(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

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

Table 1. Smith-Pasquill coefficients as function of Pasquill stability for roughness length of 1 cm.

Pasquill Category	Smith-Pasquill Coefficients			
	a	b	c	d
A	0.40	0.90	0.154	0.94
B	0.32	0.90	0.133	0.89
C	0.22	0.90	0.121	0.85
D	0.143	0.90	0.108	0.81
E	0.102	0.90	0.076	0.78
F	0.076	0.90	0.062	0.72

where

χ = the concentration at downwind distance x (gm^{-3}),
Q = source strength (gs^{-1}),
$\overline{V}$ = mean windspeed (ms^{-1}),
y = lateral distance from the plume centerline (m),
z = height of interest (m; 2 m was used in STSTCP),
σ_y = lateral dispersion length (m), and
σ_z = vertical dispersion length (m).

The dispersion lengths are given by the Smith-Pasquill (1) power laws in the form

$$\sigma_y = ax^b \quad (2)$$

$$\sigma_z = cx^d \quad (3)$$

with the coefficients for a specific roughness length given in Table 1.

Concentration is normally desired to be in units of parts per million; therefore, χ is converted by using the factor

$$\chi ppm = \chi mgm^{-3}[(T_0/T_1)(22.4/GMW)] \quad (4)$$

where

T_0 = 273.15°K,
T_1 = ambient temperature (°K), and
GMW = gram molecular weight of material under consideration.

The maximum distance downwind for a given concentration is determined by using the equation

$$x_{max} = (Q/\pi ac\overline{V}\chi)(b+d)^{-1} \quad (5)$$

Equation 5 can be derived from Equation 1 by letting y = 0 and by replacing σ_y and σ_z with Equations 2 and 3, respectively.

After x_{max} is determined for ground-level constant concentrations, Equation 1 is solved in the form

$$y = \pm\sigma_y[2\ln(Q/\pi\chi\sigma_y\sigma_z\overline{V})]^{1/2} \quad (6)$$

Thus, by evaluation of Equations 5 and 6, isopleths may be drawn for each concentration of interest for a specific chemical.

The difficult task of estimating source strengths for evaporating fuels and oxidizers was addressed by using the Clewell equation (2),

$$Q = 0.08\,\overline{V}^{3/4}A(1 + 0.0043\,T_p^2)Z \quad (7)$$

where

Q = source strength ($kg \cdot h^{-1}$);
A = spill area (m^2);
T_p = pool temperature, assumed to be ambient temperature (°C); and
Z = arbitrary correction factor determined by Equation 8.

$$Z = P_{vB}/P_{vH} \times GMW_B/GMW_H \quad (8)$$

where

P_{vB} = vapor pressure of the desired chemical,
P_{vH} = vapor pressure of hydrazine,
GMW_B = gram molecular weight of the desired chemical, and
GMW_H = gram molecular weight of hydrazine.

Z-factors for various chemical compounds are as follows:

Compound	Z-Factor
Hydrazine	1
MMH	4.3
N_2O_4	100

In actual operations the inability to estimate with precision the amount of the spill or leak causes an error that cannot be accounted for theoretically. Thus, all simplifying assumptions are biased toward the conservative, which leads to theoretical calculations on the safe side. In particular, no correction is made for plume rise or for depletion of the plume in the lateral direction over time due to the variability of the wind direction.

PASQUILL STABILITY CATEGORIES

In most operational situations involving the prediction of downwind hazard corridors that result from atmospheric diffusion and transport of toxic chemical vapors, the detailed micrometeorological measurements needed to fully characterize the atmospheric stability in the region of interest are not available.

Alternative methods are required to adequately estimate stability in the atmospheric boundary layer and the diffusive power of the atmosphere. With respect to stability and diffusion, Pasquill (1) states that the best approach for practical solutions is one that

1. Incorporates basic principles and experience in a simple, flexible way;
2. May be modified quickly as the general background of theory and practice improves;
3. May be applied with readily available meteorological observations as well as preferable special measurements; and
4. May be implemented by relatively inexperienced personnel.

Based on the above, the meteorological office 1958 system or Pasquill stability category scheme (3) was devised. By using synoptic or hourly airways observations (such as mean wind speeds, cloud cover, and ceiling height) plus estimates of insolation and vertical heat flux, stability was defined by six categories as follows:

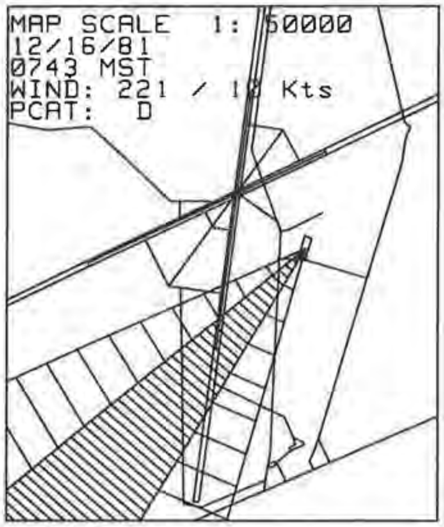
A--extremely unstable conditions,
B--moderately unstable conditions,
C--slightly unstable conditions,

Table 2. Relation of Pasquill turbulence types to weather conditions.

Surface Wind Speed (m/s)	Pasquill Category				
	Daytime Insolation			Nighttime Conditions[a]	
	Strong	Moderate	Slight	>40 Percent Cloudiness	<40 Percent Cloudiness
<2	A	A-B	B	F	F
2	A-B	B	C	E	F
4	B	B-C	C	D	E
6	C	C-D	D	D	D
>6	C	D	D	D	D

[a]The degree of cloudiness is defined as that fraction of the sky above the local apparent horizon that is covered by clouds.

Figure 1. Upwind area in which spill would be potentially hazardous to TV/PAO area.



D--neutral conditions (applicable to heavily overcast day or night),
E--slightly stable conditions, and
F--moderately stable conditions.

In turn, estimates of the matching dispersion coefficients were defined. The Pasquill scheme was later improved by Gifford (4) and Turner (5) and became the contemporary Pasquill-Gifford-Turner nomograms that relate the dispersion lengths σ_y and σ_z to downwind travel distances. The basic Pasquill category scheme as used in TOXCOP is outlined in Table 2.

Additional efforts at improving the categorization approach were accomplished by Smith (6,7), who related the categories to the geostrophic wind, heat flux, surface wind, surface stress, insolation, aerodynamic roughness of the surface, and the Obukhov length (8). Pasquill, in turn, developed power laws to express the dispersion lengths in the form of Equations 2 and 3, where the coefficients and indices are effectively stability- and roughness-related. Equations 2 and 3 are considered to be adequate for depletion calculations as a function of stability.

PROGRAM OPERATION

All TOXCOP programs operate in essentially the same way. The user enters the following parameters:

1. Time and date, by using a real-time clock in the computer or by typing manually;
2. Cloud cover in percent;
3. Cloud height in feet for greater than 40 percent cloud cover;
4. Height of the wind-measuring equipment (a 10-m height is preferred);
5. Wind direction in degrees (a 10-min average is preferred);
6. Wind speed in knots;
7. Standard deviation of the horizontal wind direction in degrees (a 10-min sample is preferred); and
8. Temperature in degrees Fahrenheit.

These programs then produce a plot on the cathode ray tube (CRT) screen that is a depiction of the upwind area in which a spill source would most likely affect the area of interest (Figure 1). In the case of Northrup Strip, the area of interest is the television and public affairs office (TV-PAO) area.

The plotted output shows two lined areas. The interior, densely lined area is bounded by lines plotted at angles ±1 standard deviation from the horizontal mean wind direction. The less densely lined area is contained within lines plotted at angles ±2.5 standard deviations from the horizontal mean wind direction. The length of lines extending from the TV-PAO area has no physical meaning.

This product is produced frequently (with latest available weather observations) and is passed to safety personnel operating away from the computer system. This ensures that the appropriate decisionmakers will be aware of the potential dangers to the TV-PAO area if the shuttle comes to rest in one of the hatched areas and a release of toxic chemical occurs. At this point, the user has the option of rerunning the program with new meteorological data or of continuing the program to analyze a chemical release. If the program is continued, the following steps are taken:

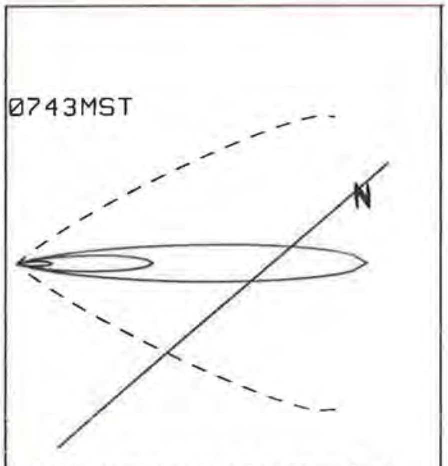
1. User specifies either the CRT screen or an external plotter to receive the plotted displays;
2. User specifies the chemical of interest; for instance, in STSTCP the user could specify dinitrogen tetraoxide (N_2O_4) (oxidizer), hydrazine (fuel), or monomethylhydrazine (fuel);
3. User specifies whether the problem is a leak or a spill; and
4. User specifies how much material has been released or is being released; for spills: specify a volume, mass, or spill surface; for leaks: specify rate of release in terms of volume or mass per minute.

The program now plots three isopleths of concentration, color-coded for the specified chemical, as well as a dashed line at 2.5 standard deviations (Figure 2). The values for the isopleths of concentration, given in the table below, have been prespecified by the WSMR environmental health officer after consultation with various health authorities.

Chemical	Concentrations (ppm)
N_2O_4	1, 5, and 50
Hydrazine	1, 2, and 80
Monomethylhydrazine	3, 5, and 30

During actual operations these isopleths are plotted on clear acetate sheets to the scale of whatever map is being used by the safety or operations personnel. A north-south line is also plotted to allow the user to orientate the plot on the map and position it at the point of the spill. Simultaneously,

Figure 2. Three isopleths of concentration for 1, 5, and 50 ppm that result from a simulated spill of 30 gal of N_2O_4 under prevailing meteorological conditions.



Note: This figure is plotted in color by using the eight-color plotter during operations.

Figure 3. Summary sheet showing meteorological data and spill parameters used to simulate spill of 30 gal of N_2O_4.

SUMMARY SHEET

DATE: 12/16/81
TIME: 0743 MST
PASQUILL STABILITY CAT. = D
CLOUD COVER (PERCENT) = 0
WIND DIRECTION (DEG) =221
WIND SPEED (KNOTS) = 10
TEMPERATURE (DEG F) = 45

N2O4 ISOPLETHS – 1,5,50(ppm)
MAX. DIST. AT 1 ppm = 9967FEET
MAX. DIST. AT 5 ppm = 3889FEET
MAX. DIST. AT 50ppm = 1012FEET
COMPUTED AREA OF SPILL 45 SqM
VOLUME OF SPILL 30 GAL

Figure 4. Mean maximum concentration versus centerline downwind distance for simulated spill of 30 gal of N_2O_4.

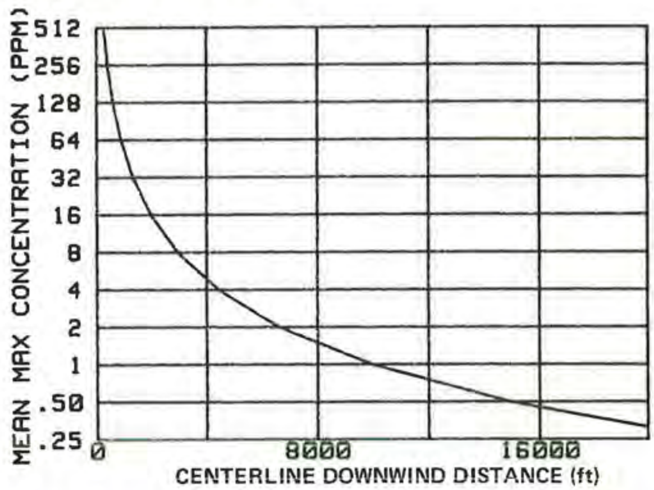
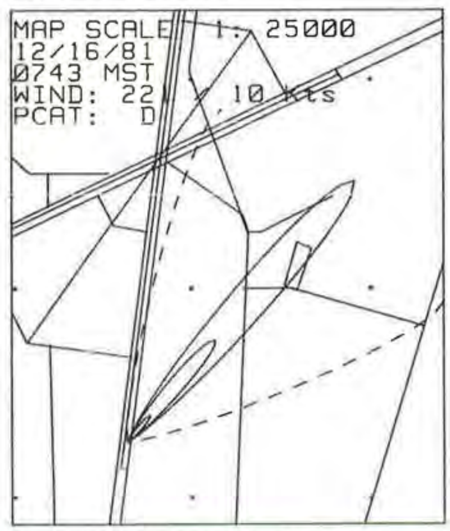


Figure 5. Isopleths and map background plotted for distribution to areas away from computer system.



Note: This figure is plotted in color by using the eight-color plotter during operations.

the computer prints a summary sheet that lists the meteorological inputs, calculated Pasquill stability category, source type, spill parameters, and maximum travel distances for each plotted isopleth (Figure 3). These two products constitute the decision aids necessary for a rapid assessment of the situation.

Further products are available to provide documentation of the event, portability of the results, and additional information. The first of these additional products is a plot of the mean maximum concentration versus centerline downwind distance (Figure 4) and a printout (not shown) at preselected downwind distances of estimates of earliest exposure, mean maximum concentration, total time of exposure, and peak concentration. Portability of the results is achieved by replotting the isopleths on a plotted map display (Figure 5) of the area at any user-specified scale. These map plots can be passed to personnel away from the computer to aid their implementation of emergency procedures in the event of a spill. Hard copies of all plots can also be made on the computer's printer to document the event and provide further portability of the program's output.

RMATCP is a program used in support of the WETEYE bomb move from Rocky Mountain Arsenal. It differs from STSTCP primarily in that it calculates isopleths of dosage rather than isopleths of concentration, and it considers the nerve agent chemical GB rather than the chemicals aboard the shuttle.

TOXCOP programs currently exist in BASIC language programs executable on the Hewlett-Packard 9845B/C desktop computers. The programs average about 65K bytes, of which 40 percent are graphics-related programming. The system uses a Hewlett-Packard 9872C X-Y graphics plotter using eight color pens.

ACKNOWLEDGMENT

The work was done on Hewlett-Packard machinery primarily because it was the most readily available system on which we could do the required development work. Other computer systems could certainly pro-

vide satisfactory results. We intend no specific endorsement of Hewlett-Packard equipment by either the government or ourselves.

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Toxic Corridor Projection Models for Emergency Response

MARK D. RYCKMAN AND JEFFREY L. PETERS

Rapid definition and communication of ground level toxic corridors during an environmental crisis are paramount concerns to protect public health and safety during an accident involving hazardous materials. Changing meteorological conditions, definition of dynamic stability conditions, and rapid identification of source strength have profound effects on the definition of horizontal and vertical transport of toxic materials released during a transportation or industrial accident. The pragmatic application of toxic corridor projection models during an agricultural chemical warehouse fire, a derailment involving the release of chloroform, and a tractor-trailer accident resulting in the release of ethyl chloroformate is reviewed.

The purpose of this paper is to provide information to assist those charged with the responsibility of rapidly assessing ground-level toxic corridors resulting from hazardous material accidents in industry and transportation. Three case histories are presented to demonstrate the application of toxic corridor projections for (a) a tractor-trailer accident resulting in the release of ethyl chloroformate, (b) a railroad derailment resulting in the discharge of chloroform, and (c) an agricultural chemical warehouse fire resulting in the release of toxic air pollutants.

The authors and engineers and scientists with REACT's National Hazardous Material Response System were directly involved with each of the incidents discussed here. Toxic corridor projections and emergency directives were issued from REACT's St. Louis-based Corporate Response Center. Toxic corridor projections were determined based on hands-on experience with more than 700 hazardous material incidents. Physicochemical and toxicological material properties and projection maps were obtained from REACT's Computer Assist Program containing information on more than 250 000 hazardous materials and more than 40 000 U.S. Geological Survey (USGS) 7.5- and 15-min topographic maps. (1).

TOXIC CORRIDOR PROJECTION CRITERIA

Two principal criteria should be met when developing toxic corridor projections: (a) protect public health, property, and the environment; and (b) provide rapid information for determining the appropriate emergency resources required, safe approach corridors, sensitive populations, potential evacuation routes, and identification of assembly areas.

Projections must be made quickly to activate the appropriate emergency services required, including fire, ambulatory, and hospital. Safe approach routes for emergency services personnel and hazardous material experts should be defined to protect their health during an emergency. Consideration should be given to sensitive populations in defining toxic corridors, including elderly people in nursing homes, hospital patients, and areas of high population density. The movement or evacuation of sensitive populations may result in undesirable negative health impacts and/or panic. Consequently, displacement impacts should be considered with potential toxic effects such that the resulting corridor will yield the minimum public health, property, and environmental impacts.

Evacuation routes should be defined such that an orderly and rapid evacuation can be conducted. Routes should be defined such that they do not interfere with emergency personnel and equipment access. Consideration needs to be given to identification of safe assembly areas for displaced personnel. Typical assembly areas include schools, auditoriums, and other areas defined by the Civil Defense or local emergency authorities.

MODELS

Toxic corridor projection models provide rapid information for emergency action decisions. It is emphasized that models serve only as a tool and should be used and interpreted by experienced personnel. The authors have developed computer programs for Texas Instrument's Programmable Fifty Nine Calculator for the Turner and Ocean-Breeze Dry-Gulch models as shown in Figures 1 and 2, respectively.

By using the same source strength and meteorological inputs, the Ocean-Breeze model projects a more conservative (longer) toxic corridor length than the