Analysis of hazard areas associated with toxic cloud releases by pipelines

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Abstract

The consequence assessment of a major accident involving a release of toxic gas by a pipeline is usually performed through the evaluation of the associated hazard area, which is an area where the concentration of the toxic substance exceeds a fixed threshold level and induces harmful effects in people and the environment; its extension represents a significant source of information required for the development of both safety and security strategies associated with dangerous pipelines. Since the threshold level adopted in the calculation strongly affects the extent of this hazard area, the purpose of this paper is to analyse such influence and the potential implications on the decisional process concerning prevention, preparedness and response actions in the case of major accidents. The paper describes the methodological approach adopted for this purpose, as well as the main results obtained using the threshold levels most commonly applied in the industrialized countries. Although the estimate of the hazard areas involves a high level of uncertainty, this study aims at supporting the development of pipeline safety and security strategies, thus increasing the overall safety level in this vital sector.

Keywords: major accident, toxic cloud dispersion, consequence assessment, pipeline safety and security.

1 Nomenclature

A	area of cross-section of the pipeline	m^2
B	half-width of the dispersing cloud	m
b	parameter of dispersing cloud half-width	m
C_d	empirical discharge coefficient	-
d_p	diameter pipeline	m

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f	pipe friction factor	-
h_c	cloud height parameter	m
h_s	source height	m
l_p	pipeline length	m
P_0	initial gas pressure	Pa
Q_0	initial total gas mass in the pipeline	kg
$q_{s,0}$	initial mass flow rate	Kg/sec
t_B	time constant in the Wilson model	sec
u_s	sonic velocity in the gas	m/sec
v	ambient wind velocity	m/sec
Z_c	cloud-height dimensionless parameter	-
β	cloud shape parameter	m
γ	specific heat ratio	-
ρ_0	initial gas density	Kg/m^3
σ	dispersion parameter	m
σ_y	standard deviation in the cross-wind direction	m
σ_z	standard deviation in the vertical direction	m

2 Introduction

The transport of chemicals in pipelines is a significant technological solution applied in various branches of the energy and industrial sectors. Pipelines are generally considered the safest and most economical way of carrying large quantities of dangerous substances (flammable, explosive and/or toxic). However, as the analysis of transmission pipeline accidents has demonstrated [1], they can potentially constitute the threat of a major accident, as defined in the European Directive 96/82/CE "Seveso II" [2], the consequences of which can seriously affect human health and the environment in the vicinity of the pipelines. Moreover, in the light of the recent escalation of the terrorist threat against critical infrastructures, such as transport or energy networks, pipelines can also be considered a vulnerable target that require appropriate security solutions for their protection, as required by the recent European Directive 2008/114/EC [3]. From this point of view, pipelines carrying dangerous substances represent a subject that necessarily requires a harmonious integration of safety and security strategies aimed at reducing the likelihood and impact of potential accidents. An issue that should be addressed in both sectors, for example, is the assessment of the areas potentially affected by the consequences of a dangerous substance release, whether caused by accident or deliberate act of terrorism. This evaluation can be considered essential for the improvement of adequate safety strategies, such as the development of emergency plans or land-use planning measures in the vicinity of dangerous pipelines, as well as for the implementation of security solutions for the protection of critical infrastructures, as required by the operator's security plan. Therefore, in this paper, the potential impact of a release of toxic substance by pipelines has been investigated in terms of hazard area, which is an area where the concentration of a toxic substance exceeds a fixed threshold level and induces harmful effects in people and the environment; the choice of the toxic release is due to the fact that this event has the potential to generate impact areas bigger than those associated with flammable or explosive substances releases. In particular, since the threshold level adopted in the calculation strongly affects the extent of this hazard area, the purpose of this paper is to analyse such influence, highlighting its potential implications on the decisional process concerning emergency needs. The different steps carried out for this purpose, combining qualitative information and quantitative techniques of risk analysis, are presented in this paper. In particular, as a preliminary stage, a critical review of the threshold levels most commonly applied in the industrialized countries was conducted in order to investigate the full range of potential health effects. Then, in order to analyze the consequences of a toxic release by pipeline, a hazard model was developed in two steps: first estimating the gas mass flow rate, then evaluating the consequent atmospheric dispersion of the toxic cloud. Finally, on the basis of the aforementioned models, the quantitative assessment of a hazard area covered by the toxic cloud was carried out through a sequence of simulations employing a commercially available software package, and a critical review of the results obtained was performed. All of the above steps shall be illustrated in the following sections.

3 Threshold levels

In the case of a major accident involving a toxic release, the decisional process concerning the selection of the most appropriate preventive, mitigating and/or emergency measures (such as, for example, the structuring of community evacuation plans, ensuring proper protective equipment, etc..), requires an accurate choice of which threshold value must be used as the level of concern to protect public health. Health risks from toxic exposure can range from mild irritation that subsides immediately upon the cessation of exposure, to acute reversible effects that might require medical intervention, to long-term irreversible serious health effects, and, in the worst case scenario, immediate or early death. In general, threshold levels can be summarized into three distinct categories: 1) guidelines for occupational health, 2) guidelines specifically developed for emergency response planning, and 3) fatality data derived from animal studies. Due to their long exposure times and applicability for chronic exposure, the occupational health values are not generally employed for assessing consequences of accidental hazardous materials releases, with the exception of the Immediately Dangerous to Life and Health limit (IDLH) [4]. These are based on conditions that pose immediate danger to life or health using an exposure time of 30 min. Workers should not be in an IDLH environment for any length of time unless they wear appropriate personal protective equipment. For emergency response application the Emergency Response Planning Guidelines (ERPG) values [5] and Acute Exposure Guideline Levels (AEGL) [6] health criteria are widely considered to be the best values available. The former are intended to provide estimates of concentration ranges below which there are no effects on the health of exposed individuals according to three different levels with a common denominator of 1 h contact duration. The latter represent concentration ranges above which there are effects on the health of exposed individuals according to three levels of effect severity, each developed for five exposure periods: 10 min, 30 min, 1 h, 4 h and 8 h. In considering substances for which AEGL or ERPG values are not available, health criteria can be derived using a lethal concentration values (LC_{50}) [7] representing the concentration at which 50% of the exposed population will die. Table 1 shows the reference values corresponding to the threshold level mentioned above for carbon monoxide and fluorine. These substances have been chosen as a case study, in order to take into account different toxicity levels (respectively toxic and very toxic, as required by the Seveso legislation), as well as different densities of released gas compared to air (respectively lighter and heavier than air).

Table 1: Threshold values for carbon monoxide and fluorine.

Threshold level/ exposure time (min)	Carbon monoxide (ppm) Toxic gas	Fluorine (ppm) Very toxic gas
IDLH/30	1200	25
LC_{50}/30	1900	224
AEGL-1/60	-	1.7
AEGL-2/60	83	5
AEGL-3/60	330	13
ERPG-1/60	200	0.5
ERPG-2/60	350	5
ERPG-3/60	500	20

It is worth mentioning that several research projects have been currently undertaken for developing additional acute exposure value to meet emergency needs and cover more chemical substances, also improving consistency in parameters used in consequences assessment of major accident hazards [8].

4 Theoretical background

A hazard model has been defined for the evaluation of the hazard areas consequent to a toxic release by pipelines. This model consists of two parts, which are, respectively, the gas mass flow rate, which predict the rate at which the chemicals are released to the atmosphere, and the atmospheric dispersion model, which calculate the dilution and spread of this material as it moves downwind the source; basis of each model, as well as the underlying assumptions, are described in the following two sections. The former is strongly influenced by the property and quantities of the released substance, the operating and release condition (pressure and temperature, hole size and release duration); the latter depends on meteorological conditions (wind speed and direction, atmospheric stability class) and external factors (topography, the presence of obstacles in the vicinity). Since the strong influence of all these parameters on the extent of the hazard areas has already been investigated in other sensitivity analysis studies [9, 10], the focus of this study is rather the analysis of the implications of the threshold levels on the same extent.

4.1 Gas mass flow rate

According to the consolidated models widely discussed in the literature [11], the initial maximum gas mass flow rate at the hole can be obtained from the continuity equation of the ideal gases law for isentropic expansion. If the pressure in the pipeline just inside an opening to the air is about 1.9 times greater than the atmospheric pressure, the flow will be sonic and can be estimated by the following equation:

$$q_{s,0} = C_d A \sqrt{\rho_0 P_0 \gamma \left(\frac{2}{\gamma + 1} \right)^{\left(\frac{\gamma+1}{\gamma-1} \right)}} \tag{1}$$

It is worth noting that, in order to take into account the most conservative assumptions, the model has been developed to describe the full-bore rupture of the pipeline. Therefore, in this case, the initial maximum mass flow rate can be estimated by assuming the diameter of the pipe as an effective hole size. To predict the mass flow rate as a function of time, the empirical Wilson model [12] for non-stationary gas flow in pipelines after a full-bore rupture has been assumed. According to this model the mass flow rate is given by:

$$q_{s,t} = \frac{q_{s,0}}{\left(1 + \frac{Q_0}{t_B q_{s,0}} \right)} \left(\frac{Q_0}{t_B q_{s,0}} e^{\left(\frac{-t}{t_B} \right)} + e^{-t t_B \left(\frac{q_{s,0}}{Q_0} \right)^2} \right) \tag{2}$$

Expressing the initial total mass Q_0 in the pipeline as:

$$Q_0 = \rho_0 A_p l_p \tag{3}$$

and calculating the time constant t_B through the following equation (4):

$$t_B = \frac{2}{3} \frac{l_p}{u_s} \sqrt{\frac{\gamma f l_p}{d_p}} \tag{4}$$

the mass flow rate $q_s(t)$ can be estimated at any time t after the full- bore rupture of the pipeline by equation (2).

4.2 Atmospheric dispersion

The second part of the hazard model describes the atmospheric toxic cloud dispersion. The distances where the toxic concentrations exceed the reference threshold levels can be estimated using as input parameters the mass flow rate, defined in the previous section. According to the type of gas, respectively neutral ore dense, different dispersion models must be used [12].

For neutral gas the Gaussian plume models (GPM) are usually employed. The equation for the Gaussian plume is a function of the mass flow rate for unit time, the mean wind speed, the crosswind and vertical standard deviations (σ_y (x) and σ_z (x)) and the height source (h_s).

The contaminant concentration at position x, y e z, C (x, y, z), is given by:

$$C(x,y,z) = \frac{q_s}{2\pi v \sigma_y \sigma_z} e^{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2} \left(e^{-\frac{1}{2}\left(\frac{z-h_s}{\sigma_z}\right)^2} + e^{-\frac{1}{2}\left(\frac{z+h_s}{\sigma_z}\right)^2} \right) \tag{5}$$

The dispersion parameters of the toxic cloud, σ_y and σ_z, are functions of the downwind distance, the atmospheric stability classes and the roughness of the terrain. For the estimation of σ_y and σ_z, Pasquill-Gifford curves have been used, and have been fitted with approximate equations shown in scientific literature [13]. For dense gas the SLAB model is used to simulate the atmospheric dispersion of the toxic substance. The plume model is based on conservation equations of mass, momentum, energy and species. The three-dimensional volume concentration distribution C (x, y, z) is obtained by assuming the following crosswind profile:

$$C(x,y,z) = 2Bh_c C(x) C_1(y,b,\beta) C_2(z,Z_c,\sigma) \tag{6}$$

where C_1 (y, b, β) and C_2 (z, Z_c, σ) are horizontal and vertical profile functions, C(x) is the crosswind-averaged volume concentration.

5 Results and discussion

Once the most appropriate equations describing the event were defined, the quantitative assessment of the hazard areas has been carried out through several simulations using a commercially available software [14] based on the mathematical models previously described. To carry out the simulations, the input parameters corresponding to a condition as close to a real accident event as possible have been selected, examining databases storing information on pipeline accidents [15] as well as legislative provisions [16]. These parameters are summarized in Table 2. As far as the spatial dimension of the problem is concerned, it is assumed that the toxic cloud originates from a leak in the pipe according to the origin of an orthogonal reference system, in which the x-axis indicates the distance in which the cloud travels in the direction of the wind, and y-axis indicates the width of the cloud in a crosswind direction. The concentrations of toxic substance are assessed at 1.5 m height, corresponding to direct inhalation for humans. On this basis, the hazard areas for carbon monoxide and fluorine have been analysed varying the threshold levels of reference. The results of the simulations are the contour plots representing the concentration isopleths at a fixed time for a given threshold level; the x-axis indicates the maximum downwind distance (D) and the y-axis the crosswind distance (W) delimiting the hazard area where the toxic gas concentration is at or above the threshold level chosen.

Table 2: Input parameters.

Pipeline sizes	Section length	1000 (m)
	Diameter	0.40 (m)
Operating conditions	Temperature	288.15 (K)
	Pressure	40 (bar)
Release condition	Duration	300 sec
Meteorological conditions	Stability classes and wind speed	D; 5 m/s (neutral); F; 2 m/s (very stable)
External condition	Roughness length, z_0	0.03 (m)

For both substances examined, the hazard areas corresponding to threshold values developed for the same exposure time have been compared; the results obtained for carbon monoxide are shown in Figures 1 and 2. As expected, it is possible to ascertain that larger hazard areas are associated to the threshold levels having lower reference values, corresponding to less heavy effects for people; this is clearly visible, for example, examining the downwind distance obtained using the AEGL-3, which results noticeably greater than distances associated with the others threshold levels. This fact is in agreement with the suggestions of the sector-based scientific literature that, for responding to toxic clouds, recommends to emergency planners the use of the AEGLs, or in a subordinate way the ERPGs values [17]. As previously stated, in fact, AEGLs apply to short term, high dose exposures, therefore providing information for the decision process by emergency responders and planners which appears most appropriate with respect to exposure limit used for workplace or ambient air, usually developed for long term and low-dose exposure. It is worth noting, however, that the choice of threshold levels implying larger areas to submit to accident prevention and mitigation measures, may have a significant impact on the socio-economic aspects of a particular region, therefore necessarily involving a wider and more complex decisional process.

For a conservative estimate of the downwind range for the hazard area, the computational analysis has been carried out with reference to the F2 meteorological condition, which represents the “worst-case” weather condition showing the largest impact areas.

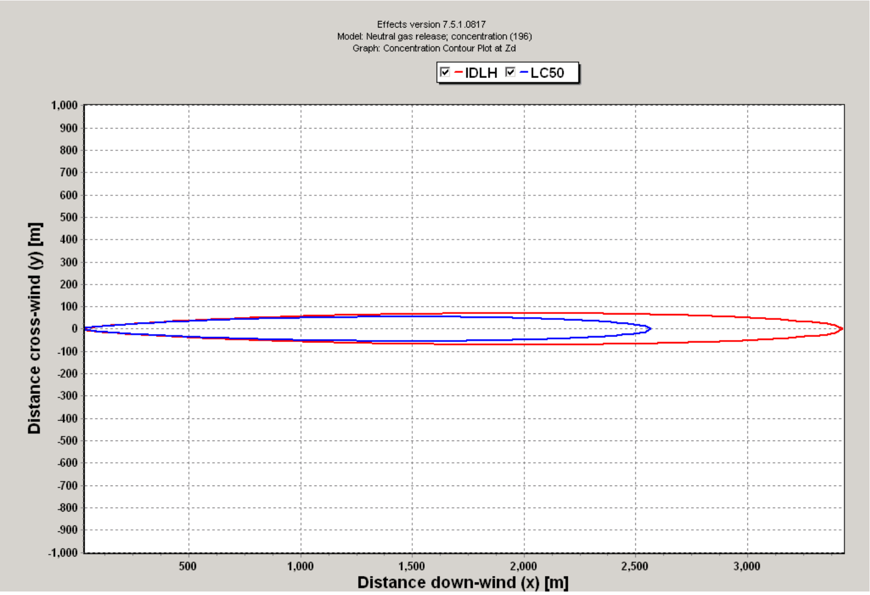

Figure 1: Concentration contour plots for CO corresponding to IDLH and LC50; F2 atmospheric stability class.

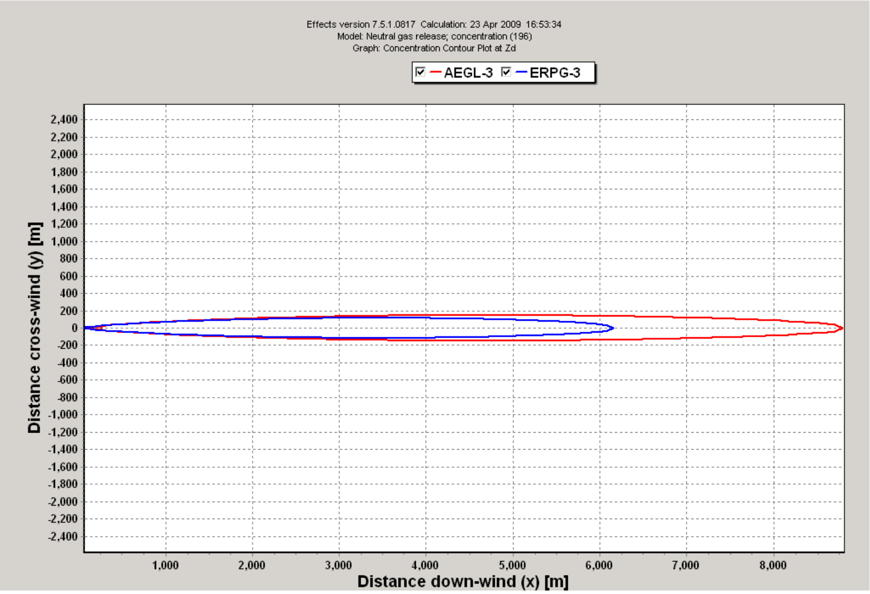

Figure 2: Concentration contour plots for CO corresponding to AEGL-3 and RPG-3; F2 atmospheric stability class.

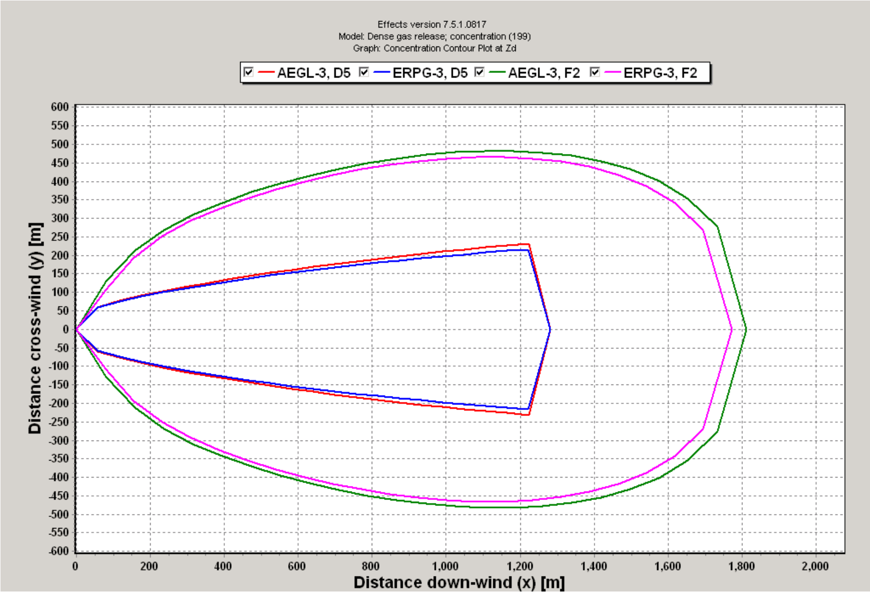

Figure 3: Concentration contour plots for F_2 corresponding to AEGL-3 and ERPG-3; D5 and F2 atmospheric stability classes.

This is due to the high stability of this class that hampers a fast dispersion of the cloud and to the low values of the wind velocity; this can be seen, for example, in figure 3, which shows a comparison between the contour plots corresponding to two set of meteorological conditions adopted in the calculation, respectively D5 and F2, for fluorine.

Besides the threshold level, also the large variations in physical properties and toxicity between chemicals can produce large variances in both the downwind toxic concentrations as well as the time scale of exposure. With respect to fluorine, carbon monoxide release involves, generally, larger maximum impact distances in downwind directions. In fact, for dense gas, the release will be concentrated in the near field surrounding the source and the downwind dispersion will be delayed until the forces of atmospheric turbulence overcome the gravity force and disperse this cloud in the far field. The net effect is a slower release resulting in a smaller far field hazard area. Moreover, it should be kept in mind that for toxic release the hazard area will depend on wind direction; as it is difficult to predict wind direction in the moment of failure, all possible wind directions should be considered in a conservative analysis, in order to produce circular hazard areas around the failure point as shown in Figure 4.

6 Conclusion

Hazard areas caused by toxic releases by pipelines associated with different threshold levels have been evaluated in this study, assuming as a worst case scenario the full-bore rupture of the pipe. In the paper it has been highlighted how the choice of the threshold level of concern could affect the extent of the hazard areas and consequently influence the decisional process concerning the emergency management in the case of accidental toxic release caused either by accident or by deliberate acts of terrorism. Moreover, the obtained results also show how the large difference in physical properties and toxicity of the substances examined produce large variability in the downwind toxic concentrations. This is an on-going study: the liquid and two-phase transport conditions are currently under examination and many other conditions will be considered in future work, for example assuming different release scenarios as well as varying parameters in table 2. The estimate of the hazard areas involves a high level of uncertainty, due to uncertainty in the input parameters as well as in the models adopted for simulating gas release and dispersion, and to the complexity of chemical-physical phenomena involved in the calculations, which lowers the accuracy and reliability of numerical results. However, this study could still provide useful information for the implementation of pipelines safety and security strategies, guaranteeing at the same that this highly productive means of transportation is not unduly penalized.

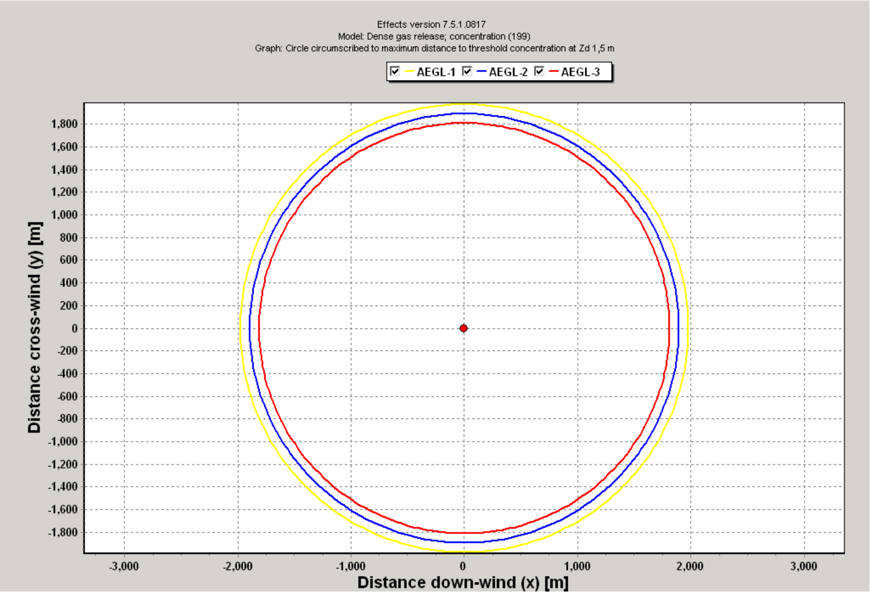

Figure 4: Potential hazard zones for F_2 release corresponding to AEGLs; F2 atmospheric stability class.

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