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Study of the Effect of Weather, Topography and Radionuclide on the TEDE in a Fire Scenario Involving a Dispersion of a Plume in the Atmosphere

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Abstract: Accidental release of radioactive substances is a major concern especially for emergency and rescue personal. Atmospheric dispersion of these releases can cause local or extended contamination that affect people and environment. The magnitude of these radioactive releases depends on several factors such as weather, nature of the source and topography area. This paper aims to assess, in emergency phase, the dosimetric consequences in terms of Total Effective Dose Equivalent (TEDE) caused by a plume following a fire that occurred in a steel foundry. The dispersion modeling is performed using a Gaussian model. The TEDE is assessed by varying weather conditions, the nature of the radioactive source and the type of topography area in which the fire occurred.

Key words: Gaussian model · Topography area · Conditions · The nature · Affect people and environment

INTRODUCTION

The threat of radiological accidents have caused a significant reflection in the world especially accidents that lead to the dispersion of the plume in the atmosphere. This dispersion can cause serious radiological and dosimetric consequences for the population and the environment. These consequences will vary depending on several factors: the effective dose, the nature of the source of radiation (alpha, beta, gamma), weather conditions (wind, stability class) and the terrain (urban, rural). To evaluate these consequences, dispersion model that allows assessing the short-term impact of atmospheric releases is used. The model used in this study is the Hotspot (version 2.07.2, August 31, 2011) developed by LLNL (Lawrence Livermore national laboratory) and recommended by NARAC (National Atmospheric Release Advisory Center) [1]. Several simulations were carried out choosing a scenario of accident causing the dispersion of a plume sequel to a fire that occurred in a steel foundry. The aim is to show the effect of weather, nature of radionuclide and topography on the TEDE to serve as a tool for decision support and to propose appropriate actions to protect population and environment.

Radiological Dose: Radiation is a form of energy that can damage a tissue. Basically the ionizing radiations affect the structure of the molecule by ionizing its constituent atoms. As a result, the cell to which the molecule belongs is damaged. If genetic material in the cell, deoxyribonucleic (DNA) is affected then the behavior of the cell is altered. These effects on tissue are proportional to the energy deposited in the tissue. The ionizing radiation is classified according to its interaction with matter.

The quantification of radiation effects on human body (dose) is based on the concept of three pyramids as proposed by International Commission of Radiological Protection (ICRP). The first is the absorbed dose, it is the energy absorbed per mass unit. The second one is the equivalent dose which indicates not only the energy absorbed but also the harmful biological effect it can produce. The use of equivalent dose becomes necessary as for the same absorbed dose; the biological effects will be different for alpha, beta and gamma radiations. The third one is called Total Effective Dose Equivalent (TEDE) which is actually the sum of the equivalent doses to the individual organs weighted to take into account their sensitivities.

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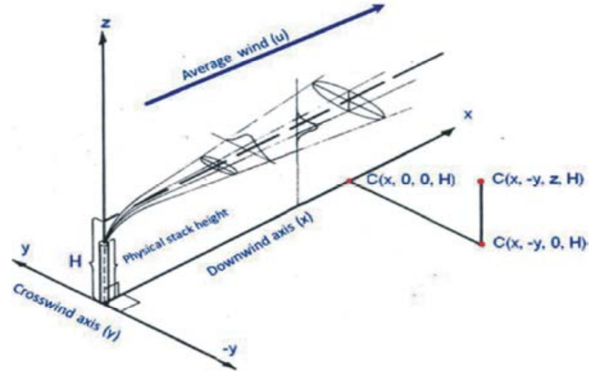

Fig. 1: Representation of the dispersion according to the Gaussian plume model.

Atmospheric Dispersion of Radioactive Substances: In the event of a release of radioactive substances into the atmosphere, the dispersion occurs depending on weather conditions, resulting in contamination of the environment and the population. This dispersion also depends on several parameters such as the release conditions (release height from the ground, the leak rate), topography (soil, presence of obstacles) and the nature of the source.

In order to assess the potential consequences of such an accidental release we use the modeling of atmospheric dispersion. The three processes to take into account in this model are transport, diffusion and deposition to the ground of the radioactive substance. To determine the concentration of the radioactive cloud, we use the following equation of advection-diffusion [2-5]:

$$\frac{\partial c}{\partial t} + \underbrace{div(\mathrm{u}c)}_{Advection} - \underbrace{div(\mathrm{K}\nabla c)}_{Diffusion} - \alpha c = Q$$

where:

C (x, t) is the volumetric concentration of activity and is expressed in Bq.m^{-3}.
Q(x,t) is the source term.
u is the wind speed in m.s^{-1}.
α represents the loss process.
K is a matrix of turbulent diffusion.

The Gaussian Model: Gaussian model is used to describe the dispersion of a gas or an Aerosol assuming only the action of air as carrier fluid. Transport and diffusion of gas depend on the wind and mechanical and thermal air turbulence. It is used for modeling the dispersion of pollutants over a few hundred meters to a few kilometers. It requires meteorological data such as wind speed and direction, atmospheric stability conditions, topography type and data related to the nature and the quantity of the source dispersed.

Description of the Hotspot Code: Hotspot model provides a first order approximation of radiation effects due to the atmospheric dispersion of radioactive substances. This code was developed by LLNL (Lawrence Livermore National Laboratory) and recommended by NARAC (National atmospheric release advisory center). It's intended primarily for emergency response teams and planners to radiological and nuclear emergencies and it has capabilities of modeling several accident scenarios by displaying areas and contaminated surfaces [1]. The code is based on a Gaussian approach to calculate the concentration by resolving the following equation:

$$\mathrm{C}\left(\mathrm{x,y,z,H}\right)=\frac{\mathrm{Q}}{2\mathrm{p}\sigma_{\mathrm{y}}\,et\,\sigma_{\mathrm{z}}\mathrm{u}}\exp\left[-\frac{1}{2}\left(\frac{\mathrm{y}}{\mathrm{s}_{\mathrm{y}}}\right)^{2}\right]\left\{\exp\left[-\frac{1}{2}\left(\frac{\mathrm{z\text{-}H}}{\mathrm{s}_{\mathrm{z}}}\right)^{2}\right]+\exp\left[-\frac{1}{2}\left(\frac{\mathrm{z+H}}{\mathrm{s}_{\mathrm{z}}}\right)^{2}\right]\right\}\exp\left[-\frac{\lambda\mathrm{x}}{\mathrm{u}}\right]\mathrm{DF(x)}$$

where:

C is concentration (Ci.s/m3),
Q is source term (Ci),
H is release height (m),
λ is decay constant(s-1),
x and **y** are horizontal coordinates (m) and **z** is vertical coordinate (m),
σ (y, z) is the standard deviation,
u is the average wind speed at the effective release height (m/s),
DF (x) is the attenuation factor of the plume (depend on x).

Study of a Radiological Accident Scenario: Fire Involving the Dispersion of Radioactive Material: The aim is to study a radiation accident scenario involving the dispersion of different radioactive sources in the atmosphere due to the fire occurred under certain weather conditions, in area with different type of topography. The impact on the value of the TEDE will be evaluated. The modeling tool that will be used is the Gaussian dispersion model Hotspot described previously. The scenario we chose is a fire that occurred in a steel foundry where a radioactive capsule was melted causing the dispersion of a plume in the atmosphere and in a wide geographical area occupied by a large population. This accident was caused by a failure of control in the steel scrap.

Initial Data: In this scenario, we study several simulations that occur in different weather conditions. The atmospheric stability is taken according to Pasquill Classification. Three types of radioactive sources are involved in the plume dispersion: Cs-137, Co-60 and Am-241 with an amount activity of 3.7 10^{+12} Bq. The dispersion of these radionuclides occurred in two types of terrain: standard terrain characterized by a low roughness length (0.01 to 0.1 meters: flat terrain, agricultural terrain, Plain with scattered trees…) and urban terrain characterized by high roughness length (city, industrial sites, important buildings, forests, scattered houses…) [3].

RESULTS

The simulations results of various radiological accident scenarios are presented in Table 2 and Table 3.

DISCUSSION

The Figures 2 (a) to (f) shows that TEDE behaves in the same way considering one radioactive source (^{137}Cs) and different stability classes or wind speed.

From Table 2 summarizing the situation shown by the Figures 2 (a) to (f), we conclude that the worst case in terms of TEDE is obtained at a very unstable atmosphere and low wind. The maximum TEDE is reached at about 7km from the point of release in stable weather conditions and at 200m in the case of unstable weather conditions independently of wind speed.

Table 1: Radiological characteristics of Am-241, Co-60 and Cs-137 radionuclides

	Période (y)	Alpha keV	%	Beta max keV	%	Gamma keV	%
Am-241	432.7	5388	1. 4			59.5	35.9
		5442.9	12.8				
		5485.6	85.2				
Co-60	5.27			317.9	99.92	1173.25	99.89
						1132.5	99.98
Cs-137	30.15			511.5	94.6	661.6	85.2

Table 2: TEDE (Sv) as a function of the distances from the release point for different Pasquill stability classes (F, C and A) and different wind speed (2-5 and 10m/s) for the Cs-137 radionuclide in standard terrain

	Total Effective Dose Equivalent (TEDE) in Sv								
	Wind speed=2m/s			Wind speed=5m/s			Wind speed=10m/s		
Distance (km)	Stability class F	Stability class C	Stability class A	Stability class F	Stability class C	Stability class A	Stability class F	Stability class C	Stability class A
0.1	0.00E+00	1.30E-09	5.90E-08	0.00E+00	5.40E-10	2.40E-08	0.00E+00	2.70E-10	1.20E-08
0.2	0.00E+00	2.30E-08	1.20E-07	0.00E+00	9.30E-09	4.70E-08	0.00E+00	4.70E-09	2.30E-08
0.3	0.00E+00	5.90E-08	9.70E-08	0.00E+00	2.30E-08	3.90E-08	0.00E+00	1.20E-08	2.00E-08
0.4	0.00E+00	8.00E-08	7.20E-08	0.00E+00	3.20E-08	2.90E-08	0.00E+00	1.60E-08	1.50E-08
0.5	0.00E+00	8.70E-08	5.40E-08	0.00E+00	3.50E-08	2.20E-08	0.00E+00	1.80E-08	1.10E-08
0.6	0.00E+00	8.50E-08	4.10E-08	0.00E+00	3.40E-08	1.60E-08	0.00E+00	1.70E-08	8.30E-09
0.7	8.80E-18	7.90E-08	3.20E-08	3.50E-18	3.20E-08	1.30E-08	1.80E-18	1.60E-08	6.50E-09
0.8	6.60E-16	7.20E-08	2.60E-08	2.70E-16	2.90E-08	1.00E-08	1.30E-16	1.50E-08	5.20E-09
0.9	1.50E-14	6.50E-08	2.10E-08	5.90E-15	2.60E-08	8.50E-09	2.90E-15	1.30E-08	4.30E-09
1	1.50E-13	5.80E-08	1.70E-08	5.90E-14	2.40E-08	7.10E-09	2.90E-14	1.20E-08	3.50E-09
2	4.60E-10	2.30E-08	4.90E-09	1.90E-10	9.50E-09	2.00E-09	9.30E-11	4.80E-09	1.00E-09
3	2.40E-09	1.20E-08	2.30E-09	9.70E-10	5.10E-09	9.50E-10	4.80E-10	2.60E-09	4.80E-10
4	4.10E-09	7.80E-09	1.40E-09	1.70E-09	3.30E-09	5.60E-10	8.40E-10	1.70E-09	2.80E-10
5	5.20E-09	5.50E-09	9.00E-10	2.10E-09	2.30E-09	3.70E-10	1.10E-09	1.20E-09	1.90E-10
6	5.60E-09	4.10E-09	6.50E-10	2.30E-09	1.80E-09	2.70E-10	1.20E-09	9.00E-10	1.40E-10
7	5.80E-09	3.30E-09	4.90E-10	2.40E-09	1.40E-09	2.00E-10	1.20E-09	7.20E-10	1.00E-10
8	5.80E-09	2.70E-09	3.80E-10	2.40E-09	1.20E-09	1.60E-10	1.20E-09	5.90E-10	8.10E-11
9	5.70E-09	2.30E-09	3.10E-10	2.40E-09	9.70E-10	1.30E-10	1.20E-09	5.00E-10	6.60E-11
10	5.60E-09	2.00E-09	2.60E-10	2.30E-09	8.40E-10	1.10E-10	1.20E-09	4.30E-10	5.50E-11
11	5.40E-09	1.70E-09	2.20E-10	2.30E-09	7.30E-10	9.20E-11	1.20E-09	3.80E-10	4.70E-11

A: Extremely Unstable C: Slightly Unstable F: Moderately Stable

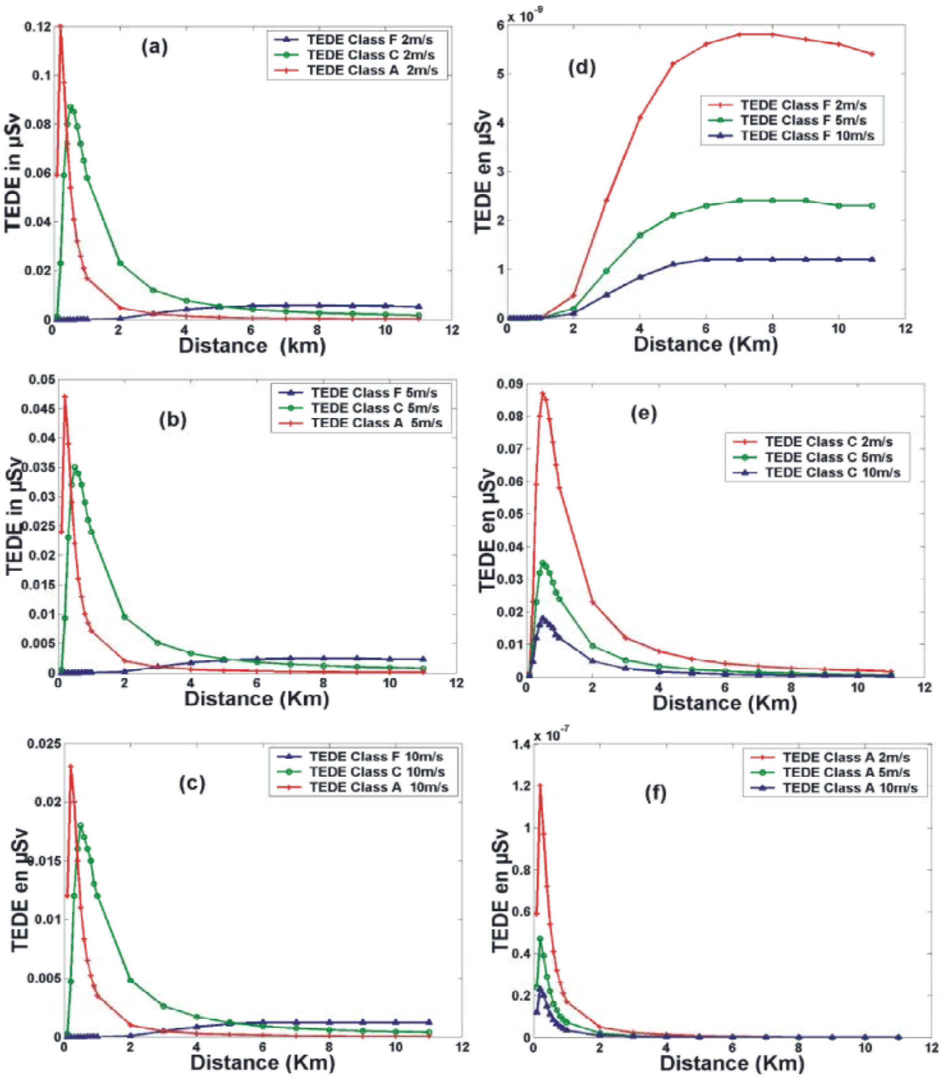

Fig. 2 (a) to (f). TEDE (µSv) vs. distance from the release point for different Pasquill stability classes (F, C and A) and wind speed (2-5 and 10 m/s) of the Cs-137.

As regards the type of the radioactive source (Table 1), Figure 3 shows that the type of radioactive source has also a significant influence on the TEDE at different distances from the release point. Indeed, the values of the TEDE caused by an alpha emitter (Am-241) are higher than those caused by beta and gamma emitters (Co-60, Cs-137) at the same dispersion conditions. This can be explained by the difference of the emission (alpha, beta or gamma) and their energy deposition.

The plume that occurred in urban terrain has a higher TEDE than in standard area for the same source at the same distance downwind and the same condition of dispersion. This can be explained by the fact that the presence of obstacles increases the local turbulence and instability which increases the values of TEDE for distances relatively close to the point of release. We also found that in a standard area, radiological effects in terms of effective dose caused during atmospheric dispersion, begins from a distance of about 700m downwind from the point of release and reach the maximum at about 7km for the three sources considered, while in urban area, radiological effects begins from a distance of about 200m and reach the maximum at about 1km. (Table 3 and Figure 3)

The TEDE decreases rapidly as a function of distance in the case of urban terrain than in the case of a standard area. This can be explained by the attenuation caused by the presence of obstacles in urban area.

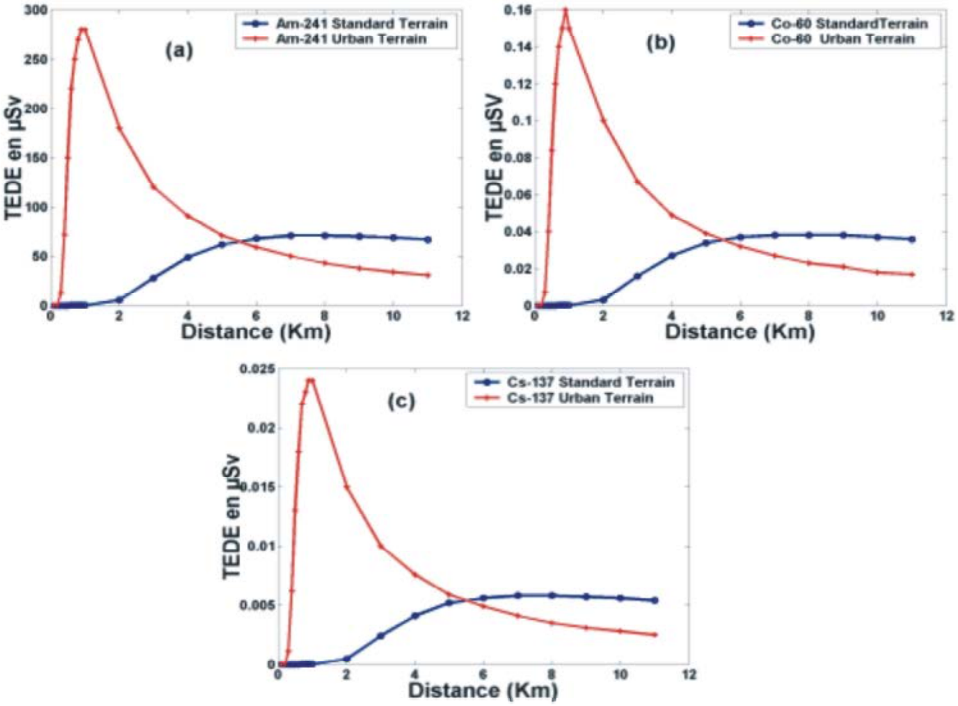

Fig. 3: TEDE (Sv) at different distances from the release point for Am-241, Co-60 and Cs-137 in two different topographies: standard and urban.

Table 3: TEDE (Sv) at different distances from the release point for sources (Am-241, Co-60, Cs-137) in two different area topography (Standard and Urban) with 2 m/s wind speed and stability class F

	Total Effective Dose Equivalent (TEDE) in Sv					
	Standard area			Urban area		
Distance (km)	Am-241	Co-60	Cs-137	Am-241	Co-60	Cs-137
0.1	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
0.2	0.00E+00	0.00E+00	0.00E+00	9.40E-08	5.20E-11	8.00E-12
0.3	0.00E+00	0.00E+00	0.00E+00	1.30E-05	7.20E-09	1.10E-09
0.4	0.00E+00	0.00E+00	0.00E+00	7.20E-05	4.00E-08	6.20E-09
0.5	0.00E+00	0.00E+00	0.00E+00	1.50E-04	8.40E-08	1.30E-08
0.6	1.90E-16	0.00E+00	0.00E+00	2.20E-04	1.20E-07	1.80E-08
0.7	1.00E-13	5.70E-17	8.80E-18	2.50E-04	1.40E-07	2.20E-08
0.8	7.70E-12	4.30E-15	6.60E-16	2.70E-04	1.50E-07	2.30E-08
0.9	1.70E-10	9.60E-14	1.50E-14	2.80E-04	1.60E-07	2.40E-08
1	1.70E-09	9.60E-13	1.50E-13	2.80E-04	1.50E-07	2.40E-08
2	5.40E-06	3.00E-09	4.60E-10	1.80E-04	1.00E-07	1.50E-08
3	2.80E-05	1.60E-08	2.40E-09	1.20E-04	6.70E-08	1.00E-08
4	4.90E-05	2.70E-08	4.10E-09	9.10E-05	4.90E-08	7.60E-09
5	6.20E-05	3.40E-08	5.20E-09	7.10E-05	3.90E-08	5.90E-09
6	6.80E-05	3.70E-08	5.60E-09	5.90E-05	3.20E-08	4.90E-09
7	7.10E-05	3.80E-08	5.80E-09	5.00E-05	2.70E-08	4.10E-09
8	7.10E-05	3.80E-08	5.80E-09	4.30E-05	2.30E-08	3.50E-09
9	7.00E-05	3.80E-08	5.70E-09	3.80E-05	2.10E-08	3.10E-09
10	6.90E-05	3.70E-08	5.60E-09	3.40E-05	1.80E-08	2.80E-09
11	6.70E-05	3.60E-08	5.40E-09	3.10E-05	1.70E-08	2.50E-09

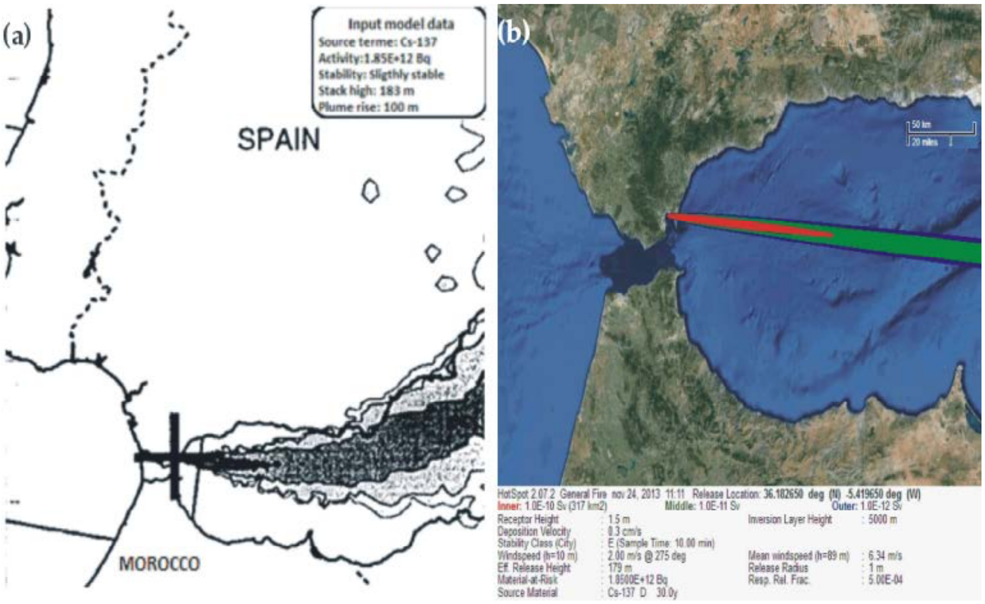

Fig. 4: TEDE values as a function of distance downwind as result of simulations of accidental plume of Cs-137 occurred at Algeciras in 1998 using a Lagrangian model **(a)** and Gaussian model **(b).**

Table 4: TEDE max for different wind speed, stability class and reaching distance

	TEDE max in µSv		Distance (km)	
Stability Class \ Wind velocity (m/s)	2	5	10	
A	0.12	0.047	0.023	0.2
C	0.087	0.035	0.018	0.5
F	0.0058	0.0024	0.0012	7

Table 5: Input data used by ARAC

Dispersion model	Lagrangien
Radioactive material	Cs-137
Release amount	1,85.10^{+12} Bq
Stability class	Slightly stable (E)
wind average speed	2 m/s
Stack high	100 m
Cloud top	283 m
Receptor height	1,5m

Method Validation: In order to validate the previous results that obtained by Hotspot, we choose a case of a radiological accident that occurs in 1998 at Algesiras in Spain where an amount of Cs-137 has been dispersed in the atmosphere from a steel mill and that led to a radiological emergency following the advection of the plume to several European countries. Fortunately the release was too small to produce any plausible health effects [6]. We have simulated this case using the Gaussian model Hotspot and we proceed to compare our results with the results obtained by the Atmospheric Release Advisory Capability (ARAC).

The ARAC is a real-time emergency response organization that evaluates effects from releases of hazardous material to the atmosphere (Sullivan *et al*. 1993). Located at University of California's Lawrence Livermore National Laboratory, ARAC's primary function is to support the Department of Energy (DOE) and Department of Defense (DOD) for radiological releases.

The data used are those used by ARAC in the simulation of the accident using a Lagrangian dispersion model [6] (Table 5).

The Figure 4 (a) and (b) shows the result of the two simulations. The area where the TEDE values are greater than 1.0E-10Sv (Dark (a) and Red (b)) is relatively similar between the two simulations. We can conclude that Gaussian model Hotspot can be used as tools to better estimate radiological dose in the emergency phase of the accident radiological.

CONCLUSION

In this work, we have studied an accident scenario causing a dispersion of radioactive substances into the atmosphere following a fire that occurred in a steel foundry. The dosimetric evaluation in the emergency phase of an area affected by the accident involving the release of radioactive cloud is mainly done using Gaussian Hotspot model which is recommended by a number of specialized agencies. The simulations studied allowed us to obtain several important results, showing that during the dispersion of a radioactive release, the weather conditions and topography area and the nature of the radioactive source have a significant influence on the TEDE received by people exposed at different distances from the point of release downwind. Indeed results show that the transition from stable to unstable conditions, with low wind speed causes a significant increase in values of the TEDE. The plume that occurred in urban area can cause higher values of TEDE than in a standard area. We found also that the TEDE caused by alpha emitting source is higher than that caused by a beta/gamma source considering the same distance and weather conditions. The results obtained in the present work using Hotspot were validated applying the same method to simulate a well known accident and compare the simulation results to another method used by ARAC. These results will allow the emergency services to know the radiological risk to which population is exposed to and to act quickly and efficiently.

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