

Atmospheric Problems from Hazardous Materials Spills in San Francisco Bay Area

RONALD Y. WADA

A program to develop a regional hazardous materials spills plan for the San Francisco Bay Area is described and early results in the area of response to toxic gas emergencies are documented. The Bay Area program involves the formation of a spills task force that is composed of representatives from a broad cross section of spill response agencies and concerned organizations. The task force has four supporting subcommittees to deal with (a) risk assessment and toxic gases, (b) spill prevention, (c) training of spill prevention and response personnel, and (d) response planning. The principal problem posed by the release of toxic gas is that of evacuating the public from the danger zone. Numerous methods, ranging from simple tables of precalculated dimensions to sophisticated computer models of atmospheric dispersion, are currently employed to identify this evacuation area. None of these methods has been subjected to performance verification or sensitivity analysis, and one of the recommendations is that these studies be conducted. For the Bay Area a two-tiered system is recommended: First, a simple guidebook of intermediate sophistication should be developed and distributed to initial response agencies (e.g., police and fire departments); second, a computer-assisted system to be shared regionally should be implemented for use during major spill events.

This paper describes interim results from a program to develop a regional hazardous material spills prevention and response plan for the San Francisco Bay Area. This program is comprehensive in its scope, including accidental releases of gaseous, liquid, and solid hazardous materials. In particular, this program will address the movement of these materials by all modes of transportation over both public and private properties, assess the probability of localized spill events, identify existing prevention and response capabilities, and determine what changes and additions need to be made to prevent and respond to these spills.

The Bay Area is comprised of the 93 cities and nine counties that surround the San Francisco Bay, one of the largest estuaries in the world. More than 5 million people currently live in this 7000-mile² area. Another 1 million are expected in the year 2000. This population is served by more than 300 fire departments, offices of emergency services, and other spill-response agencies. As a major seaport, a crossroad for several major highways and railways, a substantial industrial area (including oil refineries, chemical plants, automobile factories, and electronics plants), the base for numerous military installations, and an agricultural region, the Bay Area experiences a significant amount of hazardous material transportation activity.

On the average, at least one spill is recorded each day in the Bay Area. Coordination among the multiple agencies that respond to these spills is minimal. Policies are inconsistent for response among overlapping jurisdictions and adjacent communities. Local response personnel are inadequately trained. Improvements are being initiated in the area of response; however, little attention is being given to prevention.

The primary goal of the proposed program is to develop a coordinated hazardous materials accident prevention and emergency response program to serve the San Francisco Bay Area. This project plans to document, in a framework that would provide guidelines for other governmental agencies seeking to develop an appropriate hazardous materials program, the steps taken by the Association of Bay Area Governments (ABAG) and participating government agencies to develop this program.

Specific objectives that are targeted include the following:

1. Coordination of the many agencies responsible for spill prevention and response, such that efforts are consistent and efficient;
2. Determination of the nature and extent of hazardous material transportation in the region and associated risks;
3. Assessment of the region's existing capabilities to prevent and respond to hazardous materials incidents;
4. Resource assessment of equipment, technical capabilities, and personnel within the region;
5. Prevention of hazardous material accidents and, if an incident does occur, minimization of environmental and health effects;
6. Delineation of responsibilities where jurisdictions overlap or where there is a lack of specified authority;
7. Communication and notification of networks that will carry out response plans;
8. Training programs that are consistent and available to local personnel responsible for spill prevention and response; and
9. Examination of liability of the developed prevention and response plans.

Through a task force of representatives from industry and the numerous jurisdictions within the levels of government, the Bay Area's needs and capabilities are being identified and assessed and a management scheme developed. The program focuses on regional and local policies, equipment, and personnel capabilities for dealing with any type of spill. The task force will establish policy, formally develop the regional plan, and initiate implementation.

Four subcommittees, each composed of a broad cross section of agencies and organizations, support the task force. Figure 1 shows the relations between the task force and the subcommittees.

PROBLEMS CREATED BY RELEASES OF TOXIC GAS

Release of toxic gas may occur either as the release of a material that is contained or transported in a gaseous state or as the volatilization atmospheric suspension of a material that is normally in a liquid or solid state. In any case, once released the material cannot be contained or collected given the current state of the art of cleanup methods. Instead, the immediate problem becomes one of evacuating the population from harm's way and relying on natural atmospheric dispersion and deposition processes to eventually reduce the concentration of the material to below toxic levels.

The problem of defining evacuation areas during toxic gas release emergencies is characterized by two major constraints: (a) the need for a quick initial determination so that the proper forces can be mobilized; and (b) uncertainty regarding critical input variables such as emission rate (source strength), and microclimatic wind and stability conditions.

To illustrate the state of current practice in the Bay Area, two recent toxic gas incidents will be reviewed with regard to how evacuation areas were defined. First, a recent spill of silicon tetrachloride in South San Francisco resulted in evacuation of an industrialized area adjacent to San Francisco Bay. On escape from its tank, the chemical formed a dense white aerosol cloud that extended from ground level up to as much as 200 ft in the air. The evacuation area for this spill was determined by visual observation of the white cloud by a helicopter pilot. The pilot, because he was familiar with the wind characteristics in the area, was also able to anticipate a shift in the wind direction. This permitted the advance evacuation of additional population not included in the initial evacuation area. This shift carried the cloud toward San Francisco International Airport (see Figure 2), and only a second shift in the wind, which carried the cloud back over San Francisco Bay, prevented the evacuation of the congested airport area.

The second incident was the leakage of acids from a tank truck on Interstate 680 in Contra Costa County. A mixture of concentrated acids leaked onto the pavement, creating a visible, yellow-orange cloud of acid aerosol. Responding officers consulted the U.S. Department of Transportation (DOT) Emergency Response Guidebook (1) and ordered evacuation of downwind residential areas based on the worst case (largest area) indicated for the various acids in the mixture. Visual tracking of the cloud from the ground was used to indicate the wind direction, which was observed to shift twice by as much as 90° during the evacuation period and resulted in evacua-

tion of additional areas beyond the area identified initially.

In both incidents visual tracking of a visible cloud was heavily relied on to indicate wind direction and identify the primary evacuation area. If the materials involved did not form a visible aerosol, this method could not be used. In addition, the emergencies lasted for several hours and no backup systems or methods were consulted to provide additional information or more refined estimates on what areas should be evacuated.

TOOLS CURRENTLY AVAILABLE

Many tools are currently used to identify evacuation areas for spill incidents. Practically all of them are based on standard Gaussian dispersion equations that have been in general use since the 1950s. The differences among the methods lies in the level of detail and the range of conditions that they can address. The methods can be summarized in four categories of increasing complexity, as follows:

1. Simple manual such as the DOT Emergency Response Guidebook (1),
2. Complex manual such as the Illinois Environmental Protection Agency's Hazardous Materials Response Guide (2),
3. Computer-based systems such as Shell Oil Company's SPILLS program (3) or U.S. Coast Guard's hazardous assessment computer system (HACS) (4), and
4. Large-scale computer systems such as Lawrence Livermore National Laboratory's atmospheric release advisory capability (ARAC) system (5).

DOT Emergency Response Guidebook

The DOT Emergency Response Guidebook contains a table that gives isolation and evacuation distances for spills of 34 selected hazardous materials. The principal advantages of this table are that it is fast, simple to use, and requires no specialized training. A number of variables have been eliminated from consideration such as the magnitude of the spill (source strength), wind speed, and atmo-

Figure 1. Organization of ABAG hazardous spills program.

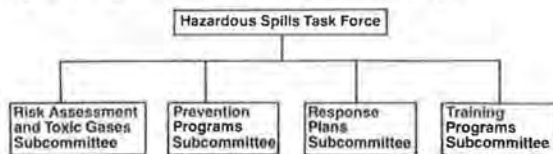
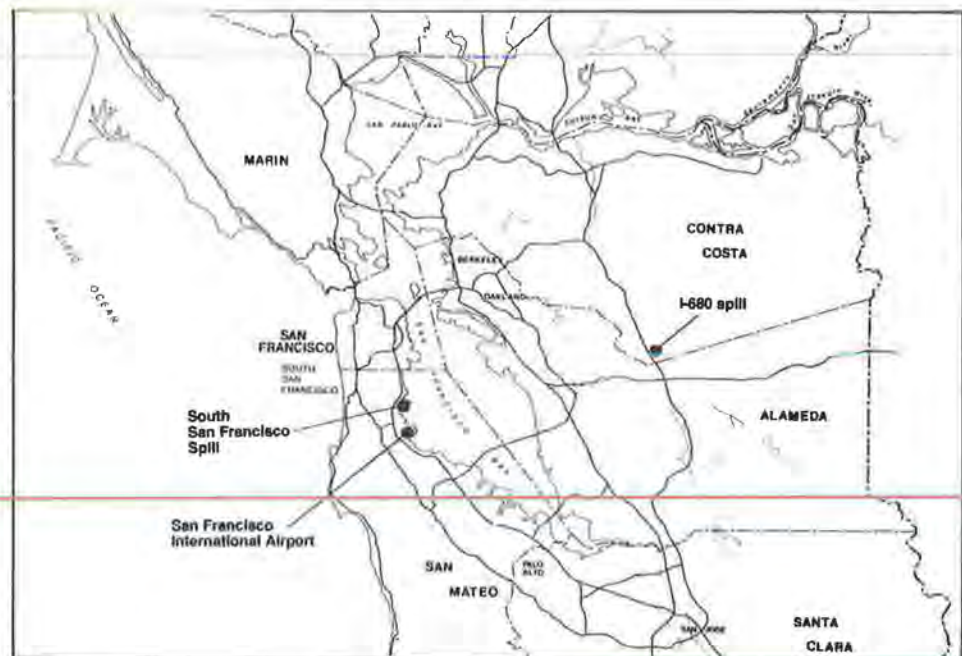


Figure 2. Sites of two 1981 toxic gas spills in San Francisco Bay Area.



spheric stability. In simplifying the problem to this degree, the table is appropriate for use only within the first 20 min following a spill and limited to only those 34 compounds listed. In order to develop the evacuation distances, a standard size spill (1.0 lb/s from a 600-ft² spill) and set of meteorological conditions (6-12 mph winds @ ±15° from centerline and neutral stability) was assumed for Gaussian dispersion calculations.

Illinois Environmental Protection Agency Hazardous Materials Response Guide

The Illinois Environmental Protection Agency (EPA) has developed a guide for estimating evacuation distances that requires that a few simple on-scene measurements and calculations be made. The procedure consists of seven steps:

1. Determine chemicals involved;
2. Record ambient temperature in °F;
3. Determine wind speed and direction (typically by using a hand-held anemometer and compass);
4. Identify stability class (one of three broadly defined categories based on cloud cover and wind speed);
5. Estimate source strength (obtained by estimating spill rate, looking up the vapor pressure of the material, and reading the resulting vapor source strength from a graph supplied in the guide);
6. Calculate an intermediate variable (K) that combines source strength, wind speed, and the threshold limit value for the material; and
7. Read downwind and crosswind evacuation distances (as a function of K and atmospheric stability) from graphs supplied in the guide.

Clearly, this procedure requires some background and training in estimating and measuring the various quantities required. On the other hand, a computer is not necessary and once learned the various measurements and calculations are not difficult to perform. Perhaps the most uncertain estimate is that of the spill rate and resulting source strength. Illinois EPA personnel report satisfactory results in actual application.

Shell Oil Company's SPILLS Model

SPILLS is a computer model that represents the evaporation of a chemical spill and the atmospheric dispersion of the vapors. The model estimates concentrations of the vapors as a function of time and distance downwind of the spill. Three options, depending on the nature of the spill, have been incorporated in the model:

1. Continuous spills, such as leaks from tank cars, tanks, or pipelines;
2. Instantaneously formed pools of liquids or liquified gases; and
3. Stacks, where the emission rate is assumed known.

For options 1 and 2, thermophysical properties of 36 potentially hazardous chemicals are used to calculate, through heat and mass transfer mechanisms, the evaporation rate, which becomes the emission rate for the atmospheric dispersion calculations.

The Gaussian puff air dispersion model can generate three different outputs: maximum concentrations at given elevations and elapsed times since the spill, concentrations at given times and positions in space, and constant concentration contour plots for given elevations and elapsed times. Input parameters used by SPILLS can be varied to predict

minimum and maximum isopleths on which conservative evacuation zones can be defined.

SPILLS is coded in Fortran V and designed for remote terminal access to an IBM 370 time-sharing system. It has been written in conversational mode to simplify the level of training required of the user. The analytical sophistication of this modeling system is considerably greater than the previous examples described. In order to take advantage of this sophistication, however, it is necessary to accurately assess the source strength and meteorological conditions. The sensitivity analysis feature may prove to be quite valuable.

U.S. Coast Guard's HACS

The U.S. Coast Guard has developed a series of guides and handbooks for spill response that, taken together, comprise the chemical hazards response information system (CHRIS). HACS is a part of CHRIS and can be described as the computerized counterpart of the CHRIS Hazardous Chemical Data Manual and the Hazard Assessment Handbook. It consists of a number of models of spill phenomena connected by a hazard assessment tree.

Models were developed for phenomena such as liquid spread and fire, dispersion of vapor, radiation from fires, and dissolution and dispersion in water of a variety of chemicals. Chemicals are grouped according to physical and chemical characteristics. The branches of the hazard assessment tree represent various physical mechanisms that different chemicals undergo, with each branch ending in a hazard situation such as vapor dispersion, fire, or water pollution.

The system is operated via remote terminal connection to the CDC Cybernet Service and has a reported turnaround time of 30 min from receipt of a call for assistance to transmittal of results to the requesting officer.

Lawrence Livermore National Laboratory's ARAC

ARAC was designed in 1973 to provide nuclear materials sites with the capability to monitor real-time dose levels during accidental atmospheric releases of radionuclides. ARAC has since been expanded to assess, on a global basis, the actual or potential release of radionuclides that result from nuclear weapons accidents and to provide the Federal Aviation Administration (FAA) with estimates of radiation dose to passengers on aircraft that may intercept a debris cloud from an atmospheric nuclear test. ARAC provides estimates on geographic scales that vary from regional (up to 100 km) to global, depending on the type of release involved. It consists of several components: the laboratory's computer center equipped with four CDC 7600 computers that run both the regional, three dimensional transport-diffusion models; Air Force Global Weather Central; four U.S. Department of Energy (DOE) nuclear sites; the DOE emergency response team; and the FAA.

Access to the ARAC system was scheduled to be installed at the Rancho Seco nuclear power plant and at the California and New York State Offices of Emergency Preparedness during 1980 and 1981. The system requires substantial technical and financial resources to maintain and is suitable for use only for major emergencies such as might be caused by accidents that involve potential release of substantial quantities of radioactive materials (e.g., Three Mile Island).

EVALUATION OF ATMOSPHERIC DISPERSION MODELS

Although none of the methods in use for defining evacuation areas appears to have been subjected to performance evaluation, numerous evaluations of atmospheric dispersion models have been published (6,7).

These evaluations all indicate that, regardless of the specific theory or construction of the model, an uncertainty of a factor of 2 or more in the predicted concentrations may be expected. The numerous explanations for this somewhat disappointing record all boil down to the problems of ambient measurement and mathematical simulation of the real world. In order to make the mathematics manageable, many approximations and simplifications are introduced; major governing processes are retained, but enough of the details are lost both in the model formulation and in the preparation of input data that an uncertainty factor of two in the result (when compared with ambient measurements) has been the invariable outcome.

In terms of defining evacuation areas, the uncertainty factor of 2 in predicted concentrations does not translate proportionately to an uncertainty factor of 2 in the evacuation area defined. The uncertainty in the definition of evacuation area would vary according to the size of the spill, the threshold limit value of concern, and the resulting downwind distance where significant concentrations would be expected. As a rough guess, an uncertainty factor of 4 or 5 in the specification of the evacuation area is the likely range, assuming that proper measurements and observations are used as input to the calculation. If only rough guesses are available for critical input variables, the uncertainty may increase to a factor of 100 or more.

This range of uncertainty is significant; however, it is probably at least a factor of 10 improvement over the blind application of the DOT Emergency Response Guidebook (1). At the same time, the on-site judgment of an experienced, trained individual may be equal to or better than what a model could do. Unfortunately, no evidence is available to verify the relative performance of any of these methods so that an objective judgment can be made.

ISSUES

The most obvious issue here is what level of sophistication is appropriate for defining evacuation areas. The answer seems to be that it depends on the nature, magnitude, and duration of the spill, as well as on the level of training given to response agency personnel for making the appropriate estimates. A commonly held view is that sophisticated models are of little value in an emergency spill situation, either because of the time required to access the models, prepare the proper inputs, and receive an answer, or because of uncertainties in estimates of critical input variables. Responding personnel that are first on the scene must make a quick decision to mobilize the proper forces to evacuate a given area. However, spills serious enough to warrant evacuation will probably continue to be serious for more than one or two hours. This should be enough time to prepare more reliable estimates of the source strength and meteorological conditions so that more precise estimates of evacuation corridors may be made and secondary evacuations conducted. This suggests that a two-stage system could be used for identification of evacuation areas. Much depends on how quickly appropriately trained personnel can arrive on the scene. The Illinois EPA method is a compromise between the simple look-up table and the sophisticated computer models, but

presumes that a trained individual will be on the scene to make the proper observations.

A related issue is that often, particularly in the Bay Area, microclimatic variations make determinations of atmospheric conditions difficult, thereby creating substantial uncertainty in the results of any dispersion calculation. To this may be added special conditions such as the behavior of a cold vapor cloud that is not well described by ordinary Gaussian dispersion equations.

Perhaps the most nagging problem with all of the methods in use or potential use today is the uniform lack of performance evaluation. Some evaluation has occurred for models of similar generic type; however, none of the models or methods in use for spills appears to have been tested or statistically verified against field measurements. Further, the sensitivity of the estimated evacuation area to uncertainties in source strength and meteorological conditions should be a standard capability in all of the more advanced methods, since such uncertainties are the major stumbling block once the methods are put into use.

RECOMMENDATIONS

Based on the foregoing information, the Subcommittee in Risk Assessment and Toxic Gases has approved the following recommendations for consideration by the full task force.

Spill response agencies should maintain or have access to more refined methods and commensurate training for defining evacuation zones than that provided by the DOT Hazardous Materials Emergency Response Guidebook (1). ABAG should work with the Bay Area Air Quality Management District and other interested agencies to develop a two-tiered system for eventual implementation in the Bay Area: First, a handbook that is intermediate in sophistication to the DOT guidebook and the Illinois EPA guidebook (2) should be developed for wide distribution to local police and fire department personnel. This handbook should require a minimum level of training and no specialized instrumentation for its use. Second, access to an appropriate computer model should be provided to all spill response agencies in the Bay Area. (All necessary computer hardware and communication equipment should be designed to be portable such that they may be transported to spill sites via either van or helicopter.)

DOT and other appropriate federal and state agencies should sponsor verification and sensitivity tests for the variety of methods currently in use to define evacuation zones during toxic gas release emergencies. Special problems posed by microclimatic variations with cold vapor clouds should also be assessed, and appropriate methods developed for handling these situations.

ACKNOWLEDGMENT

This work was supported by the U.S. Department of Transportation.

REFERENCES

1. Hazardous Materials 1980 Emergency Response Guidebook. U.S. Department of Transportation, DOT P-5800-2, July 1980.
2. J. Kelty. Hazardous Materials Response Guide. Emergency Response Unit, Division of Air Pollution Control, Illinois Environmental Protection Agency, Springfield, 1980.
3. M.T. Fleischer. Mitigation of Chemical Spills--An Evaporation-Air Dispersion Model for Chemical Spills on Land. Shell Development Com-

- pany, Westhollow Research Center, Houston, Dec. 1980.
4. R.V. Harding and others. The Development and Implementation of the Hazard Assessment Computer System (HACS). Proc., 1978 National Conference on Control of Hazardous Materials Spills (G.F. Bennett, ed.), U.S. Environmental Protection Agency, Miami Beach, April 11-13, 1978.
 5. M.H. Dickerson and others. ARAC Update--1979. Lawrence Livermore National Laboratory, Livermore, CA, UCRL-52802, July 9, 1979.
 6. S. Hameed. Modelling Urban Air Pollution. Atmospheric Environment, Vol. 8, No. 6, 1974, pp. 555-561.
 7. R.C. Koch and S.D. Thayer. Validity of the Multiple-Source, Gaussian Plume Urban Diffusion Model Using Hourly Estimates of Input. Conference on Urban Environment and Second Conference on Biometeorology, American Meteorological Society, 1972.

Integrated Modeling of the Release and Dispersion of Hazardous Gases in the Atmosphere

BRENNER MUNGER, PAUL HURT, PETER HAYDEN, AND EILEEN IRVINE

Accidental or uncontrolled releases of heavy, flammable, or toxic gases may occur during production, storage, or transport of such gases and may pose a serious hazard to the public. A modeling system is presented that describes the behavior of such gases during several phases: (a) release; (b) gravity spreading, heating, and air entrainment; (c) dispersion; and (d) safety assessment. Specific phenomena considered include vapor flash-off, entrainment of liquid droplets and air, evaporation from a pool, slumping, cloud heating and dilution, changing meteorological conditions, and downwind transport. The safety assessment component provides spatial distributions of time-averaged concentrations and dosages; maximum concentrations, dosages, and their locations; and isopleths for specified concentration and dosage levels. The model may be used in real-time evaluation or as a predictive tool to describe instantaneous and continuous releases from multiple sources.

Safety studies associated with toxic and flammable gases have received much attention during the last two decades. As a result of various legislation enacted recently [e.g., Toxic Substances Control Act of 1976 and Occupational Safety and Health Administration (OSHA) regulations], such studies are playing an increasingly important role in emergency planning, impact assessments, and regulatory programs. An important component of such studies is an accurate prediction of potential human exposure due to an accidental or uncontrolled release of hazardous chemicals. With this information adequate emergency measures can be formulated and put into effect to prevent and minimize the potential impacts on public safety and welfare.

The dispersion of toxic chemicals is known to be more complex than the dispersion of gases released from conventional source stacks. Some toxic gases have unique dispersion characteristics because of their negative buoyancy due to temperature or molecular weight differences with ambient air. To account for the behavior of variable-density gases, to provide flexibility in characterizing the modeling system for specific types of applications, and to facilitate continued refinement of the system, four components are used to represent the major phases:

1. Release,
2. Gravity spread,
3. Dispersion, and
4. Safety assessment.

The release phase describes the emissions released during the spill to the atmosphere. The conditions of the release may contribute to flash-off

of vapor, entrainment of liquid droplets as well as air, and the resultant formation of a cold, denser-than-air mixture.

The gravity-spread phase simulates spreading and dilution of a negatively buoyant cloud under the influence of gravity and edge mixing or entrainment. The horizontal dimension of the cloud increases due to gravity spread (slumping), and the cloud is heated from below and from air entrainment. Downwind transport is also considered during the gravity-spread phase.

The dispersion phase accounts for downwind transport and turbulent dispersion of the gas from the time at which atmospheric turbulence dominates the spread of the cloud. The safety-assessment phase output is dependent on the application and the information needs of the user. Alternative outputs may include concentrations and dosages at the grid nodes of a rectilinear grid covering the study area, maximum dosage and concentration and location, and isopleths for user-specified concentration and dosage levels.

FORMULATION OF RELEASE PHASE

The circumstances that surround the release of gas into the atmosphere play an important part in characterizing the initial gas cloud that is formed. Significant factors include storage characteristics such as container size, pressurization, or refrigeration; release features such as release height, rupture dimensions, and escape rate; and initial gas dilution. Typical release scenarios include relief valve venting, tank or pipe leaks, and tank or pipeline failures. Events following release for each type of chemical and gas storage system vary but may be generalized as follows:

1. Buoyant gases--Gases that are buoyant on release experience buoyant plume rise, plume dilution, and subsequent Gaussian dispersion.
2. High molecular weight gases--These gases experience gravity spreading with entrainment and turbulent mixing in the atmosphere.
3. Pressurized, liquefied gases--These gases, stored as liquids at ambient temperatures and elevated pressures, exhibit gas releases from two effects: (a) flash evaporation due to a reduction of vapor pressure to reach equilibrium pressure with