A MODELED RADIOLOGICAL DISPERSIVE DEVICE RELEASE AND THE IMPACT TO DECISION-MAKING IN AN URBAN ENVIRONMENT

by

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Technical paper
https://doi.org/10.2298/NTRP2004316O

A radiological dispersion device is a weapon that combines radioactive material with conventional explosives for spreading radioactive material across an inhabited area. This study is focused on evaluating key parameters in an radiological dispersion device scenario. The calculations were performed to include two different situations: by using explosives and by simple mechanical release. Simulations were conducted with the use of the HotSpot Health Physics Codes. The results suggest the existence of significant correlations between stability classes in scenarios where they evolve with time, producing alternations between them. As long as the stability class remains constant, this latter finding offers the possibility of creating a suitable response, based on temporal evolutions. Therefore, the purpose of this study is to: estimate the size of the potentially affected population, estimate absorbed doses, and estimate the cost-effectiveness in order to help initial responses by providing time-sensitive information about the event. A methodology capable of providing useful information allows prompt decisions and initial assessments of future risks to be made efficiently. This approach can also provide a training environment for the personnel responsible for the decision-making at an early stage of the response.

Key words: atmospheric dispersion, contamination, radiation, cost-effectiveness

INTRODUCTION

A radiological dispersion device (RDD) is a weapon that combines radioactive material with conventional explosives. This weapon is designed for spreading radioactive material across an inhabited area in a way that considerable resources are needed to mitigate its effects. An RDD can generate damages, and potential threats of social origin to the public [1-3].

This study seeks to assess the impact of key parameters such as dose (total effective dose equivalent - TEDE) and plume area on an RDD scenario. Also, it is intended to investigate the relationship between the radiological release type (explosion or puff), time, cost, local climate features, and consequences in the event of a large-scale radionuclide release from an RDD.

The calculations were performed to assess the effect of two different situations: the use of explosives and the mechanical release of the material. The influence of local climatic conditions on both the radioactive material dispersion and on the collective dose of radiation of a potentially affected population are also addressed. Finally, the possible cost of the corresponding detriment is also evaluated.

Similar studies were recently conducted by two separate groups. Cao *et al*. [4] assessed the TEDE and ground deposition by using the HotSpot health physics computer code with site-specific meteorological conditions. The results indicated that the TEDE and ground deposition decreased with the increase of the downwind distance, nevertheless, remain larger than the regulatory limit for the public. Another group headed by Kim *et al*. [5] focused on the radioactive decontamination waste following the Fukushima nuclear power plant accident in 2011. The study addressed im-

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provements in the transportation plans and guidelines for decontamination waste transportation. The group assessed the external dose rates around a transportation vehicle, the collective doses, and the maximally exposed individual doses by computational means.

The release scenario was simulated by using the HotSpot health Physics software [6]. This tool is capable of producing simulations, through Gaussian modeling, that may be of interest for the first responders in the first hours of an RDD event. Even though more complex models with relatively fast responses are also good alternatives [7], some authors have suggested that the Gaussian modeling may be of interest for decisions in the initial phase of the event [1, 8, 9].

An additional contribution may be represented by the ability to use local climatic conditions, represented by the Pasquill-Gifford atmospheric stability classes [10], to evaluate the evolution of the potential consequences. This evaluation may be of interest if it is associated with the type of release (explosion or non-explosive mechanical release). Decision-makers can rely on the support provided by comparing simulation results, thus enabling a more realistic threat-assessment to be made.

In general, simulation studies via computational platforms suggest improvements in the applied methods, whether from a mathematical or system perspective. In many cases, simulations are applied to a real scenario and assessments can help to clarify problems, improve decision strategies, and even help identify errors that can be avoided in the future. In a slightly more general approach, this work seeks to apply existing methods accepted by the scientific community to general scenarios. The study was conducted in this way so that the focus was always on its creative application. In this way, the HotSpot program was used without the concern with implementing improvements in its programming, although attention was paid to the results aiming to verify any divergences in relation to theoretical predictions about the studied phenomena. The fact that generic scenarios are treated without the intention of comparison, as already mentioned, the input data are not related to a specific location and the results are not compared to other available values in the literature.

METHODOLOGY

The radiation released to the environment is a key parameter in assessing the radiation dose. This information was considered during the simulation using HotSpot Health Physics software 3.0.3. The program provides a first-order approximation of the radiation effects associated with the atmospheric release of radioactive materials. More accurate predictions are to be expected for short-range simulations (less than 10 km) in the near future (less than a few hours in advance) [6]. Its calculations are based on a Gaussian model, which is suitable for immediate support to decision-making [6]. Hence, providing accurate results for the period of 48 hours from the incident, as required.

The simulation of the event scenario was performed considering the possibility of triggering the RDD either by a general explosion (GE) or by mechanical release (general – GP). Once the scenarios were simulated two major results were obtained: the area of the contamination plume and its dependence on the Pasquill-Gifford classes as a function of the observation time, and the collective dose of radiation based on the TEDE. The HotSpot output dose values, due to plume passage, have always included the cloud submersion effective dose equivalent with the inhalation committed effective dose equivalent (CEDE). The TEDE is considered as the sum of CEDE (inhalation) and effective dose equivalent (submersion) [6]. The code provides the TEDE, for a whole-body exposure that an individual present in a particular position absorbs after a specified time. Measurements were taken at 18 different points of the plume, six for each dose limit taken along the main axis. This procedure enabled the recording of an average dose value for each dose limit. Subsequently, this average was multiplied by the population size, which was estimated by multiplying plume area and local population density.

Those key parameters are then used, respectively, as input for the calculation of the potentially affected population size and the detriment cost. The input data provided to HotSpot calculations were: source material: ^{137}Cs; Material-at-Risk (MAR): 3.7 10^{14} Bq; respirable fraction: 0.200; respirable source term: 7.40 10^{13} Bq; non-respirable source term: 2.96 10^{14} Bq; wind speed (h = 10 m): 3.00 ms^{-1}, for it represents the wind speed occurring in all Pasquill-Gifford atmospheric stability classes [10]; High Explosive: 25.00 Pounds of TNT; Stability Class: A to F; Receptor Height: 1.5 m; Distance Coordinates: All distances are measured along the centerline of the plume.

The size of the potentially affected population is estimated by multiplying the area of the contamination plume by the local population density of a large city center, typically considered as 10000 inhabitants per km². Similarly, the detriment cost, due to the exposure of individuals of the public to environmental radiation, is calculated by multiplying the collective dose by the convenient monetary factor, here considered as the US $ 10000 [11]. The collective dose is the sum of the individual doses absorbed during a given period by a specified population. It is calculated by multiplying the mean value of the dose provided by Hotspot for each location inside the plumes. The collective dose is expressed in *person x sievert* (man-Sv). Since the 1980, in quantitative optimization evaluations, experts recommended for the value of the monetary coefficient per unit of collective dose not to be lower than the national currency equivalent to US$ 10000 per unit of collective dose per individual [12-14].

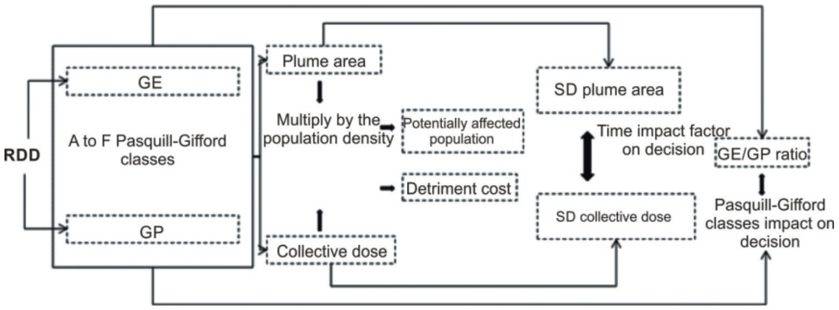

Figure 1. Summary of the methodology used in this work

The concept of detrimental cost, which derives from the collective dose, is defined as the cost of injury obtained per unit dose received by each individual. Or the total health damage experienced by a group exposed to a radiation source. It is a multidimensional concept. The ICRP in its publication No. 22 [9] suggests that it would be useful to express the collective dose assessment in monetary units. Thus, the advantage of reducing the collective dose can be compared directly against the cost to produce such a reduction.

Examples of values suggested by the ICRP are: developed world: US$ 20000, Japan: US$ 25000, and Brazil: US$ 10000 [9]. The detriment cost Y was calculated by the relation $Y = \alpha S$, where S is the collective dose in men-sieverts, and α is the monetary factor expressed by (US$/(individual x sievert).

The scenario was simulated considering two possibilities: GE, which considers the use of conventional explosives in the RDD, and GP, where the release is done without the use of explosive means. The simulated data for both GE and GP, organized and shown in figs. 2 and 3, convey both dependences on time and the Pasquill-Gifford atmospheric stability classes. This led to the idea of choosing key parameters that could be used to quantitatively describe the development of the event scenario as a function of time for each Pasquill-Gifford class. Time (at 1, 6, 12, 24, and 48 hours intervals) and atmospheric stability classes (A to F) were considered as variables.

To study the effects of the release mode (GE or GP) on the development of the scenario, the ratio (R = = GE/GP) was used for evaluation of plume expansion, potentially affected population, dose, and cost of detriment. All variables are linearly related to each other as they result from the multiplication by a constant.

The release type (either GE or GP) can lead to different demands in terms of the strategic support to the emergency response. The R-factor can assume the set of values in the ranges: $R > 1$, $R = 1$, and $R < 1$. The $R < 1$ range indicates that the GP release (denominator) is more important for the observed atmospheric stability class. Using the same rationale, $R > 1$ indicates greater influence for GE (numerator). For $R = 1$, the release mode is indifferent. Therefore, the R-factor can drive decision-makers towards a strategic approach.

Time variations within the same atmospheric stability class can be observed regarding the standard deviation (SD), which can be directly used to evaluate the impact of the time on each Pasquill-Gifford class background for a release. However, it is important to note that it is necessary to calculate SD only for the plume area and the collective dose variables. That is due to the significant correlation between them, the potentially affected population, and the cost of detriment. Figure 1 illustrates the methodology used in this work.

RESULTS

Figure 2 shows the calculated values for simulated GE type of release: (a) area of the contamination plume, (b) potentially affected population, (c) collective dose of radiation, and (d) cost of detriment. All are provided as a function of the Pasquill-Gifford atmospheric stability classes and time.

Figure 3 shows the calculated values for the simulated GP type of release: (a) plume area, (b) potentially affected population, (c) collective dose of radiation, and (d) cost of a detriment as a function of the Pasquill-Gifford atmospheric stability classes and time.

Table 1 shows the ratio, R, between the values for GE and GP (GE/GP) for (a) plume area and (b) collective dose.

Figure 4 shows the SD for each Pasquill-Gifford atmospheric stability class as a function of time for the plume area and collective dose.

DISCUSSION

The effects and possible consequences of the radioactive material released in the environment are functions of time and Pasquill-Gifford atmospheric stability classes. It is important to note that this paper does not consider PG class' variations throughout the event. A more realistic approach might also include this evolution mode for dispersion of the contaminated plume in the environment.

Data for the GE release type, fig. 2, indicate that there is a more pronounced increase in the size of the

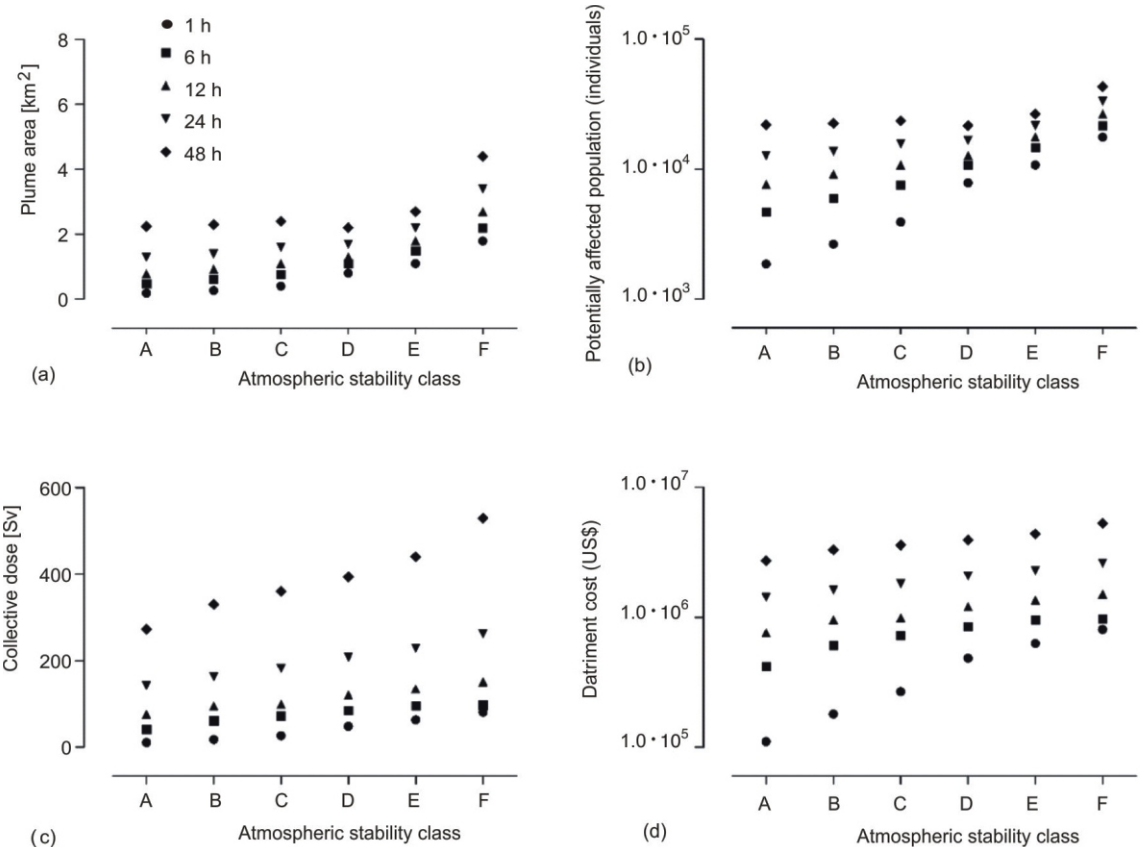

Figure 2. Calculated values for simulated GE type of release as a function of the Pasquill-Gifford atmospheric stability classes and time: (a) plume area, (b) potentially affected population, (c) collective dose of radiation, and (d) cost of detriment

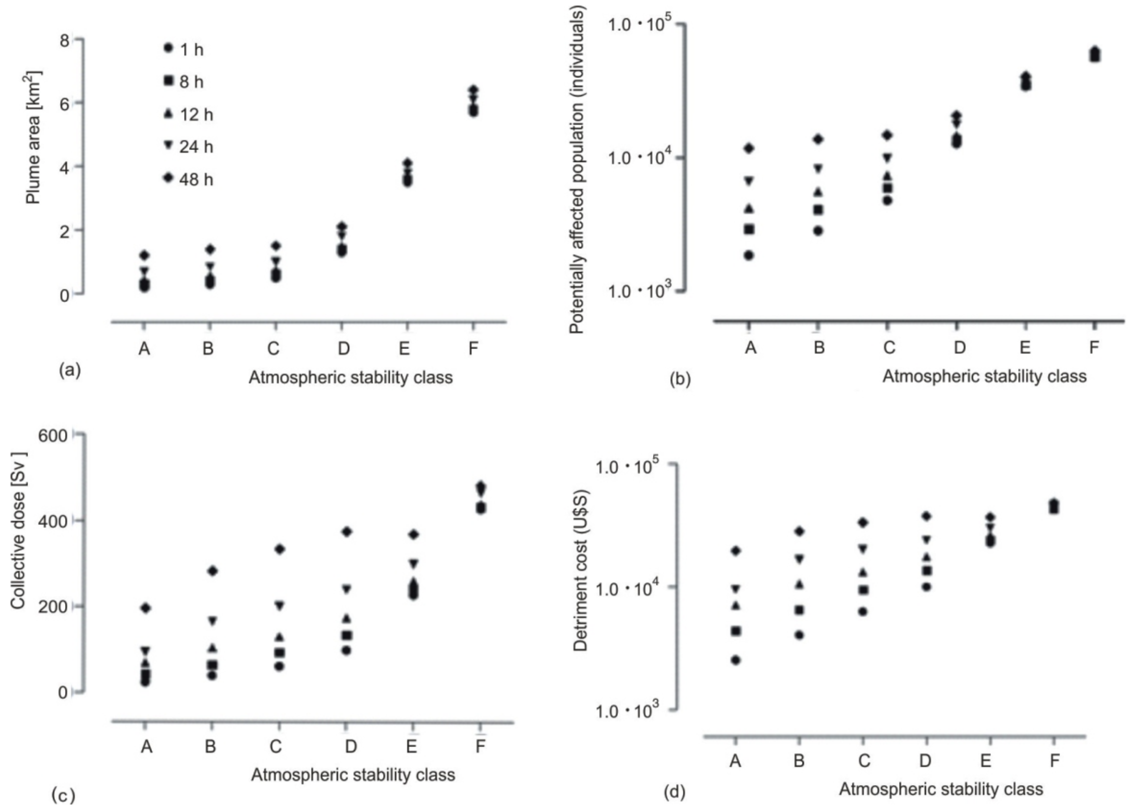

Figure 3. Calculated values for simulated GP type of release as a function of the Pasquill-Gifford atmospheric stability classes and time, (a) area of the plume, (b) potentially affected population, (c) collective dose of radiation, and (d) cost of detriment

Table 1. Dose ratios, *R* for GE and GP (GE/GP)

Atmospheric stability class (Pasquill-Gifford)	Ratio, *R* – GE/GP		
	Time [h]	Area [km²]	Collective dose [Sv]
A	1	1.000	0.434
	6	1.600	0.952
	12	1.814	1.077
	24	1.912	1.495
	48	1.867	1.385
B	1	0.931	0.445
	6	1.452	0.938
	12	1.632	0.901
	24	1.667	0.982
	48	1.643	1.164
C	1	0.816	0.426
	6	1.262	0.765
	12	1.467	0.754
	24	1.600	0.903
	48	1.600	1.078
D	1	0.615	0.486
	6	0.786	0.624
	12	0.867	0.691
	24	0.944	0.867
	48	1.048	1.046
E	1	0.314	0.275
	6	0.417	0.398
	12	0.500	0.518
	24	0.579	0.764
	48	0.659	1.191
F	1	0.316	0.188
	6	0.379	0.225
	12	0.458	0.344
	24	0.557	0.563
	48	0.688	1.099

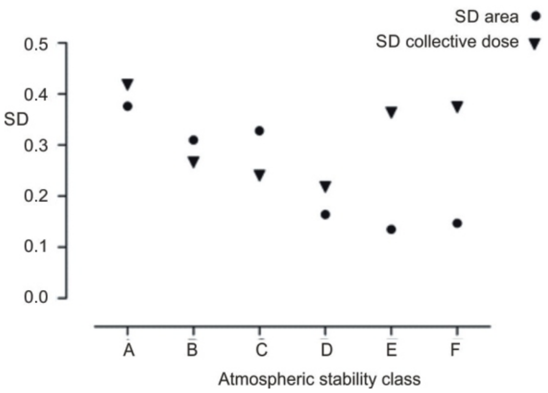

Figure 4. The SD with respect to time for each Pasquill-Gifford atmospheric stability class

contamination plume for atmospheric stability classes E and F, considering the same interval of time elapsed since the explosion. Similar behavior is shown in the simulated results for atmospheric stability classes A, B, and C.

The size of the potentially affected population is a result of the multiplication of the projected transversal area of the radiation plume by the local population density, which is considered constant in this paper. Thus, that parameter depends on the contaminated area, as well as on the prevailing atmospheric stability classes that could undergo changes as the plume expands. This fact implies the existence of a direct relationship between local atmospheric conditions and the number of people potentially affected by the contamination.

The collective dose parameter shows an increasing trend as the Pasquill-Gifford class ranges from A to F. The finding is relevant for decisions concerning the potentially affected population, such as the need for sheltering and relocation, during the first stages of the response. The present results could help determine which atmospheric stability class has the greatest impact on the collective dose. The cost of detriment is obtained from the collective dose, hence changes in the detriment cost can be correlated to changes in the collective dose. Both as a function of the atmospheric stability classes, but also as a function of time. Taking into consideration the variation within a single atmospheric stability class. This internal stability can be monitored by the SD for each Pasquill-Gifford stability class, and each release mode (GE or GP).

For GP release type, (results shown in fig. 3) there is similar behavior of the calculated values in relation to the atmospheric stability classes. However, there are also significant variations in the spread of the simulated data for each class when examined with reference to time variations. Considering that the plume area and the collective doses are to be used as input data for the calculation of the potentially affected population, and the cost of detriment. Table 1 was prepared for providing an improved evaluation of the phenomenon, including the ratio *R* between GE and GP, presented in the methodology.

Thus, an evaluation of the *R* values presented in tab. 1 and SD of the values of differences concerning time for plume areas and collective doses presented in fig. 4, suggests that:

– For atmospheric stability class A: the elapsed time of the 1h event presents the only point in which the type of release of radioactive material to the environment is indifferent (R = 1). Considering the variable plume area, for all times, except 1 hour, R > 1, suggests that the GE release type has a preference for damage generation regardless of the Pasquill-Gifford atmospheric stability class. However, for the collective dose variable, the preponderance of the GE release type appears only after 6h of the event. Before that, GP release type is determinant. This finding suggests that the reaction time for response depends on the release type.
– For atmospheric stability classes B and C: the plume area changes significantly in 1 hour, presenting a tendency for damage preference for GP release type (R < 1). For the remaining times R > 1, indicating that GE release type is preferred for damage generation. For the collective dose variable, the preponderance of GP release type is for all times (R < 1), this preference being more ac-

centuated for 1 hour. However, for class C in 48 hours, the GE release type is more important.

– For atmospheric stability class D: for both the plume and the collective dose variable, there is a damage preference for the GP release type ($R < 1$). Except for 48 hours, when both present a GE release type equally preponderant for damage generation. This result suggests that for atmospheric stability classes B and C, decisions involving the parameters: area of the plume and collective dose, have a time limit of 48 hours in cases when the type of release is not known.
– For atmospheric stability classes E and F and both parameters: plume and collective dose, there is a preference for damage in the GP release type ($R <$ 1). Except for the collective dose after 48 hours, when it presents GE release type as preponderant for damage.

Another set of parameters supporting the RDD event scenario evaluation is presented in fig. 4 and refers to the SD of the GE/GP ratio with respect to time for each Pasquill-Gifford class. The quantity SD allows estimating with reasonable accuracy the consistency of data related to the temporal variations within the same class of atmospheric stability.

Considering the expanding area of the contamination plume, as depicted in fig. 4, atmospheric stability classes A, B, and C are associated with faster changes. Atmospheric stability classes D, E, and F are less sensitive to time changes, may offer temporal advantage and flexibility for actions within the same scenario. The change from one PG class to another impacts the number of potentially affected individuals, which changes not only with time but also with the atmospheric stability classes.

Considering how the collective dose is distributed, fig. 4 shows that atmospheric stability classes A, E, and F exhibit greater changes as a function of time. On the other hand, classes B, C, and D are less sensitive. Under the same conditions, class D can be associated with the lowest sensitivity of scenario conditions as a function of time, which facilitates the estimation of the detriment cost. Lower variations within the same atmospheric stability class suggest greater stability of the variable and less temporal bond, usually tending to make decision requirements less stringent.

CONCLUSION

A simulation of event scenarios and evaluations of the respective results were performed considering two types of radiation release (GE and GP). The results were mostly discussed in terms of two major parameters: contaminated area, and collective dose. They also suggest the possibility of significant correlations between atmospheric stability classes in event scenarios where they evolve over time, producing alternations between them. It has been verified that there are non-uniform temporal evolutions within the same atmospheric stability class, for the variables studied. This latter finding offers the possibility of modeling adequate responses based on temporal evolutions, assuming the Pasquill-Gifford atmospheric stability class remains constant. The findings from this study may be an important piece of information for determining an effective response strategy.

AUTHORS' CONTRIBUTIONS

The simulations of atmospheric dispersion and organization of the results were conducted by P.U.N. Oliveira. The research plan, calculation of the estimated dose, and cost of detriment in the simulated scenario were carried out by E. R. Andrade, P. U. N. Oliveira, U. C. Oliveira, and M. Prah. Theoretical and written revision of the final text was done by A. X. Silva, R. M. Stenders, and H. C. Vital. The writing of the final text and follow-up as a correspondent was the responsibility of E. R. Andrade.

ACKNOWLEDGMENT

This work was supported by the Brazilian National Council for Scientific and Technological Development (CNPq Grant PQ n° 305463/2020-9).

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Received on November 6, 2019
Accepted on December 21, 2020

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МОДЕЛОВАНО ОСЛОБАЂАЊЕ РАДИОЛОШКО ДИСПЕРЗИЈСКОГ УРЕЂАЈА И УТИЦАЈ НА ДОНОШЕЊА ОДЛУКА У УРБАНОМ ОКРУЖЕЊУ

Уређај за радиолошку дисперзију је оружје које комбинује радиоактивни материјал са конвенционалним експлозивима за ширење радиоактивног материјала по насељеном месту. Рад је усредсређен на процену кључних параметара сценарија са радиолошко дисперзијским уређајем. Прорачуни су изведени како би обухватили две различите ситуације: коришћење експлозива и једноставно механичко ослобађање. Симулације су спроведене уз употребу HotSpot Health Physics кодова. Резултати сугеришу постојање значајних корелација између класа стабилности у сценаријима који се развијају с временом, производећи алтернације између њих. Све док класа стабилности остаје константна, овај последњи податак нуди могућност стварања одговарајућег одзива заснованог на временским еволуцијама. Стога је сврха истраживања да процени величину потенцијално погођене популације, процени апсорбоване дозе и исплативост, како би се помогло иницијалним одзивима, пружајући временски осетљиве информације о догађају. Методологија способна да пружи корисне информације омогућава ефикасно доношење брзих одлука и почетних процена будућих ризика. Овај приступ такође може пружити подлоге за обуку особља одговорног за доношење одлука у раној фази одзива.

Кључне речи: атмосферска дисперзија, загађење, зрачење, исплативост