Calculation of Evacuation Distances During Toxic Air Pollution Incidents

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Calculations of evacuation distances necessitated by toxic air pollution incidents have characteristically been carried out in an overreactive manner that sometimes needlessly creates public safety problems. This has been due primarily to the need for immediate action, but also has been caused by a lack of satisfactory guidelines for an accurate determination of realistic and safe evacuation distances. The Emergency Response Unit of the Illinois Environmental Protection Agency has developed a system for rapid calculation of safe evacuation distances, thereby avoiding overevacuations based on worst-case philosophy. This is particularly valuable when dealing with densely populated areas as well as with areas that may include hospitals, nursing homes, and institutions.

The Emergency Response Unit of the Illinois Environmental Protection Agency (IEPA) has developed and successfully used calculations for evacuation distances during air pollution incidents. The formulas are based on work done by Turner (1) in the early 1970s, when Turner was with the U.S. Environmental Protection Agency (EPA). These formulas incorporate Pasquill (2) dispersion coefficients as modified by Gifford (3) in 1961, and have been developed for three meteorological weather stability classes.

Calculation of maximum ground-level concentrations can be performed as follows:

$$X = Q/\pi \mu \sigma_y \sigma_z \qquad (1)$$

where

X = concentration (gm/m^3),
Q = source strength (gm/s),
π = 3.14,
σ_y = horizontal dispersion coefficient,
σ_z = vertical dispersion coefficient, and
μ = wind speed (m/s).

The practical application of this formula is based on several assumptions:

1. The material diffused is a stable gas or aerosol (less than 20 microns in diameter) that remains suspended in the air over long periods of time,
2. None of the material emitted is removed from the plume as it moves downwind and there is complete reflection at the ground, and
3. The plume constituents are distributed normally in both the horizontal and the vertical directions.

In standard air modeling downwind pollutant concentrations are plotted and compared with established ambient air quality standards or to levels known to cause adverse health effects. During air pollution emergencies time constraints do not allow this type of modeling even in the age of computers. Often this calculation must be made in the field by emergency response engineers.

In order to provide a formula that would be easy to use and would also be fast and accurate, a relation was established among source strength, wind speed, and safe maximum allowable air concentration levels. Because public safety was paramount, development of maximum allowable levels that would provide optimum safety for public health was mandatory. In this critical area this system differs from others that are in current use. Outdoor air

maximum allowable limits exist today only for a small number of gases and vapors that are regulated by national ambient air quality standards and also a few chemicals regulated under national emissions standards for hazardous air pollutants (NESHAPS). These levels are for chronic exposures and are not suitable for emergency situations. An acute exposure safe level, or excursion threshold limit value (ETLV), has been developed by IEPA for approximately 500 toxic gases and vapors, chemicals that were selected from existing lists of hazardous substances. This list is keyed toward Illinois, based on manufacturing and transportation statistics, and additions were made based on incident statistics. ETLVs could not be developed for many chemicals, but most of the substances commonly encountered in emergency situations had well-documented health effects that allowed an ETLV determination to be made.

ETLVs were established for two categories of toxic substances: severely toxic and moderately toxic. For severely toxic chemicals, the calculations are based on the principle of guarding the general population from the earliest easily defined clinical sign of toxic effects for a 1-h acute exposure. A safety factor of 10 is used to guard against the many pitfalls of direct mathematical extrapolation of toxicological data, to protect hypersensitive classes of individuals, and to allow for variations in pulmonary ventilation rates of active individuals. The ETLV is not intended to protect the most sensitive individual in the most sensitive class, who may have a reaction to any concentration. This group is estimated to make up not more than 0.01 percent of the population (1 in 10 000).

For moderately toxic chemicals, the calculations are based on the principle of guarding the general population from typical first level effects, such as irritation and narcosis. A safety factor of two is used due to the nonserious and readily reversible nature of irritating and narcotic effects. The final determination of chemicals to be listed as severely toxic or moderately toxic also had to take into account volatility so that two categories were included:

1. Highly volatile and at least moderately toxic substances with regard to inhalation or skin absorption and
2. Moderately volatile and severely toxic substances with regard to inhalation, skin absorption, or irritation.

Substances to be placed in the severely toxic and moderately toxic categories were determined by comparing their evaporation rates to critical evaporation rates for each of the two categories.

The evaporation rate (E) for each substance is calculated by using the following formula (4):

$$E = 0.0012 \times c \times \phi/(760 - d\phi) \qquad (2)$$

where

E = evaporation rate $(gm/s - cm^2)$,
c = molecular weight of substance/28.9,
d = 1-c, and
ϕ = vapor pressure (mm Hg at 20°C).

Given the molecular weight and vapor pressure of a substance, this equation can be used to calculate an evaporation rate that may then be compared with the appropriate critical evaporation rate. If the calculated evaporation rate is greater than the critical value, the substance should be assumed to be capable of exceeding the maximum allowable ambient concentration for that toxic substance category (5).

The maximum allowable concentration for the severely toxic category was determined to be 0.3 mg/m³, based on a typical cholinestevase inhibitor.

The maximum allowable concentration for the moderately toxic category was determined to be 200 mg/m³, based on a typical irritant's concentration known to cause that clinical symptom.

By using the above values and the ground-level Gaussian dispersion equation, the following critical evaporation rates were calculated:

6.3×10^{-8} gm/s-cm² for the severely toxic category and
4.2×10^{-5} gm/s-cm² for the moderately toxic category.

for

      spill area = 600 ft² = 55.7 m²,
      stability = category F (stable),
      windspeed = 1 m/s, and
   receptor distance = 0.1 km

These critical evaporation rates were used to develop a list of volatile liquids for IEPA's Hazardous Materials Response Guide (6). Many gases and solids are also included on this list because they are considered hazardous and spill-prone.

Each gas and vapor on the list were evaluated to determine minimum inhalation dosages or skin exposure levels that would produce selected clinical symptoms, and then the appropriate safety factors were applied.

An ETLV is the calculated outdoor ceiling level and is usually greater than the threshold limit value (TLV), but not always because the toxic effect must be considered. It is never less than the TLV. Thus, a gas or vapor that has good warning properties and reversible acute effects will have a higher ETLV than one that has irreversible systemic effects and poor warning properties. The type of toxic effect and the levels needed to cause minimal health effects are the determining factors in setting ETLVs. Each compound in the Hazardous Materials Response Guide (6) had to be evaluated individually in order to set an ETLV. The available reference material in many cases did not allow an ETLV to be determined accurately. ETLVs are expressed as milligrams per cubic meter and can be converted from parts per million by the equation,

$$mg/m^3 = PPM \times MW/24 \qquad (3)$$

where MW is the molecular weight and 24 is a constant from the ideal gas law.

The source strength (Q) is expressed either as a leak (gm/s) or as a total instantaneous discharge (gm). The actual determination of the discharge to air depends on the physical state of the pollutant and will fall into one of three categories.

DETERMINATION OF Q FOR ENVIRONMENTAL POLLUTION DISCHARGES

The discharge of gas to air (air pollution) is as follows:

For leak,

Q = 1000 gm/s

For instantaneous discharge,

Q = (Total lb/2.2) x density x 10³ = gm

For the spill of a volatile liquid to the ground (land pollution, air pollution, or possible water pollution),

For leak,

Q = 3000 gm/s

For instantaneous discharge,

Q = gal spilled x 3.8 x density x percentage of spillage rate x 10³ = gm

Obtain the vapor pressure of the chemical involved from the chemicals list in the Hazardous Materials Response Guide (6). Divide this value by 760 to obtain the percentage of one atmosphere. Then, use this percentage to read the percentage spillage rate from the figure on page 11 of the IEPA guide (6).

The spill of volatile liquid to water and material is water insoluble and lighter than water (water pollution, air pollution, and possible land pollution).
For a leak,

Q = 3000 gm/s

For instantaneous discharge,

Q = gal spilled x 3.8 x density x percentage of spillage rate x 10³ = gm

Obtain the percentage spillage rate as for the spill of volatile liquid to the ground.

If in the ground-level Gaussian dispersion equation (Equation 1), X equals ETLV, then a relation can be established between the relative concentration ($X\mu/Q$) and downwind distance for an airborne contaminant under various stability categories. The reciprocal relative concentration ($Q/X\mu$) is used to develop a positive relation with downwind distance, and the equation becomes

$$K = Q/\pi \sigma_y \sigma_z \mu ETLV \qquad (4)$$

Since μ is consistent, and $\sigma_y \sigma_z$ is constant for specific downwind distances and specific stability categories (1), K can then be plotted against downwind evacuation distances for selected stability categories (B,D,F), and the equation becomes

$$K = Q \times 10^3/\mu \times ETLV \qquad (5)$$

    Q = source strength (gm/s),
    μ = wind speed (m/s), and
    ETLV = excursion threshold limit value (mg/m³).

The reciprocal relative concentration can also be used to plot downwind evacuation distances against crosswind evacuation distances for stability categories unstable (B), neutral (D), and stable (F).

The recommended upwind evacuation distance is selected arbitrarily as one-half the crosswind distance and serves as a buffer safety zone in the event of an unexpected change in wind direction.

In using the Hazardous Materials Response Guide

(6) to determine evacuation distances, the downwind distance is read from the calculated value of K and then this distance is used to read the crosswind evacuation distance. The plume configuration is determined by the respective weather stability plots. Safety factors are not added to the K plots, but rather are built into the ETLV determination, as mentioned previously.

This system is easy, fast, and reliable, and has been field-tested many times. In several incidents this type of determination has been used to countermand apparent overevacuations, which saves much time, money, and needless high-tension emergency movement of children, elderly people, and nonambulatory and infirm segments of the population.

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Toxic Corridor Prediction Programs

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The U.S. Army Atmospheric Sciences Laboratory has developed toxic corridor prediction (TOXCOP) computer programs on portable desktop computers to depict graphically downwind hazard corridors that result from the accidental release of toxic chemicals. TOXCOP programs use standard meteorological measurements that are entered manually into the program to rapidly calculate and plot isopleths of dosage and concentrations of a variety of chemicals. These programs have been used to support safety personnel during the space shuttle mission at White Sands Missile Range, New Mexico, and the movement of WETEYE bombs from Rocky Mountain Arsenal, Colorado.

The Atmospheric Sciences Laboratory (ASL) of the U.S. Army Electronics Research and Development Command has developed several near-real-time computer programs that depict the hazard corridors that would result from the accidental release of toxic chemicals. These programs are known collectively as toxic corridor prediction (TOXCOP) programs. To date, ASL has used these programs at White Sands Missile Range (WSMR), New Mexico, during space shuttle missions to provide decision aids for WSMR safety and environmental health officers and at Rocky Mountain Arsenal, Colorado, during the movement of WETEYE bombs to Utah. The TOXCOP program used at WSMR is discussed here. This program is named STSTCP.

The major features of all TOXCOP programs can be summarized as follows:

1. TOXCOP uses equations of the well-established Gaussian form;
2. TOXCOP uses modified Pasquill stability categories;
3. TOXCOP requires relatively simple meteorological measurements and input data;
4. TOXCOP accepts chemical source data in several different forms;
5. TOXCOP can be easily modified to form a program for a specific chemical, assuming chemical parameters such as evaporation rates are known;
6. TOXCOP is small enough to operate on easily portable equipment;

7. TOXCOP produces graphical and printed outputs that are tailored to the specific needs and understanding of the end user; and
8. TOXCOP programs execute in less than 1 min on current equipment, and thus can provide a decision aid in situations where time is critical.

TOXCOP is popular because of its speed of operation and its ability to produce graphical displays and plots that are easily understood and used by ASL's customers. These customers are, in general, untrained in meteorology or in transport and diffusion work and require a product that needs no specialized interpretation.

The TOXCOP program STSTCP was developed together in approximately four weeks to support the environmental health officer at WSMR during the first space shuttle mission. His concern was for the safety of visitors and television crews located at Northrup Strip, WSMR, in the event the shuttle landed there. Plans called for the shuttle to land at WSMR if rains closed Edwards Air Force Base runways or the shuttle had an emergency. The viewing area of Northrup Strip was located downwind (climatologically) from the desired nominal landing roll-out point of the shuttle. Thus, a leak or spill of toxic chemicals would probably have been directly upwind of the viewing area. To evaluate any threat during an actual landing, rapid decision aids had to be available to the appropriate safety personnel. STSTCP was developed to provide these decision aids.

DIFFUSION EQUATIONS

TOXCOP programs use a diffusion equation of the well-established and tested Gaussian form. The principal STSTCP equation has the form

$$\chi = (Q/\pi \sigma_y \sigma_z \bar{V}) \exp \left\{ -1/2 [(y/\sigma_y)^2 + (z/\sigma_z)^2] \right\} \qquad (1)$$