



# TRANSPORTATION RESEARCH RECORD 902

## Atmospheric Emergencies: Existing Capabilities and Future Needs

001418811

Transportation Research Record Issue:  
902

LIBRARY  
TRANSPORTATION RESEARCH BOARD  
2101 CONSTITUTION AVE.  
WASHINGTON, DC 20418

**TRRB**  
TRANSPORTATION RESEARCH BOARD  
NATIONAL ACADEMY OF SCIENCES

## 1983 TRANSPORTATION RESEARCH BOARD EXECUTIVE COMMITTEE

### OFFICERS

**Chairman:** *Lawrence D. Dahms*, Executive Director, Metropolitan Transportation Commission, Berkeley, California  
**Vice Chairman:** *Richard S. Page*, President, Washington Roundtable, Seattle, Washington  
**Executive Director:** *Thomas B. Deen*, Transportation Research Board

### MEMBERS

*Ray A. Barnhart*, Administrator, Federal Highway Administration, U.S. Department of Transportation (ex officio)  
*Francis B. Francois*, Executive Director, American Association of State Highway and Transportation Officials, Washington, D.C. (ex officio)  
*William J. Harris, Jr.*, Vice President, Research and Test Department, Association of American Railroads, Washington, D.C. (ex officio)  
*J. Lynn Helms*, Administrator, Federal Aviation Administration, U.S. Department of Transportation (ex officio)  
*Thomas D. Larson*, Secretary of Transportation, Pennsylvania Department of Transportation, Harrisburg (ex officio, Past Chairman, 1981)  
*Darrell V. Manning*, Director, Idaho Department of Transportation, Boise (ex officio, Past Chairman, 1982)  
*Diane Steed*, Acting Administrator, National Highway Traffic Safety Administration, U.S. Department of Transportation (ex officio)  
*Kent Woodman*, Acting Administrator, Urban Mass Transportation Administration, U.S. Department of Transportation (ex officio)

\* \* \* \* \*

*Duane Berentson*, Secretary, Washington State Department of Transportation, Olympia  
*John R. Borchert*, Professor, Department of Geography, University of Minnesota, Minneapolis  
*Arthur J. Bruen, Jr.*, Vice President, Continental Illinois National Bank and Trust Company of Chicago, Chicago  
*Joseph M. Clapp*, Senior Vice President, Roadway Express, Inc., Akron, Ohio  
*John A. Clements*, Commissioner, New Hampshire Department of Public Works and Highways, Concord  
*Ernest E. Dean*, Executive Director, Dallas-Fort Worth Airport, Texas  
*Alan G. Dustin*, President and Chief Executive Officer, Boston and Maine Corporation, North Billerica, Massachusetts  
*Robert E. Farris*, Commissioner, Tennessee Department of Transportation, Nashville  
*Jack R. Gilstrap*, Executive Vice President, American Public Transit Association, Washington, D.C.  
*Mark G. Goode*, Engineer-Director, Texas State Department of Highways and Public Transportation, Austin  
*Lester A. Hoel*, Chairman, Department of Civil Engineering, University of Virginia, Charlottesville  
*Lowell B. Jackson*, Secretary, Wisconsin Department of Transportation, Madison  
*Marvin L. Manheim*, Professor, Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge  
*Fujio Matsuda*, President, University of Hawaii, Honolulu  
*James K. Mitchell*, Professor and Chairman, Department of Civil Engineering, University of California, Berkeley  
*Daniel T. Murphy*, County Executive, Oakland County, Pontiac, Michigan  
*Roland A. Ouellette*, Director of Transportation Affairs, General Motors Corporation, Washington, D.C.  
*Milton Pikarsky*, Director of Transportation Research, Illinois Institute of Technology, Chicago  
*Walter W. Simpson*, Vice President-Engineering, Southern Railway System, Washington, D.C.  
*John E. Steiner*, Vice President, Corporate Product Development, The Boeing Company, Seattle  
*Richard A. Ward*, Director-Chief Engineer, Oklahoma Department of Transportation, Oklahoma City

The **Transportation Research Record** series consists of collections of papers in a given subject. Most of the papers in a Transportation Research Record were originally prepared for presentation at a TRB Annual Meeting. All papers (both Annual Meeting papers and those submitted solely for publication) have been reviewed and accepted for publication by TRB's peer review process according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The views expressed in these papers are those of the authors and do not necessarily reflect those of the sponsoring committee, the Transportation Research Board, the National

Academy of Sciences, or the sponsors of TRB activities.

Transportation Research Records are issued irregularly; approximately 50 are released each year. Each is classified according to the modes and subject areas dealt with in the individual papers it contains. TRB publications are available on direct order from TRB, or they may be obtained on a regular basis through organizational or individual affiliation with TRB. Affiliates or library subscribers are eligible for substantial discounts. For further information, write to the Transportation Research Board, National Academy of Sciences, 2101 Constitution Avenue, NW, Washington, DC 20418.

*TRANSPORTATION RESEARCH RECORD* 902

Atmospheric  
Emergencies:  
Existing Capabilities  
and  
Future Needs

*TRANSPORTATION RESEARCH BOARD*

*NATIONAL RESEARCH COUNCIL  
NATIONAL ACADEMY OF SCIENCES  
WASHINGTON, D.C. 1983*

LIBRARY  
TRANSPORTATION RESEARCH BOARD  
WASHINGTON, DC 20418  
2101 CONSTITUTION AVE.  
91402

Transportation Research Record 902  
Price \$6.40  
Edited for TRB by Susan Singer-Bart

modes  
1 highway transportation  
3 rail transportation

subject areas  
17 energy and environment  
51 transportation safety

**Library of Congress Cataloging in Publication Data**  
National Research Council. Transportation Research Board.  
Atmospheric emergencies.

(Transportation research record; 902)  
Reports prepared for the 62nd annual meeting of the Transportation Research Board.  
1. Hazardous substances—Transportation—Safety measures—Addresses, essays, lectures. I. National Research Council (U.S.). Transportation Research Board. II. Series.  
TE7.H5 no. 902 [T55.3.H3] 380.5s [363.1'79] 83-13464  
ISBN 0-309-03516-3 ISSN 0361-1981

Sponsorship of the Papers in This Transportation Research Record

**GROUP 1—TRANSPORTATION SYSTEMS PLANNING AND ADMINISTRATION**

*Kenneth W. Heathington, University of Tennessee, chairman*

**Environmental Quality and Conservation of Resources Section**

*Earl C. Shirley, California Department of Transportation, chairman*

**Committee on Transportation and Air Quality**

*Norman L. Cooper, U.S. Department of Transportation, chairman*  
*Salvatore Bellomo, George A. Bonina, Earl H. Bowman, David L. Calkins, William A. Carpenter, Walter F. Dabberdt, Denis E. Donnelly, Alan Eschenroeder, John H. Gastler, Charlotte J. Hopper, Joel L. Horowitz, William C. Lockett, Paul F. Maxwell, Roderick D. Moe, Carlton Thomas Nash, Kenneth E. Noll, Ronald J. Piracci, Tom K. Ryden, Phillip S. Shapiro, N. Thomas Stephens, Lawrence R. Taylor*

Stephen E. Blake, Transportation Research Board staff

The organizational units, officers, and members are as of December 31, 1982.

# Contents

---

FOREWORD .....	v
ENVIRONMENTAL EMERGENCIES: PREPARING FOR CRITICAL HOURS Al J. Smith, Jr. ....	1
NATIONAL OVERVIEW OF EMERGENCY RESPONSE UNDER SUPERFUND H. D. van Cleave .....	3
ATMOSPHERIC PROBLEMS FROM HAZARDOUS MATERIALS SPILLS IN SAN FRANCISCO BAY AREA Ronald Y. Wada .....	5
INTEGRATED MODELING OF THE RELEASE AND DISPERSION OF HAZARDOUS GASES IN THE ATMOSPHERE Brenner Munger, Paul Hurt, Peter Hayden, and Eileen Irvine .....	9
U.S. AIR FORCE AIR WEATHER SERVICE METHODOLOGIES FOR CALCULATING TOXIC CORRIDORS J. P. Kahler and J. L. Dicke .....	14
CALCULATION OF EVACUATION DISTANCES DURING TOXIC AIR POLLUTION INCIDENTS James Kelty .....	19
TOXIC CORRIDOR PREDICTION PROGRAMS John T. Marrs, Ernest B. Stenmark, and Frank V. Hansen .....	21
TOXIC CORRIDOR PROJECTION MODELS FOR EMERGENCY RESPONSE Mark D. Ryckman and Jeffrey L. Peters .....	25
RADIATION HAZARDS ANALYSIS IN TRANSPORT OF LOW SPECIFIC ACTIVITY WASTE MATERIAL C. F. Smith, J. J. Cohen, A. J. Toy, and J. D. Colton .....	30
AEROMETRIC INSTRUMENTATION FOR REAL-TIME MONITORING AT HAZARDOUS SPILL SITES: OVERVIEW OF NEEDS AND RESOURCES Walter F. Dabberdt .....	31
APPLICATIONS OF REMOTE SENSING TO HAZARDOUS SPILL INCIDENTS Edward E. Uthe and James G. Hawley .....	36

## Authors of the Papers in This Record

---

Cohen, J. J., Science Applications, Inc., 1811 Santa Rita Road, Pleasanton, CA 94566  
Colton, J. D., SRI International, Menlo Park, CA 94025  
Dabberdt, Walter F., Atmospheric Science Center, SRI International, Menlo Park, CA 94025  
Dicke, J. L., 1004 Collins Drive, Raleigh, NC 27609; reserve officer assigned to the Headquarters Air Weather Service, Scott Air Force Base, IL  
Hansen, Frank V., U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM 88002  
Hawley, James G., Systems Techniques Laboratory, SRI International, Menlo Park, CA 94025  
Hayden, Peter, Environmental Research and Technology, Inc., 2625 Townsgate Road, Westlake Village, CA 91361  
Hurt, Paul, Environmental Research and Technology, Inc., 2625 Townsgate Road, Westlake Village, CA 91361  
Irvine, Eileen, Environmental Research and Technology, Inc., 2625 Townsgate Road, Westlake Village, CA 91361  
Kahler, J. P., U.S. Department of the Air Force, Air Force Weapons Laboratory, Kirtland Air Force Base, NM 87117; formerly stationed at the Headquarters Air Weather Service, Scott Air Force Base, IL  
Kelty, James, Illinois Environmental Protection Agency, Emergency Response Unit, 2200 Churchill Road, Springfield, IL 62706  
Marrs, John T., U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM 88002  
Munger, Brenner, Environmental Research and Technology, Inc., 2625 Townsgate Road, Westlake Village, CA 91361  
Peters, Jeffrey L., Ryckman's Emergency Action and Consulting Team, 2208 Industrial Court, P.O. Box 27310, St. Louis, MO 63141  
Ryckman, Mark D., Ryckman's Emergency Action and Consulting Team, 2208 Welsch Industrial Court, P. O. Box 27310, St. Louis, MO 63141  
Smith, Al J., Jr., U.S. Environmental Protection Agency, Region IV, 345 Courtland Street, N.E., Atlanta, GA 30365  
Smith, C. F., Science Applications, Inc., 1811 Santa Rita Road, Pleasanton, CA 94566  
Stenmark, Ernest B., U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range, NM 88002  
Toy, A. J., Science Applications, Inc., 1811 Santa Rita Road, Pleasanton, CA 94566  
Uthe, Edward E., Atmospheric Science Center, SRI International, Menlo Park, CA 94025  
Van Cleave, H. D., Office of Emergency Response, U.S. Environmental Protection Agency, Mail Code WH-548, Washington, DC 20555  
Wada, Ronald Y., Association of Bay Area Governments, Hotel Claremont, Berkeley, CA 94705

## Foreword

During the past decade the number of casualties from transportation incidents involving hazardous materials increased fourfold. The number of incidents increased by a factor of eight during the same period. The actual number of casualties in any single incident has been relatively low (less than 10); however, the potential for large-scale disaster is great. For example, a recent major train derailment in the Toronto suburb of Mississauga endangered hundreds of thousands and forced tens of thousands to evacuate their homes. Fortunately, there were no deaths.

The objectives of the two sessions of the 1982 TRB meeting on atmospheric emergencies were to obtain a better understanding of spills of toxic substances from transport vehicles, review the existing regulatory framework and emergency response, and review the state of the art of dispersion assessment and monitoring instrumentation. These presentations should be viewed as a representative survey of the state of the art in mid-1981 and not necessarily as new research developments. In many cases the meth-

ods used are unsophisticated. They do, nonetheless, fulfill a real need for rapid analysis of potential dangers from toxic spills. They also establish a baseline from which future improvements can be made.

The proceedings are organized into three broad categories: background, modeling, and monitoring. The background section contains three papers that address the nature of the emergencies and response methods, national legislation, and an urban planning study that seeks to develop a regional response plan. The second section on modeling contains six presentations. One reviews the physics of the problem, including release, gravity spread, and dispersion. Four papers summarize assessment methods currently used by two military groups, one state agency, and one private firm. The last paper in this section addresses radiation hazards from low specific activity wastes. Two papers comprise the monitoring section. One gives an overview of potentially applicable techniques and the constraints imposed by the unique nature of emergency incidents, and the other reviews the potential for the use of remote-sensing systems.

# Environmental Emergencies: Preparing for Critical Hours

AL J. SMITH, JR.

An otherwise useful chemical may become a villain in an instant simply because it is released to an unprepared environment. The air quality significance of such an event can be profound when air-active chemicals are involved. We can exert little control over the effects of such chemicals on man or environment for some length of time; therefore, what is done or not done by all persons involved during the first 4-6 h is critical. Consequently, how governments, industries, and local communities prepare for the event eventually dictates the outcome in terms of damage and even death.

The field of environmental emergencies brings into focus a wide spectrum of interests and concerns. The potential exists for water, soil, and air contamination and, of course, public welfare and long-term public health need to be considered. Specific special interests also are involved: the three levels of government (federal, state, and local), the chemical industry, the transportation industry, the persons and property immediately affected, and others whose interests are not so direct.

An event involving the transportation of certain chemicals may bring all of the above concerns and interests into play. This interaction makes the field an interesting (if difficult) one. At any one event as many as 200 officials, representing various local, state, and federal agencies may be in attendance. This group will usually include multiple representatives from individual agencies. In addition, a number of industry representatives are likely to be present. Obviously, many jurisdictions and applicable statutes are involved, and at times these will conflict or overlap. Most of the officials and other involved persons arrive on the scene sometime between 4-6 h following the event.

For many reasons, the time frame of 0-6 h after the start of the event is critical. This period is referred to generally as the first responder phase of a chemical release and is typified by the following most obvious immediate effects:

1. Escaping liquids,
2. Mixed and uninhibited releases of gases,
3. Fires and explosions,
4. Persons injured or killed, and
5. Curious onlookers.

The first responder arrives, initial evacuation is performed, and decisions are made as to recovery of injured and containment of liquids and gases and fire control. Local leadership and control of initial activities is developed and communications are established. Early-arrival secondary responders include (a) industry officials, (b) state and federal officials, and (c) the press. State officials and industry officials should arrive 3-4 h after the event. Federal officials historically take 4-6 h and, in some cases, up to 10 h.

Early actions and decisions made at the scene have broad implications for later activities. Whether the consideration is technical, sociopolitical, or logistic, the impact on later decisions is considerable. Consequently, on-scene coordination of effort must begin as early in the event as possible. Many experienced and sincerely dedicated persons subscribe to the idea that one person should be in charge of the entire operation. Conceptually, this would be ideal but, as a practical matter, it will probably never happen. There are simply too many jurisdictions involved that have a legally constituted basis. For example, there are three sets of laws (federal, state, and local) that immediately

apply as well as the constitutionally protected property rights involved. Also, no entity or person is clearly capable, either technically or in terms of existing authority, to legally maintain absolute control over every operation during the entire term of the event.

There is, however, a concept that approximates the "one person in charge idea" and is workable. This is an on-scene operation that establishes on-scene coordinators (OSCs) for all three levels of government backed by a team of individuals. This concept has its roots in the National Contingency Plan for Hazardous and Oil Spills that was first developed in response to edicts laid out by the Congress in the Clean Water Act of 1972 (Public Law 92-500). Today this same national plan has been completely rewritten as a result of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (Public Law 96-510), or as it is frequently referred to, Superfund.

Executive Order 12316, signed by President Reagan on August 14, 1981, assigns to several federal agencies specific areas of emergency response responsibility. So, although institutional arrangements are such that no one person is in charge, one person may very well be responsible to the Congress for at least the federal behavior at the accident scene. The OSC is the federal creation that has this responsibility. The OSC is backed by a regional response team (RRT) made up of representatives of federal, state, and local agencies. The RRT is the advisory body to the OSC.

The problem with this system is that sheer numbers of people can make it awkward. However, if involved groups of agencies can designate representatives to be OSCs, the group becomes the RRT shown by Figure 1. This size team is not only manageable but is also extremely functional.

Finally, a realistic view must be taken by all concerned of the various interest levels as the accident coordination proceeds. For example, note in Figure 2 how the leadership or coordination function may shift from government to government as time progresses. (The shaded areas in the figure indicate time zones that are vulnerable to conflicts of jurisdiction and interests. The curves suggest how peaks of interest can develop among various governments because of such things as existing laws, bounded jurisdictions, and time-of-response logistics.)

The above remarks are directed at current methods of government's response to chemical releases. Preparation for the response is equally confounding. Contingency planning, of course, is a large portion of the solution to this problem, but at the local level even contingency planning falls short of the ultimate goal of total preparation. For example, the National Contingency Plan (40 CFR Part 1510) is a summation of parts that, in fact, do not all exist. An underlying assumption of the national plan is that state and local governments maintain an equivalent state of readiness for the chemical event. This is only partly true. In fact, a 1978 detailed study of state emergency response readiness by the Arthur D. Little Company indicated that, although state governments are interested and willing, funds and resources to respond on a full-time basis were reported as adequate by only a few of the states. At the local level prior planning is a more complex issue. Readiness at this level involves



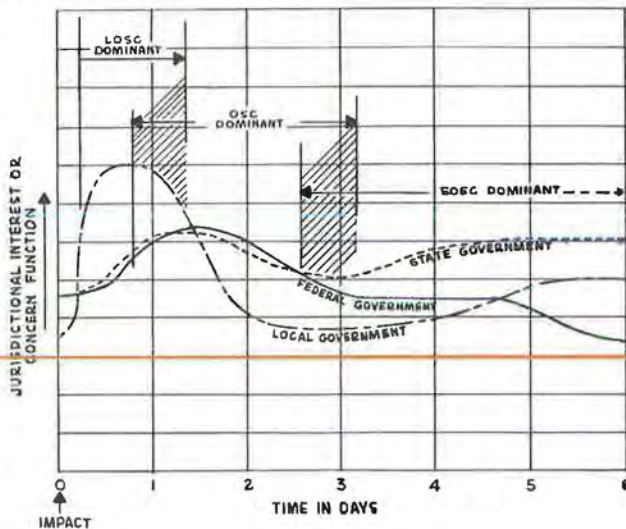
such things as evacuation plans, traffic control, hospitalization and housing plans, continuity of social services, and zoning. State and federal agencies can be largely concerned with response, but the local agencies must be profoundly interested in prevention as well as response.

A number of dangerous situations may affect the local community during or after a large release of chemicals. Some of these are explosion, fire, gaseous releases, and spilling or leaking of liquids. These may be immediate or delayed events. A long list of natural and man-made circumstances may also impact the magnitude of effect that these situations may impose on the local community. Climate, topography, soil mechanics, structures, forestation, water bodies, roads, people proximity, public awareness, and other factors can influence the outcome of the release. Of the situations described above, the most significant in the short-term, as far as public health, welfare, and safety are concerned, is the sudden release of a noxious or toxic gas. Although this is not said to downplay the long-term potential effects that may accompany such an event, the evidence is simply much clearer for local and short-term effects that are more quantifiable. Figures 3-7 indicate the significance of the short-term phenomena.

Figure 1. RRT meeting.



Figure 2. Jurisdictional interest or concern function or impact among various levels of government.



The forecasting of an event or determining the amounts and kinds of chemicals transported through a community are not normally controlled by the community. As an example, a county ordinance that prohibits the transport of any toxic chemical through the county may be in conflict with federal law at its inception. Federal law provides that interstate

Figure 3. Extreme local conditions.



Figure 4. Dispersion and winds aloft.



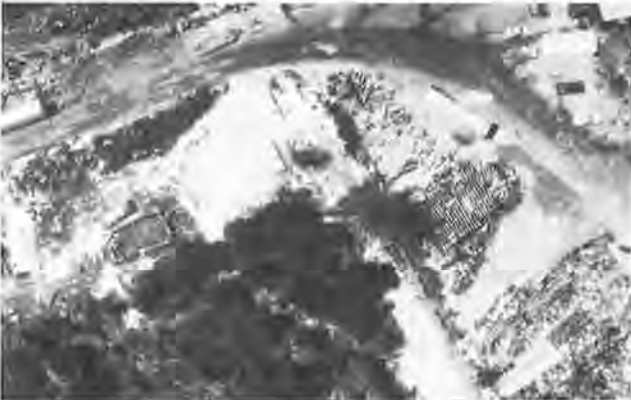
Figure 5. Dispersion and surface winds.



Figure 6. Implications involving surface winds and winds aloft.



Figure 7. Potentials from poorly stored waste chemicals.



carriers cannot refuse to transport a chemical that is properly labeled, contained, and loaded. Simply put, there is no way to keep chemicals away from the people; the people must be kept away from certain

chemicals. The word that comes to mind is zoning—not zoning in the classical sense and certainly not sterile zoning in which huge areas of land are left bare. Perhaps a concept of land use and time management that recognizes some of the ideas usually associated with classical zoning would at least provide a basis for study.

Zoning in this country has always been a local issue, but it is not inconceivable that federal and state regulators as well as local officials and industry advisory groups could draw on fundamental zoning ideas and land use concepts as laws are reviewed, rewritten, or created. Some of the ideas being tossed about here are as follows:

1. Time schedules of chemical deliveries in certain heavily populated areas;
2. Direction a building may face or where windows may be placed and style of ventilation systems, in circumstances involving structures located in close proximity to major chemical transportation routes or chemical storage areas;
3. Strategic use of natural wind or dispersion buffers as land is developed near these zones of chemical storage or transportation;
4. System whereby local or state governments would notify major interstate carriers of interim or short-term congestion in specific areas such as state fairs, major sports, or recreation events; and
5. Zones of concern, with degrees of concern relating to such things as natural hazards (bad roads, low speed limits, or frequent local flooding) being lined up or correlated with transportation vectors, and storage areas all transposed to a matrix that depicted times of high population risk.

The list goes on. Admittedly, these are shots in the dark and to some even the mention of the above ideas in the same breath with true zoning may be offensive. But, clearly, we are talking about risk analysis, responsibilities, and competing interests. Industry has made great effort in the past 5-6 years to prevent accidents and to be responsive to them when they occur. Government has worked side by side with the industrial sector to make positive things happen and this side of the story is rarely told. Nonetheless, all of these efforts will not close the circle. The public must participate to achieve this goal.

## National Overview of Emergency Response Under Superfund

H. D. VAN CLEAVE

This paper discusses the U.S. Environmental Protection Agency's program for hazardous material emergency response and the Superfund created by Congress to support federal cleanup of chemical spills and abandoned waste sites that threaten people or the environment. The active participation of state and local governments during hazardous waste emergencies is advocated. Efforts toward federal, state, and local cooperation are seen as the key to timely and effective response to the dangers from hazardous materials.

The primary responsibility of the U.S. Environmental Protection Agency's (EPA) oil and hazardous substance emergency response program is to protect the quality of the environment by preventing or minimizing the effects of spills or releases from hazardous waste sites. The program concentrates on environmental emergencies that pose an immediate threat to public health and welfare. EPA's Emergency Response Division is headquartered in Washington, D.C., and

Falls within the jurisdiction of the Office of Solid Waste and Emergency Response. It is separate from the Hazardous Site Control Division, which addresses long-term remedial actions at hazardous waste sites. Rapid response throughout the United States is achieved through the efforts of the Emergency Response Division's 10 regional offices and the special emergency response teams based in Cincinnati, Ohio, and Edison, New Jersey.

Two major pieces of legislation form the basis of the emergency response program. The Federal Water Pollution Control Act (FWPCA), as amended in 1972, outlines federal responsibilities for spills of oil (primarily) and hazardous substances into or on the navigable waters of the United States, the adjoining shorelines, or the waters of the contiguous zone. The Comprehensive Environmental Response, Compensation, and Liability Act of 1980, known as Superfund, broadens the scope of response to include inland areas. It also allows the federal government to enter into cooperative agreements with states to perform the removal actions authorized under Superfund.

The national oil and hazardous substances pollution contingency plan was originally prepared pursuant to Section 311 of FWPCA and later revised and republished in compliance with Section 105 of Superfund. The plan provides for coordinated federal response to releases or threatened releases of hazardous substances into all media. The plan also promotes federal-state coordination by encouraging state and local governments to develop capabilities for responding to releases.

Section 104 of Superfund authorizes EPA to take response measures necessary to protect the public health and welfare and the environment. Federal emergency response is initiated through telephone notification of the U.S. Coast Guard National Response Center in Washington, D.C. The National Response Center is notified of

1. All discharges,
2. Oil to navigable waters, and
3. Hazardous substances to all media (i.e., water, land, air, and groundwater).

It disseminates the report to the appropriate response agency or on-scene coordinator (OSC). The National Response Center has a toll-free telephone number within the continental United States.

The OSC is the official appointed by EPA or the U.S. Coast Guard to direct federal response efforts under the plan. The U.S. Coast Guard responds to hazardous material spills onto or threatening the coastal zone; EPA attends to incidents that involve the inland zone. A recently signed interagency agreement makes EPA responsible for all responses that involve releases from hazardous waste sites regardless of location.

The federal OSC assesses the nature and magnitude of the situation and decides either to assist local officials in monitoring the removal efforts by the responsible party to declare federal removal action. A federal removal action is declared in those

cases where the discharger is unknown, the discharge is caused by an act of nature or war, or the responsible party cannot or will not respond in a proper manner.

Stiff penalties are associated with a failure to notify the National Response Center. Under the provisions of Section 311 of the Clean Water Act of 1977 as amended, the criminal penalty for failing to notify the proper officials of an oil spill is \$10 000 fine, one year of imprisonment, or both. The civil penalty assessed for each discharge is \$5000. The federal government must also be reimbursed for costs incurred in removing the oil spill and restoring the natural resources. The same criminal penalty is assessed under Superfund for failure to notify the appropriate officials of a release of hazardous substances. Punitive damages up to three times the cost of federal removal may be assessed for failure to provide removal under Superfund. Destruction of records is eligible for a \$20 000 fine, one year of imprisonment, or both. Both laws make provisions for reimbursement of the costs of federal removal and restoration of natural resources; therefore, all costs related to response must be documented carefully by OSC.

The OSC determines not only the need for federal response but also the extent of removal or remedial action. Removal action, in the context of Superfund operations, means the cleanup of released hazardous substances from the environment or the taking of other actions to prevent, minimize, or mitigate damage to the public health or welfare of the environment. Remedial action involves those actions required for permanent remedy.

The OSC is responsible for devising the site safety plan--those safety procedures taken to protect the health and welfare of workers during site operations--and for implementing a community relations plan. Typical community relations activities might include the issuing of news releases and progress reports to the media, the briefing of citizens directly affected by the response operation, and the offering of special public information services for official visitors.

Essentially, the national contingency plan charges the OSC with coordinating all public and private efforts during a response operation. Recently, however, EPA has been successful in bringing state and local governments in as full and active partners in the achievement of environmental goals. OSCs are encouraging state and local officials to assume greater leadership roles in response operations.

Naturally, the federal OSC will retain an important advisory role, and Superfund will continue to be the major source of cleanup money. The vast scientific support resources, such as the multidisciplinary expertise of the environmental response teams, the technical assistance teams, the field investigation teams and specialized monitoring, sampling, and safety equipment, will continue to be available to support the regional efforts. However, the desirable and successful emergency responses of the future will be multigovernmental efforts.

# 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-mile<sup>2</sup> 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.

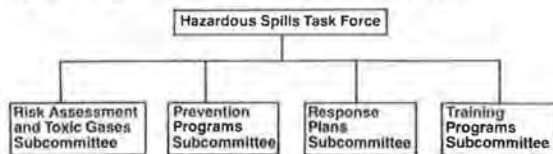
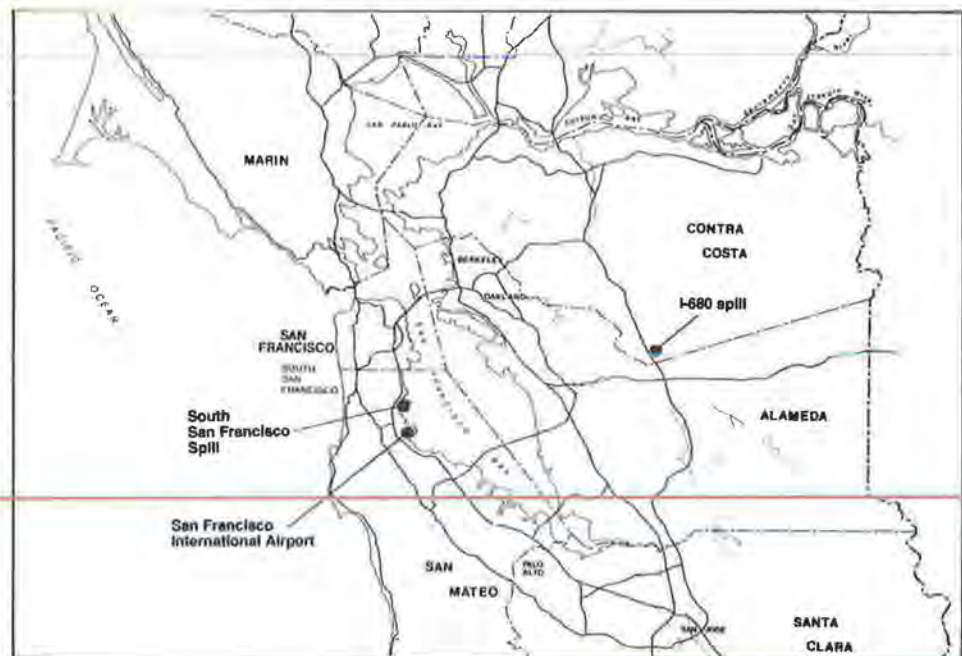


Figure 2. Sites of two 1981 toxic gas spills in San Francisco Bay Area.



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-ft<sup>2</sup> 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



the atmosphere and the concomitant reduction in temperature and (b) slow pool evaporation, which results from heat transfer to the cold liquid pool. Gravity spread and dispersion of the cold gas are also influenced by surface heating of the cloud because the vapors emitted are at the boiling temperature of the gas. As a result, cloud mixing is enhanced with heating along the cloud path.

4. Refrigerated, liquefied gases--Gases such as liquified natural gas (LNG) vapor emanate from pool evaporation after a spill. The resultant vapor is denser than air and disperses with a gravity-spread component until mixing and cloud heating cause the gas to become neutrally or positively buoyant with respect to air.

5. Refrigerated, pressurized, liquefied gases--This category combines pressurization and cooling to store gases as liquids. Accidental releases of such liquids would combine flash and pool evaporation and cloud heating.

Releases can also be subdivided based on duration and are categorized as continuous or instantaneous. Releases from storage vessels that have a duration greater than the specified simulation period are treated as continuous sources. All other sources are treated as instantaneous sources. This will require some judgment in modeling specific situations and in specifying the length of the simulation period.

#### Plume Rise of Buoyant Gases

For buoyant gases released from elevated sources, the release height ( $h_{eff}$ ) is determined from the sum of the physical source height ( $h_s$ ) and the plume rise ( $h_p$ ). The formulas developed by Briggs (1) are used to calculate the plume rise with a given set of source parameters and as a function of atmospheric stability. For unstable and neutral conditions when  $h_{eff} < H$  (i.e., plume does not rise into an elevated stable layer),

$$h_p = 1.6 F^{1/3} (3.5 x^*)^{2/3} u^{-1} \quad (1)$$

for unstable and neutral conditions when  $h_{eff} > H$  (i.e., the plume penetrates into an elevated stable layer),

$$h_p = \text{MIN} [h_{eff} (1.8 z_b^3 + 18.75 F u_m^{-1} S^{-1})^{1/3}] \quad (2)$$

for stable conditions when  $u \geq 1.37$  m/s,

$$h_p = 2.6 F^{1/3} S^{-1/3} u^{-1/3} \quad (3)$$

and for stable conditions when  $u < 1.37$  m/s,

$$h_p = 5.0 F^{1/4} S^{-3/8} \quad (4)$$

where

$$F = \text{buoyancy flux (m}^4/\text{s}^3) = (gV_f/\pi) (1 - T_s/T_a);$$

$$g = 9.8 \text{ m/s}^2;$$

$$V_f = \text{stack gas volume flow (m}^3/\text{s)};$$

$$T_s = \text{stack gas temperature (}^\circ\text{K)};$$

$$T_a = \text{ambient temperature (}^\circ\text{K)};$$

$$x^* = 34.49 F^{0.4} \text{ for } F > 55 \text{ and } 14.0 F^{0.625} \text{ for } F \leq 55;$$

$$S = \text{stability parameter} = (g/T_a) (\partial\theta/\partial z);$$

$$\partial\theta/\partial z = \text{potential temperature gradient} = 0.01^\circ\text{K/m for A, B, C, and D stability, } 0.02^\circ\text{K/m for E stability, and } 0.025^\circ\text{K/m for F stability};$$

$$h_s = \text{stack height (m)};$$

$$H = \text{mixing depth (m)};$$

$$z_b = H - h_s \text{ (m)};$$

$$u = \text{wind speed (m/s)}; \text{ and}$$

$$u_m = \text{MAX}(u, 1.37) \text{ (m/s)}.$$

If a buoyant gas is released at ground level, its release height is set equal to the actual height of the source. No adjustment in release height is made for buoyant plume rise.

#### Flash Vaporization

Pressurized liquefied gases are subject to two components of vaporization on release. In the first phase a fraction of the liquid is vaporized rapidly or flashed as the liquid vapor pressure adjusts from the pressure vessel environment to the ambient air pressure and cools the liquid to its boiling point at ambient pressure.

The fraction of released gas flashed ( $f$ ) can be determined by relating the saturated liquid enthalpy ( $h_{1s}$ ) at the storage pressure to the enthalpies of the saturated liquid and saturated vapor at ambient pressure ( $h_{1a}$  and  $h_{va}$ , respectively),

$$h_{1a} = f h_{va} + (1 - f) h_{1s} \quad (5)$$

where

$$f = \text{flash fraction,}$$

$$h_{1s} = \text{enthalpy of saturated liquid at storage pressure (cal/gm),}$$

$$h_{1a} = \text{enthalpy of saturated liquid at ambient pressure (cal/gm), and}$$

$$h_{va} = \text{enthalpy of saturated vapor at ambient pressure (cal/gm).}$$

#### Liquefied Gas Vaporization

The second phase of vaporization of liquefied gases results from heat transfer to the liquid pool from the substrate. In the typical spill for liquefied gases the liquid is spilled into an impounded area, vapor is released by flash vaporization, and heat for vaporization is added to the liquid by the substrate.

The total evaporation rate ( $\dot{M}$ ) is given by

$$\dot{M} = A L^{-1} \sum_{i=1}^n \dot{q}_i \quad (6)$$

where

$$A = \text{area of the spill (m}^2\text{),}$$

$$L = \text{latent heat of vaporization (cal/gm), and}$$

$$\dot{q}_i = \text{heat transferred to the liquid per unit area sources (n) (cal/s).}$$

The most significant heat source ( $\dot{q}_i$ ) identified is heat transfer from the substrate ( $\dot{q}_s$ ). Reid and Wang (2) express this as

$$\dot{q}_s = (k_s \rho_s c_s / \pi)^{1/2} (T_s - T_l) t^{-1/2} \quad (7)$$

where

$$k_s = \text{substrate thermal conductivity (cal/s - m - }^\circ\text{K),}$$

$$\rho_s = \text{substrate density (gm/m}^3\text{),}$$

$$c_s = \text{substrate specific heat (cal/gm),}$$

$$t = \text{time after spill (s),}$$

$$T_s = \text{substrate temperature (}^\circ\text{K), and}$$

$$T_l = \text{liquid temperature (}^\circ\text{K).}$$

This is a solution to a classical heat-conduction equation for a semiinfinite slab.

### Entrainment of Liquid Droplets and Air into Initial Cloud

If the pressure inside a storage vessel falls rapidly, the vigor of the boiling process may result in a significant fraction of the released chemical being entrained in the chemical cloud as droplets. These droplets appear to be sufficiently small such that they have negligible settling velocity. The liquid mass fraction may vary from 0.0 to 0.8 of the airborne chemical (3). In general, the liquid mass fraction increases with the release rate and the storage pressure. The position of the escape orifice also influences this fraction; an opening below liquid level may result in a large entrained liquid mass fraction even in slow leak situations.

The same values for entrained liquid mass fraction are used for instantaneous and continuous releases, which is a conservative treatment for continuous releases. The following assumed values for the fraction of nonflashed chemical that is entrained into the initial cloud provide a conservative estimate for the different storage modes:

1. Pressurized, liquefied gases--1.0 times the mass of nonflashed liquid;
2. Refrigerated, pressurized, liquefied gases--0.5 times the mass of the nonflashed liquid; and
3. Refrigerated, liquefied gases--none of the nonflashed liquid is entrained as droplets.

The vigor with which the gas escapes results in entrainment of air into the initial cloud. The quantity of air entrained depends on the nature of the release (i.e., the factors that govern the entrainment of liquid droplets). Initial dilution estimates based on actual observations result in an air-gas mass ratio of 20:1 for ammonia and freon-12 (4).

The temperature differential of the released chemical and the entrained ambient air will result in evaporation of the entrained liquid chemical droplets and the concomitant cooling of the entrained air. Deposition of entrained liquid droplets may also occur, but the assumption that all entrained liquid in the initial cloud evaporates provides a conservative estimate of the gas in the initial cloud. Another conservative assumption is that only that quantity of air needed to evaporate all liquid droplets has been entrained in the initial cloud and leaves a gas and air cloud at the boiling point of the gas. The moisture content of the air is considered in calculating the mass of entrained air, but chemical reactions between the water and released chemical are not considered.

### FORMULATION OF GRAVITY-SPREAD PHASE

The gravity-spread phase of the dispersion of dense gas encompasses the spreading and dilution of the cloud under the influence of gravity and edge mixing, as well as heating due to temperature differences among the cloud, the ground, and the entrained air. As the cloud spreads by gravity, both the heating and dilution of the cloud by the environment will vary locally and the instantaneous thermodynamic state of the cloud will show some radial and vertical gradients. However, to simplify the model formulation, the cloud is represented only by its average spatial thermodynamic state, a state that is assumed to be spatially uniform but that varies with time. That is, the model computes the evolution of the size, average temperature, density, and concentration of the cloud.

### Gravity Spread (Slumping)

Once formed, the initial cloud begins to slump as would a column of liquid (3-6). The velocity of the edge of the cloud is based on a formula for a one-dimensional density intrusion:

$$\partial R/\partial t = c\sqrt{g(\rho - \rho_a)h/\rho} \quad (8)$$

or

$$\partial R^2/\partial t = 2c\sqrt{g(\rho - \rho_a)V/\pi\rho} \quad (9)$$

where

- R = cloud radius (m),
- g = gravitational acceleration (m/s<sup>2</sup>),
- V = volume of cloud (m<sup>3</sup>),
- h = height of cloud (m),
- $\rho$  = density of cloud (gm/m<sup>3</sup>),
- $\rho_a$  = density of air (gm/m<sup>3</sup>), and
- c = 1.4 [from Germeles and Drake (6)] or 1.0 [from Van Ulden (4)].

### Entrainment of Air During Slumping Phase

During the gravity-spread phase air will be entrained both at the edges of the cloud and at the top. Entrainment at the cloud edge during this time appears to be unimportant (4). If the local velocity difference is small over the top surface of the cloud, atmospheric turbulence assumes a dominant role, and the entrainment velocity ( $U_e$ ) is dependent on a form of the Richardson number (Ri) presented by Cox and Roe (7):

$$U_e = (\alpha U_1)/Ri \text{ (m/s)} \quad (10)$$

and

$$Ri = (g\ell/U_1^2)(\rho_c - \rho_a)/\rho_a \text{ (dimensionless)} \quad (11)$$

where

- $U_1$  = longitudinal turbulence velocity (m/s),
- $\ell$  = turbulence length scale = 0.4 h where h is height of puff (m),
- $\alpha$  = entrainment constant (0.5) (dimensionless),
- $\rho_c$  = density of cloud (gm/m<sup>3</sup>), and
- $\rho_a$  = density of air (gm/m<sup>3</sup>).

The rate of air entrainment is

$$\partial m_a/\partial t = \rho_a (\pi R^2) U_e \quad (12)$$

where R is the cloud radius (m) and  $m_a$  is the mass of air (gm).

### Cloud Heating

Due to the temperature difference between the ground and the vapor, the cloud can absorb heat. An important effect is the heating of the cloud by turbulent natural convection ( $Q_c$ ), the rate at which heat is supplied per unit area. This is given by Equation 13 (8):

$$Q_c = (k_f/L) 0.1457 \{ [L^3 \rho_f^2 g \beta_f \Delta T_g / (\mu_f r)^2] [(C_p \mu / k) r] \}^{1/3} \Delta T_g \quad (13)$$

where

- $C_p$  = specific heat of mixture (cal/gm),
- $\Delta T_g$  = difference between cloud and ground temperature (°K),

f = subscript denoting quantities measured at film temperature  $(T_{\text{cloud}} + T_{\text{ground}})/2$ ,  
 L = diameter of the cloud (m),  
 $\beta$  = volumetric coefficient of expansion of cloud  $[\text{m}^3/(\text{m}^3 - ^\circ\text{K})]$ ,  
 $\mu$  = viscosity (centipoise)  $[\text{gm}/(\text{s} - \text{m})]$ , and  
 $k$  = thermal conductivity of cloud  $[\text{cal}/(\text{s} - \text{m} - ^\circ\text{K})]$ .

or

$$Q_c = Z(\Delta T_g)^{4/3} \quad (14)$$

where Z is the coefficient of  $(\Delta T_g)^{4/3}$  in Equation 13 for the rate of cloud heating by turbulent natural convection.

The rate of temperature change then becomes (3)

$$\partial T/\partial t = [(\partial m_a/\partial t) C_{p_a} \Delta T_a + Z(\pi R^2)(\Delta T_g)^{4/3}]/(m_a C_{p_a} + m C_p) \quad (15)$$

where

$m_a$  = mass of air (gm),  
 $C_{p_a}$  = specific heat of air at constant pressure (cal/gm),  
 $\Delta T_a$  = temperature difference between the cloud and the air ( $^\circ\text{K}$ ),  
 R = radius (m),  
 $\Delta T_g$  = temperature difference between the ground and the cloud ( $^\circ\text{K}$ ),  
 m = mass of chemical in puff, and  
 $C_p$  = specific heat of chemical at constant pressure (cal/gm).

Inclusion of heating by forced convection does not alter the results significantly (9). Heating by solar radiation of heat liberated due to the dissolution of the chemical in water droplets or reaction with other chemicals has been neglected.

#### Dominance of Atmospheric Turbulence

With time the cloud of dispersing gas becomes so dilute that a conventional atmospheric model can be used. The atmospheric turbulence is taken to dominate the spread when  $\partial R/\partial t$  has decreased such that (10)

$$\partial R/\partial t = c\bar{u} \quad (16)$$

where c is a constant, depending on atmospheric stability (dimensionless), and  $\bar{u}$  is the mean wind speed (m/s).

#### FORMULATION OF ATMOSPHERIC DISPERSION PHASE

After assessing the gravitational spreading of vapors, we have estimates of the general dimensions of the spread cloud and its mean concentration. After this point, the cloud is near enough to neutral buoyancy that the usual analyses for dispersion of atmospheric pollutants may be employed.

The concentration within the cloud is described by a Gaussian puff formula (11,12). The instantaneous concentration at any point (x,y,z) for a ground-level release is given by

$$\chi(x,y,z,t) = [2Q/(2\pi)^{3/2}\sigma_y^2\sigma_z] \exp\left\{-\left[(x-Ut)^2/2\sigma_x^2\right] - \left(y^2/2\sigma_y^2\right) - \left(z^2/2\sigma_z^2\right)\right\} \quad (17)$$

where

x = distance downwind (m),  
 y = distance across the wind (m),

z = height above the ground (m),  
 U = mean wind speed (m/s),  
 t = travel time (s),  
 Q = mass of gas released (gm),  
 $\sigma_y$  = standard deviation of the puff concentration distribution in the crosswind direction (m), and  
 $\sigma_z$  = standard deviation of the puff concentration distribution in the vertical direction (m).

The puff center concentration is calculated first and then adjusted to calculate concentrations at the locations of interest. For the puff center and ground level,  $x - Ut = 0$ ,  $y = 0$ , and  $z = 0$ . Equation 17 simplifies to

$$\chi(ut,0,0;t) = 2Q/(2\pi)^{3/2}\sigma_y^2\sigma_z \quad (18)$$

where the variables are as defined for Equation 17.

A virtual point source scheme is used to account for the initial dimensions of the cloud when it makes the transition from a gravity-dominated, slumping cloud to an atmospheric turbulence-dominated, dispersing cloud. If the actual source is located a distance  $X_v$  downwind of a virtual source, then downwind travel distances are actually  $(X + X_v)$ . The value of  $X_v$  is determined to be that distance at which the center point concentration described by the Gaussian puff equation is equal to the center point concentration that occurs at the end of the gravity spread.

The Gaussian dispersion formulation used in the model includes parameters that characterize the atmospheric turbulent mixing in the vertical ( $\sigma_z$ ) and horizontal ( $\sigma_y$  and  $\sigma_x$ ) directions. Gifford (10), using the results of many experimental studies, proposed that  $\sigma_y$  and  $\sigma_z$  could be correlated with downwind distance and six atmospheric stability categories that range from A (extremely unstable) to F (moderately stable). Dispersion coefficients for both urban and rural settings are available.

#### FORMULATION OF SAFETY-ASSESSMENT PHASE

Once the downwind path and gas concentrations are calculated by the dispersion formulation, the extent of the area affected by the toxic cloud can be assessed. The hazard potential can be estimated by the spatial distribution of concentrations and dosage, maximum concentrations and dosages, as well as isopleths for specified levels of concentration and dosage.

A table may be generated that lists time after release, downwind distance of cloud center point, cloud radius, time for cloud to pass that downwind point, centerline (maximum) concentration, and dosage. The time at which the maximum concentration in the cloud is reduced to safe levels may be estimated from this table.

Line printer plots can be generated for isopleths for specified dosages and concentrations and for the spatial distribution of time-averaged concentrations at specified receptor locations. The isopleths will indicate the area that has concentrations above a specific exposure level for the predicted wind direction.

#### CONCENTRATION FLUCTUATIONS - PEAK TO MEAN RATIO

To establish some criteria for safe dispersal of toxic vapor, note that certain portions of the vapor cloud may still be locally toxic even when average concentrations are below the lower threshold limit. Thus, an additional criterion beside the mean con-

centration is needed to define the safe level. This is necessary because the concentrations predicted by the model are averaged over a specified time interval. Use of a parameter, such as the ratio of the peak concentration to the mean concentration, will help ensure that areas that have hazardous levels of gas will not likely occur when the averaged concentration is below the safe level.

Burgess and others (13) reported concentration fluctuations observed downwind of a small continuous LNG spill. They report some peak-to-average concentration fluctuations as high as 20:1. However, these tests were conducted in gusty weather and fluctuations due to meandering of the plume back and forth over the fixed sensors most likely contributed much of the variability. The American Gas Association (14) land spill tests provide some information on the large scale (tens of meters) fluctuations of interest. These data indicate peak-to-average ratios of about two or three. The American Gas Association tests were conducted under neutral or slightly gusty weather conditions.

Based on fluctuation studies from continuous and instantaneous releases at ground level (6), peak-to-average ratios of about two appear reasonable for dispersion criteria under stable weather conditions and smooth terrain (typical of conditions over water). Somewhat higher values, such as three, are more appropriate as a criterion for unstable weather. These factors can be used to estimate peak concentrations given the time-averaged concentration estimates provided by the modeling system.

#### DOSAGE CALCULATIONS

Cumulative, ground-level dosage is calculated at any specified point by using Equation 19 (15):

$$D_T(x,y,0;H) = (Q_T/\pi\sigma_y\sigma_z u) \exp[-1/2(y/\sigma_y)^2 - 1/2(H/\sigma_z)^2] \quad (19)$$

where

- $Q_T$  = total amount of gas released (gm),
- $x$  = distance downwind (m),
- $y$  = distance across the wind (m),
- $H$  = effective source height (m),
- $u$  = mean wind speed (m/s), and
- $\sigma_y, \sigma_z$  = standard deviation of the puff concentration in the cross-wind and vertical direction, respectively (m).

The units of  $D_c$  are (g-s)/m<sup>3</sup>. As a conservative estimate, the effective source height for the toxic gas cloud is taken as zero after the cloud has made the transition from the slumping phase to the dispersing phase.

#### RELEASE ALGORITHMS

As identified above, releases are categorized as instantaneous or continuous. This refers to the duration of release from the storage vessel. However, even an instantaneous source may be quasi-continuous if a pool of liquid is formed and evaporation from the pool produces a continuous release to the atmosphere. Continuous sources, whether from vessel release or pool evaporation, are simulated by superimposing a number of discrete puffs. Each puff undergoes advection in a Lagrangian sense--its time history is independent of preceding or succeeding puffs. The puff representation of continuous sources allows the model to simulate changes in meteorological parameters (e.g., wind speed and direction, atmospheric stability, and ambient temperature).

For proper simulation, the puffs must overlap

sufficiently to allow the plume to appear smooth and continuous to the sampling function. This is done by altering the advection time step. As a single puff is released at each time step, any division in the time step results in puffs being released more frequently and reduces the distance that a puff travels in one time step. The ability of the model to recreate a continuous plume is strongly influenced by the distance between adjacent puff center points. When adjacent puff center points are separated by less than a puff radius, concentrations will not vary immensely as the puff separation distance goes to zero. If the center points are separated by more than a puff width, the deviations can be large. However, since the puff dimensions after the release phase (i.e., at the site of release) are substantial, the multiple puff representation of continuous sources will be sufficiently accurate in the near field.

All sources (continuous from vessel release, continuous from pool evaporation, instantaneous from vessel release) are modeled through the same four phases of release, slumping, dispersion, and safety assessment. The release phase for puffs from vessel release is different from the release phase for puffs from pool evaporation. However, after the release phase, all puffs are treated similarly.

The release modules yield values of the total amount of gas in the puff and the dimensions of the puffs subsequent to evaporation or air entrainment, if any. The puffs undergo advection by the mean wind speed while slumping and entraining air is dictated by the gravity-spread module. When atmospheric turbulence begins to dominate the gravity spread, the virtual source scheme is used to account for the puff dimension and to convert the puff to the dispersion phase. After transition to the dispersion phase, the puffs grow in the manner described by the Gaussian puff model. The pollutant path is altered by changes in wind direction specified by the user.

If a pool of liquid is formed during the release phase, evaporation from the pool is treated in subsequent time steps. The modeling system can accommodate a pool that remains throughout the simulation or a pool that is depleted. Changes in pool area may be considered via a user-specified function.

Each puff resident on the grid is sampled, by using the puff sampling function, to evaluate the average concentration experienced at each location of interest during the previous time step. For example, consider a hypothetical puff that has the puff center point at (x,y). The puff radius is truncated at  $3\sigma_y$  during the atmospheric dispersion phase. This is a reasonable simplification because less than 1 percent of the area under a Gaussian distribution function lies beyond  $3\sigma_y$  from the peak value. During the time step considered, the points of interest within  $3\sigma_y$  of the puff center are each impacted by the hypothetical puff; each location is assigned a certain concentration increment that results from the presence of the puff during the time step  $\Delta t$ . The total concentration at the specific location is the sum of the concentration increments due to each puff impacting that location. If a continuous plume has been properly simulated, a location impacted by the plume will receive individual doses from more than one puff.

#### SUMMARY

The model system described in the paper is a highly modularized approach for simulating the release and dispersion of hazardous gases in the atmosphere. The major components cover the following four phases: (a) release; (b) gravity spread, heating, and air

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.

#### REFERENCES

- G.A. Briggs. Research Required for Predicting the Behavior of Pressurized Gases Escaping into the Atmosphere. National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Rept. ATDL-7515, 1975.
- R.C. Reid and R. Wang. The Boiling Rates of LNG on Typical Dike Floor Materials. *Cryogenics*, Vol. 18, No. 7, 1978, pp. 401-404.
- G.D. Kaiser and B.C. Walker. Release of Anhydrous Ammonia from Pressurized Containers--The Importance of Denser-than-Air Mixtures. *Atmospheric Environment*, Vol. 12, 1978, pp. 2289-2300.
- A.P. Van Ulden. On the Spreading of a Heavy Gas Released Near the Ground. Loss Prevention Symposium (C.H. Buschmann, ed.), Elsevier, Netherlands, May 1974, pp. 221-226.
- J.A. Fay. Unusual Fire Hazard of LNG Tanker Spills. *Combustion Science and Technology*, Vol. 7, 1973, pp. 47-49.
- A.E. Germeles and E.M. Drake. Gravity Spreading and Atmospheric Dispersion of LNG Vapor Clouds. Presented at 4th International Symposium on Transport of Hazardous Cargoes by Sea and Inland Waterways, Jacksonville, FL, U.S. Coast Guard, Rept. CG-D-24-76, 1975.
- R.A. Cox and D.R. Roe. A Model of the Dispersion of Dense Vapour Clouds. Loss Prevention Symposium, Heidelberg, West Germany, Preprints, 1977, pp. 359-366.
- W.H. McAdams. Heat Transmission. McGraw-Hill, New York, 1954.
- L.S. Fryer and G.D. Kaiser. DENZ: A Computer Program for the Calculation of the Dispersion of Dense Toxic or Explosive Gases in the Atmosphere. Safety and Rehabilitation Directorate, United Kingdom Atomic Energy Authority, Culcheth Warrington, 1979.
- F.A. Gifford. A Review of Turbulent Diffusion Typing Schemes. *Nuclear Safety*, Vol. 17, 1976, pp. 68-86.
- R.A. Dobbins. Atmospheric Motion and Air Pollution. Wiley, New York, 1979.
- D.H. Slade, ed. Meteorology and Atomic Energy. U.S. Atomic Energy Commission, July 1968.
- D. Burgess, J. Biordi, and J. Murphy. Hazards of Spillage of LNG into Water. U.S. Bureau of Mines, U.S. Department of the Interior, Pittsburgh, 1972.
- American Gas Association. LNG Safety Program--Interim Report on Phase II Work. Battelle Memorial Institute, Columbus, OH, American Gas Project IS-3-1, 1974.
- D.B. Turner. Workbook of Atmospheric Dispersion Estimates. Public Health Service, U.S. Department of Health, Education, and Welfare, Cincinnati, 1969.

## 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 accidentally 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:

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

where

- $C_p$  = 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,  
 $\Delta T$  = 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:

$$C_p/Q = 0.00211X^{1.96} \sigma(\theta)^{-0.506} (\Delta T + 10)^{4.33} \quad (2)$$

where

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

Note that the wind speed is not contained in Equation 2. Although wind speed was found to be independently correlated to  $C_p/Q$ , 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  $C_p/Q$ . Figure 1 shows the results (by using the independent data set) of plotting the observed versus predicted values of  $C_p/Q$ . His plot of the cumulative percentage frequency distribution of the logarithms of the ratios of observed to predicted  $C_p/Q$  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  $\Delta T$  was developed for use at TITAN II launch sites (3):

$$C_p/Q = 0.000175X^{1.95} (\Delta T + 10)^{4.92} \quad (3)$$

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)],

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

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):

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

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 ( $^{\circ}F$ );
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 ( $\Delta T$ ). 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 mate-

rial (<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.

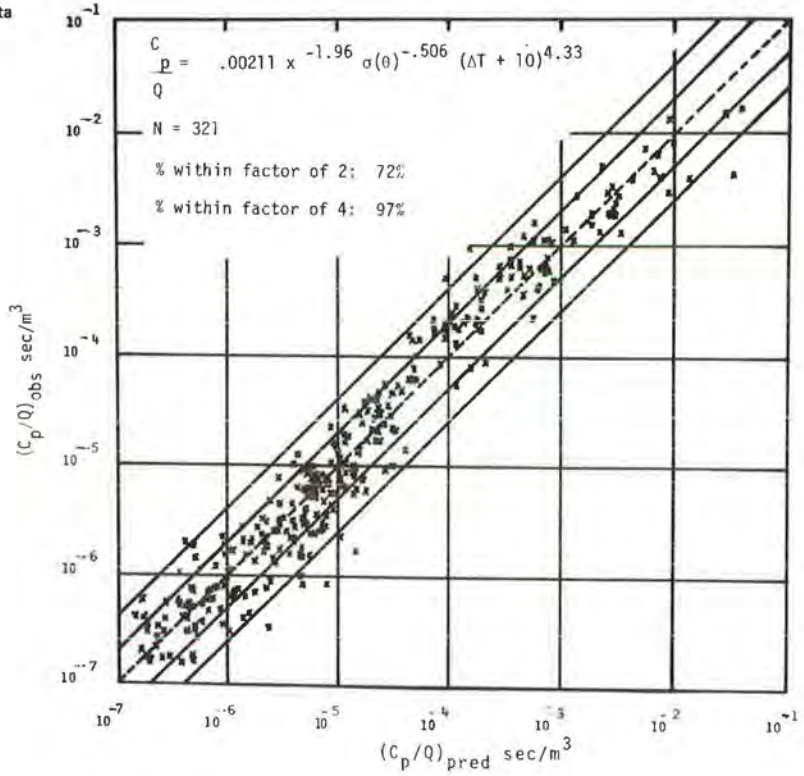


Figure 2. Percentage frequency distribution of logarithm of ratios,  $C_p/Q$  observed to  $C_p/Q$  predicted for complete independent data sample.

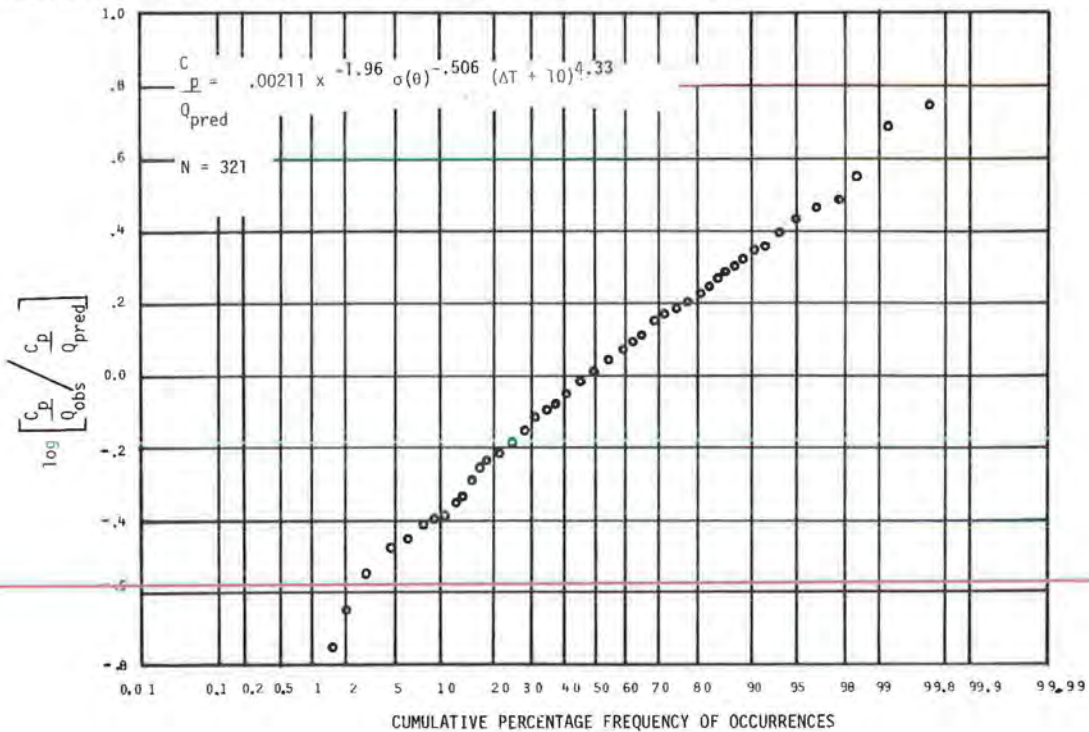
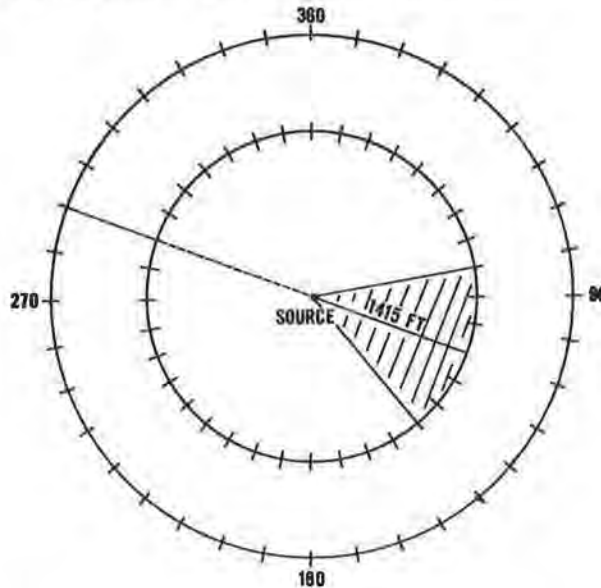


Figure 3. Toxic corridor forecast worksheet with sample calculations.

- 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  $\Delta T$  is to use a 10-min record from a 54- to 6-ft  $\Delta T$  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  $\Delta T$  from a table in the technical report (5).

Once the source strength has been estimated and  $\Delta T$  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  $\Delta T$ .

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 a 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  $\Delta T$ , 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 forecaster 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  $\Delta T$ . 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  $\Delta T$  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  $\Delta T$  values used. A 1°F error in  $\Delta T$  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  $\Delta T$  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  $\Delta T$  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  $\Delta T$  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  $\Delta T$  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.

#### REFERENCES

- O.G. Sutton. *Micrometeorology*. McGraw-Hill, New York, 1953.
- F. Pasquill. *Atmospheric Diffusion*. C. Van Nostrand Co., Ltd., London, 1962.
- R.L. Miller and F.H. Miller. *Diffusion Forecasting for TITAN II Operations*. U.S. Air Force Air Weather Service, Scott Air Force Base, IL, Tech. Rept. 176, Feb. 1964.
- Calculation of Toxic Corridors*. U.S. Air Force Air Weather Service, Scott Air Force Base, IL, Air Weather Service Pamphlet 105-57, Nov. 1978.
- J.P. Kahler, R.G. Curry, and R.A. Kandler. *Calculating Toxic Corridors*. U.S. Air Force Air Weather Service, Scott Air Force Base, IL, AWS/TR-80/003, Nov. 1980. NTIS: AD-A101267.
- D.A. Haugen. *A Range Safety System for Missiles with Toxic Propellants*. Proc., Air Force Science and Engineering Symposium, San Antonio, TX, 1962.
- J.V. Nou. *Development of the Diffusion Prediction Equation*. *The Ocean Breeze and Dry Gulch Diffusion Programs*, Vol. 2, Air Force Cambridge Research Laboratories, Hanscom Air Force Base, MA, Dec. 1963.
- G.A. Beals. *Guide to Local Diffusion of Air Pollutants*. U.S. Air Force Air Weather Service, Scott Air Force Base, IL, AWS/TR-214, May 1971. NTIS: AD 726 984.

# Calculation of Evacuation Distances During Toxic Air Pollution Incidents

JAMES KELTY

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:

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

where

- X = concentration (gm/m<sup>3</sup>),
- Q = source strength (gm/s),
- $\pi = 3.14$ ,
- $\sigma_y$  = horizontal dispersion coefficient,
- $\sigma_z$  = vertical dispersion coefficient, and
- $\mu$  = 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):

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

where

- E = evaporation rate (gm/s - cm<sup>2</sup>),
- c = molecular weight of substance/28.9,
- d = 1-c, and
- $\phi$  = 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/m<sup>3</sup>, based on a typical cholinestevase inhibitor.

The maximum allowable concentration for the moderately toxic category was determined to be 200 mg/m<sup>3</sup>, 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 x 10<sup>-8</sup> gm/s-cm<sup>2</sup> for the severely toxic category and  
4.2 x 10<sup>-5</sup> gm/s-cm<sup>2</sup> for the moderately toxic category.

for

spill area = 600 ft<sup>2</sup> = 55.7 m<sup>2</sup>,  
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,

$$\text{mg/m}^3 = \text{PPM} \times \text{MW}/24 \quad (3)$$

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,

$$Q = 1000 \text{ gm/s}$$

For instantaneous discharge,

$$Q = (\text{Total lb}/2.2) \times \text{density} \times 10^3 = \text{gm}$$

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

For leak,

$$Q = 3000 \text{ gm/s}$$

For instantaneous discharge,

$$Q = \text{gal spilled} \times 3.8 \times \text{density} \times \text{percentage of spillage rate} \times 10^3 = \text{gm}$$

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,

$$Q = 3000 \text{ gm/s}$$

For instantaneous discharge,

$$Q = \text{gal spilled} \times 3.8 \times \text{density} \times \text{percentage of spillage rate} \times 10^3 = \text{gm}$$

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<sub>μ</sub>/Q) and downwind distance for an airborne contaminant under various stability categories. The reciprocal relative concentration (Q/X<sub>μ</sub>) is used to develop a positive relation with downwind distance, and the equation becomes

$$K = Q/\pi \sigma_y \sigma_z \mu \text{ETLV} \quad (4)$$

Since μ is consistent, and σ<sub>y</sub> σ<sub>z</sub> 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

$$K = Q \times 10^3 / \mu \times \text{ETLV} \quad (5)$$

Q = source strength (gm/s),  
μ = wind speed (m/s), and  
ETLV = excursion threshold limit value (mg/m<sup>3</sup>).

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.

#### REFERENCES

1. D.B. Turner. Workbook of Atmospheric Dispersion Estimates. Environmental Health Services, U.S. Environmental Protection Agency, No. AP-26, 1970.
2. F. Pasquill. The Estimation of the Dispersion of Windborne Material. *Meteorological Magazine*, Vol. 90, No. 1063, 1961, pp. 33-49.
3. F.A. Gifford. Use of Routine Meteorological Observations for Estimating Atmospheric Dispersions. *Nuclear Safety*, Vol. 2, No. 4, 1961, pp. 47-51.
4. D.C. Gray. Solvent Evaporation Rates. *American Industrial Hygiene Association Journal*, Vol. 33, No. 11, Nov. 1974, pp. 695-710.
5. G.L. Melvin and K.K. Knuck. A Method for Identifying Toxic Substances Capable of Achieving Specified Ambient Concentrations Through Evaporation. Illinois Environmental Protection Agency, Springfield, 1975.
6. J.T. Kelty. Hazardous Materials Response Guide. Illinois Environmental Protection Agency, Springfield, 1980.

## Toxic Corridor Prediction Programs

JOHN T. MARRS, ERNEST B. STENMARK, AND FRANK V. HANSEN

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

- $\chi$  = the concentration at downwind distance  $x$  ( $\text{gm}^{-3}$ ),  
 $Q$  = source strength ( $\text{gs}^{-1}$ ),  
 $\bar{V}$  = mean windspeed ( $\text{ms}^{-1}$ ),  
 $y$  = lateral distance from the plume centerline (m),  
 $z$  = height of interest (m; 2 m was used in STSTCP),  
 $\sigma_y$  = lateral dispersion length (m), and  
 $\sigma_z$  = 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,  $\chi$  is converted by using the factor

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

where

- $T_0 = 273.15^\circ\text{K}$ ,  
 $T_1$  = ambient temperature ( $^\circ\text{K}$ ), and  
 $\text{GMW}$  = gram molecular weight of material under consideration.

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

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

Equation 5 can be derived from Equation 1 by letting  $y = 0$  and by replacing  $\sigma_y$  and  $\sigma_z$  with Equations 2 and 3, respectively.

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

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

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),

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

where

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

$$Z = P_{vB}/P_{vH} \times \text{GMW}_B/\text{GMW}_H \quad (8)$$

where

- $P_{vB}$  = vapor pressure of the desired chemical,  
 $P_{vH}$  = vapor pressure of hydrazine,  
 $\text{GMW}_B$  = gram molecular weight of the desired chemical, and  
 $\text{GMW}_H$  = gram molecular weight of hydrazine.

Z-factors for various chemical compounds are as follows:

Compound	Z-Factor
Hydrazine	1
MMH	4.3
$\text{N}_2\text{O}_4$	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:

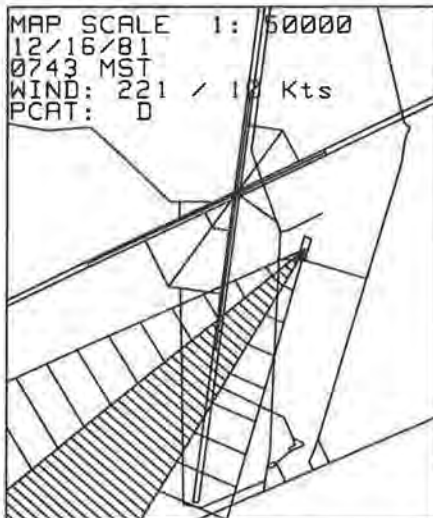
- A--extremely unstable conditions,  
 B--moderately unstable conditions,  
 C--slightly unstable conditions,

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

Surface Wind Speed (m/s)	Pasquill Category			Nighttime Conditions <sup>a</sup>	
	Daytime Insolation			>40	<40
	Strong	Moderate	Slight	Percent Cloudiness	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

<sup>a</sup>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  $\sigma_y$  and  $\sigma_z$  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  $\pm 1$  standard deviation from the horizontal mean wind direction. The less densely lined area is contained within lines plotted at angles  $\pm 2.5$  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 decision-makers 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 pre-specified 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.

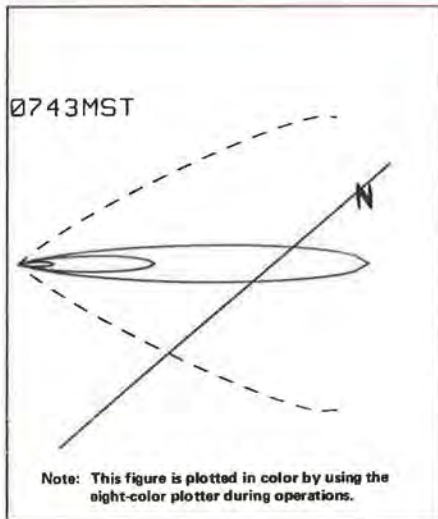


Figure 3. Summary sheet showing meteorological data and spill parameters used to simulate spill of 30 gal of  $N_2O_4$ .

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

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

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

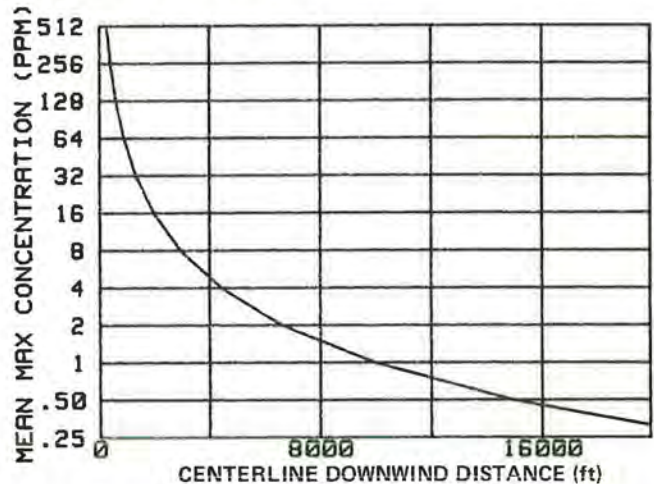
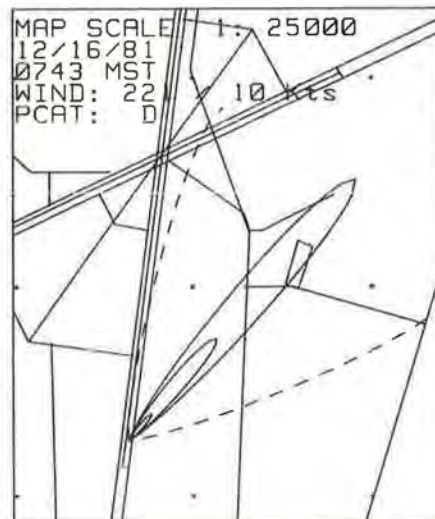


Figure 5. Isopleths and map background plotted for distribution to areas away from computer system.



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

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.

#### REFERENCES

1. F. Pasquill. *Atmospheric Diffusion*. Halsted Press, New York, 1974, 429 pp.
2. H.B. Clewell. *Estimation of Hazard Corridors for Toxic Liquid Spills*. Presented at 1980 JANNAP Hazard Working Group Propulsion Meeting, Monterey, CA, 1980.
3. F. Pasquill. *The Estimation of the Dispersion of Windborne Material*. *Meteorology Magazine*, Vol. 90, No. 33, 1961.
4. F.A. Gifford. *Use of Routine Meteorological Observations for Estimating Atmospheric Dispersion*. *Nuclear Safety*, Vol. 2, No. 4, 1961, pp. 47-51.
5. D.B. Turner. *A Diffusion Model for an Urban Area*. *Journal of Applied Meteorology*, Vol. 3, No. 1, 1964, pp. 83-91.
6. F.B. Smith. *A Scheme for Estimating the Vertical Dispersion of a Plume from a Source Near Ground Level*. *Proc., 3rd Meeting of the Expert Panel on Air Pollution Modeling, NATO CCMS, Paris, France, 1972*.
7. F.B. Smith. *The Prediction of High Concentration of Sulphur Dioxide in London and Manchester Air*. *In Proc., Atmospheric Turbulence and Diffusion and Their Influence on Air Pollution*, Von Karman Institute for Fluid Dynamics, Rhode Saint Genese, Belgium, 1973.
8. A.M. Obukhov. *Turbulence in an Atmosphere with a Nonuniform Temperature*. *Boundary Layer Meteorology*, Vol. 2, 1971, pp. 7-29.

## 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) pro-

vide 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.

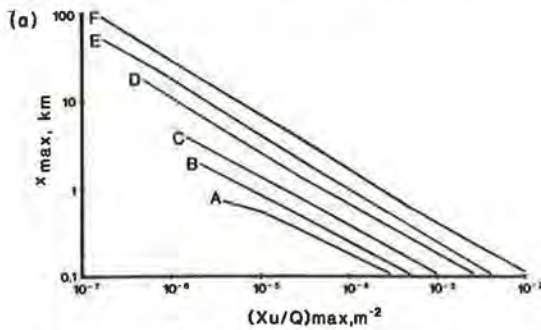
#### MODELS

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



Figure 1. (a) Distance of maximum concentrations and maximum Xu/Q as a function of stability and (b) stability categories.



(b) KEY TO STABILITY CATEGORIES

Surface Wind Speed (at 10 m) m sec <sup>-1</sup>	Day			Night	
	Incoming Solar Radiation			Thinly Overcast or	≈3/8
	Slight	Moderate	Strong	≈4/8 Low Cloud	Cloud
< 2	A	A-B	B		F
2-3	A-B	B	C	E	
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
> 6	C	D	D	D	D

The neutral class, D, should be assumed for overcast conditions during day or night (Turner, 1970)

Turner model for distances less than 10 000 ft. For distances greater than 15 000 ft, both models converge and yield approximately the same corridor lengths as given below:

	Corridor Length (ft)		
	Turner	Ocean-Breeze	Deductive Experience
Ethyl chloroformate	2 300	4 000	2 500
Chloroform	3 300	6 600	5 280
Phosgene	18 150	19 750	10 560

Consequently, the authors recommend use of the Ocean-Breeze Dry-Gulch equation for initial time zero toxic corridor estimates.

However, both models must be put in perspective with actual experience gained from other accidents. Threshold odor levels, skin irritation, dizziness, or other symptoms observed around an accident may be used to adjust toxic corridors to site-specific characteristics and conditions. Injuries or fatalities seldom occur from fragments or toxic exposures at distances greater than 2500 ft from the source as reported by the authors and the National Transportation Safety Board accident reports. Victims treated and released from toxic exposures are seldom located in excess of 1 mile from the source (2-6).

A combination of deductive experience and the use of the Ocean-Breeze Dry-Gulch model provides for rapid estimates of toxic corridors to protect public health and safety during a hazardous material emergency.

MODEL INPUTS

The following information is required to estimate a toxic corridor: material identification and properties, location, source strength, meteorological conditions, and topical conditions. A material's lethal, serious, and noxious concentrations are defined as the concentration at which more than 50 percent of the exposed population may be expected to expire;

Figure 2. (a) Estimation of temperature differential, ΔT, and (b) downwind travel distance, X, estimated from Ocean-Breeze model.

(a) OCEAN-BREEZE ΔT ESTIMATE

SURFACE WIND SPEED (ft)	Day				Night					
	Incoming Solar Radiation (at 54 ft. above ground)				Clear		1/8-3/8		4/8-8/8	
	Clear Sky or Scattered Clouds				SHOW	NO SHOW	SHOW	NO SHOW	SHOW	NO SHOW
7-3	-2	-1	-1	0	0	5	5	4	4	3
4-10	-3	-2	-2	0	6	5	5	4	4	3
>10	-2	-1	-1	0	5	4	4	3	2	1
Broken Clouds										
+7000 ft. - A(°) / +7000 ft. - B(°)										
	A	B	A	B	A	B	A	B		
+3	-1	-1	-1	-1	0	0	0	0		
4-10	-2	-2	-2	-2	0	0	0	0		
>10	-1	-1	-1	-1	0	0	0	0		
Overcast Clouds										
+3	-1	0	-1	0	-1	0	0	0		
4-10	-2	0	-2	0	-2	0	0	0		
>10	-1	0	-1	0	-1	0	0	0		

(b) 
$$X = 1.63 [3.28 (\frac{29.75}{GMW})^{.513} (\frac{C}{Q})^{-.513} (\Delta T + 10)^{.253}]$$

- where:
- GMW=gram weight of material
- C=peak concentration 5 ft. above ground(ppm)
- Q=source strength(lbs./min.)
- ΔT=temperature at 54 ft.-6 ft. (°F)

the concentration at which irreversible health impacts may be expected; and the concentration at which reversible but irritating health effects may be experienced, respectively. This information is available from REACT's Computer Assist Program for more than 250 000 materials. Information on several thousand materials can be obtained from the U.S. Environmental Protection Agency (EPA) OHM/TADS System (7), Patty (8), and Sax (9).

The accident source and toxic corridors should be immediately located on a 7-min or a 15-min USGS topographical map. This will facilitate identification of egress corridors, sensitive populations, and potential toxic vapor sinks.

Source strength is probably the most difficult model input to obtain. Consequently, it is recommended that for volatile liquid releases the source strength be determined by assuming the complete release of the entire container's contents over a 10-min period. For fires involving volatile liquids, it is recommended that the source strength be estimated by selecting the most toxic combustion product as emitted over a 60-min period. However, it should be noted that both these assumptions are subject to revision for material and site-specific circumstances as interpreted by an experienced environmental health engineer.

ESTIMATION OF TOXIC CORRIDORS

Meteorological conditions, topical conditions, and material properties have profound effects on ground level toxic corridor lengths and widths. Information on the wind speed, incoming solar radiation angle, time of day or night, ground cover conditions, percentage of cloud cover, and cloud elevations will determine selection of a stability category for Turner's model or the Delta T estimate for the Ocean-Breeze Dry-Gulch equation.

Toxic corridors are projected with Turner's model

by calculating  $Xu/Q$  (where  $X$  is the limiting concentration in grams per cubic meter,  $u$  the wind speed in meters per second, and  $Q$  the source strength in grams per second) for the noxious and lethal conditions. For a given stability class, the corridor length can be calculated from Figure 1 [an abbreviated version of Table 1 from Kaehn (10)] for the noxious and lethal conditions.

The corridor length is determined for the Ocean-Breeze Dry-Gulch equation, shown in Figure 2, for a given source strength,  $\Delta T$ , and peak ground concentrations for the noxious and lethal conditions.

The ground level toxic corridor widths for both models may be defined as the sum of two areas:

1. Area 1--A circle with a radius for the lethal concentration corridor length drawn from the centroid of the accident source; and
2. Area 2--The downwind arc distance as calculated for the noxious concentration drawn from centroid of the accident source. (For wind speeds greater than 10 knots, the arc length is  $45^\circ$  centered on the prevailing downwind vector. For wind speeds from 4 to 10 knots, the arc length is  $90^\circ$  centered on the prevailing downwind vector. The side boundaries are located by drawing lines from both ends of the arc, tangent to Area 1 as defined above. For wind speeds of less than 4 knots, Area 2 is a circle with a radius for the noxious concentration corridor length drawn from the centroid of the source.)

Toxic corridors are redefined with changing meteorological conditions and source strengths. It is important to have technical feedback from the field in redefining toxic corridors as meteorological, sorption characteristics, and other site-specific changing conditions may have significant effects on the definition of toxic corridors.

#### CASE HISTORIES

##### Ethyl Chloroformate Spill

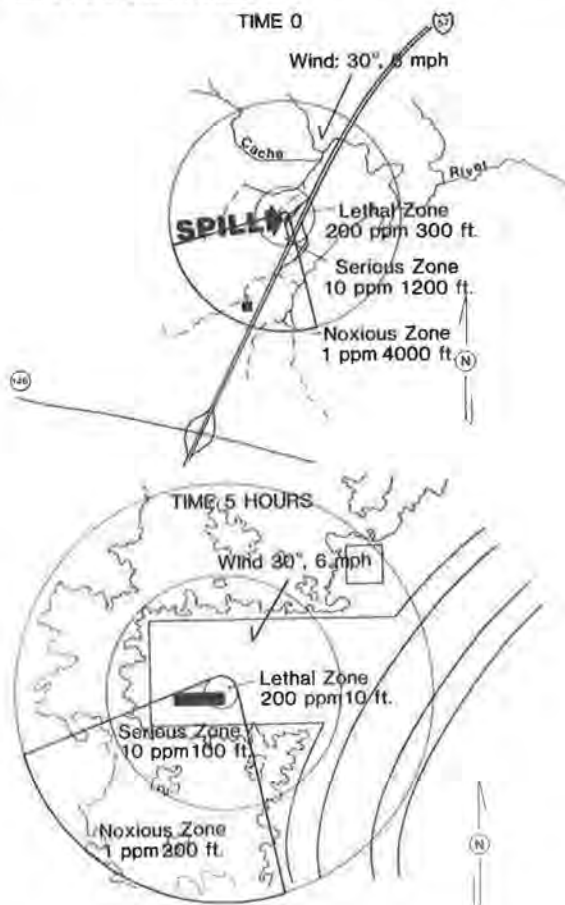
At 9:00 a.m. on August 15, 1980, a tractor-trailer carrying 80 55-gal drums of ethyl chloroformate, traveling southbound on Illinois Interstate-57, experienced a load shift and one drum was punctured. The driver's eyes immediately began to lacrimate and he experienced difficulty in breathing. The driver pulled off the road to a rest stop and staged his unit in an isolated area, as shown in Figure 3. He then placed a call for emergency assistance.

By using the Ocean-Breeze Dry-Gulch equation, the toxic corridor was projected at time zero for the lethal, serious, and noxious zones, as shown in Figure 3.  $\Delta T$  for the Ocean-Breeze Dry-Gulch equation at time zero was estimated to be  $-2$  (see Figure 2). The Turner Stability Class was estimated for the prevailing meteorological conditions at time zero. The rest stop area was closed, and a decision was made not to close southbound I-57 as the travel time through the noxious zone was estimated to be less than 1 min.

At time 5 h after the incident, REACT engineers collapsed the toxic corridor to 200 ft downwind from the prevailing wind direction. The toxic corridor was redefined by using threshold odor observations and Bendix tube air testing equipment. REACT emergency response personnel donned full protective gear and proceeded to remove the skid-mounted pump that had punctured one of the drums of ethyl chloroformate. Contaminated crating material and the damaged drum were overpacked using recovery drums.

U.S. Department of Transportation regulations stipulate that shipments of ethyl chloroformate

Figure 3. Toxic corridor projects for ethyl chloroformate spill at time 0 and time 5 h after product release.



transported in 55-gal drums be shipped in dedicated loads. This incident would not have occurred if the pump and crated materials had not been loaded on the rear of the trailer.

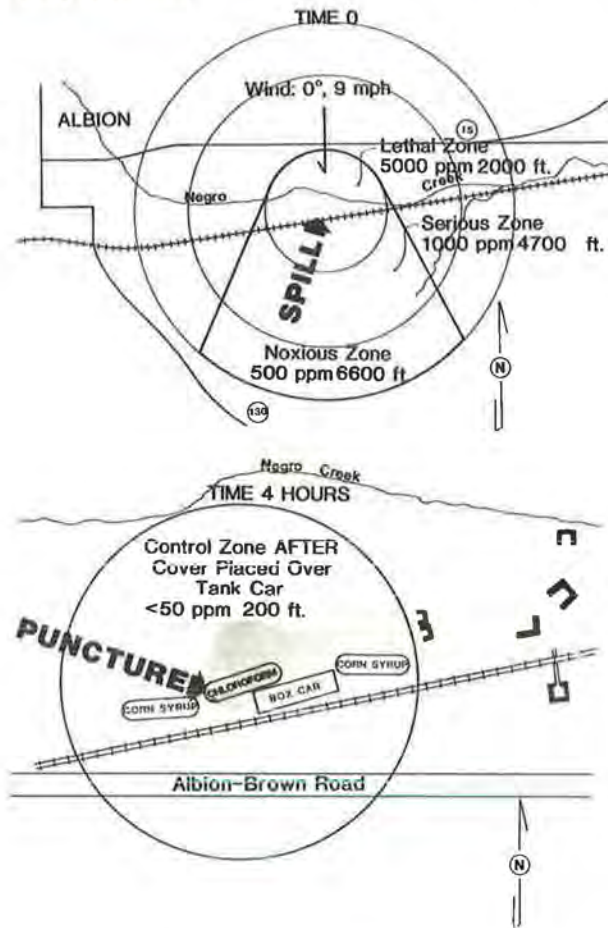
##### Chloroform Spill

On January 26, 1981, a train derailment occurred near Albion, Illinois, as noted in Figure 4. A coupler from an adjacent corn syrup tank car punctured the chloroform tank car, resulting in the release of an estimated 20 000 gal of chloroform. By using the Ocean-Breeze Dry-Gulch equation, an estimated source strength of 25 000 lb/min and a  $\Delta T$  of zero projected a time zero toxic corridor length of 6600 ft for the noxious zone and 2000 ft for the lethal zone.

All residents were evacuated from the projected corridor, including residents in a farmhouse. REACT engineers and scientists covered the punctured tank car with a polyvinyl canopy to reduce the vapor emissions from an estimated 2000 gal of product remaining in the tank car.

An unknown quantity of corn syrup was released from two adjacent tank cars. Interceptor containment barriers were constructed and the water/corn syrup solution formed a vapor barrier over the spilled chloroform that reduced the control zone to 200 ft at time 4 h after the incident. To prevent soil and water transport of the dense chloroform plume, which is only slightly soluble in water, from entering shallow wells in the vicinity, a containment and decontamination plan was developed.

Figure 4. Toxic corridor projects for chloroform spill at time 0 and time 4 h after product release.



#### Agricultural Chemical Fire

On April 24, 1981, an agricultural chemical warehouse was set on fire by arsonists at approximately 5:00 a.m. The warehouse was located near Hillsboro, Illinois (see Figure 5). The warehouse contained an estimated 40 000 lb of 21 different agricultural chemicals.

The time zero toxic corridor was projected by using the Ocean-Breeze Dry-Gulch equation, assuming that 50 percent of the total inventory would be converted to phosgene, as a combustion by-product over a 60-min burn time. A Delta T of zero yielded a toxic corridor length of 20 000 ft for the noxious zone and 6000 ft for the lethal zone, as depicted in Figure 5. More than 400 families were evacuated from Hillsboro and Schram City from within the lethal zone. Also, the schools located within the lethal zone were evacuated.

A hospital and a nursing home were located in the lethal zone, approximately 2000 ft downwind from the burn site. It was determined that movement of these sensitive populations would pose a greater health risk than potential toxic exposure from the burning agricultural chemicals. All intake systems, windows, and air vents at both of these facilities were closed during the fire to minimize the influx of toxic gases. Firefighters applied water to the fire to attempt to knock down toxic fumes and reduce the source strength of toxic air pollutants generated from the fire.

REACT engineers and scientists at the accident scene reduced the source strength by 10 percent at

Figure 5. Phosgene toxic corridor projections for agricultural chemical fire at time 0 and time 6 h.

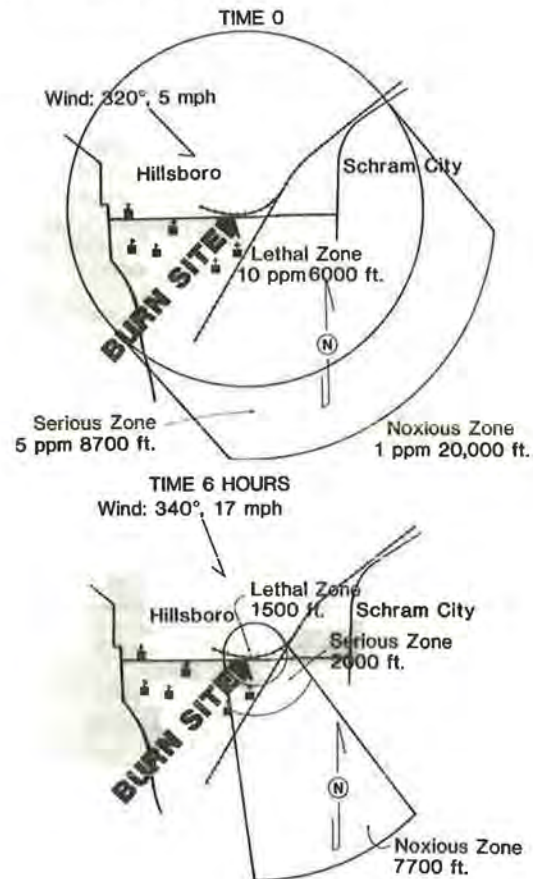


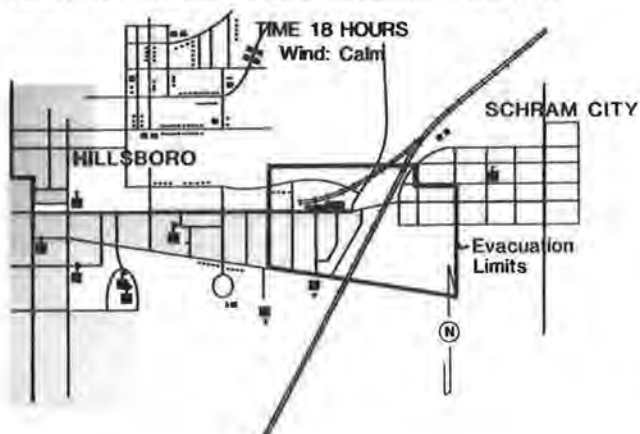
Figure 6. Phosgene toxic corridor projection for agricultural chemical fire at time 12 h.



time 6 h. The corridor was redefined, as depicted in Figure 5, with a new Delta T of -1. Fortunately, there were no roads or significant population in the southeast quadrant. Consequently, evacuation limits were confined to the serious zone.

At time 12 h, REACT engineers redefined the toxic corridor as shown in Figure 6. The source strength at time 12 h was reduced an additional 10 percent and the new Delta T of zero was used. Due to variable wind conditions experienced during the day, evacuation limits were extended for the corridor vector from zero to 360° for the noxious zone, or 1700 ft from the burn site.

Figure 7. Evacuation limits for agricultural chemical fire at time 18 h.



At time 18 h, all burning and smoldering residues had been extinguished. Consequently, phosgene was no longer considered to be the critical toxic air emission. Since the toxic characteristics of the remaining burn residues were unknown, threshold odor analysis and sensitivity analysis were conducted by experienced engineers and scientists to redefine evacuation limits, as shown in Figure 7. These evacuation limits were maintained during the period time 18 h through time 24 h.

Several engineering control measures were used to collapse the toxic corridor area to the control area, as depicted in Figure 8, for the period time 1 day through 24 days. These procedures included (a) reduction of evaporative surface areas through the construction of a network of interceptor trenches and pits; (b) containerization of concentrated contaminant runoff at the burn site; (c) application of powdered activated carbon and soda ash, which controlled odors and accelerated pesticide destruction via alkaline hydrolysis; (d) construction of an impoundment dam in the run-off area where more than 200 000 gal of contaminated fire-fighting waters were pumped into a treatment lagoon; and (e) treatment of the lagoon contents with powdered activated carbon at a self-flocculating dosage of 1000 parts/million where pesticide residues were adsorbed and clarified out of the water matrix and released to the adjacent stream.

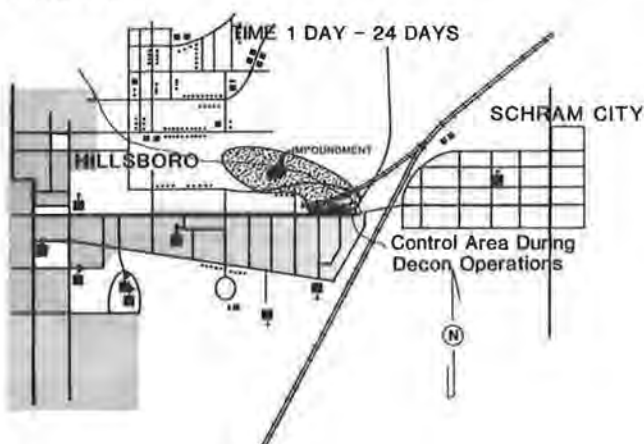
#### SUMMARY

Toxic corridor projection models such as the Ocean-Breeze Dry-Gulch and Turner models are useful tools in providing information for emergency action decisions. However, these models only generate estimates and the Turner model may underestimate corridor lengths for distances of less than 10 000 ft by factors of 2 or 3. Consequently, it is recommended that the Ocean-Breeze Dry-Gulch model be used for initial estimates.

Experienced personnel who are familiar with the many factors that affect toxic corridor projections should be consulted. A combination of deductive experience and the use of the Ocean-Breeze Dry-Gulch model provides for rapid estimates of toxic corridors to protect public health and safety during a hazardous material emergency.

Development of control plans will greatly reduce response times and potential environmental health impacts. Knowledgeable environmental health person-

Figure 8. Control area during decon operations for agricultural chemical burn residues.



nel should be made an integral part of control plans and should be available 24 h/day, 365 days/year, to assist emergency response personnel with projection of toxic corridors. Mock drills should be conducted to test communication systems and to develop time zero toxic corridor projections in less than 1 min.

#### REFERENCES

1. REACT, Computer Assist Program: Ethyl Chloroformate Print-Out, Chloroform Print-Out, and Phosgene Print-Out. REACT Corporate Response Center, St. Louis, MO, 1981.
2. D.W. Ryckman and M.D. Ryckman. How to Cope with Hazardous Material Spills That Threaten Water Supplies. Presented at 1979 American Water Works Association Annual Conference and Exposition, San Francisco, 1979.
3. M.D. Ryckman and others. REACT's Response to Hazardous Material Spills. Proc. of 1978 National Conference on Control of Hazardous Material Spills, Miami, 1978.
4. M.D. Ryckman and others. Flammable Liquid Spills--Response and Control. Proc. of 1980 National Conference of Hazardous Material Spills, Louisville, KY, May 1980.
5. M.D. Ryckman, J.L. Peters, W.H. Busch, and J.R. Renkes. Emergency Response to a Major Agricultural Chemical Warehouse Fire. Presented at 36th Annual Purdue Industrial Waste Conference, West Lafayette, IN, May 1981.
6. Hazardous Materials Accident Spill Reports, 1977-1980. National Transportation Safety Board, Washington, DC, (various years).
7. Oil and Hazardous Materials Technical Assistance Data System (OHM/TADS). U.S. Environmental Protection Agency, 1980.
8. F.A. Patty, ed. Industrial, Hygiene and Toxicology, Volume 2. Interscience Publishers, New York, 1963.
9. N.I. Sax. Dangerous Properties of Industrial Materials. Van Nostrand Reinhold Company, New York, 1979.
10. A.J. Kaehn. Calculation of Toxic Corridors. U.S. Air Force, AWS Pamphlet 105-57, Nov. 1, 1978.
11. D.B. Turner. Workbook of Atmosphere Dispersion Estimates. U.S. Environmental Protection Agency, Research Triangle Park, NC, 1970.

# Radiation Hazards Analysis in Transport of Low Specific Activity Waste Material

C. F. SMITH, J. J. COHEN, A. J. TOY, AND J. D. COLTON

An analysis of potential radiation hazards from transporting low specific activity (LSA) waste materials was carried out in support of an effort to evaluate the implications of proposed changes in regulations that govern such activities. The approach in this work was to assess the hazards to cleanup personnel and members of the general public from various transportation accident scenarios that involve the dispersion of LSA materials. Although wastes currently transported are relatively innocuous, those permitted under current and proposed regulations could present hazards under worst-case scenario assumptions. A probabilistic approach to future efforts is recommended.

An analysis of potential radiation hazards from transporting low specific activity (LSA) radioactive waste materials was carried out in support of an effort to evaluate the implications of proposed changes in regulations that govern such activities (1,2). The approach in this work was to assess the hazards to cleanup personnel and members of the general public from various transportation accident scenarios that involve the dispersion of LSA materials. Although wastes currently transported are relatively innocuous, those permitted under current and proposed regulations could present hazards under worst-case scenario assumptions.

## SURVEY OF LSA SHIPMENTS

Data were collected on LSA shipments during 1980 for radioactive ores and for LSA waste (2). Data on waste shipments were collected from the three commercial waste disposal sites in the United States. These data were analyzed to characterize LSA shipments in terms of general material description, container type, activity level, and radionuclides present. The most significant results of this survey of LSA shipments are as follows:

1. Of the 85 000 curies (Ci) shipped annually as LSA materials, most (81 000 Ci) are shipped as LSA waste;
2. Virtually all LSA shipments are made by truck;
3. The average concentration is 0.004 mCi/g, much less than the 0.3 mCi/g permitted under present regulations for other than transport group I radionuclides;
4. More than 80 percent of the packages shipped are 55-gal drums, but they contain only 15 percent of the total activity shipped; and
5. Large liners (>100 ft<sup>3</sup>) that carry cobalt 60 and cesium 137 in solidified cement and resin shipped to the waste disposal site at Barnwell, South Carolina, make up only 3 percent of the total number of packages, but they contain 50 percent of the total activity.

## BASIC RADIATION HAZARDS

Four mechanisms of radiation exposure were considered in this study:

1. Gamma radiation to the external body,
2. Internal radiation by ingestion,
3. Internal radiation by inhalation, and
4. Beta radiation to the skin.

For each mechanism, potential hazards were analyzed for single-container and partial-truckload spills of LSA materials, both at existing (3) and proposed (4)

maximum permitted concentrations and from actual average and maximum concentrations. Actual concentrations shipped were determined from the survey of LSA shipments. Hazards to cleanup workers and the general public were considered.

For external gamma radiation the calculations support the conclusion that a spill of LSA material that contains radioactivity at the current maximum theoretical concentrations (0.3 mCi/g) could be hazardous to both workers and the general public. In particular, members of the general public could receive a maximum annual dose in minutes if they were at the edge of the spilled material. Since the proposed regulations would generally permit greater concentrations of radioactivity to be shipped as LSA, the same or greater potential external gamma hazards would exist. For accidents that involve average and maximum actual shipments of LSA, workers are unlikely to be overexposed as long as some caution is used. Further, members of the general public are adequately protected by a 10-m buffer distance for the case of a single-package accident and a 100-m buffer distance for the more serious partial-truckload spill. The exclusion of spent resins from the actual shipments at maximum concentrations results in a significant reduction in potential external gamma radiation hazard. For members of the general public, the buffer distances would be reduced to 1 m for single-package spills and 10 m for partial-truckload spills.

Ingestion of most radionuclides would not result in overexposure for emergency workers or for members of the public for LSA shipments at the theoretically allowable maximum concentrations permitted under existing regulations. The proposed regulations could allow overexposure to workers from the ingestion of eight radionuclides: sulfur 35, calcium 45, nickel 63, strontium 89, iodine 126, praseodymium 143, mercury 203, and radium 226. Because none of these radionuclides is a major component of the total activity actually shipped and because the assumed hazard could be eliminated through reduced concentrations or longer storage time for all but Ra-226, we believe these exceptions are not of great enough significance to warrant special concern. The same conclusions apply to members of the public if we assume that they would ingest no more than 1 mg of LSA (as compared with the assumption of 10 mg ingested by cleanup workers).

For inhalation of LSA material, the degree of hazard depends greatly on the particle size of the material. The controlling parameter is the upper limit of the range of particle size. Particles that have a maximum diameter significantly smaller than 50  $\mu$ m are not likely to be inhaled in significant amounts. Inhalation doses for emergency workers and members of the public were found to be well below routine exposure guidelines for these average LSA compositions. The only event that would produce doses greater than annual background doses is the spill of a partial truckload of material at maximum permitted concentrations.

Calculation of downwind population doses from accidents involving actual waste compositions indicates a population dose equivalent to 15 percent of the annual background dose for the 7900 people in a downwind sector as a result of a partial-truckload

accident of maximum actual composition LSA. Radiation doses to the skin from beta-emitting nuclides were calculated for each scenario and waste composition. For the average and maximum actual compositions, beta skin exposure is not a significant problem.

For maximum theoretical shipment of LSA under the present regulations, skin doses as high as 20 rad to the emergency worker could result from the partial-truckload accident. Although this does not exceed recommended emergency dose limits, the doses under the proposed regulations could be higher. Skin deposition is a more significant problem for emergency workers than for members of the general public.

#### CONCLUSIONS AND RECOMMENDATIONS

The primary potential hazard of concern would be the external gamma radiation from shipments near the maximum permitted concentrations. In actual shipments, concentrations approach maximum permitted levels only for spent resins and materials solidified in cement. If these materials are excluded from the LSA category, this potential hazard is not excessive.

The foregoing analyses have considered the potential hazards due to theoretical maximum shipment accidents under current and proposed regulations, as well as the hazards of typical and maximum actual shipments that might be better indicators of the range of likely hazards given an accident involving a shipment of LSA. By studying the survey of materials currently shipped we can determine whether current regulations or generator practice limits shipping activities. We suspect that generator practice limits shipping activity because few shipments even approach the permitted maximum.

If such is the case, the proposed changes in the regulations would allow increased flexibility of operations without materially affecting public

safety. Isolated shipments that have one isotope at a higher activity than now permitted would not result in a significant increase in the average activity per shipment. On the other hand, if the shipment activity were regulation limited, a change in regulations could affect the actual hazards of shipment of LSA significantly.

As a more general comment on hazard assessments, we would suggest the use of the probabilistic approach in future efforts. It is possible to postulate hazardous situations under either the present or proposed regulations for transport of LSA. It would be appropriate, however, to temper these conclusions with information on the likelihood of such unusual events. This is the basis of probabilistic risk assessment, a tool that would be applied beneficially to such efforts in support of regulatory decisions.

#### REFERENCES

1. C.F. Smith, J.J. Cohen, and A.J. Toy. Radiation Hazards Analysis in Transport of LSA and LLS Materials. Science Applications, Inc., Pleasanton, CA, SAI Rept. SAI/PL-81-13, Aug. 25, 1981.
2. J.D. Colton, J.S. Krebs, R.E. Boswell, C.R. Thompson, C.F. Smith, J.J. Cohen, and A.J. Toy. Transport of Low Specific Activity Radioactive Materials. U.S. Nuclear Regulatory Commission, Rept. NUREG/CR-2440, Dec. 1981.
3. A.W. Grella. A Review of the Department of Transportation (DOT) Regulations for Transportation of Radioactive Materials. Office of Hazardous Materials Operations, U.S. Department of Transportation, Rept. TD 1.2:R 11, 1976.
4. Packaging of Radioactive Material for Transport and Transportation Under Certain Conditions; Compatibility with IAEA Regulations. Federal Register, Vol. 44, No. 161, Aug. 17, 1979.

## Aerometric Instrumentation for Real-Time Monitoring at Hazardous Spill Sites: Overview of Needs and Resources

WALTER F. DABBERT

The last decade has seen a fourfold increase in the number of casualties from transportation incidents involving hazardous materials. Responder groups often cannot manage such incidents effectively because they lack knowledge of the chemicals involved, the peak concentrations present in the atmosphere, or the spatial extent of the hazardous zone. A systematic approach to providing responder groups with appropriate instrumentation needs to be developed. An introduction to the categorization of user needs is presented in terms of four types of constraints: time available for response, nature of the spill and the chemicals involved, responder expertise, and spatial extent of the impacted area. An overview is also provided of the general classes of instrumentation that should be considered.

Over the past decade, there has been a fourfold increase in the number of casualties from transportation incidents involving hazardous materials. In turn, the number of reported incidents over the same period has increased about eightfold (perhaps partly the result of stricter reporting pressures). Figure

1 illustrates the increases in incidents and casualties according to mode--(a) highway and rail and (b) air and water. Figure 2 provides corresponding information on the distribution of the hazardous materials (a) involved in the incidents and (b) responsible for the associated fatalities, respectively.

The distribution and concentration of toxic and hazardous substances in the air (and, correspondingly, the dangers) at a spill site are often poorly understood or simply unknown. The many possible reasons include the following--the identity of the chemicals is often unknown, in one-third of all railroad incidents it was impossible to read the placard on the car, and manifests could not be obtained for one-half of these incidents. Even if the chemicals are known, instruments to detect them in the field at the concentrations present may not exist or may be unavailable to the responders. In

some cases the hazard potential may be too great to risk obtaining in situ samples. Remote sensors, however, may not exist for the particular chemical or they may require special expertise not available in the normal makeup of the on-scene response team or logistics may delay their transport and deployment to the point where they are no longer useful. Beyond these limitations, the nature of the atmosphere itself, coupled with the often dynamic nature of the incident (e.g., fire or explosion), compound and exacerbate the problem. The speed and direction of the wind, together with its turbulence intensity and stability, determine where and when the chemicals will be transported; they also determine their concentration or dilution and control the production of secondary products through chemical reactions in the air. The unsteady nature of the atmosphere and the modifying influence of local topographic and terrain conditions further complicate the problems of understanding existing conditions and forecasting future conditions.

The current state of the art of ambient chemical instrumentation and meteorological sensors offers many possibilities for improving the ability of response teams to assess (and predict) the intensity and location of dangerous substances. There are (at least) two ways in which the needs of the responders and the capabilities of the measuring devices can be matched.

1. Individual instruments that are potentially useful can be reviewed and the most promising candidates evaluated and ultimately made available to the responders. This approach focuses on the advantages of the individual instruments but suffers from its failure to address in a systematic way the specific needs of the responders.

2. The various needs of the responders (as a function of the time and personnel available and the nature of the chemicals and the affected groups of

people) can be quantified and stratified into a hierarchy of monitoring requirements and then the candidate instruments reviewed and evaluated insofar as they can be assembled into systems that are designed for one or more of the various categories of user needs. For example, one set of needs might consider (a) phase 1 activities (<8 h after the incident) (1), (b) protection of workers at the accident site, (c) several known chemicals, and (d) technical expertise of local first responders, but not special engineers. This approach has the advantage of being user-oriented but may suffer if other useful, available techniques fall outside of the user-needs categories given first priority.

The optimum approach is one that follows the second method but also recognizes the particular advantages of promising candidate instruments and sensing techniques.

Much of the discussion in this paper may be abstract or asoteric. It is intended to provide an introduction to the type of framework that should first be established to best define the needs of the responders. With this in hand, the acquisition of useful instrumentation can proceed in an organized and focused way.

#### FRAMEWORK FOR DEFINITION OF USER NEEDS AND CONSTRAINTS

The types of instrumentation and other techniques that can be used at a spill site are governed by four classes or sets of constraints and considerations:

1. The time frame available for response,
2. The nature of the spill and the substances involved,
3. The expertise of the responders, and
4. The spatial extent of the impacted area.

Figure 1. Yearly variation of incidents and casualties in U.S. by mode.

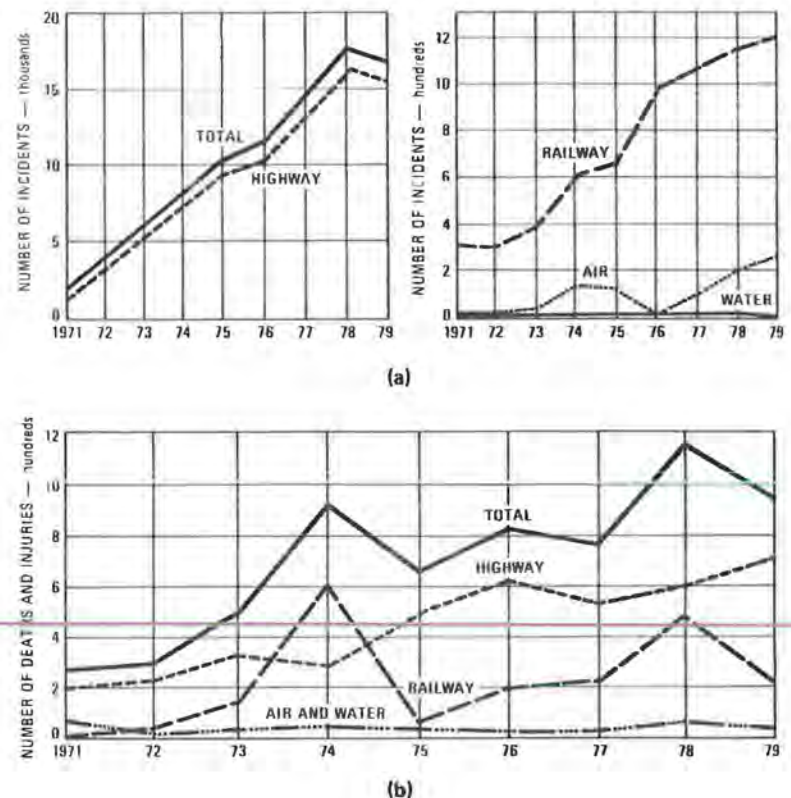
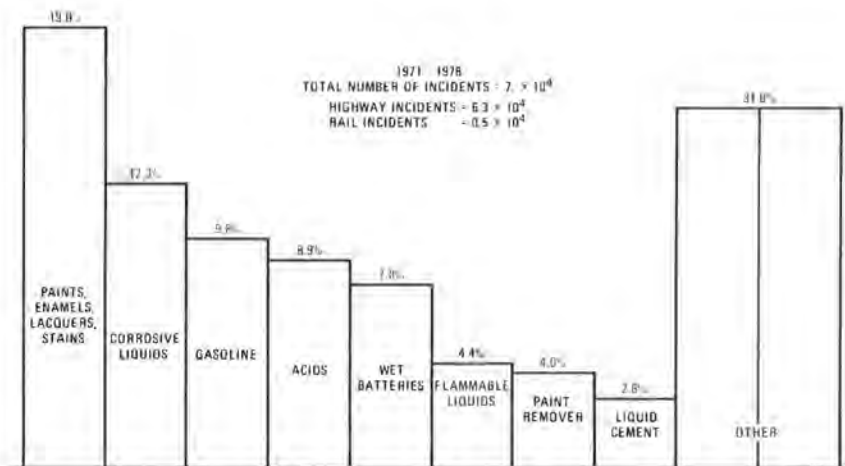
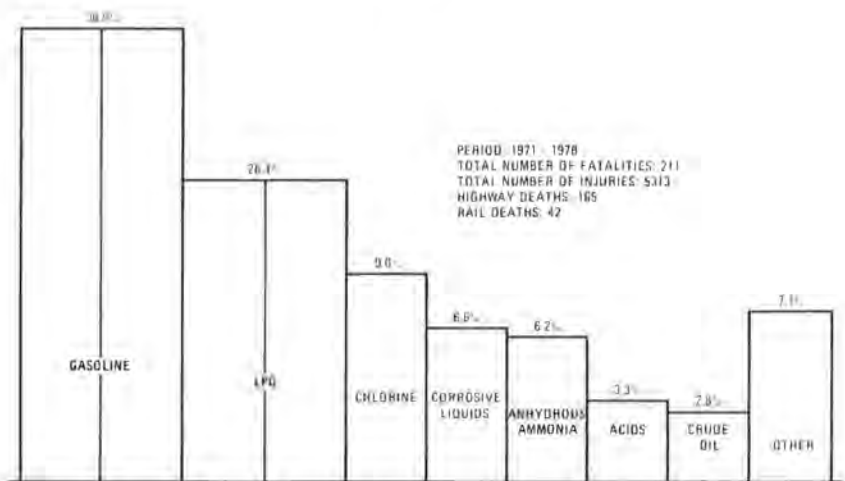


Figure 2. Hazardous materials involved in transportation incidents in U.S.



(a)



(b)

Spanning each of the four sets is the effect of the existing meteorological conditions and the way in which they may change with time (or location) (see Figure 3).

Time Frame

Time can be a factor in several ways but, basically, there is a need to consider what monitoring resources can be employed in each of the three logical phases of an accident, as introduced by Smith (1). Phase 1 is the initial period of response that lasts from 2 to 8 h and usually involves local responders. The principal object is to evaluate the emergency, contain it as much as is practical, and prevent injury to workers and the nearby population. Phase 1 instrumentation will of necessity be restricted to widely available devices that can be used easily by first responders. Phase 2 is the mature period of the incident and may last up to several days or more for major emergencies. Time is available to bring specialists and sophisticated hardware to the scene. Phase 2 is concluded when the emergency is controlled. Phase 3 may last several weeks (or more) and focuses on the restoration of the site. The purpose of monitoring during this phase is to assess potential residual effects that may involve long-term hazards.

Nature of Spill

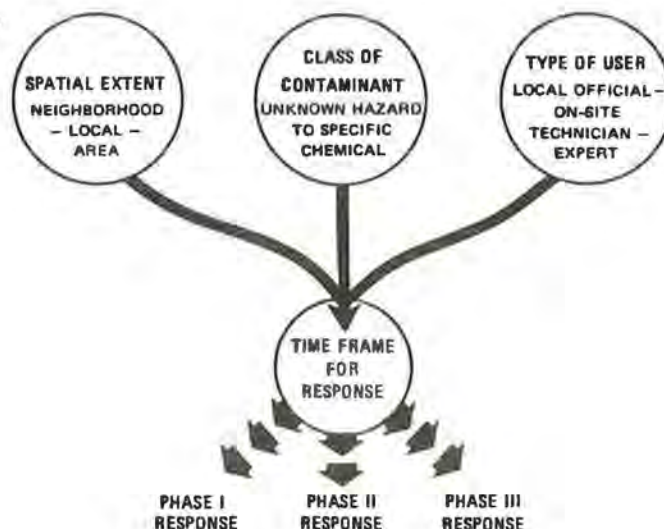
The hardware used to monitor during each of the three phases is a function of the nature of the primary or secondary contaminants. Two scenarios that must be considered are as follows: (a) the contaminants are either known with certainty or can be assumed to fall within a short list of possibles, or (b) the identity of the contaminants is virtually unknown. Even if the contaminant is known, appropriate instrumentation may not be available. Because the list of hazardous substances is so large, a priority listing will need to be prepared and appropriate methods considered according to the priority of the substance and the potential for obtaining a sensor that can serve in the field.

Spatial Extent

Monitoring requirements for emergency situations will vary with the spatial aspects of the problem. Conditions immediately adjacent to the accident may necessitate different instrumentation from that used to assess the extent of the public evacuation zone further downwind. At the accident site concentrations are apt to vary rapidly in time and space and require the use of one or more continuous or near-continuous sensors to protect workers. Further



Figure 3. Four classes of constraints that dictate nature of atmospheric emergency response system.



downwind harmful secondary products may form that do not exist at the accident site or ambient levels may need to be monitored to assess the likelihood of chronic effects to unprotected citizens.

#### User Expertise

The personnel available to operate the instrumentation (and perhaps interpret the output) is a major consideration in the selection process. Local first responders will often be unable to afford the more sophisticated hardware nor would they normally be skilled in its operation and maintenance. Accordingly, Phase 1 hardware will need to allow these users to assess whether the concentrations are hazardous, yet they will need to be relatively inexpensive, readily available, and easy to use properly. Phases 2 and 3 will usually provide enough time to bring instrumentation specialists to the scene.

#### Accident Scenarios

Taken together, the four classes of constraints define most accident scenarios and the associated aerometric instrumentation requirements. Summarized below is the broad range of scenarios that can exist at a major accident:

Time Frame	Spatial Extent	Nature of Spill	User Expertise
Phase 1	Accident scene	Known chemicals	Public safety officials
Phase 2	Downwind populated areas	Unknown chemicals	Trained response team
Phase 3			Specialists

Not all subdivisions are mutually exclusive. The tabulation indicates that 36 scenarios may come into play. The development of monitoring devices and systems should be done in the context of an integrated plan that recognizes the scope of the physical problem and the specific needs of the users.

#### EXAMPLES OF AVAILABLE RESOURCES

A wide range of different sampling and detection techniques is available, both for monitoring of gases and aerosols and for meteorological measurements. These are the range of resources potentially available to support the air-monitoring needs of the emergency response teams.

#### Grab Samples

Instrumentation for grab samples can vary from substance-specific detector tubes to highly sophisticated interferometers and gas chromatograph-mass spectrometers. Draeger tubes, for example, are well suited for a first-on-the scene responder or a phase 1 response team. These devices are simple to use, require minimal operator training, and can usually identify a chemical class but often are not capable of specific identification. In fact, they are already in use for environmental emergency situations.

More sophisticated instrumentation such as portable infrared (IR) or portable gas chromatographs (GCs) or photoionization detectors offers more specificity and sensitivity of detection but is less portable and more complex to operate. Where extremely toxic materials are involved in a spill, much more complex instrumentation is required to monitor these chemicals at the minute concentrations that can represent a health hazard. Examples of this latter instrumentation are IR interferometers; GCs with sensitive, specific detectors; and mass spectrometers (2). These sophisticated instruments can be installed in vehicles to provide some portability, but only at considerable expense and difficulty. The more sophisticated analytical tools are well suited for phase 2 response teams and have some usefulness in the longer-term, phase 3 responses.

#### Remote Sensing

One problem facing the emergency response team when hazardous gases are released into the atmosphere is to define the size and concentration of the plume. Surveillance of the plume is needed as soon as possible after the accident until later periods (phase 1,2), possibly weeks (phase 3), when effects are residual from the outgassing of soil and water. Definition of the plume is also critical when certain actions are contemplated, such as increasing the release rate or combusting the material. In addition, the plume may be laden with toxic aerosols or aerosols may form downwind. Remote sensing, because of wide area coverage, offers a way of defining these gas and aerosol plumes.

Remote measurement systems always make a measurement along a line of sight, and multidimensional mapping is made possible by moving the line of sight by motion or scanning. Van-mounted scannable systems and aircraft-mounted systems are used rou-

Table 1. Specifications for remotely controlled sampling aircraft.

Parameter	Requirement
Weight	Total weight, including all sampling, control, and support equipment not to exceed 35 lb
Size	Overall size, including all equipment and the sampling case not to exceed 2.5 ft <sup>3</sup>
Control range	Maximum radio-control range to exceed 1.5 miles
Deployment	Deployable at wind speeds $\leq$ 35 knots
Altitude	Operable 20-500 ft above the surface
Speed	20-65 mph
Fuel	Should be powered by a nonpetroleum fuel
Flight duration	Should be 30 min before refueling or recharging of batteries
Safety	Sampling system shall not be a source of ignition for a flammable vapor
Crew	Transported, deployed, and operated by a single person
Maintenance	Maintainable in field by using commercially available materials and parts

tinely. The diversity of remote-sensing instrumentation is wide; however, these instruments may be classified in a simple four-parameter tabulation:

1. Active or passive,
2. Range resolved or range averaged,
3. Airborne or ground based, and
4. Material specific or nonspecific.

Remote systems use the principle that the concentration of a gas or aerosol can be determined by the absorption or backscattering of light along the path. Passive systems use natural sources of radiation, such as sunlight, diffused sunlight, earth, and sky radiation. Active systems use artificial sources, such as lasers. Systems may also be range resolved or may estimate gas concentration averaged along the path. Passive systems usually have the latter characteristic. Systems may be flown, driven, or scanned across the plume. Finally, remote-sensing systems are classified as material specific or nonspecific. Many remote-sensing systems tend to be in the former category (see the paper by Uthe and Hawley in this Record).

Remote sensing could be of particular value when spills involve highly toxic materials or when toxic materials are combusted after the accident. Mapping can be accomplished at hazardous locations without the risks involved with grab sampling.

#### Remotely Controlled Sampling and Measurement Vehicles

An approach to collect grab samples safely in hazardous locations could make use of a remotely-controlled land vehicle, boat, or model aircraft. The following discussion, however, is an example specific only to the application of a model aircraft.

A sampling aircraft suitable for use in this application should be easily transportable and carry an adequate payload for either sample collection in containers or for lightweight analytical instrumentation. Table 1 provides specific requirements for an existing model aircraft sampling platform that is suitable for use as a remotely piloted vehicle (RPV) operated by a phase 1 or 2 response team.

The RPV has an amphibious hull and can be adapted to collect either air or water samples. The RPV has a payload weight of 4.5 kg and payload volume of 17 L. Within the context of this design payload weight-volume constraint, several analysis techniques are practical:

1. Draeger tubes,
2. Photoionization detector,
3. Combustible gas detector,

4. Ion selective electrodes,
5. Conductivity detector,
6. Radioactivity detector, and
7. Particulate and gas collection.

#### Artificial Tracers

Artificial, gaseous tracers can be injected into the hazardous spill at a known rate to provide at least four types of useful information:

1. Definition of the distribution of the toxic gases and their dispersion by acting as a surrogate for the gases of concern;
2. Estimation of the actual concentration of the toxic gases (even when the latter cannot be measured), provided the rate of release of the toxic gases can be estimated;
3. Estimation of the rate of release of the toxic gases, provided there are simultaneous ambient measurements of the tracer gas and the toxic gases at one or more representative locations; and
4. Real-time evaluation of atmospheric dispersion models; with the tracer data to provide an objective measure of confidence, the models can be used for real-time in situ contingency planning.

Tracer gases such as sulfur hexafluoride can now be measured continuously at concentrations as low as  $10^{-11}$ , and grab sampling and batch analysis can provide reliable measurements to  $10^{-12}$ . Active remote-sensing systems for SF<sub>6</sub> that use infrared differential absorption principles are now being developed.

#### Meteorological Data

Both large-scale (synoptic) and microscale meteorological data are vital to the protection of the response team and the citizenry. Synoptic data are available from the National Weather Service, although surface and upper air weather data available by teletype (e.g., Services A and C) can be obtained at the accident site most easily and quickly via telephone or terminal access to one of several private companies that offer this service around the clock. No special installation is required. Satellite and facsimile data are also invaluable and can easily be obtained in many locations that use receivers designed for marine use.

Microscale or local effects often dominate the observed weather conditions at the accident site, particularly when dispersion conditions are poor. Local meteorological measurements are a necessity. These should include wind measurements at multiple heights and different locations, particularly when the terrain is hilly or the area heavily forested. Temperature stratification near the ground is also important to assess air drainage patterns and the rate of diffusion of the toxic plume. When the plume is buoyant due to fire or explosion, upper-level winds and temperatures will be important. These can most easily be obtained by tether-sonde or Doppler acoustic radar.

#### Role of Dispersion Models

Properly used, dispersion models can provide valuable information to the on-scene coordinator for evaluating conditions that are potentially hazardous to cleanup and repair crews and for assessing the extent of public evacuation zones. Models are particularly useful for extending and supplementing the information obtained from several point measurements of gas or aerosol concentration. However, to be used with confidence, the models should be evaluated

on the scene against such measurements or on the basis of measurements of tracer gases. In this way the absolute accuracy and uncertainty of the model outputs can be used to provide a measure of confidence of their validity. Not only can models be used to describe the spatial structure of the plume of contaminants, but they can also be used to forecast the impact of changing weather or emission conditions. Thus, the effect of shifting wind directions or changing wind speeds can be quantified. When actions such as vent-and-burn are contemplated, models can be helpful in describing the impacts and selecting the optimum meteorological conditions. Models are available that can easily be adapted to this application, but they need to be integrated into a real-time assessment system that incorporates on-site meteorological data, terrain features, emission estimates and concentration measurements (for validation), and weather forecast data.

#### CONCLUDING REMARKS

The number of hazardous spills from transport acci-

dents has steadily increased over the past decade in response to the availability of new chemicals and increased demand. Risk to the nearby population is initially greatest as a result of atmospheric transport. The need is pressing to provide first-responder groups with instrumentation and other resources that will enable them to assess the magnitude and extent of the hazard rapidly and to develop effective control or protective actions. This paper does not present solutions. Rather, it attempts to organize the considerations that must be made in acquiring or specifying an appropriate system of response instrumentation, and it provides a brief introduction to the general types of measurement techniques available and their advantages.

#### REFERENCES

1. A.J. Smith. *Managing Hazardous Spills*. McGraw-Hill, New York, 1981.
2. E. Starino. *Analysis of Hazardous Pollutants*. *Pollution Engineering*, Feb. 1982, pp. 32-39.

## Applications of Remote Sensing to Hazardous Spill Incidents

EDWARD E. UTHE AND JAMES G. HAWLEY

Remote sensing techniques may be particularly well suited for monitoring the distribution of hazardous spill concentrations. These techniques provide the means for real-time viewing of large atmospheric volumes over remote distances that have extremely high spatial and temporal resolution. Atmospheric remote sensing has been used extensively in air pollution research programs and is currently being developed for the military for toxic agent applications. This paper discusses some previous studies that demonstrate capabilities that should be considered for application to hazardous spill incidents.

Remote sensing techniques are classified as either active or passive and capabilities differ greatly between these classifications. Active systems provide their own energy sources; passive systems point at naturally occurring energy sources (e.g., sunlight, thermal radiation from terrain, and atmospheric species). Most active systems used for atmospheric observation use laser transmitters and optical receivers; passive systems have only optical receivers. Because lasers operate at only a finite number of wavelengths and because the cost of the sensor increases greatly as the number of wavelengths increases, only one or two wavelengths are typically used.

Passive sensors can perform wavelength scans economically over large wavelength intervals and thus are well suited for discriminating between agents that have different wavelength-dependent absorption or emission spectra. The major advantages of the active system are that the energy can be transmitted in pulse form (hence, range information can be obtained by using radar principles) and discrimination against background radiation is simplified. Because of the differences in active and passive sensor techniques, they are complementary and their com-

bined capabilities are being considered in several development programs.

#### REMOTE SENSING EXAMPLES

SRI International has pioneered laser radar concepts since 1963, when the first observations in the lower atmosphere were conducted. Earlier light detection and ranging (lidar) systems were typically single wavelength and observed range-resolved energy backscattered from atmospheric particulate material. These systems did not realize their potential because of limitations in band pass and the dynamic range of electronic circuits for processing high-speed signals ( $\sim 0.000\ 000\ 01$  s). Later systems have evolved that can measure particulate concentrations with high spatial resolution. These particulate backscatter systems have evolved so that 1.5 m of spatial resolution is now possible.

Gaseous-measuring laser radar systems (termed differential absorption lidar) have been developed recently. They depend on absorption of laser radiation at two frequencies by the gas being measured. Their emergence has depended on advances in tunable laser technology. Both van-mounted and aircraft-based lidar systems that measure particulates and gases are being routinely applied on air pollution and military programs. As an example of an existing system, the Mark IX mobile lidar (shown in Figure 1) can scan across a pollution plume downwind or the source and display the cross plume signature data in the form presented in Figure 2. In this figure the lidar is located at the lower left corner of the picture and is scanned in elevation at an azimuth direction that intersects the plume nearly perpendicular to the transport direction. Picture

brightness is proportional to the logarithm of plume backscatter and therefore is a measure of relative aerosol concentration. Concentration profiles at several distances from the lidar are plotted in Figure 2. A plume cross section can be obtained in about 1 min (greatly reduced with new systems) so that the three-dimensional distribution of plume constituents can be determined rapidly.

A second example illustrates the capabilities of the airborne lidar plume and haze analyzer (ALPHA-1), a two-wavelength, downward-directed lidar operated from the SRI Queen Air aircraft (Figure 3). In this example (shown in Figure 4) the lidar was flown across a smoke plume about 500 m downwind of a small forest fire. Relative concentration patterns provide quantitative information on transport and diffusion downwind of the source. Surface returns have been analyzed in terms of vertical plume transmission, and the two-wavelength (0.53 and 1.06  $\mu\text{m}$ )

Figure 1. Mark IX lidar system observing downwind distribution of smoke.



Figure 2. Example of computer-generated vertical plume density profile. Lidar is located in the lower left corner. Plume vertical concentrations (relative to clear air with a scale of 75 m/div) are plotted (lower left), and horizontal position associated with each photograph is plotted (upper right).



Figure 3. SRI Queen Air aircraft used to support ALPHA-1 lidar system.



transmissions provide information on particle size needed for estimates of absolute concentration (1).

A third data example illustrates the capabilities of a differential absorption lidar (DIAL) for observing the distribution of gaseous constituents. A DIAL system transmits energy at two closely spaced

Figure 4. Smoke plume distribution and vertical transmissions, based on surface returns, derived from ALPHA-1 observations.

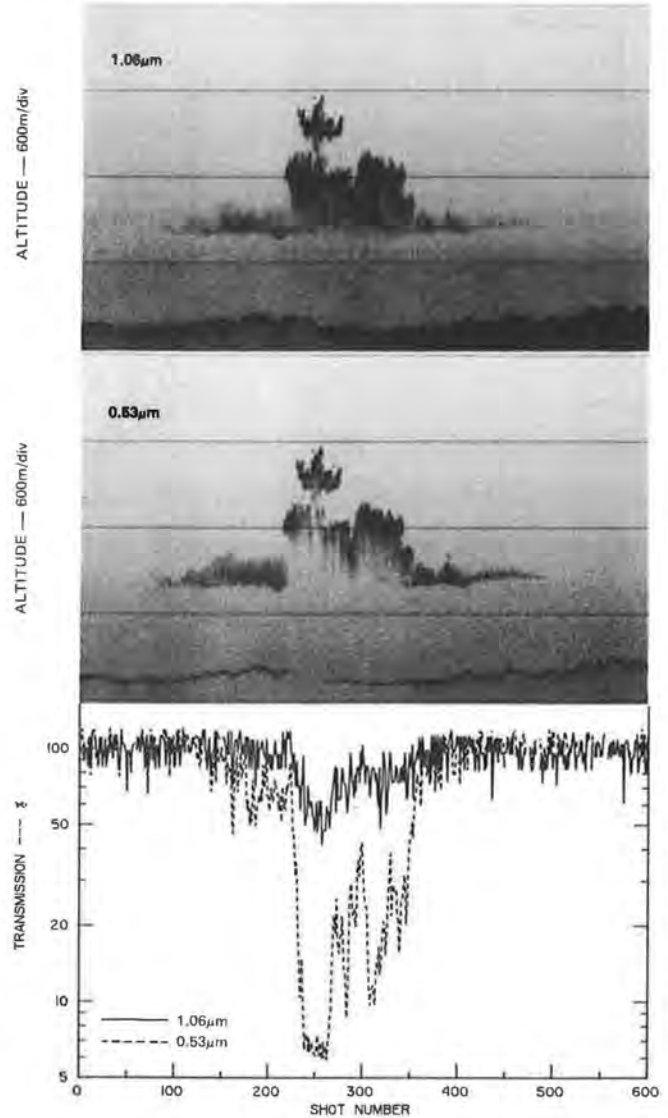
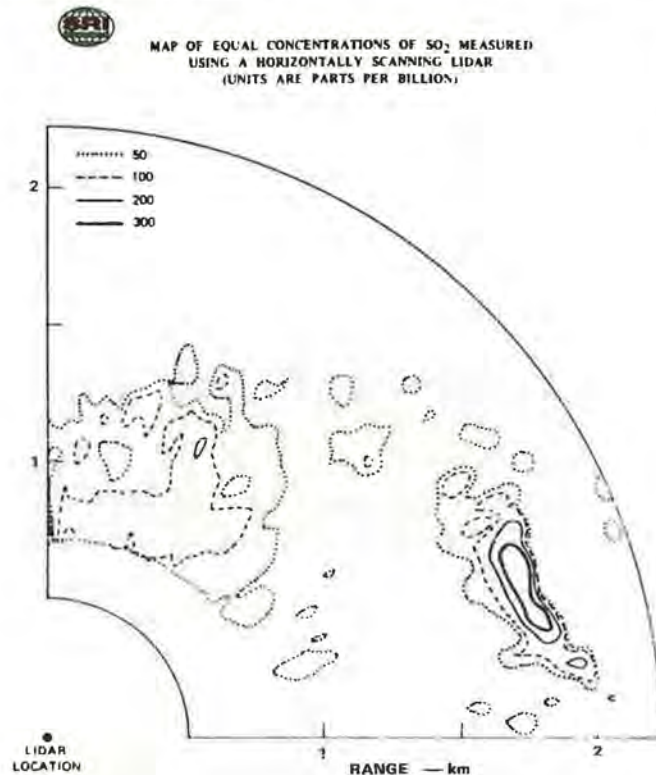


Figure 5. DIAL gas-measuring lidar system.



Figure 6. Horizontal cross section of sulfur dioxide concentrations derived downwind of Kincaid coal-burning power plant (3 km to right of lidar location) derived with the DIAL system.

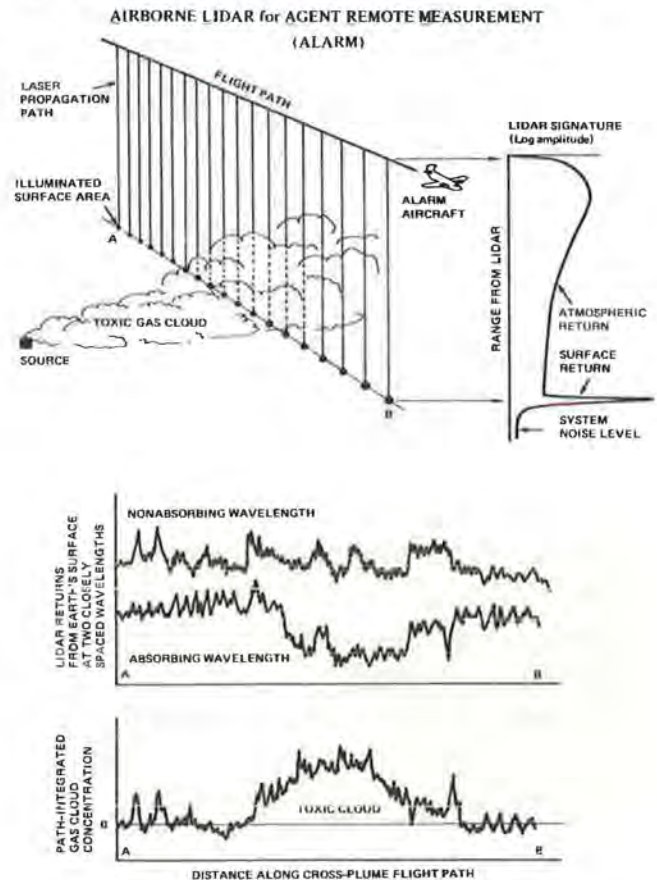


wavelengths such that energy at one wavelength is absorbed by a gas species and the energy at the other wavelength is only minimally affected by the presence of gas. Because the wavelengths are closely spaced, aerosol effects can be eliminated and absolute profiles of gas concentrations can be evaluated. In this example, the mobile DIAL system constructed and operated by SRI (Figure 5) was used to map the distribution of sulfur dioxide near the surface downwind of a coal-burning power plant (Figure 6). The ultraviolet wavelength system has also been used to map distributions of ozone and nitrogen dioxide (2). Extension of this technique to infrared wavelengths would allow observation of many toxic chemicals that have unique infrared absorption spectra.

We have proposed to develop under Army support an airborne lidar system, airborne lidar for agent remote measurement (ALARM), that would use two infrared line-tunable lasers to combine the surface return analysis (example 2) with the DIAL technique (example 3) to map column content concentrations of military agents over large regional areas (Figure 7). Such a system would provide a strong tool for mapping the distribution of agents released from hazardous spill incidents.

Honeywell, Inc., has developed and demonstrated a system (XM-21) for toxic agent detection for the U.S. Army (3). The system makes rapid wavelength scans in the 9- to 12- $\mu$ m wavelength region and can make observations over large areas. However, application of the technique from a moving platform (e.g., aircraft) has not yet been demonstrated. Future programs may investigate the combined capabilities of the active and passive methods for improved detection, identification, and mapping of toxic agents suspended in the atmosphere.

Figure 7. Application of proposed ALARM airborne lidar system.



## CONCLUSIONS

Although remote sensing techniques have yet to be applied to the observation of hazardous spills, applications to observation of air pollution and military toxic agents have demonstrated their unique capabilities for detection, identification, and mapping of concentration distributions for particulate and gaseous materials. Remote sensing systems are available in ground mobile and airborne configurations to facilitate rapid movement to isolated incidents. Because of their ability to make observations in real time over extended remote distances with high spatial and temporal detail, remote sensors may be ideally suited for application to hazardous spill incidents.

## REFERENCES

1. E.E. Uthe, B.M. Morley, and N.B. Nielsen. Airborne Lidar Measurements of Smoke Plume Distribution, Vertical Transmission, and Particle Size. *Applied Optics*, Feb. 1, 1981.
2. J.G. Hawley, L.D. Fletcher, G.F. Wallace, and M. Herron. A Mobile Differential Absorption Lidar (DIAL) for Range Resolved Measurements of  $\text{SO}_2$ ,  $\text{NO}_2$ , and  $\text{O}_3$ . *American Meteorological Society, Extended Abstract, Vol. 10, International Laser Radar Conference, Silver Spring, MD, 1980.*
3. J.R. Bryson and M.J. Flanagan. The Infrared Characterization of Smokes and Obscurants Utilizing the Honeywell Background Measurement Spectroradiometer, Vol. 1, Proc., Smoke and Obscurants Symposium 5, DRCPM-SMK-T-001-81, 1981.