known as a dirty bomb, against regular troops. This might produce a new combat environment, and perhaps a new paradigm in decision-making in the field of military sciences.

The simulations enable the creation of a scenario where the information, generated in a conservative way, can support decision making in real time. The software HotSpot Health Physics version 3.1.2[13] was used to simulate an attack against regular troops operating on the ground by triggering an RDD. This fast computer simulation can be valuable for assessing threats and the potential consequences from the event. This data can be of value for defining a response strategy, and for supporting decision making in regards to the radiological protection of the troops. For some time RDDs were restricted to the field of radiological terrorism. However, there are enough arguments to believe that it can be used in the context of regular military operations by opponents in non-conventional actions.

In a recent related work, Bulhosa and colleagues investigated the development of a simulated radiological event involving the environmental release of Cs-137[6]. The work shows that the effects of the Pasquill-Gifford atmospheric stability classes on the total effective dose equivalent (TEDE) is decisive to model both the consequences and the cancer risk. These results corroborate the central idea of this study which is to reduce risks by applying simulations with the aim of establishing effective support for the initial decision. Nevertheless, the difference in this study compared to that developed by Bulhosa and collaborators is a potential fight. The information generated in the simulations is of value not only for reducing risk but also to be a theoretical basis for elaborating countermeasures plans.

The findings discussed in this paper can inform decisions and ultimately serve as a warning for a new potential element of land combat, dirty bombs or RDDs. Additionally a discussion

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on the need to update the safety equipment in operations can be expected to include radiation detectors at the platoon level, and training to apply computer simulation techniques in real time and in real combat missions.

2. MATERIAL AND METHODS

The land-based environment simulation considers a hypothetical situation where a radiological dispersal device (RDD) is activated producing a contaminated plume carrying radioactive material. The plumes from the explosion may be significantly affected by local atmospheric stability conditions. In this study such stability conditions are represented by the Pasquill-Gifford stability classes (PG classes)[7]. Although the environmental radiation dose rate is of fundamental importance, the study considered the integrated radiation dose after 4 days (TEDE)[8,9]as the key parameter to assess the radiological threat.

In the initial assessment and response phase data is usually very scarce, and responders may have to rely on less realistic estimates for airborne releases. The deadlines involved in decision making are short and preparation is critical in an environment of insufficient data. The main protective actions for the initial phase are evacuation and shelter on site[10]. These actions are interesting for cases where doses, in the whole body, are expected to exceed 10 to 50 mSv in four days[10]. In this study the period of 4 days refers to the conservative estimates of the evolution of contamination taken after the environmental release.

Regarding the risk to human health arising from the exposure to ionising radiation, this study also considers it a good approximation that radiological risk is proportional to TEDE. This choice is supported by benchmarking epidemiological models indicating this variable as fundamental in the assessment of radiological risk[11,12].

In general, health effects due to exposure to ionising radiation are classified as stochastic or deterministic. Stochastic effects occur at random and the probability of the effect occurring (not its severity) is considered a linear dose function without a limit. Stochastic effects can result from damage to a single cell leading to future results that include hereditary and carcinogenic effects. The deterministic effects result from the collective injury of a substantial number of cells in the affected tissues. In this case the severity of the tissue damage is a function of the dose. The limits of radiological protection are generally defined in order to prevent the occurrence of deterministic effects, in addition to trying to limit the chances of occurrence of stochastic effects[13].

Usually the interest for deterministic effects in extreme conditions like the one treated in this study falls on consequences such as the acute radiation syndrome (ARS)[14]. Although the limits for the development of ARS are still considered with some uncertainty, in this work the value of TEDE with a limit of 700 mSv is considered sufficient to trigger serious biological processes in a few hours[15]. The first biological effects of high-level acute doses appear within minutes to weeks depending on the dose received, and the fraction of the total body exposed to radiation[13].

The TEDE was defined as the radiation producing the equivalent dose by both external and internal exposure. This radiation dose concept (TEDE) includes all applicable radiological exposure pathways[13]. The TEDE measure uses the international system unit (SI) for a radiation dose equivalent of 1 joule per kilogram, the sievert (Sv) and its sub-multiples along with the text. Although it is a part of TEDE, in this study ground shine is examined separately. The reason for that is because it remains the main source of exposure after the passage of the contamination plume. The source-term used in the simulations is Cs-137, and the reason for that is due to the usage of Cs-137 as a source material inside the blood/tissue irradiators (IAEA)[11]. TEDE is taken by Hotspot as the total effective dose equivalent, being calculated as[13] shown in equation 1.

$$\text{TEDE} = \text{CEDE (inhalation)} + \text{EDE (submersion)} \qquad (1)$$

where EDE is equivalent to the effective dose by submersion in the cloud (external), and CEDE is equivalent to the effective dose compromised by inhalation (internal).

The contamination routes consider only dry deposition of the plume and consequent soil contamination. The contaminated plumes evolution was calculated according to Gaussian modelling. The application of this model, although less rigorous in relation to the uncertainties associated with the results, gathers sufficient information in order to offer support to decision-makers. HotSpot is an advantageous tool for field work in situations requiring fast processing, and on demand information availability[13].

The Gaussian model is suitable for estimating the atmospheric concentration of an aerosol at any point in space, and it may be found in previous works from our group[2-4]. In this study it is considered that the troops under radiological threat have the means to identify both the presence of radiation and the radioactive element in the environment by means of simple identifiers detectors. The Gaussian model used by HotSpot is given by the governing equation 2.

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

where C is the concentration (Bq-s)/(m^3), Q is the activity of the radiation source (Bq), H is the effective release height (m), λ is the physical radioactive decay factor (s^{-1}), coordinates x, y and z are related of the downwind, crosswind and vertical distance (m) respectively, σ_y and σ_z are the standard deviations of the concentration distribution in both the horizontal and vertical direction (m), u is the mean wind velocity at the effective release height (m/s), and DF(x) is the plume depletion factor[13].

On a time-scale basis the study was limited to calculations within the first 100 hours since the initial event. Overall the radiological exposure window lasts approximately 4 days assuming that 100% of the time is spent inside the plume.

HotSpot takes the wind speed local PG class, ranging from A to F where PG class A is assumed as extremely unstable and class F as moderately stable, into consideration[7,13,16]. HotSpot's developer recommends limiting the range of the modelling to 10 km. According to the developer, for greater distances there may be mathematical fluctuations that imply additional increments to the associated uncertainties.

HotSpot offers a choice between two types of terrain, those being city or standard (rural). The standard mode was chosen because the simulation takes place outdoors and outside the urban area. This option offers the most conservative estimates thus maximising resources management. Possible effects of the soil surface roughness are conservatively incorporated into the simulation. Also, from a conservative perspective, the airborne fraction (ARF) of the source-term which is the fraction of material at risk that is aerosolised and released into the atmosphere was considered totally aerosolised without associated ballistic terms[13]. Additionally HotSpot considers that small particles and gases or vapors are deposited on surfaces because of turbulent diffusion and Brownian motion. It is also considered that chemical reactions, impaction, biological, chemical, and physical processes combine to keep the material released at ground level, this process is called dry deposition. The algorithm defines the effective deposition speed as the ratio between the observed deposition flow and the air concentration estimated near the soil surface[13].

The main results under evaluation are: (a) Arrival Time, (b) Area of the zone of interest (inner, middle, outer), (c) TEDE, (d) ground shine, (e) ground deposition and (f) Exceeding distance. All results are calculated for all PG classes. The main input data for HotSpot can be found in Table 1. This study does not consider mechanical effects caused by the explosion of the RDD. Also contaminating the environment without being detected is considered to be a strategy of the non-conventional opposing force, hence we considered that the RDD was triggered before the arrival of the troops.

The amount of explosives was determined at 25 pounds based on two premises: ease of transport and low damage to the local physical structure. The receptor height is the height above the ground at which the TEDE is estimated. The default value adopted by HotSpot is 1.5 meters, the body region close to the chest in an average man of 1.7 meters. The actual height of the plume may not be the physical height considered for dose estimates. The rise of the plume results in an increase in the release height. For a conservative estimate, release at ground level must be considered[13]. The source term considered is a typical component of blood irradiators in hospital facilities. The activity used (4.44E+14 Bq) considered an average value for this type of application[11], and therefore, easier to acquire in the formal market.

The equations for the standard deviation of the Gaussian concentration distribution in the direction of the ordinate (y) axis are representative of the observation of plume characteristics over an observation period, known as the sampling time. Due to the explosion the release of radioactive material into the environment is expected to be an instantaneous phenomenon. Nonetheless, HotSpot assumes the sampling time as 10 minutes by default. The concentrations of radioactive material released downwind decrease with increasing sampling time due to the spread of the plume as it progresses spatially.

Table 1. HotSpot main input simulation data

Variable (input)	Value
High Explosive	25.0 Pounds of TNT
Stability Class	A to F
Receptor Height	1.5 m
Sample Time	10 min
Distance Coordinates	All distances are on the plume centerline
Source-Term	Cs-137 D 30.0y
Material-at-Risk (MAR)	4.44E+14 Bq (blood/tissue irradiators)
Damage Ratio (DR) Airborne Fraction (ARF)	1.00 (conservative default)
Respirable Fraction (RF)	0.20 (conservative default)
Leakpath Factor (LPF)	1.00 (conservative default)
Wind Speed (h=10 m)	3.0 m/s (all PG classes register this value)

Material at Risk (MAR) is the total amount of the radionuclide involved in the release scenario. Damage Ratio (DR), is the fraction of MAR that is really impacted in the release scenario. The Leak path Factor (LPF) is the fraction of the Material at Risk that goes through some containment or filtration mechanism. Airborne Fraction (ARF) is defined as the fraction of the MAR that is aerosolised and released into the atmosphere in dimensions that do not have any ballistic effects. The respirable fraction (RF) is the fraction of the aerosol material that is respirable (Aerodynamic Diameter (AD) ≤ 10 microns)[13].

The radioactive plume can be projected onto the ground and the dimensions of the affected areas were estimated by HotSpot for each PG class. These contaminated areas are named according to both the isodoses they represent and their position in relation to the plume[15,17]: (a) inner (maximum < D < 700 mSv, at this level deterministic effects are expected); (b) middle (700 mSv < D < 100 mSv – at this level emergency situation is defined) and (c) outer (100 mSv < D < 10 mSv - at this level sheltering procedures may occur). A summary of the method applied to the simulation can be found in Fig. 1

A simple way to highlight the importance of the PG classes' influence on selected results is to evaluate the standard deviation (SD) of these results within their groups. This procedure was applied to the TEDE evaluation (Fig. 3a) and to the Exceeding distance (Fig. 4b) in order to qualify the importance of the PG classes in each one. The Exceeding distance is the distance from the release point to the isodose limit of any of the zones of interest (inner, middle, and outer). Therefore the higher the standard deviation for a considered group is, the higher the PG classes interchanging significance becomes. The mathematical formula used to calculate the SD is well known as presented by equation 3.

$$STD = \sqrt{\sum \frac{(x-\overline{x})^2}{n}} \tag{3}$$

where x is the variable value and each PG class, $\overline{x}$ is the mean of all values in the data set and n is the number of values in the data set.

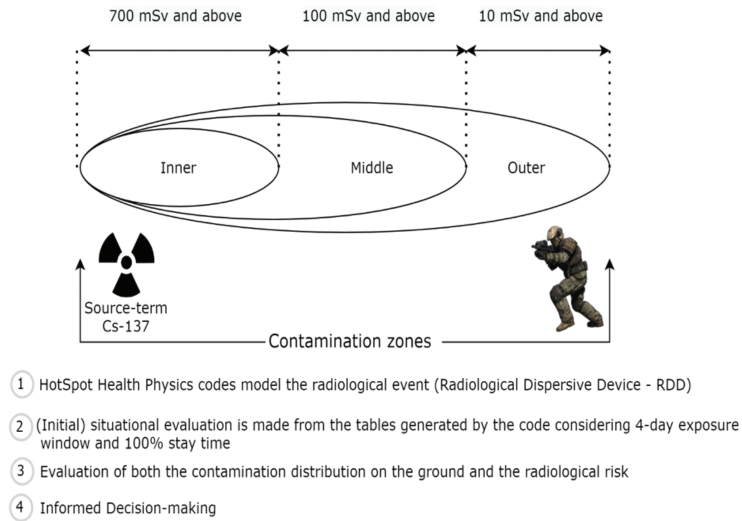

Figure 1. Summary of the method applied to the scenario simulation.

3. RESULTS

Figure 2 to 4 show the main variables under evaluation which are: (a) arrival time, (b) area of the zone of interest, (c) TEDE, (d) ground shine, (e) ground deposition and (f) exceeding distance.

Figure 2 shows results for the time of arrival of the plume as a function of the distance to the release point (2a) and the expected size of the area (2b) for each zone of interest (inner, middle, and outer) for each PG class.

Figure 3 presents results for TEDE (3a) and ground shine (3b) as a function of the distance to the release point, both for each PG class. Wherever TEDE is above 100 mSv are highlighted in Fig. 3(a) (0.1, 0.5 and 1 km).

Figure 4 shows results for ground deposition (4a) as a function of the distance to the release point and the exceeding distance (4b) for each zone of interest (inner, middle, and outer), both for each PG class.

4. DISCUSSION

This study simulates an off-site military operation environment. The simulations outputs essentially play the key role of supporting decision strategies towards risk reduction.

An important factor in decision-making is the timeframe and its intervening variables. Figure 2(a) shows a set of results that suggests a dependence between the arrival time and the PG classes. Notably up to 2 km from the release point there is no influence of PG classes on arrival time. However, from 2 km onwards an increase of the influence of the PG classes is predictable.

Figure 3(a) shows that for the 10 km location, a comparison between the results generated considering classes A and F produces differences of approximately 30 min in the arrival of the contamination plume. This might have an impact on the actions taken in order to achieve a safer environment. In contrast the estimated areas for each zone of interest do not show significant variations following the PG classes' changes (Fig. 2b). These findings may lead to an unrealistic sense

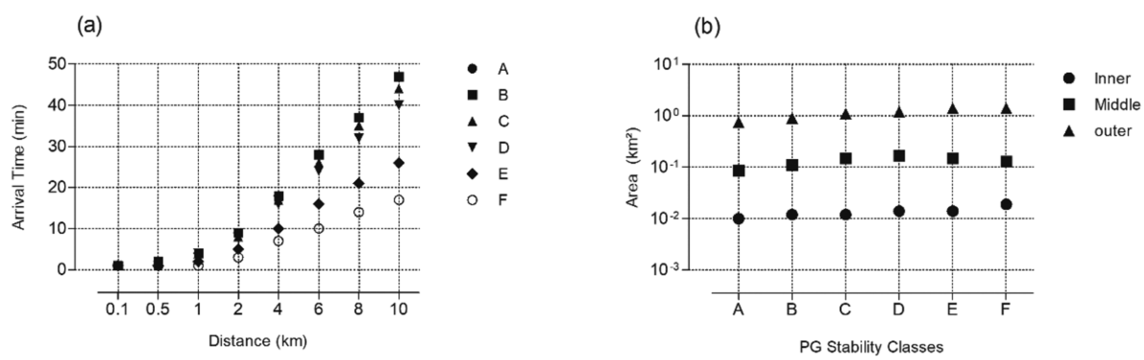

Figure 2. Arrival time (2a) and the expected area of each zone of interest inside the main plume (2b).

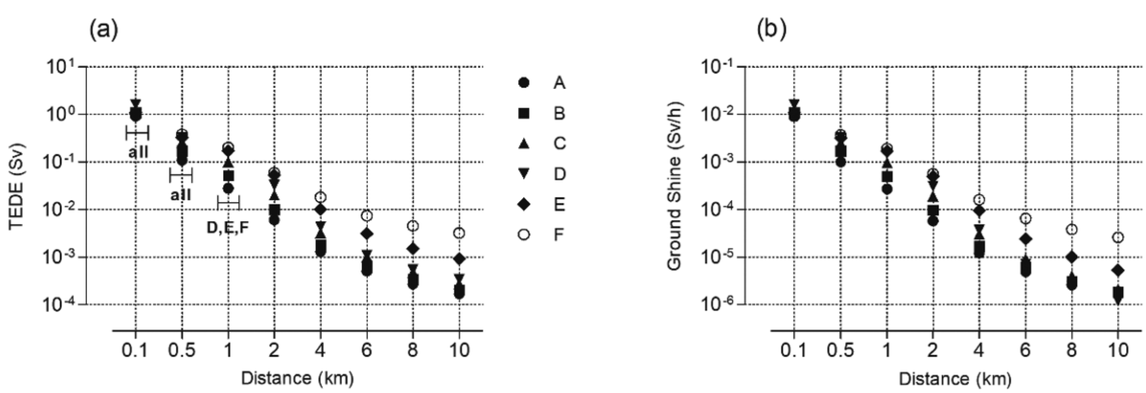

Figure 3. TEDE (3a) and ground shine (3b) are presented as a function of the distance to the release point for each PG class.

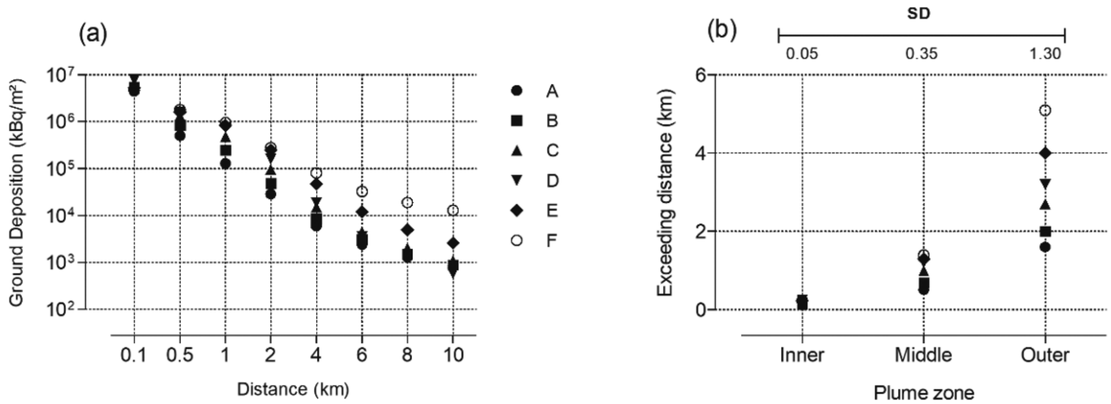

Figure 4. Ground deposition is presented as a function of the distance to the release point (4a), and exceeding distance (4b) is presented for each zone of interest. Both ground deposition and exceeding distance depend on PG classes.

of advantage. Remaining stationary due to the fact that the affected areas are not modified by variations in the PG classes may increase the radiological risk. It is crucial to notice that local PG classes' changes can have an effect on the plume shapes even if the plume's area remains the same. Also for each PG class the dose rate becomes inversely proportional to the distance from the release point thus showing what direction to move first. In fact variations in the local PG classes occurring simultaneously with the troop's movement can lead to bias in the decision-making. These biases hinder the definition of both the moment of displacement and the safest direction to follow.

Variations in the shape of the contaminated plumes are expected, including narrowing and stretching according to the estimated values for the exceeding distance (Fig. 4). Moving soldiers around may be an alternative to be considered in order to avoid additional radiological exposure as a result of the PG classes' changes. The movement of the troops may be an issue since the resources are limited in the field and the soldiers may be under additional stress. The difficulty to understand and even perceive the non-conventional context can lead to delays in decision making. Once there are signs of an RDD, these delays can be compensated by applying field modelling.

The central concept of TEDE is sensitive to variations in PG classes as shown in Fig. 3(a). Regardless of the PG class, up to 0.5 km the TEDE values are always higher than the limit considered for radiological emergencies (100 mSv). Moving a little further, at the 1 km location, only classes D, E and F raise the TEDE to levels above 100 mSv. For this location (1 km) an important concern is the PG class change which may impact the decision of moving towards low exposure sites nearby. Locations between 1 and 10 km are always under 100 mSv, and the PG classes that mostly increase radiological risk are E and F (Fig. 3a). Figure 3(b) shows the ground shine levels deriving from the ground deposition (Fig. 4a) which in turn is a fundamental parcel of TEDE (eq. 2).

Figure 4(b) shows the exceeding distance, and represents how much the major axis of the ellipse can vary due to changes in the PG classes. It is crucial information that can influence decisions by changing the perception of safety (Fig. 2b). The standard deviation (SD) results confirm that the PG classes' variations impact the length of the zones of interest (inner, middle, outer). Low values of SD in the inner zone suggest that little or no influence is exerted on a location near the release point. On the other hand, by comparing PG classes A and F in the outer zone a variation of around 300% can be found. Changing the elongation of the plumes in combination with an unchanged plume area may cause bias in the decision and influence the troop's displacements.

5. CONCLUSIONS

The findings of this study although taken as a first-order response to an RDD event in the field show the importance of using HotSpot codes along with environmental data for providing valuable information for supporting decision. The method introduced in this work may count on HotSpot both as a field and/or remote tool giving results to support decision-making in a radioactive scenario. The findings also provide information on how to move the troops to lower radiological risk sites. Complementary studies are necessary for a more complete assessment of the scenario and may be performed by adding more advanced technologies. Such improvements come from the use of a radiation detection system along with computational resources. Also radioepidemiological models may enhance the results and ultimately the decision process. However, advanced studies like the one previously mentioned fall outside the scope of this work which addresses simple, fast, portable, and scientifically valuable solutions to support immediate decision-making in the field.

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He is responsible for conceptualising the design and supervised the project