SPATIAL DISTRIBUTION OF THE PROBABILITY OF DEATH DUE TO HEAVY GAS ACCIDENTAL RELEASES

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***Abstract**. This paper describes a procedure to evaluate the spatial distribution of death probability in a region covered by the release of a toxic dense gas. The computer program DEGADIS (DEnse GAs DISpersion) was used to estimate the atmospheric dispersion of chlorine, the dense gas used for the study. By using the program, a series of runs allowed the generation of results with time steps of one second, and, by combining the outputs, it was possible to calculate the time and spatial distributions of the gas concentration as a function of the distance to the release point. The analysis of vulnerability was done with the use of the Eisenberg model PROBIT equation for chlorine to determine the probability of death of a person exposed to a given concentration of gas during a given time interval. By using the Eisenberg vulnerability model and the time and spatial gas concentration distribution it was possible to evaluate the distribution of the death probability as a function of the distance to the release point. Typical results of the performed simulations are the results obtained for a release of 58 kg.s^{-1} of chlorine, with wind speed of 2,40 m.s^{-1} and atmospheric stability class D, where the probability of death corresponding to 1% of fatality extends to the distance of 1140 m in the plume centerline. The results obtained with this procedure make it possible to map the region around the release point with a clear definition of risk areas that would be the focus of attention in case of an accident.*

Keywords. *Risk analysis, loss prevention*

1. Introduction

A practical formulation to estimate the expected number of fatalities in accident scenarios involving the accidental release of a toxic dense gas will be presented in this paper. When carrying out a quantitative risk analysis, after identifying the representative accident scenarios for the plant, one estimates the expected frequencies for the selected accident scenarios and, in order to calculate the risk, it is necessary to assess the associated number of deaths. A new formulation to obtain the number of victims will be presented – the fatality spatial distribution, which makes the evaluation of individual and social risks much easier. The fatality spatial distribution when combined with the population matrix distribution representing the spatial distribution of the population near the industrial facility, allows the calculation of the scenario resulting expected number of fatalities. Thus, by combining the number of deaths with accident frequency, it is possible to estimate both, societal and individual, risks.

The proposed procedure is applicable to accidental releases of both dense and neutral gases. But in this study, the focus will be on the dense gas case, which is computationally more difficult. The program DEGADIS (DEnse GAs DISpersion) was used to calculate the time and spatial distribution of the dense gas concentration in the atmosphere, as a function of the distance to the source (Havens, 1985).

The calculation of the fatality probability spatial distribution requires the use of the Eisenberg vulnerability model to combine gas spatial distribution and time of people exposure to the toxic gas, in order to calculate the probability of death. The Eisenberg vulnerability model requires the use of the PROBIT equations which are specific for each substance, where the combination of concentration and time exposure result in the probability of death. By using this approach, it is possible to construct a spatial distribution of the probability of death along the path of the toxic gas released.

2. Dense gas dispersion

A gas is considered dense if its density is greater than the density of the surrounding air. This can happen either because the gas molecular weight is heavier than 28,95 kg/kmol, the average molecular weight of air, or its temperature is low enough.

The process of mixing of dense gases with air has distinctive features that have been recognized for quite a long time. Field experiments such as in Koopman, 1984, Puttock, 1982 e Van Ulden, 1974, confirmed that the mechanisms of atmospheric dispersion of dense gases are different from the ones governing the dispersion of neutral or light gases. During the dispersion of a dense gas, there is an initial phase where a lateral spreading happens due to the higher density of the gas originating a low "pancake shaped" cloud. The process of mixing of a dense gas with air is different from neutral or light gases.

Mathematical models are widely used for simulating atmospheric dispersion of flammable and/or toxic dense gases. Nowadays, the modeling of dense gas dispersion is done through the use of computer codes developed by several research groups such as DEGADIS developed for the US Coast Guard and SLAB written in the Lawrence Livermore Laboratory, in California. For this work, DEGADIS was used to estimate dense gas dispersion.

As mentioned, DEGADIS was, originally, developed for the US Coast Guard to assess the dispersion of flammable cryogenic heavy gases, and later the code was extended to simulate vertical jets too, under the sponsorship of the USEPA.

3. Spatial distribution of probability of death

As mentioned before, the importance of spatial distribution of probability of death resides in the possibility of its combination with the population distribution to estimate the expected number of fatalities resulting from an accident scenario. When performing a quantitative risk analysis, the calculation of societal and individual risks, requires the availability of both frequency and number of deaths for each of the accident scenarios identified.

The spatial distribution of probability of death was calculated as a set of points, shaping a matrix, as a function of two variables: distance to the release point and the distance to the plume axis. These probabilities were computed by combining levels of concentration and duration of releases (data supplied by DEGADIS) with the vulnerability model.

The spatial and time distribution of concentrations as a function of distance was calculated by the DEGADIS program which is widely used to calculate dense gas dispersion. So as to represent a real situation better, the results generated by DEGADIS were produced by using concentrations in one square meter cells, up to the maximum distance where the probability of death was one percent.

The concentration calculation in any of the coordinate points (x, y, z), can be made with information supplied by DEGADIS through the Eqs. (1) and (2) below:

$$C(x,y,z) = C(x,0,0)\cdot e^{\left(\frac{-z^2}{\sigma_z^2}\right)} \quad \text{for } y \le b \tag{1}$$

$$C(x,y,z) = C(x)\cdot e^{\left(\frac{-(y-b)^2}{\sigma_y^2}-\frac{z^2}{\sigma_z^2}\right)} \quad \text{for } y > b \tag{2}$$

where C(x,y,z) is the concentration one wishes to calculate [kg/m^3]; C(x,0,0) is the concentration calculated on the plume axis, at ground level [kg/m^3], at distance x measurement from the source in the direction and course the wind is blowing in [m], z is the height one wants to calculate the concentration at [m]; σ_z is the Pasquill–Gifford vertical dispersion coefficient [m]; y represents the distance measured laterally from the cloud axis [m]; b represents the half-width of the cloud [m] and σ_y is the Pasquill–Gifford lateral dispersion coefficient [m].

After obtaining the concentration and exposure time, at a given point, the probability of death may be obtained by using the Eisenberg vulnerability model (Eisenberg, 1975) which uses the PROBIT equation, whose general formula is given in Eq. 3

$$y = k_1 + k_2 \cdot \ln(\text{Dose}) \tag{3}$$

where parameters k_1 e k_2 are specified for each substance. The variable y is the Probit (Probability Unit) which is related to the probability of death, the Dose or D is the result of exposure to a concentration C to the power of n, during exposure time t (in minutes) at that concentration.

When the concentration varies throughout exposure time, the dose or toxic discharge received by a person from a toxic cloud is worked out by using the formula in Eq. 4 (Purple Book, 1999):

$$D = \int_0^t C^n \cdot dt \tag{4}$$

After obtaining the dose, the PROBIT number (y) can be calculated and consequentially the probability of death P, through Eq. (5) (Lees, 1996)

$$P = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{y-5} e^{\frac{-u^2}{2}} \cdot du \tag{5}$$

Therefore, with the spatial distribution of the concentration and its time variation, in a given area, it is possible to calculate the dose a person would receive due to exposure to the toxic gas, at any point of interest. The results of the range of concentrations resulting from a dense gas release were combined with the vulnerability model, generating a spatial distribution of the probability of death, throughout the region that would be affected by the cloud. As an example of the results obtained, in Fig. 1 it is shown part of the plume probabilities of death for a dense gas in a wind direction.

The results correspond to a continuous release of 58,33 $kg.s^{-1}$ of chlorine, with wind speed of 2,40 $m.s^{-1}$, where the probability of death extends to the distance of 1140 m in the plume centerline.

In the upper part of Fig. 1 there is an upper view of the half-plume and in the lower part an illustration with a spatial view (3D). As there is plane symmetry in relation to the vertical plane defined by the plume axis, the other half of the plume can be automatically generated by symmetry. The figure shows that the probability of death would be 100% on a plateau that ranges from the release point, in the wind direction and laterally to the plume axis, for distances of some hundreds of meters and tends to become negligible at more distant points, as would be expected. Calculations were made until the probability of death was 1%.

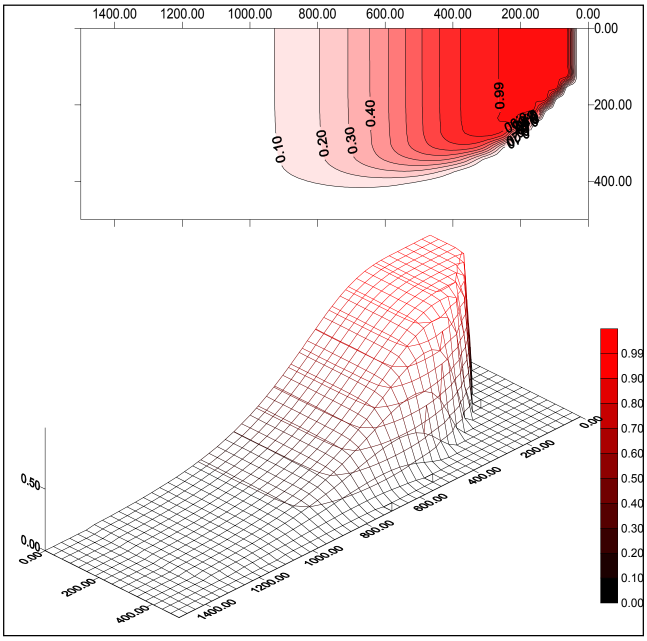

Figure 1. Representation of the probability cloud in the simulation carried out.

A FORTRAN 90 program was developed to calculate the probability of death to apply the evaluation system. In Fig. 2, there is a simplified routine system of the calculation made by the program.

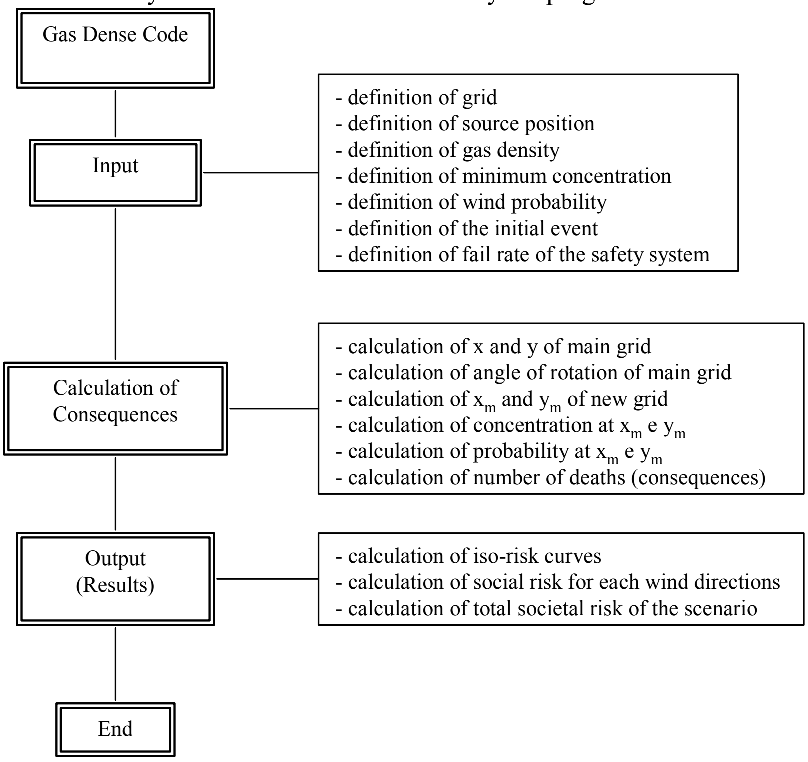

Figure 2. Simplified representation of the program developed.

Using this system, once a given wind direction has been defined, to evaluate the number of people who could perish due to an initiating event where calculations have already been made for the spatial distribution of the concentrations, the spatial distribution of the probability of death can be generated and, superimposing this distribution with population distribution. This simplifies the process of calculating the number of deaths associated to the accident scenario.

It is worth mentioning that in cases where dispersion conditions do not vary with wind direction, at the same speed, the same spatial distribution of death may be used.

As may be observed the probability cloud is an intermediary result obtained by using the program that was developed. By using the probability data, results are generated which are used to evaluate the risk the company represents. As examples of results the isorisk and societal risk curves may be cited. The isorisk and societal risk curves are some of the main results generated by a Quantitative Risk Analysis.

4. Conclusions

In this paper, a new approach to estimate the expected number of fatalities due to accidental release of toxic gas was presented. The main idea is the use of the spatial and time distributions of concentrations combined with the exposure time to generate a spatial distribution of probability of death. When this spatial distribution of death probability is superimposed on the population distribution around the plant, it is possible to calculate the expected number of fatalities.

Because, in general, the results for atmospheric dispersion, especially for dense gases, are presented in a tabulated form or tabulated parameters, the most convenient way to process the results in order to generate the desired results, is to shape matrices where lines can be used for different distances to the source and columns to represent the distance to the plume axis or the path of puffs.

Once the result is obtained in the shape of a matrix, the expected number of fatalities in a given cell where the population is known can be easily estimated by a simple product of the number of people in the cell by the probability of death in the center of the cell, which can be estimated by interpolation of values of the probabilities in points near the center of the cell of interest. An example was presented to illustrate the use of the proposed scheme for a release of 58 $kg.s^{-1}$ of chlorine, with wind speed of 2,40 $m.s^{-1}$ and atmospheric stability class D, where the probability of death corresponding to probability higher than 1% of fatality extends to the distance of 1140 m in the plume centerline

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