entrainment; (c) dispersion; and (d) safety assessment. The modular structure facilitates refinement of the modules and also specialization for specific applications. No verification tests against field data have been completed to date, but verification tests and model comparison studies are being planned.

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U.S. Air Force Air Weather Service Methodologies for Calculating Toxic Corridors

J.P. KAHLER AND J.L. DICKE

Four related methods for calculating toxic corridors are described. The methods incorporate techniques that are based on the Ocean Breeze and Dry Gulch diffusion equation. Meteorological inputs include the vertical temperature difference near the ground together with the speed, direction, and variability of wind at the surface. The methods are designed for use by weather forecasters to estimate quickly the transport and dispersion of a toxic chemical accidently released to the atmosphere. Given the source strength of the toxic chemical, the forecaster's end product is a toxic corridor for which there is a 90 percent probability that spilled or released chemicals that exceed a specified exposure limit will be contained within the dimensions of the corridor.

Air Weather Service (AWS) interest in prediction methods for quick response to emergencies involving accidental toxic chemical spills began more than 20 years ago. For background, activities beginning with the Ocean Breeze and Dry Gulch diffusion projects in 1961 represent a timely starting point. Works by Sutton (1) and Pasquill (2) provide background information on previous developments in diffusion meteorology. Not only do missile and test range safety offices need meteorological assistance to ensure that their operations can be conducted without exceeding chemical exposure limits, but forecasters must also be able to respond appropriately to the hypothetical telephone caller who says, "A truck carrying liquid chlorine has jackknifed near the main gate, and it is spewing chlorine all over. What areas should we evacuate?" Specific meteorological systems and procedures were developed for such situations (3,4) and updated and expanded procedures have recently been published (5). These procedures allow toxic corridors based on atmospheric diffusion considerations to be calculated swiftly and provided to users such as disaster-response-force teams. These calculation procedures are simple, rapid, and suited to emergency situations. The end product is a forecast of a toxic corridor for which the probability is 90 percent that exceedances of the toxic chemical concentration, normally the short-term public emergency limit (SPEL), will be contained within the corridor.

TECHNICAL DEVELOPMENTS AND RESULTS

In 1962 Haugen (6) summarized the inherent difficulties in using Sutton's diffusion equation for addressing exposures to toxic chemicals that might result from TITAN II missile operations. Under similar situations concentration estimates were found to vary by up to four orders of magnitude, depending on professional judgment in the selection of input parameters for the equation. Efforts to resolve these discrepancies gave rise to the Ocean Breeze and Dry Gulch diffusion programs at Cape Canaveral, Florida, and Vandenberg Air Force Base, California, respectively. Data from these experiments as well as from Project Prairie Grass in 1956 were used to derive a diffusion prediction equation for operational use (7). The generalized form of the prediction equation can be expressed as follows:

$$Cp/Q = KX^a \bar{U}^b \sigma(\theta)^c (\Delta T + k)^d \quad (1)$$

where

Cp = peak concentration at a given downwind travel distance (X),
Q = source strength,
$\bar{U}$ = mean wind speed,
K = empirical constant,
X = downwind travel distance,
$\sigma(\theta)$ = standard deviation of the wind direction,
ΔT = difference between the temperatures at two levels above ground, and
k,a,b,c,d = parameters of fit (estimating equation coefficients) determined by least-squares regression techniques.

Based on the dependent data set and testing on an independent data set, a diffusion equation was chosen that is reliable and valid for vastly different terrains and climatic regimes:

$$Cp/Q = 0.002\,11 X^{1.96} \sigma(\theta)^{-0.506} (\Delta T + 10)^{4.33} \quad (2)$$

where

Cp/Q = normalized peak concentration (s/m^3),
X = downwind travel distance (m),
$\sigma(\theta)$ = standard deviation of wind direction (degrees of azimuth), and
ΔT = temperature difference [i.e., the temperature at 54 ft - temperature at 6 ft (°F)].

Note that the wind speed is not contained in Equation 2. Although wind speed was found to be independently correlated to Cp/Q, the prediction accuracy of the multiple regression equation was not improved significantly when it was included.

Nou (7) observed that the points appeared to have a Gaussian distribution about the line that represents perfect prediction of Cp/Q. Figure 1 shows the results (by using the independent data set) of plotting the observed versus predicted values of Cp/Q. His plot of the cumulative percentage frequency distribution of the logarithms of the ratios of observed to predicted Cp/Q values (Figure 2) corresponds to a log-normal distribution with a median value of 1.0. In Figure 2 the distribution between 5 and 95 percent approximates a straight line that has a mean of zero.

Wind direction fluctuation statistics [$\sigma(\theta)$] are difficult to compute accurately without a computer; therefore, a simplified equation that uses only X and ΔT was developed for use at TITAN II launch sites (3):

$$Cp/Q = 0.000\,175 X^{1.95} (\Delta T + 10)^{4.92} \quad (3)$$

Equation 3 was then evaluated with independent data. For 65 percent of the cases, the calculated concentrations were within a factor of 2 of those observed; 94 percent were within a factor of 4.

In most applications the question is asked, "At what distance downwind of the source will the concentration be below a specified value?" Equation 3 can be converted to yield that distance [X (ft)],

$$X = 0.0388 (Cp/Q)^{-0.513} (\Delta T + 10)^{2.53} \quad (4)$$

Usually, solutions of Equation 4 have been provided in graphical or tabular form for use by field personnel (3,4,8). The number of toxic chemicals that may be accidentally spilled is quite large and each provides a unique solution of Equation 4; therefore, the number of requested tables is correspondingly large.

The generalized equation used to produce the tables of toxic corridor lengths is as follows (5):

$$X\,(ft) = P\,[3.28\,(29.75/GMW)^{0.513}\,(Cp/Q)^{-0.513}\,(\Delta T + 10)^{2.53}] \quad (5)$$

where P is a probability factor used to determine the probability that a specified concentration is not exceeded outside the corridor and GMW is the gram molecular weight of the toxic chemical.

Although Equation 5 is the basis for most AWS diffusion support involving accidental releases of toxic industrial chemicals, other models and other versions of this model are used by a few AWS units.

GENERAL PROCEDURES AND INPUT DATA

Four methods for calculating the dimensions of a toxic corridor are presented by the AWS (5). For each method the instructions are outlined as a series of steps and preferred and alternate approaches are given. All require the following:

1. An estimate of the source strength of the toxic chemical (lb/min);
2. The temperature difference between 54 and 6 ft above the ground (°F);
3. The surface wind direction (degrees of azimuth) and speed (knots) measured as close to the spill site as practicable; and
4. The variability of the wind direction (degrees of azimuth).

Three of the methods require the gram molecular weight of the chemical and its exposure limit as additional input. From this information the toxic corridor length in feet is determined as well as the corridor width in degrees. A toxic corridor worksheet is available for recording all data and calculations, including a sketch of the corridor. The toxic corridor orientation and dimensions are then relayed to the disaster-response team or other appropriate user where they are plotted on an appropriate map. The forecaster also adds a forecast of the trend in wind direction for the next hour or two so that the response team is aware of any significant changes that may affect the shape and size of the dispersing chemical plume. The forecaster monitors the weather conditions closely until the spill is under control and updates the corridor forecast periodically.

Method 1: Toxic Corridor Length Tables

Method 1 is most likely to be used if there is a toxic corridor length table for the spilled chemical. Such tables are provided for 31 chemicals and are based on solutions to Equation 5 for given source strengths and values of the 54- to 6-ft temperature difference (ΔT). The preferred approach to determine the source strength is to obtain the best estimate possible from the disaster-response force. Although AWS personnel are not responsible for determining the source strength, a toxic corridor length calculation cannot be made without it. An appendix in the technical report (5) can be used to assist the agency responsible for estimating source strengths. The following alternate means of estimating source strengths will result in any error being on the high side:

1. For small amounts of liquid or gaseous material (<2000 lb), the worst case can be assumed to be a total release in 1 min;
2. For large amounts of gas (≥2000 lb), total release is assumed over a 5-min period;
3. For large amounts of a liquid, a source strength of 2000 lb/min is assumed; and

Figure 1. Observed versus predicted C_p/Q: independent data test of final diffusion prediction equation, Equation 2.

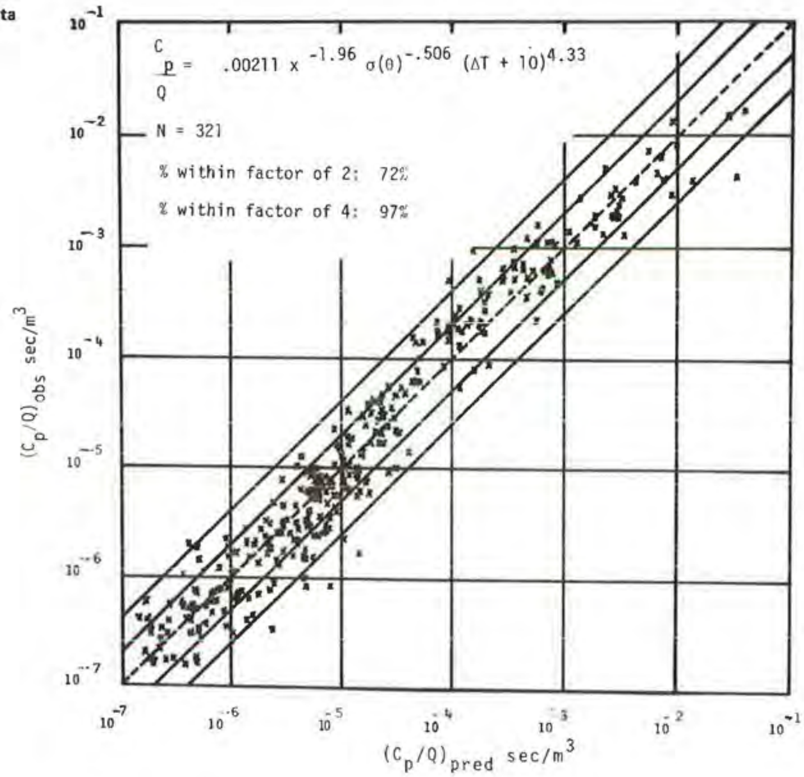


Figure 2. Percentage frequency distribution of logarithm of ratios, C_p/Q observed to C_p/Q predicted for complete independent data sample.

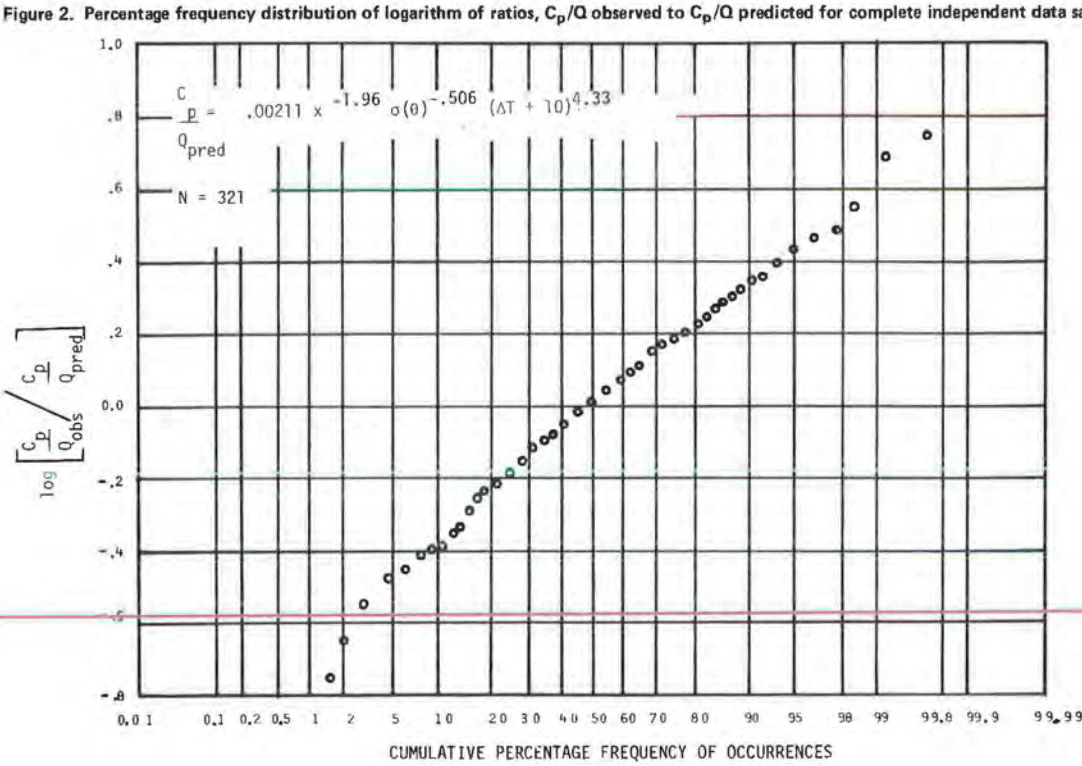


Figure 3. Toxic corridor forecast worksheet with sample calculations.

Name of Chemical Aerozine 50

1. Source strength 40 lbs/min (from environmental health service, disaster response force, or estimated)

2. 54-6 foot delta-T -2 °F (from instrument or table)

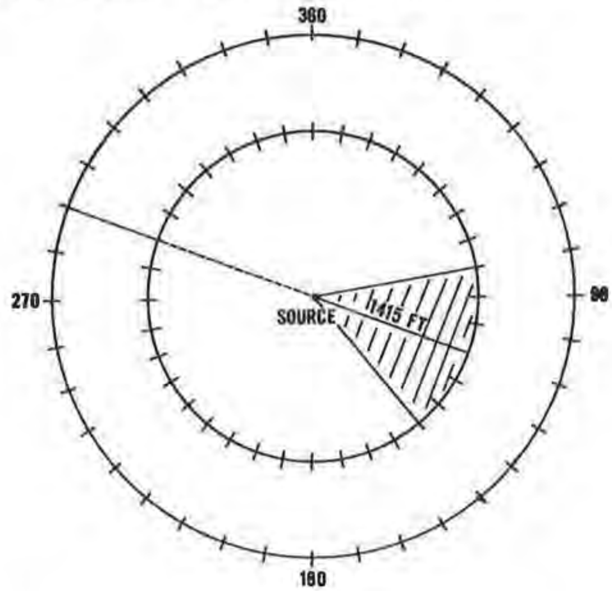
3. Toxic Corridor length 1415 feet (from toxic corridor table)

4. Mean surface wind 290°/4 kt ; wind variability (R) 40 degrees (from wind trace, instrument dial, or estimated)

5. Corridor width (W) 60 degrees (W = 1.5R)

6. Toxic corridor plot

7. Surface wind trend forecast (no change/change to °/ kt)



4. For releases where the amount of material is unknown, the downwind distance the wind would carry the material in 1 h is used; this is considered an interim forecast and should be updated as soon as better information becomes available.

The preferred approach for determining ΔT is to use a 10-min record from a 54- to 6-ft ΔT instrument. Such measurements can also be made by using a sling psychrometer at the 54- and 6-ft levels of a radar tower. As an alternate, surface wind speed category, solar elevation angle, and sky condition can be used to estimate ΔT from a table in the technical report (5).

Once the source strength has been estimated and ΔT value is known, the appropriate toxic corridor length table can be used to obtain the corridor length in feet. A separate toxic corridor length table for each of 31 different toxic chemicals lists corridor lengths as a function of source strength and ΔT.

Next, the mean wind direction and the variability in the wind direction (R), which is an index of the lateral diffusion of a toxic chemical in the atmosphere, are determined. The preferred approach is to use a 10-min wind direction trace and eliminate the two farthest direction fluctuations on each side of the mean. Variability (R) is the difference in degrees between the third largest fluctuation on each side of the mean direction. As an alternate, the wind fluctuations indicated by an anemometer dial over a 2-min period are noted. Variability (R) is the difference in degrees between the largest fluctuation on each side of the mean direction. As an approximation when no wind fluctuation data are available, R is assumed to be 60° when the wind speed is between 4 and 10 knots and 30° if the wind speed is greater than 10 knots. Any time the wind speed is equal to or less than 3 knots, the toxic corridor is assumed to be a circle around the spill or release location that has radius equal to the corridor length determined above. The corridor width (W) in degrees is assumed to be equal to 1.5R.

The toxic corridor can be plotted with this information. The corridor centerline is drawn from the spill or release point to the point on the wind direction circle that corresponds to the direction the mean wind is blowing toward (i.e., 180° from the recorded mean direction). One-half the corridor width (W/2) is plotted on each side of the centerline. Lines drawn from the origin through W/2 define each side of the corridor. As previously mentioned, if the wind speed is equal to or less than 3 knots, the toxic corridor is assumed to be a circle that has a radius equal to the corridor length.

Figure 3 shows a toxic corridor worksheet (5) filled out with a sample exercise. Note that a wind direction trend forecast has been prepared for transmission along with the toxic corridor dimensions to the disaster-response force. The toxic corridor is the forecast area within which the probability is 90 percent that the concentration of a toxic chemical will exceed a specified exposure limit. Monitoring of weather conditions continues and the corridor forecast is updated periodically.

Method 2: Chemical and Diffusion Factors

Method 2 will most likely be used if a toxic corridor length table is not available for the spilled or released chemical. The diffusion equation (Equation 5) has been separated into its chemical and diffusion components. A table of chemical factors and a nomogram for determining chemical factors are provided. The table contains chemical factors based on 30-min SPELs, 30-min energy exposure limits, and 10-min short-term public limits. The nomogram is constructed with exposure limit as the abscissa, varying from 0.1 to 100.0, and gram molecular weight as the ordinate. The chemical factor is then read from the diagonal line at the intersection of the gram molecular weight and exposure limit. Similarly, there are a table of diffusion factors and a nomogram for determining diffusion factors. The toxic corridor length is defined as the product of the chemical factor and the diffusion factor. In other respects, there are no differences between method 1 and method 2 and the forecaster follows the same steps as outlined under method 1.

Method 3: Universal Nomogram

Method 3 requires more independent data and would be applicable for unusual combinations of toxic chemical and exposure limits. A universal nomogram is provided for determining toxic corridor length. The estimated source strength, observed ΔT, appropriate exposure limit, and gram molecular weight for the spilled or released chemicals are entered into the three-part nomogram and a corridor length is read from the intersection point of two projected lines. Once the toxic corridor length is known, the forcaster follows steps identical to those in method 1.

Method 4: Programmable Calculator

Method 4 may be preferred by those skilled in using programmable calculators. Specific situations can be handled by executing the general equations in the technical report (5). The technical report contains a list of a TI-59 calculator program, sample input and output, and procedures for making a toxic corridor length calculation. Required input data include gram molecular weight and exposure limit of the spilled or released chemical, source strength, and ΔT. Once the corridor length has been determined, the forecaster follows steps identical to those in method 1.

SOURCES OF ERROR

Several potential sources of error may contribute to an erroneous estimate of toxic corridors. Errors can occur when measuring or estimating ΔT and when estimating source strength and trends in weather conditions. Other errors may stem from peculiarities of the toxic chemical, terrain effects that alter the wind and diffusion characteristics of the atmosphere, and the assumption that meteorological elements are homogeneous in the horizontal. For example,

1. Toxic corridor lengths are extremely sensitive to the ΔT values used. A 1°F error in ΔT can result in an error as large as 40 percent in the corridor length.

2. Although errors in source strength are not as critical as ΔT errors, source strength is much more difficult to estimate and may, therefore, contribute a disproportionate share of the error. Corridor lengths are approximately proportional to the square root of the source strength.

3. Gases, such as chlorine, that are considerably denser than air do not disperse initially in the same way as do gases that have densities nearly the same as air. Clouds of heavy gases may travel against the wind and their lateral spread may initially be larger than normal. The dense gas effect may cause toxic corridors to be longer than calculated, especially when ΔT is negative (unstable conditions).

4. Terrain and surface roughness elements can affect not only atmospheric dispersion but also the wind speed and direction. Although a correction factor to ΔT is suggested to compensate for increased surface roughness or when the spill or release is in a forest, the forecaster must adjust the transport wind more subjectively. Use of the correct wind-speed category is as important as use of the correct ΔT value.

5. Forecasts of weather conditions represent best judgments and contain uncertainties. Continual monitoring of weather conditions should allow a forecaster to refine corridor estimates. The ability to anticipate weather changes should ensure appropriate, timely, and flexible reactions by disaster-response forces.

SUMMARY

Four related methods for calculating toxic corridors were described (5). The methods, which are based on the Ocean Breeze and Dry Gulch diffusion equation, were designed for use by weather forecasters to produce rapid estimates of the atmospheric diffusion of toxic chemicals. These methods are used to predict toxic corridors with a 90-percent probability that toxic chemical concentrations in excess of a specified exposure limit will be contained within the corridor dimensions.

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