

Stacy, Lem, Amy → JF
Comments?
JL

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RECEIVED
AUG 8 1985

TO: R. D. Gamblin

FROM: J. C. Ledvina

DATE: August 6, 1985

Interoffice Communication
SUBJ: TOXIC GAS RELEASES

VISTA

I attended a Toxic Gas Release seminar on July 31 put on by Trinity Consultants. The following day the Air Pollution Control Association held a conference on the same subject. Below are highlights that may be of use in formulating Vista's program.

1. Britian passed a law about a year ago requiring industries to notify the general public near facilities handling toxic materials. The law also requires industry to do prior training and notify the public directly in the event of a release. I can get a copy of the British law if more details are needed.
2. The Texas Railroad Commission Rule 36 requires immediate notice to near neighbors in the event of a sour gas release from a well. This rule is in response to the death of several people outside of Denver City, TX in the mid-1970's from exposure to H₂S.
- ③ 3. Dow has placed speakers in homes near their chlorine plant in Placquinine, LA.
4. Approximately 20 SaferTM systems have been installed in the United States. This system is a computerized air dispersion model to predict downwind concentrations of toxic gases from a release. Eastman Kodak management has mandated their plants to install SaferTM Systems. I talked to two engineers from Texas Eastman at Longview who are working with SaferTM on the installation for their Plant. Although not yet installed, they feel that this system has more Public Relations value than practical value in predicting downwind toxic concentrations. Eastman's Longview system will cost \$100M.

Public relations
can be worth
a lot - look at
the bad press
Union Carbide got
the last week

I agree
JWW

The same is
true for VCM -
models don't work

Dick Schultz of Trinity Consultants installed two SaferTM systems for clients in Mississippi. He is very skeptical that they will ever be used.

5. There is no proven mathematical model to reliably predict concentrations of heavy gases. A heavy gas is one such as ammonia or chlorine where a sudden release emits both gas and an aerosol of droplets. Classical dispersion equations do not accurately predict concentration until all the droplets have vaporized and the cloud starts moving with the wind. However, vapor releases of ammonia or chlorine are "modelable".

R. D. Gamblin
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6. In many cases, neighbors are likely to be exposed to less toxic gas if they remain in their homes. This is especially true if the release is a "puff" and there is a wind.
7. Dispersion modelling is best used as a planning tool. By speculating on likely release scenarios and using dispersion modelling, decisions can be made as to which neighborhoods, if any, should be given special attention.

I have some written material on dispersion modelling as well as a bibliography of references related to toxic gas releases. Let me know if any of this is of interest to you.

J. C. Ledvina
J. C. Ledvina

ajo/3

cc RTF, WLM

Dispersion calculations make this sound like a technical question which it is not. Our basis for initiating community evacuation is "immediate health hazard". This decision is one of judgement and basing this on dispersion calculations gives you more opportunity to err in the wrong direction.

JWW

PRACTICAL PLANNING FOR TOXIC GAS RELEASES

REGISTRATION LIST

Houston, TX - July 31, 1985

**Mr. Allen Jurisich
Senior Program Advisor, Environmental Service
Cigna Loss Control
139 West Livingston Place
Metairie, LA 70005
(504) 831-1617**

**Mr. John Brau
Employee Relations Manager
Sohio Chemical Company
Box 659
Port Lavaca, TX 77979
(512)552-8218**

**Mr. Joe Ledvina
Director of Environmental Activities
Vista Chemical Company
P.O. Box 19029
Houston, TX 77224
(713)531-3451**

**Ms. Aileen Teng
Senior Environmental Health Specialist
Cigna Loss Control Service
12815 Leader
Houston, TX 77072
(713)933-1826**

**Mr. Ron Pertuit
Texas Eastman Company
P.O. Box 7444
Longview, TX 75607
(214) 236-5000 ext. 2760**

**Mr. Joe Woolbert
Texas Eastman Company
P.O. Box 7444
Longview, TX 75607
(214) 236-5000 ext. 2760**

SERVICES TO ESTIMATE AIR QUALITY

Trinity Consultants, Inc. has specialized in making estimates of air quality and in obtaining air pollution permits since 1974. All employees devote their time exclusively to this narrow area of the environmental field and they are unusually familiar with rules, regulations, and current practices. The client benefits in terms of reduced costs and quick response time. As a small firm with 7 employees and its own computer, overhead is low and individuals working on study deal directly with the client.

Dispersion Modeling Studies. These studies are performed to help clients evaluate the air quality either to pinpoint the sources of current problems or to evaluate the effect of proposed changes. Since 1978, Trinity Consultants has prepared over 300 dispersion modeling studies for clients in 40 states. Typical categories of work include:

- Trinity Consultants is a leading firm in preparing "Prevention of Significant Deterioration" (PSD) applications. Since 1977, 115 PSD reports have been prepared for nearly every type of industrial plant. Applications have been prepared for plants located in all 10 EPA regions and in 29 states.
- SIP Revisions - Since 1978 Trinity Consultants has helped 9 clients obtain permits to construct in non-attainment areas. In 15 other cases Trinity Consultants has been involved in State Implementation Plan revisions.
- Stack Heights - Trinity Consultants has conducted more than a dozen studies of stack design to optimize investment.

Training Seminars. Three courses are conducted: a two-day course on the fundamentals of dispersion modeling, a two-day laboratory applications course using dispersion models on an IBM-PC and a one-day seminar entitled "Permits Under the Clean Air Act". These courses have been taught a total of over 90 times and have been sponsored by professional associations for their members, major corporations for their employees and Trinity Consultants for the public.

Sale of Models and Met Data. Clients can purchase dispersion models and meteorological data in one of 3 ways: First, 21 firms currently use Trinity Consultants timesharing service devoted almost exclusively to air quality dispersion models. Second, over 70 customers have purchased IBM-PC versions of popular air pollution dispersion models. Third, since 1976 some 20 firms have purchased IBM mainframe version of the UNAMAP models. Trinity Consultants also processes and sells meteorological data from its extensive library. Delivery is generally overnight.

Toxic Gas Releases. 20 firms have been served with studies of the possible effects of a potential gas releases, estimated effects of actual releases, building ventilation studies and testimony in court. Both puff models and steady state models have been used in these analyses.

January 1, 1985

214/234-8567

PARTIAL LIST OF CLIENTS

Firms Purchasing Dispersion Modeling Studies/Consultation

Petroleum/Refineries

- Allied Materials Corp.
- + American Petrofina, Inc.
- Calumet Refining Co. Inc.
- + Champlin Petroleum, Inc.
- * Crystal Oil Company
- Dorchester Refining Company
- Getty Refining & Marketing Co.
- + Gulf Oil Co. - U.S.
- Kerr-McGee Corp.
- Lake Charles Refining Co.
- + Murphy Oil Corp.
- + Pennzoil Oil Corp.
- Plateau Refining Co.
- Rock Island Refining
- * Sigmor Refining Co.
- + Standard Oil Co. (Indiana)(AMOCO)
- Standard Oil Co. (Ohio)
- + Sun Company
- Union Oil Company
- * Vidette Refining Co.

Petroleum/Production

- + Aminoil U.S.A., Inc.
- Arco Oil & Gas Co.
- Mid-American Oil & Gas (Centex)
- Cities Service Company
- Delhi Gas Pipeline Co.
- + Endevco, Inc.
- Exxon Production Research
- + Farmland Industries
- + Getty Oil Co.
- Haliburton Resource Management
- * Hunt Energy Co.
- Husky Oil Co.
- + Kerr-McGee Corp.
- Koch Hydrocarbon Co.
- Leede Oil & Gas Inc.
- Mesa Petroleum Co.
- Moore McCormick Energy
- + Pursue Gas Processing
- + Shell Oil Co.
- + Sun Exploration & Production
- Texas Oil & Gas Corp.
- Tipperary Corp.
- * Tomlinson Interests
- + Union Texas Petroleum

Pulp & Paper

- + Boise-Cascade
- + Bowater Southern Paper Corp.
- Celotex
- Container Corporation of America
- + Fort Howard Paper Co.
- Georgia-Pacific
- * Hammermill Paper
- + Owens-Illinois, Inc.
- Temple Eastex, Inc.

Chemicals

- + Airco Carbon
- + Agrico, Inc.
- + American Cyaminid
- + CF Industries, Inc.
- Cabot Corp.
- Calgon Corporation
- Chemische Werke Huls AG
- + Chevron Chemical Co.
- Colombian Chemical Co.
- Conoco Chemical Co.
- Cosden Oil - Chemical Co.
- Coulton Chemical Co.
- + Dow Chemical Co.
- + E. I. DuPont de Nemours
- + Ethyl Corp.
- FMC Corporation
- + Firestone Synthetic Rubber & Latex
- + Freeport Chemical Co.
- Georgia Pacific Co.
- + Goodyear Tire & Rubber Co.
- + W.R. Grace (Davidson Chemical Div.)
- + Kerr-McGee Chemicals
- Mississippi Chemical Corp.
- + Monsanto Corp.
- Olin Chemical
- Petro United, Inc.
- Procter & Gamble Co.
- Rohm & Haas, Inc.
- Sintech, Inc.
- Stauffer Chemical
- Sid Richardson Carbon & Gasoline
- + Union Carbide Corp.
- Vulcan Chemical Co.

Coal and Mining

Energy Fuels Nuclear, Inc.
Kerr-McGee Corp.
Texas Industries
+ Pittston Coal
* Sohio

Consultants

Argento, Vittorio
Benham Group, Inc.
Louis Berger & Assoc.
+ Bovay Engineers, Inc.
Breisch Engineering Co.
Browning-Ferris Industries
Castel Consulting Service
CE-Maguire
Chittenden Engineering Co.
Clark, Dietz & Associates
Controls for Environmental Pollution
+ Cooper Engineers
Daniel Construction Co.
Davis & Floyd Engineers, Inc.
Evergreen Environmental Management
F.E. Courtney & Associates
+ Ford, Bacon & Davis
Gibbs and Hill
Kaiser Engineers
George E. McVehil
MITRE
Metro Environmental Application
+ Moore Engineering
J.F. Mullen & Associates
Ortloff Corp.
Petro Project Engineering, Inc.
Petrochem Consultants, Inc.
R.W. Beck & Associates
Resource Consultants, Inc.
Rist, Frost Associates
+ Scott Environmental
Simons Eastern
+ Stanley Consultants
Steuver & Associates
+ J.E. Thibault & Associates
Tippet & Gee
Trovillion, Al
TRW, Inc.
+ Turner Engineering
+ Turner, Mason & Associates
Roy F. Weston Co.

Metals

* Arco Aluminum
+ Blaw-Knox
Chaparral Steel (TXI)
Kaiser Aluminum & Chemical Corp.
LTV Steel
National Steel
* National Zinc
+* NL Industries
+ RSR Corporation
* Ross Metals

Attorneys

George R. Alexander, Jr.
Baker & Daniels
Greenberg, Traurig
Lynberg & Nelson
Millbank, Tweed
Popham, Haik, Schnobrick,
Kaufman & Doty
Rooks, Pitts & Poust
Sewell, Junell & Riggs
+ Thompson & Knight
Wachtell, Lipton, Rosen & Katz

Cement, Stone, Lime & Glass

Acme Brick
* B.L. Anderson
+ Capitol Aggregates, Inc.
+* Chemical Lime
* Centex Corp.
Dal-Tex Cement
Englehard Minerals & Chemicals
+ General Portland, Inc.
Genstar Building Materials Co.
Gifford Hill Portland Cement
Ideal Basic Industries
Lehigh Portland Cement
Libbey-Owens-Ford
* Lone Star Cement
Loomis Construction
* Nevada Cement
+ Owens-Corning
Owens-Illinois, Inc.
+ Southwestern Portland Cement
+ Texas Industries, Inc.
+* U.S. Brick
+ U.S. Gypsum

Utilities/Energy

- * Arizona Public Service, Inc.
- * Brazos Electric Power Cooperative
- +* Cajun Electric Power Cooperative
Foothills Pipeline, Ltd.
- * Golden Valley Electrical Co-op, Inc.
- +* General Electric Co.
- + Hawaiian Electric Company
- Louisiana Power & Light
- Mississippi River Transmission Corp.
- * Nebraska Power & Light
- New Orleans Public Service, Inc.
- + Panhandle Eastern Pipeline
- * Oklahoma Gas & Electric Co.
- + Southwestern Electric Power Co.
- Tennessee Gas Transmission Co.
- Transcontinental Gas Pipeline Co.
- * United Gas Pipeline, Inc.
- * Valley View Energy

Miscellaneous

- Alexander & Baldwin
- Amstar Corp.
- Bunge Corp.
- * City of Detroit
- Dresser Industries
- Ford Motor Co. (Boiler)
- + Frito Lay, Inc.
- Gearhart Industries
- City of Indianapolis
- + Intec, Inc.
- * Iowa Beef Processors
- Manville Building Corp.
- McDonnell-Douglas Corp.
- * City of San Diego
- TD Mechanical
- Texas Instruments
- * University of Vermont
- Varo, Inc.
- * Warwick, Rhode Island

States in Which Studies Have Been Done

Alabama	Indiana	Montana	Rhode Island
Alaska	Iowa	Nebraska	South Carolina
Arkansas	Kansas	New Jersey	Tennessee
California	Kentucky	New Mexico	Texas
Colorado	Louisiana	Nevada	Utah
Connecticut	Maine	North Dakota	Vermont
Florida	Maryland	Ohio	Virginia
Georgia	Michigan	Oklahoma	West Virginia
Hawaii	Mississippi	Pennsylvania	Wisconsin
Illinois	Missouri	Puerto Rico	Wyoming

Countries in Which Studies Have Been Done

Brazil	Belgium	Canada	Gulf of Mexico
New Zealand	Netherlands	Saudi Arabia	Indonesia

Firms Purchasing Specialized Training Programs/Seminars

Air Pollution Control Association	+Mobil Oil
American Cyanamid	PEDCO Environmental
American Society of Mechanical Engineers	Republic Steel
Aramco Services Company	Standard Oil Co. (Indiana)(AMOCO)
Ashland Chemical	Tennessee, State of
City of Indianapolis	Texas Chemical Council
Damson Oil	Timken Company
IBM	U.S. Environmental Protection Agency
Inland Steel Co.	Regions IV and VII
Kerr-McGee Corp.	United Technologies
	University of Texas (for EPA)

- * Served through a consulting firm
- + Performed more than one study

January 1, 1985 (84-62)

EMPLOYEE QUALIFICATIONS

Richard H. Schulze

President

Mr. Schulze received a BSE degree in Mechanical Engineering from Princeton University in 1954 and a MBA degree from Northwestern University in 1958. Following 13 years of work in corporate long-range planning and product development, he joined Core Laboratories Inc. in 1971 as President of their environmental affiliate, Ecology Audits, Inc. He supervised activities in stack sampling, ambient air monitoring networks, water quality studies and preparation of environmental impact statements. In 1974, he founded Trinity Consultants, a firm responsible for over 300 dispersion modeling studies including over 115 PSD permits and 15 SIP revisions. In 1975 he started teaching a two-day short course on dispersion modeling. To date, there are over 1000 graduates of this course which has been offered 80 times throughout the world. Since 1978 he has taught all the Air Pollution Control Association (APCA) short courses dealing with the fundamentals of dispersion modeling as well as selected EPA courses. He is a registered Professional Engineer, a Diplomate of the American Academy of Environmental Engineers, the founder of the North Texas Chapter of APCA, the author of numerous papers on air pollution, and a member of more than 10 professional organizations. He is the sole owner of Trinity Consultants, Inc.

James C. Clary, Jr.

Project Manager

Mr. Clary has over 10 years experience in work as a consulting meteorologist. He holds both the BS and MS degrees in Meteorology from Florida State University. After completing his active military obligation as an officer, Mr. Clary joined Dames & Moore Consultants where he worked on meteorological and safety studies for nuclear power plants as well as on the dispersion of conventional pollutants, including preparation of several PSD permits. Mr. Clary has continued his work in meteorology since joining Trinity Consultants in 1978. He has served as project manager for over 28 PSD permit applications and over 50 other modeling studies. He is also the director of data processing and has installed two computer systems at Trinity. Mr. Clary has been responsible for converting most of EPA's UNAMAP models to be executable on IBM-PC or compatible computers and for developing a two-day Dispersion Modeling Laboratory course which he has now taught 6 times. Mr. Clary is a Certified Consulting Meteorologist of the American Meteorological Society. He taught a semester-length course on modeling of air pollutants at the University of Texas at Dallas.

Deborah K. Fusselman

Project Manager

Ms. Fusselman graduated cum laude in Chemical Engineering from Texas A&M University in 1980. After graduation, she joined Trinity Consultants and became involved with the development of emission inventories and the preparation of state and federal permit applications. Subsequently, her work also included over 70 dispersion modeling studies. More than half of these dispersion modeling studies were performed for state and federal permit applications. The majority of the permit applications have focused on petroleum refineries, chemical plants, natural gas processing plants and compressor stations. Ms. Fusselman has also assisted timesharing customers with the use of the computer and with technical modeling advice. She has converted most of the EPA's UNAMAP models to execute on the IBM mainframes. She has satisfied the written requirements for registration as a Professional Engineer in the State of Texas. She is a member of the American Institute of Chemical Engineers and the Air Pollution Control Association.

Tammy S. Rippetoe

Project Meteorologist

Ms. Rippetoe graduated cum laude in Meteorology from Texas A&M University in 1983. She joined Trinity Consultants in July, 1984, and has become involved in preparing emission inventories, dispersion modeling and processing meteorological data. She is a member of the American Meteorological Society and the Air Pollution Control Association.

Scott R. Humphrey

Project Meteorologist

Mr. Humphrey graduated magna cum laude in Meteorology from Texas A&M in 1983 and received his Master of Science degree in Meteorology from Texas A&M in 1985. His graduate study was in the areas of atmospheric diffusion and boundary layer turbulence. He joined Trinity Consultants in March, 1985, and his duties include dispersion modeling, processing meteorological data, and aiding in the preparation of project reports. He is a member of the American Meteorological Society and the Air Pollution Control Association.

TRPUF

YOUR SOLUTION FOR EVALUATING TOXIC GAS RELEASES

INTRODUCTION

Trinity Consultants, a leader in the field of IBM-PC applications for the air pollution professional, has developed a software package for evaluating releases of toxic gases. This package consists of both the EPA Puff model and TRPUF, a puff model developed by Trinity Consultants. TRPUF is based upon the EPA Puff model. A graphics system is also included in this package.

System characteristics include:

- Simple data entry using interactive and menu-driven screens
- Complex input variables are not required
- Graphical output of concentration versus distance produced on your printer

EPA PUFF MODEL

This model is described in the EPA publication "Estimating Concentrations Downwind from an Instantaneous Puff Release" (PB82-261959), August 1982. The model is based upon the Gaussian Puff equation using the dispersion parameters presented in Meteorology and Atomic Energy.

This program has been converted for the IBM-PC with all of the features included in the original model. Verification test files are included.

TRPUF

TRPUF is based on the Puff EPA model. Several enhancements have been made to make the program easier to use in the PC environment.

All input parameters are specified with simple interactive commands. When TRPUF is started a screen of input items is presented. This screen contains the data used in the last run made. You simply enter the variable number you wish to modify. The computer will prompt you for the entry, verify the entry and then present the input screen again.

The input screen is shown in Figure 1. Notice that all of the entries are relatively simple. There are no complicated variables to define. You also have complete control of the output format from units through fixed or scientific presentations.

When you select option zero from the input screen, TRPUF begins executing. The results are automatically printed on your printer as the model executes. Total execution times vary with different printers, but will be under two minutes for most printers.

An example of the output is shown in Figure 2. This compact output displays both instantaneous and average concentrations at several downwind distances. Concentrations are included for all three stabilities as well as the maximum concentrations. All input parameters are also shown.

GRAPHICS

The results of your TRPUF run are not only sent to the printer but are also placed in a disc file. Another program included in this package, PDIST, allows you to produce plots of concentration versus downwind distance. Again, you may design your output with simple interactive responses as shown in Figure 3. The output of PDIST is processed by the Golden Software package to produce high quality plots on your dot-matrix printer. Examples are included as Figures 4 and 5.

GOLDEN SOFTWARE GRAPHICS SYSTEM

This complete graphics system is included in the TRPUF package. This system, developed by Golden Software of Golden, Colorado, is used to produce the concentrations versus distance plots. However, this package contains many additional capabilities including contour and three-dimensional plots, XY, graphs, bar charts, pie charts, line graphs and scatter charts.

PRICE AND HARDWARE REQUIREMENTS

The complete TRPUF package is available for \$995.00 for a single-use license. This package includes:

- o Both source and executable versions of the EPA Puff model and test data files
- o Both source and executable versions of TRPUF
- o Executable version of PDIST
- o Complete Golden Software Graphics System with all documentation
- o EPA guide for the EPA Puff model and Trinity Consultants guide for TRPUF
- o Telephone support services to help you get started.

Hardware requirements are an IBM-PC, PC/XT or AT, or compatible; two floppy disc drives or one floppy and one hard drive; 256 kb of RAM; and a dot-matrix printer. A math coprocessor will decrease execution time, but is not required.

COMPANY-WIDE LICENSE

A company-wide license of the software. This license removes the restriction that only copies for backup purposes be made. The user is free to copy and distribute the software and manuals within a single company. The user is responsible for all reproduction. Questions about the software must be made by one person. The additional cost of this option is \$500. You must have also purchased one copy of our single-use product.

TRPUF - MOD5

COPYRIGHT 1985 TRINITY CONSULTANTS, INC.

- 1) TITLE - EXAMPLE OF TRPUF5
- 2) RELEASE AMOUNT (POUNDS) = 2.20500
- 3) MOLECULAR WEIGHT = 64.00
- 4) AMBIENT TEMPERATURE (DEGREES F) = 88.00
- 5) AMBIENT PRESSURE (MB) = 1013.00
- 6) RECEPTOR HEIGHT ABOVE GRADE (FEET) = 5.
- 7) AVERAGING TIME (SECONDS) = 300.
- 8) EXIT VELOCITY (FEET PER SECOND) (USE 0 IF NOT A VERTICAL RELEASE) 5.000
- 9) STACK DIAMETER (FEET) = 1.500
- 10) DISTANCE FACTOR (USE 1 FOR THE STANDARD DOWNWIND DISTANCES) = 1.0000
- 11) WIND SPEED (MPH) = 5.0
- 12) STACK HEIGHT (FEET) = 60.00
- 13) CONCENTRATION UNITS = UG/M3
- 14) INITIAL PUFF CENTER CONCENTRATION (PPH) 5.00E+05
- 15) DISTANCE AT WHICH INITIAL PUFF SIZE IS KNOWN (FEET) = 0.
- 16) INITIAL HORIZONTAL STANDARD DEVIATION (FEET) = .00
- 17) INITIAL VERTICAL STANDARD DEVIATION (FEET) = .00
- 18) OUTPUT FORMAT - SCIENTIFIC

ENTER VARIABLE NUMBER TO BE MODIFIED, 0 TO RUN, 99 TO STOP

TRPUF - MDIS
 COPYRIGHT 1985 TRINITY CONSULTANTS, INC.
 A PUFF MODEL DEVELOPED BY TRINITY CONSULTANTS, RICHARDSON, TEXAS 214/234-8567

EXAMPLE OF TRPUF5

RELEASE AMOUNT (POUNDS) = 2.20500 RECEPTOR HEIGHT ABOVE GRADE (FEET) = 5. INITIAL CONCENTRATION (PPH) = 5.00E+05
 MOLECULAR WEIGHT = 64.00 EXIT VELOCITY (FEET PER SECOND) = 5.000 INITIAL HORIZONTAL SIGMA (FEET) = .00
 AMBIENT TEMPERATURE (DEG F) = 68.00 STACK DIAMETER (FEET) = 1.50 INITIAL VERTICAL SIGMA (FT) = .00
 AMBIENT PRESSURE (MB) = 1013.00 WIND SPEED (MPH) = 5.0 DOWNWIND DISTANCE (FT) = 0.
 STACK HEIGHT (FEET) = 60.00

COMPUTED VIRTUAL DISTANCES (FT) HORIZONTAL VERTICAL
 UNSTABLE 3.3 3.3
 NEUTRAL 16.4 16.4
 STABLE 85.3 85.3

DOWNWIND DISTANCE (FEET)	PEAK INSTANTANEOUS CONCENTRATIONS (UG/M3)				AVERAGE CONCENTRATIONS FOR 300. SECONDS (UG/M3)				TRAVEL (MINUTES)	--- SIGMAS (FEET) ---					
	UNSTABLE	NEUTRAL	STABLE	MAXIMUM	UNSTABLE	NEUTRAL	STABLE	MAXIMUM		UNSTABLE HOR VER	NEUTRAL HOR VER	STABLE HOR VER	STABLE HOR VER	STABLE HOR VER	STABLE HOR VER
20	5.5409E-07	2.2128E-09	6.7703E-09	5.5409E-07	1.7591E-09	4.5425E-12	1.1093E-11	1.7591E-09	.045	3	7	2	3	1	1
40	2.0281E+01	7.2767E-10	4.4680E-09	2.0281E+01	1.1391E-01	2.2348E-12	8.5457E-12	1.1391E-01	.091	3	11	3	4	2	2
60	1.9562E+03	3.3662E-10	3.1362E-09	1.9562E+03	1.5383E+01	1.3668E-12	6.8435E-12	1.5383E+01	.136	7	15	4	4	2	2
80	1.2150E+04	1.8649E-10	2.3043E-09	1.2150E+04	1.2461E+02	9.3783E-13	5.6399E-12	1.2461E+02	.182	9	18	4	5	2	2
100	2.8975E+04	1.1553E-10	1.7539E-09	2.8975E+04	3.6224E+02	6.9102E-13	4.7519E-12	3.6224E+02	.227	11	22	5	6	2	2
120	4.5077E+04	4.2469E-10	1.3728E-09	4.5077E+04	6.6321E+02	2.9391E-12	4.0747E-12	6.6321E+02	.273	13	25	6	7	3	2
140	5.6339E+04	1.9488E-07	1.0993E-09	5.6339E+04	9.5187E+02	1.5296E-09	3.5444E-12	9.5187E+02	.318	15	27	7	7	3	2
160	6.2312E+04	1.7899E-05	8.9711E-10	6.2312E+04	1.1873E+03	1.5694E-07	3.1199E-12	1.1873E+03	.364	17	30	8	8	3	2
180	6.4114E+04	5.3571E-04	7.4386E-10	6.4114E+04	1.3586E+03	5.1847E-06	2.7738E-12	1.3586E+03	.409	19	33	8	9	3	2
200	6.3107E+04	7.4087E-03	6.2525E-10	6.3107E+04	1.4710E+03	7.8394E-05	2.4873E-12	1.4710E+03	.455	20	35	9	9	3	2
220	6.0408E+04	5.9064E-02	5.3177E-10	6.0408E+04	1.5350E+03	6.7793E-04	2.2469E-12	1.5350E+03	.500	22	38	10	10	4	3
240	5.6808E+04	3.1416E-01	4.5695E-10	5.6808E+04	1.5621E+03	3.8856E-03	2.0429E-12	1.5621E+03	.545	24	40	11	10	4	3
260	5.2823E+04	1.2322E+00	3.9622E-10	5.2823E+04	1.5620E+03	1.6331E-02	1.8680E-12	1.5620E+03	.591	26	43	12	11	4	3
280	4.8773E+04	3.8245E+00	3.4633E-10	4.8773E+04	1.5427E+03	5.4052E-02	1.7168E-12	1.5427E+03	.636	28	45	12	12	4	3
300	4.4843E+04	9.8854E+00	3.0491E-10	4.4843E+04	1.5103E+03	1.4836E-01	1.5848E-12	1.5103E+03	.682	30	47	13	12	5	3
320	4.1134E+04	2.2095E+01	2.7017E-10	4.1134E+04	1.4692E+03	3.5084E-01	1.4690E-12	1.4692E+03	.727	31	50	14	13	5	3
340	3.7693E+04	4.3934E+01	2.4079E-10	3.7693E+04	1.4228E+03	7.3567E-01	1.3666E-12	1.4228E+03	.773	33	52	15	13	5	3
360	3.4536E+04	7.9416E+01	2.1575E-10	3.4536E+04	1.3733E+03	1.3983E+00	1.2756E-12	1.3733E+03	.818	35	54	15	14	5	3
380	3.1659E+04	1.3271E+02	1.9424E-10	3.1659E+04	1.3225E+03	2.4508E+00	1.1942E-12	1.3225E+03	.864	37	56	16	14	5	3
400	2.9050E+04	2.0776E+02	1.7566E-10	2.9050E+04	1.2717E+03	4.0143E+00	1.1212E-12	1.2717E+03	.909	38	58	17	15	6	3
420	2.6688E+04	3.0788E+02	1.5949E-10	2.6688E+04	1.2215E+03	6.2112E+00	1.0553E-12	1.2215E+03	.955	40	60	18	15	6	4
440	2.4554E+04	4.3556E+02	1.4536E-10	2.4554E+04	1.1726E+03	9.1568E+00	9.9557E-13	1.1726E+03	1.000	42	62	18	16	6	4
460	2.2625E+04	5.9227E+02	1.3294E-10	2.2625E+04	1.1252E+03	1.2952E+01	9.4130E-13	1.1252E+03	1.045	44	65	19	16	6	4
480	2.0882E+04	7.7844E+02	1.2198E-10	2.0882E+04	1.0797E+03	1.7680E+01	8.9179E-13	1.0797E+03	1.091	45	67	20	17	6	4
500	1.9305E+04	9.9350E+02	1.1225E-10	1.9305E+04	1.0361E+03	2.3400E+01	8.4648E-13	1.0361E+03	1.136	47	69	21	17	7	4
520	1.7877E+04	1.2360E+03	1.0359E-10	1.7877E+04	9.9452E+02	3.0148E+01	8.0487E-13	9.9452E+02	1.182	49	71	21	17	7	4
540	1.6583E+04	1.5038E+03	9.5846E-11	1.6583E+04	9.5490E+02	3.7935E+01	7.6657E-13	9.5490E+02	1.227	51	72	22	18	7	4
560	1.5408E+04	1.7940E+03	8.8899E-11	1.5408E+04	9.1724E+02	4.6751E+01	7.3121E-13	9.1724E+02	1.273	52	74	23	18	7	4
580	1.4339E+04	2.1035E+03	8.2645E-11	1.4339E+04	8.8147E+02	5.6565E+01	6.9849E-13	8.8147E+02	1.318	54	76	24	19	7	4
600	1.3366E+04	2.4290E+03	7.6997E-11	1.3366E+04	8.4753E+02	6.7328E+01	6.6813E-13	8.4753E+02	1.364	56	78	24	19	8	4
620	1.2478E+04	2.7668E+03	7.1881E-11	1.2478E+04	8.1534E+02	7.8978E+01	6.3992E-13	8.1534E+02	1.409	57	80	25	20	8	4
640	1.1667E+04	3.1135E+03	6.7234E-11	1.1667E+04	7.8480E+02	9.1440E+01	6.1363E-13	7.8480E+02	1.455	59	82	26	20	8	4
660	1.0924E+04	3.4656E+03	6.3002E-11	1.0924E+04	7.5585E+02	1.0463E+02	5.8910E-13	7.5585E+02	1.500	61	84	26	21	8	4
680	1.0244E+04	3.8200E+03	5.9138E-11	1.0244E+04	7.2838E+02	1.1847E+02	5.6616E-13	7.2838E+02	1.545	62	86	27	21	8	5
700	9.6184E+03	4.1736E+03	5.5602E-11	9.6184E+03	7.0232E+02	1.3285E+02	5.4467E-13	7.0232E+02	1.591	64	87	28	21	9	5

TRPUF - MOD5
 COPYRIGHT 1985 TRINITY CONSULTANTS, INC.
 A PUFF MODEL DEVELOPED BY TRINITY CONSULTANTS, RICHARDSON, TEXAS 214/234-8567

EXAMPLE OF TRPUF5

RELEASE AMOUNT (POUNDS) = 2.20500 RECEPTOR HEIGHT ABOVE GRADE (FEET) = 5. INITIAL CONCENTRATION (PPM) = 5.00E+05
 MOLECULAR WEIGHT = 64.00 EXIT VELOCITY (FEET PER SECOND) = 5.000 INITIAL HORIZONTAL SIGMA (FEET) = .00
 AMBIENT TEMPERATURE (DEG F) = 88.00 STACK DIAMETER (FEET) = 1.50 INITIAL VERTICAL SIGMA (FT) = .00
 AMBIENT PRESSURE (MB) = 1013.00 WIND SPEED (MPH) = 5.0 DOWNWIND DISTANCE (FT) = 0.
 STACK HEIGHT (FEET) = 60.00

COMPUTED VIRTUAL DISTANCES (FT) HORIZONTAL VERTICAL
 UNSTABLE 3.3 3.3
 NEUTRAL 16.4 16.4
 STABLE 85.3 85.3

DOWNWIND DISTANCE (FEET)	PEAK INSTANTANEOUS CONCENTRATIONS (UG/M3)				AVERAGE CONCENTRATIONS FOR 300. SECONDS (UG/M3)				TRAVEL (MINUTES)	--- SIGMAS (FEET) ---					
	UNSTABLE	NEUTRAL	STABLE	MAXIMUM	UNSTABLE	NEUTRAL	STABLE	MAXIMUM		UNSTABLE HOR VER	NEUTRAL HOR VER	STABLE HOR VER	STABLE HOR VER	STABLE HOR VER	STABLE HOR VER
800	7.1553E+03	5.8462E+03	4.1752E-11	7.1553E+03	5.9044E+02	2.0986E+02	4.5504E-13	5.9044E+02	1.818	72 96	32 23	10 5			
900	5.4742E+03	7.2158E+03	3.2330E-11	7.2158E+03	5.0321E+02	2.8807E+02	3.8755E-13	5.0321E+02	2.045	81 105	35 25	11 5			
1000	4.2882E+03	8.2037E+03	2.5660E-11	8.2037E+03	4.3417E+02	3.6025E+02	3.3524E-13	4.3417E+02	2.273	89 113	39 27	11 6			
1100	3.4273E+03	8.8252E+03	2.0786E-11	8.8252E+03	3.7870E+02	4.2249E+02	2.9373E-13	4.2249E+02	2.500	97 122	42 29	12 6			
1200	2.7867E+03	9.1378E+03	1.7128E-11	9.1378E+03	3.3350E+02	4.7338E+02	2.6012E-13	4.7338E+02	2.727	105 129	45 31	13 6			
1300	2.2997E+03	9.2101E+03	2.2435E-11	9.2101E+03	2.9620E+02	5.1310E+02	3.6422E-13	5.1310E+02	2.955	113 137	49 33	14 7			
1400	1.9225E+03	9.1056E+03	3.2298E-10	9.1056E+03	2.6504E+02	5.4262E+02	5.5789E-12	5.4262E+02	3.182	121 145	52 34	15 7			
1500	1.6255E+03	8.8774E+03	4.2657E-09	8.8774E+03	2.3874E+02	5.6329E+02	7.8081E-11	5.6329E+02	3.409	129 152	56 36	16 7			
1600	1.3882E+03	8.5673E+03	4.0331E-08	8.5673E+03	2.1634E+02	5.7651E+02	7.7955E-10	5.7651E+02	3.636	137 160	59 38	17 7			
1700	1.1962E+03	8.2069E+03	2.8638E-07	8.2069E+03	1.9709E+02	5.8361E+02	5.8267E-09	5.8361E+02	3.864	145 167	62 39	18 8			
1800	1.0390E+03	7.8191E+03	1.6029E-06	7.8191E+03	1.8041E+02	5.8578E+02	3.4233E-08	5.8578E+02	4.091	152 174	66 41	19 8			
1900	9.0896E+02	7.4205E+03	7.3509E-06	7.4205E+03	1.6587E+02	5.8401E+02	1.6438E-07	5.8401E+02	4.318	160 181	69 43	20 8			
2000	8.0039E+02	7.0225E+03	2.8491E-05	7.0225E+03	1.5310E+02	5.7917E+02	6.6561E-07	5.7917E+02	4.545	168 188	72 44	21 8			
2500	4.5860E+02	5.2344E+03	4.1562E-03	5.2344E+03	1.0768E+02	5.2927E+02	1.1757E-04	5.2927E+02	5.682	206 221	89 51	25 10			
3000	2.8996E+02	3.9020E+03	9.5734E-02	3.9020E+03	8.0500E+01	4.6614E+02	3.1695E-03	4.6614E+02	6.818	244 252	105 58	29 11			
3500	1.9643E+02	2.9558E+03	7.9806E-01	2.9558E+03	6.2828E+01	4.0661E+02	3.0201E-02	4.0661E+02	7.955	281 283	121 65	33 12			
4000	1.4003E+02	2.2832E+03	3.6077E+00	2.2832E+03	5.0615E+01	3.5495E+02	1.5335E-01	3.5495E+02	9.091	317 311	136 71	37 13			
4500	1.0382E+02	1.7977E+03	1.1004E+01	1.7977E+03	4.1762E+01	3.1133E+02	5.1837E-01	3.1133E+02	10.227	354 339	152 77	41 14			
5000	7.9402E+01	1.4406E+03	2.5727E+01	1.4406E+03	3.5087E+01	2.7478E+02	1.3288E+00	2.7478E+02	11.364	390 366	167 83	45 14			
5500	6.2281E+01	1.1727E+03	4.9876E+01	1.1727E+03	2.9893E+01	2.4412E+02	2.8004E+00	2.4412E+02	12.500	425 393	183 89	49 15			
6000	4.9885E+01	9.6808E+02	8.4380E+01	9.6808E+02	2.5747E+01	2.1827E+02	5.1133E+00	2.1827E+02	13.636	461 419	198 95	53 16			
6500	4.0665E+01	8.0917E+02	1.2893E+02	8.0917E+02	2.2371E+01	1.9635E+02	8.3816E+00	1.9635E+02	14.773	496 444	213 100	57 17			
7000	3.3651E+01	6.8386E+02	1.8222E+02	6.8386E+02	1.9579E+01	1.7762E+02	1.2643E+01	1.7762E+02	15.909	531 468	228 105	61 18			
7500	2.8210E+01	5.8368E+02	2.4233E+02	5.8368E+02	1.7242E+01	1.6151E+02	1.7867E+01	1.6151E+02	17.045	566 493	243 111	65 18			
8000	2.3918E+01	5.0261E+02	3.0710E+02	5.0261E+02	1.5266E+01	1.4756E+02	2.3965E+01	1.4756E+02	18.182	600 516	258 116	68 19			
8500	2.0482E+01	4.3625E+02	3.7435E+02	4.3625E+02	1.3582E+01	1.3541E+02	3.0816E+01	1.3541E+02	19.318	635 540	272 121	72 20			
9000	1.7694E+01	3.8138E+02	4.4211E+02	4.4211E+02	1.2137E+01	1.2475E+02	3.8274E+01	1.2475E+02	20.455	669 563	287 126	76 21			
10000	1.3510E+01	2.9706E+02	5.7276E+02	5.7276E+02	9.8079E+00	1.0700E+02	5.4414E+01	1.0700E+02	22.727	737 608	316 135	83 22			
10500	1.1923E+01	2.6438E+02	6.3328E+02	6.3328E+02	8.8642E+00	9.9554E+01	6.2811E+01	9.9554E+01	23.864	771 630	331 140	87 23			
11000	1.0583E+01	2.3647E+02	6.8952E+02	6.8952E+02	8.0378E+00	9.2879E+01	7.1257E+01	9.2879E+01	25.000	805 651	345 145	91 23			
11500	9.4439E+00	2.1247E+02	7.4102E+02	7.4102E+02	7.3110E+00	8.6865E+01	7.9645E+01	8.6865E+01	26.136	838 673	360 149	94 24			
12000	8.4680E+00	1.9172E+02	7.8752E+02	7.8752E+02	6.6695E+00	8.1422E+01	8.7887E+01	8.7887E+01	27.273	872 694	374 154	98 25			
12500	7.6266E+00	1.7368E+02	8.2893E+02	8.2893E+02	6.1012E+00	7.6473E+01	9.5908E+01	9.5908E+01	28.409	905 715	388 158	102 25			
13000	6.8971E+00	1.5790E+02	8.6532E+02	8.6532E+02	5.5960E+00	7.1957E+01	1.0365E+02	1.0365E+02	29.545	938 736	402 163	105 26			
13500	6.2609E+00	1.4404E+02	8.9682E+02	8.9682E+02	5.1454E+00	6.7820E+01	1.1107E+02	1.1107E+02	30.682	971 757	417 167	109 26			

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READING DATA...

PLOT TYPE (LIN=LINEAR, LOG=LOG-LOG)? LOG

MINIMUM DOWNWIND DISTANCE (FEET) (USE 0 FOR ALL DISTANCES)? 0

MAXIMUM DOWNWIND DISTANCE (FEET) (USE 0 FOR ALL DISTANCES)? 0

ENTER I FOR INSTANTANEOUS, A FOR AVERAGE CONCENTRATIONS I

SELECT THE STABILITY CLASS - ENTER

U - UNSTABLE

N - NEUTRAL

S - STABLE

M - MAXIMUM OF THE THREE STABILITIES

ENTER U, N, S, OR M? M

C>

EXAMPLE OF TRPUF5

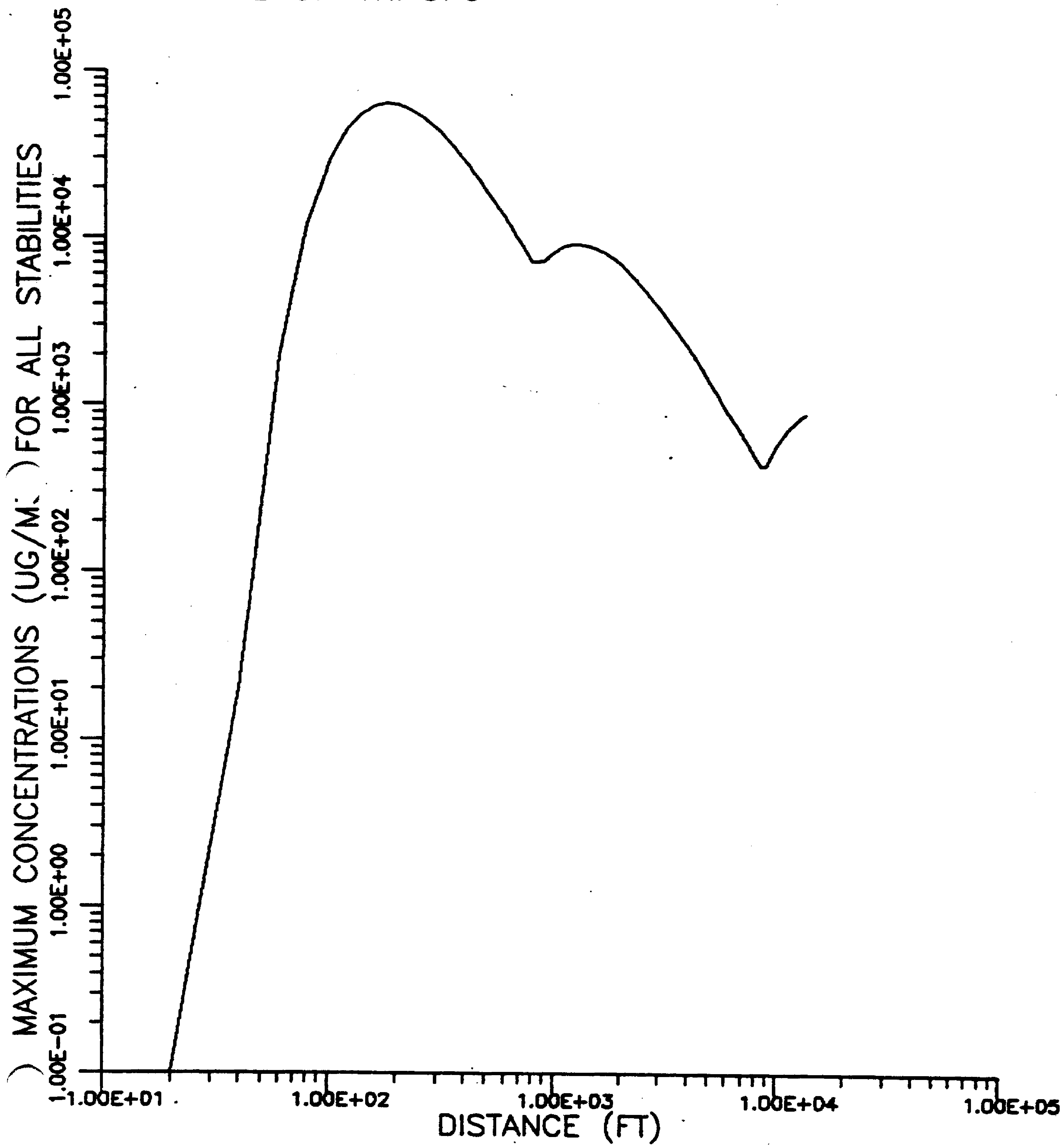


FIGURE 4

VAB.0001093750

EXAMPLE OF TRPUF5

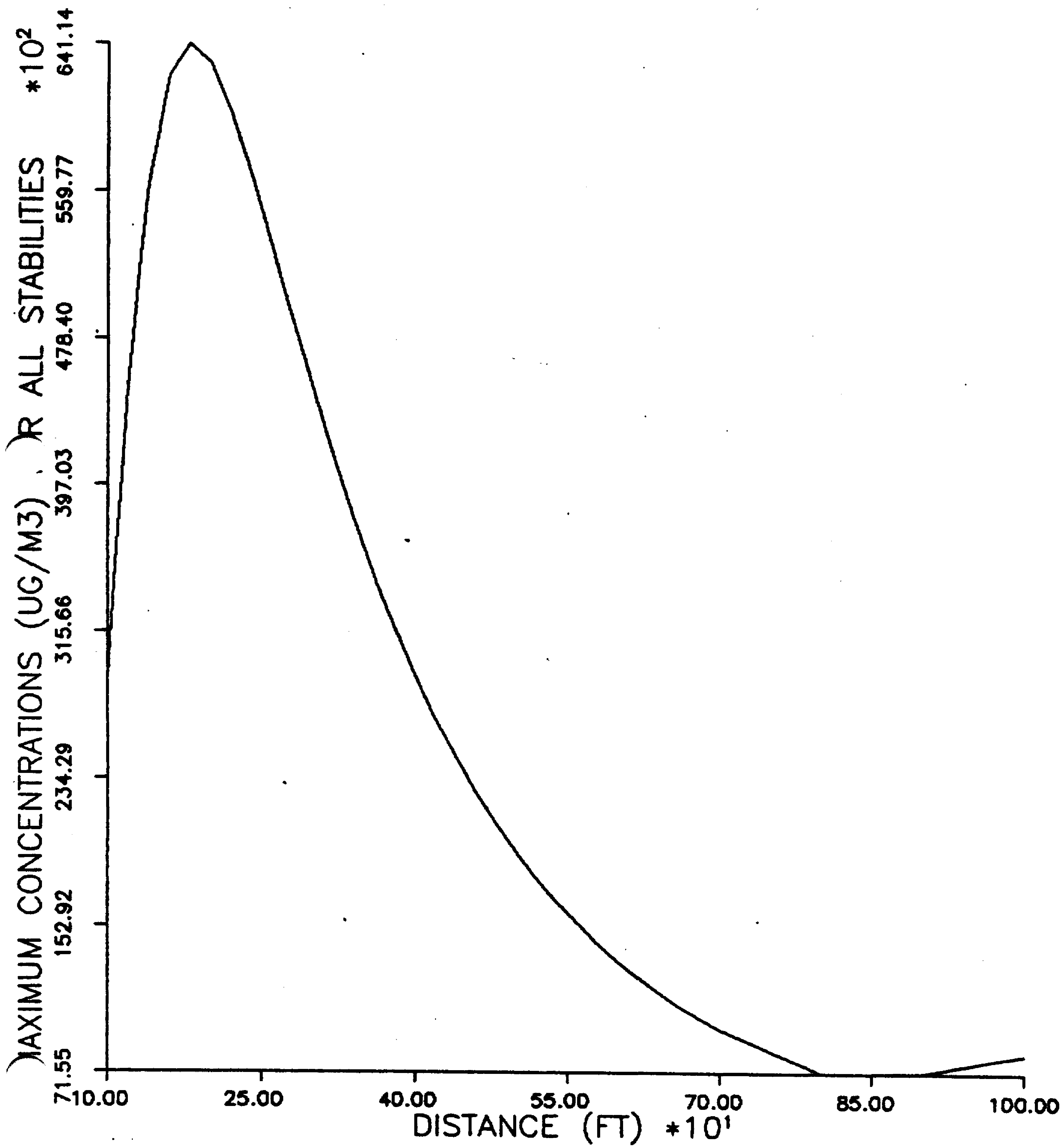


FIGURE 5 VAB.0001093751

EVALUATION SHEET

PRACTICAL PLANNING FOR TOXIC GAS RELEASES

July 31, 1985

Your evaluation of this course would help make future workshops more useful to others. Would you please fill out this evaluation and return it in the enclosed stamped envelope.

Information Presented

Coverage of Subject	☐ Appropriate	☐ Too Little	☐ Too Much
Technical Depth	☐ Appropriate	☐ Too Simple	☐ Too Advanced
Usefulness	☐ Very Practical	☐ Average	☐ Limited

Quality of Presentation

Organization of Material	☐ Well Planned	☐ Average	☐ Poor
Presentation	☐ Good	☐ Average	☐ Poor
Length of Course	☐ Too Long	☐ Too Short	☐ About Right

Overall Evaluation

How would you rate the course overall?

☐ Excellent	☐ Good	☐ Adequate	☐ Unsatisfactory
------------------------------------	-------------------------------	-----------------------------------	---

If given again, would you recommend the course to your associates?

☐ Yes ☐ No

PLEASE CONTINUE ON REVERSE SIDE

TRINITY CONSULTANTS, INC.

VAB.0001093752

Suggestions For Improvement

List those topics that you would like to have more time spent on.

List those topics that you would like to see omitted or covered only briefly.

List suggestions for improvement in regard to material, lectures, or facilities.

THANKS !

**PRACTICAL PLANNING FOR
TOXIC GAS RELEASES**

**Richard H. Schulze
July 31, 1985**

**Trinity Consultants, Inc.
100 N. Central Expressway
Suite 600
Richardson, Texas 75080
(214) 234-8567**

1. Dow - D/Aguirine - speakers in houses next to Cl_2 plant. Stay inside if a release.
2. 2 "Safer" systems in So. Miss. H_2S from gas wells feeding sulfur removal plant.
3. British Regs.
4. Speculate on what is most likely to happen.
5. Ground level releases will be greatest under stable conditions.
6. Elevated releases will be greatest at unstable conditions.
7. Canadian DOT - Manual for Spills of Hazardous Materials.

Environment Canada

EP Service.

Tech Services Branch

EPS

Env. Can.

Ottawa Canada.

Cat. No. En 40-320/1984E

PRACTICAL PLANNING FOR TOXIC GAS RELEASES

REGISTRATION LIST

Houston, TX - July 31, 1985

**Mr. Allen Jurisich
Senior Program Advisor, Environmental Service
Cigna Loss Control
139 West Livingston Place
Metairie, LA 70005
(504) 831-1617**

**Mr. John Brau
Employee Relations Manager
Sohio Chemical Company
Box 659
Port Lavaca, TX 77979
(512)552-8218**

**Mr. Joe Ledvina
Director of Environmental Activities
Vista Chemical Company
P.O. Box 19029
Houston, TX 77224
(713)531-3451**

**Ms. Aileen Teng
Senior Environmental Health Specialist
Cigna Loss Control Service
12815 Leader
Houston, TX 77072
(713)933-1826**

**Mr. Ron Pertuit
Texas Eastern Company
P.O. Box 7444
Longview, TX 75607
(214) 236-5000 ext. 2760**

**Mr. Joe Woolbert
Texas Eastern Company
P.O. Box 7444
Longview, TX 75607
(214) 236-5000 ext. 2760**

PREFACE

This manual is designed for use with a one-day short course entitled "Practical Planning For Toxic Gas Releases". I decided that it was best to prepare a manual instead of a set of notes.

This course was offered for the first time in April, 1985. This manual is prepared as a result of comments on the first course and research I conducted since then.

I would welcome any ideas or suggestions for making this manual a more effective teaching tool.

RICHARD H. SCHULZE

Richardson, Texas

July 24, 1985

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I. INTRODUCTION

The purpose of this manual is to help the engineer, safety specialist or other technically trained person prepare for and evaluate the dispersion of a potentially toxic gas. Some compounds will enter the atmosphere as a gas while others will be the result of evaporation from a liquid pool.

Interest in this subject, at least judged by inquiries to our firm, has increased steadily since 1980. It was the tragic events in Bhopal, India, in December, 1984, that has galvanized corporations and regulatory agencies to re-examine their contingency plans.

A. Regulations affecting Toxic Gas Accidents

For the most part, toxic gas releases are not subject to environmental regulations. In contrast, oil spill planning is. In 40CFR112, detailed requirements are set forth for the preparation of Spill Prevention Control and Countermeasure Plans (SPCC Plans). The preparation of plans is required if an organization stores more than 42,000 gallons in an underground tank or 1,320 gallons in above ground containers. Surprisingly, no such plan is required for the discharge of hazardous substances in waste waters but the reporting of such a discharge is required by 40CFR116 and 117.

In general, the response to any toxic gas accident is handled by

local public safety personnel such as the State Police, a city fire department, the Sheriff or special disaster response teams.

In nearly all cases, the scope and detail of any contingency plan is a decision made by the organization which manufactures, transports or stores hazardous materials.

In some instances local emergency response organizations are involved with the planning performed by the manufacturer, storer or transporter of hazardous materials.

Outside the United States, the British have led the world in addressing the problem of toxic and hazardous substances. S.I. 1982 No. 1357 is entitled "The Notification of Installations Handling Hazardous Substances Regulation". S.I. 1984 No. 1902 is entitled "The Control of Industrial Major Accident Hazards Regulations". The first of these regulations enabled the Health Safety Executive to identify installations and define priorities for inspection programs.

The second requires, among other things, the preparation of a hazards analysis, an emergency plan, and an off-site emergency plan. It also requires that members of the public living in the vicinity of an industrial activity be informed about the activity and associated hazards. The Appendix contains a flow chart of the regulations taken from the Health Safety Executive Guide for the 1984 regulations.

These regulations implement Directive 82/501/EEC of the European

A

Communities.

In February, 1985, the World Bank issued a draft guideline entitled "World Bank and IFC Guidelines for Identifying, Analyzing and Controlling Major Hazard Installations in Developing Countries". It is based on the two British regulations and is currently used to evaluate proposed facilities in developing countries that are seeking funding from the World Bank. This draft is included in the Appendix.

B. Affected Industries

There are certain industries and organizations that have risks associated with toxic gas releases. Broadly speaking, releases can occur in transportation accidents or at plant or warehouse sites.

The chemical industry manufactures materials such as chlorine and ammonia. In addition, the plant chemical industry uses a number of toxic gases as intermediates in the production of final products. These include phosgene, phosphine and the cause of the Bhopal disaster, methyl isocyanate.

Chlorine is the most ubiquitous of the hazardous gases. It is widely used throughout the country for drinking water treatment and in the sterilization of swimming pools. Ammonia is also widely used, primarily as a fertilizer.

Ethylene oxide is used in the sterilization of equipment,

supplies and disposable items used in the medical field. Although large volume sterilizers such as the manufacturers of plastic disposables have facilities equipped with scrubbers, many smaller users, such as hospitals, do not.

About 20 percent of the natural gas produced in the United States contains some hydrogen sulfide which must be removed before the gas is delivered to common-carrier pipelines. There is risk both in drilling for gas and in processing the gas. Hydrogen sulfide is also of concern in refineries where up to several tons of the compound can be contained in pipelines or process vessels. The liquid extraction of elements such as sulfur or bromine often involves processing hydrogen sulfide.

The semi-conductor industry uses some unusually toxic gases such as arsine, hydrogen selenide and phosphine in the manufacture of wafers. As the use of metal-organic vapor phase epitaxy reactors come into wider use, increased quantities of these hazardous gases will be used.

Human error is another major cause of toxic gas releases. Water in place of nitrogen was introduced to the storage tank of methyl isocyanate in Bhopal. Operators have pumped a caustic solution into a sulfuric acid tank. Maintenance personnel have used inappropriate chemicals to clean a contaminated tank. Material in an epoxy resin blending tank got too warm and started a reaction which caused a cloud of gas to drift over a nearby school.

A

Transportation spills are difficult to assess. The most elaborate system is operated for the Department of Defense by Lawrence Livermore Laboratory. If a nuclear weapon accident occurs anywhere in North America as a result of a plane crash, a missile silo accident or other cause, the direction and concentrations in the released material can be forecasted.

More commonly, however, a trucking or railroad accident occurs and local public safety officials do the best they can to reduce the risk to those nearby. The most difficult task, however, is to determine the quantity of gas released. When a tank car is laying in a ditch it is difficult to determine whether the tank has a small puncture or a large gash.

The major uncertainty in most situations is the value of the "source term", that is the quantity that is or was actually introduced into the atmosphere. Next, in order of uncertainty, are the meteorological parameters. Finally, there is the inherent uncertainty regarding the accuracy of the model. In summary, there is usually a great deal of uncertainty, and thus, most analyses of actual or potential accidents tends to stress the "worst case".

II. ATMOSPHERIC TURBULENCE

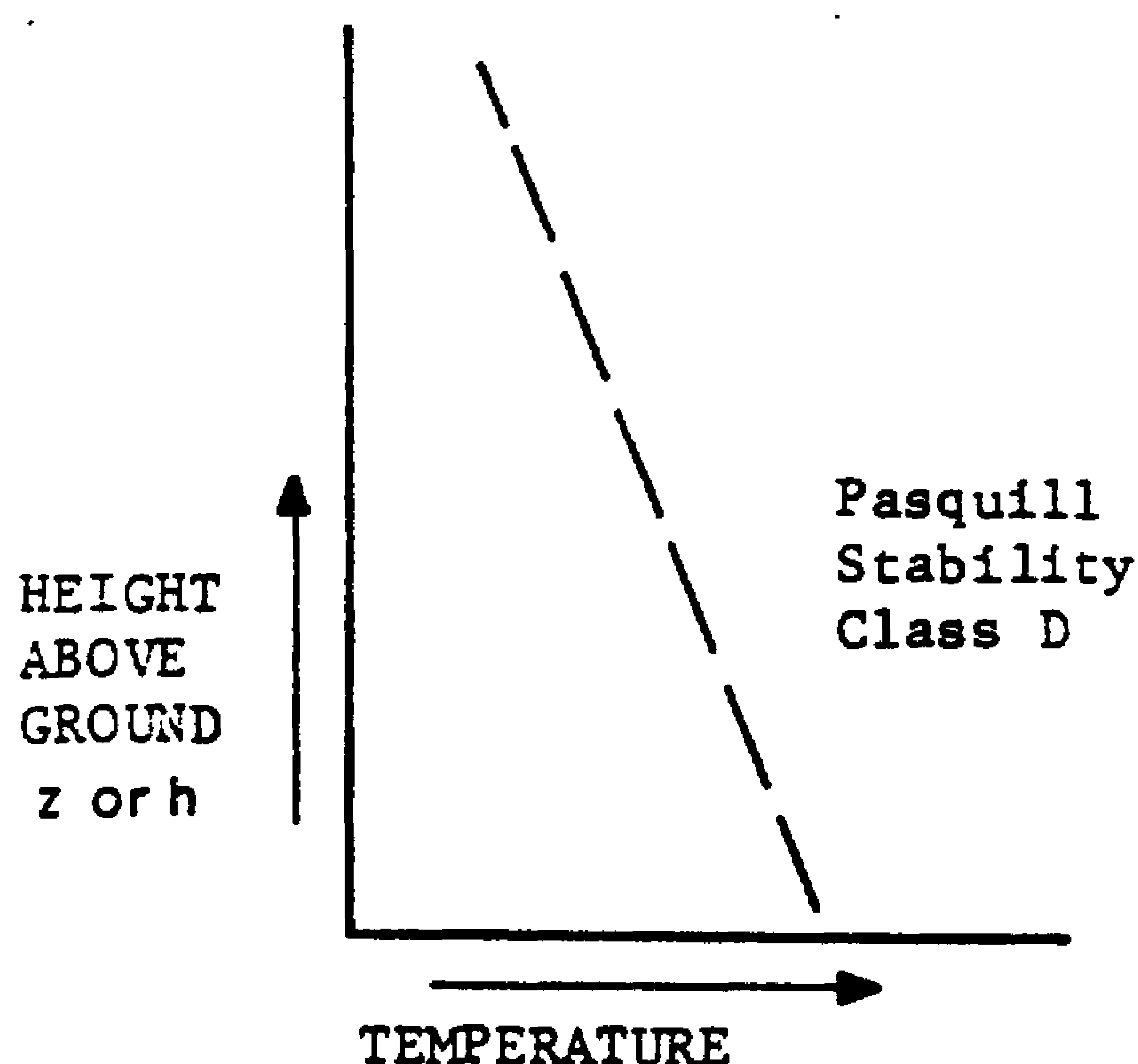
A. Description of Turbulence

Atmospheric turbulence is caused both by the wind and by surface heating and cooling (thermal) effects. The meteorological terms are mechanical and convective turbulence.¹

wind

surface heating

An atmosphere that is well mixed because of strong winds - vigorous mechanical mixing in meteorological terms - under overcast skies is termed "neutral." Under these conditions, there are no surface heating or cooling effects and the temperature decreases with altitude at the "ADIABATIC LAPSE RATE". Lapse rate is the change in temperature with elevation. This is illustrated as follows:



ADIABATIC LAPSE RATE IS $-5.4^{\circ}\text{F}/1000\text{ FT}$
OR $\sim -0.01^{\circ}\text{C}/\text{METER}$
DUE TO MECHANICAL TURBULENCE ONLY.

This condition is typical of overcast days and nights with strong winds.

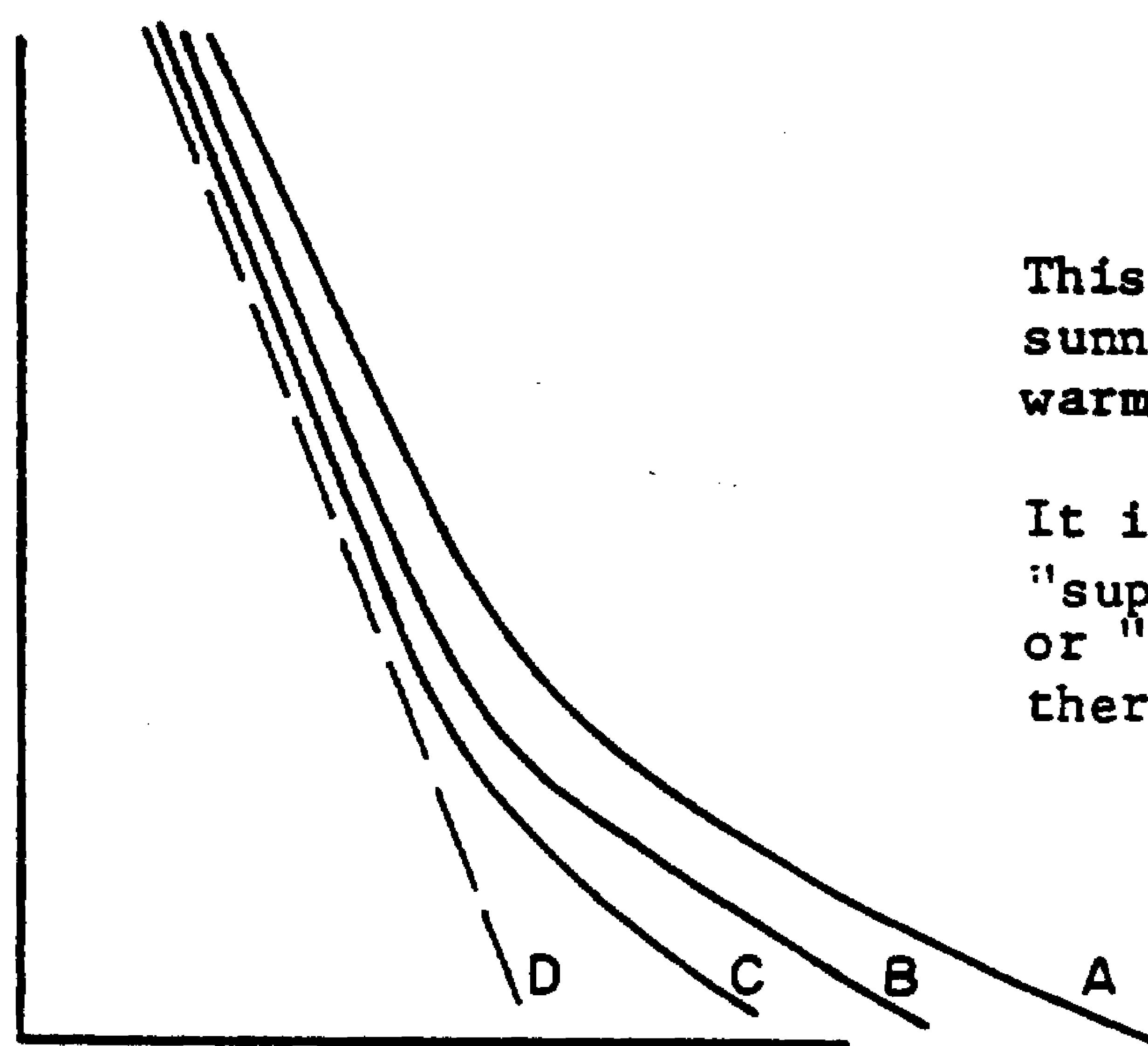
This is an idealized illustration. The actual lapse rate shows a variable change in slope, particularly with lighter winds. In

the Pasquill system of categorizing stability, this condition is called D. Sometimes meteorologists refer to the potential lapse rate. This term is equal to the actual temperature lapse rate less the adiabatic lapse rate. For example if the actual lapse rate is $0.01^{\circ}\text{C}/\text{m}$, the potential lapse rate is $0.02^{\circ}\text{C}/\text{m}$ ($0.01 - (-.01)$).

If the winds are moderately strong, in excess of 10 m/sec, the atmosphere is well mixed from the surface to the top of the boundary layer. The boundary layer is usually defined by an upper air inversion, where the slope of lapse rate becomes positive or nearly so. When the winds are lighter under overcast skies, the atmosphere can be considered to consist of a number of mixing zones. Surface friction will create a turbulent zone between 10 and 100 meters thick. Above this will be zones that exhibit relatively laminar flow. The transition between the zones is quite gradual.

The primary source of surface heat on the earth is the sun, or more exactly, solar radiation. As the sun rises in the morning or as an overcast sky becomes partly cloudy, a larger amount of solar radiation reaches the earth's surface. This causes the air near the surface to warm and "cells" of this warm air start to rise much as steam is formed on the bottom surface of a pot of boiling water. The amount of solar radiation reaching the surface is determined largely by the cloud cover and

the elevation of the sun (solar insolation). The more direct the sunlight, the more heating of the surface and the greater the thermally induced, convective, turbulence. As the cells of warm air leave the surface, they are replaced by downward moving cells of colder air.



This condition is typical of sunny days when the sun has warmed the earth.

It is called "unstable," "superadiabatic," "overturning," or "advecting" because of thermally induced turbulence.

The unstable conditions have been subdivided into three categories by Pasquill: A, B, or C.² Turner refined Pasquill's definitions somewhat to facilitate the use of computers to determine stability from routine surface observations.³ Category A applies when the sun is 60° or more above the horizon and the sky is cloudless or nearly so. Category B applies when the sun has less elevation or the sky is cloudier. Category C is only slightly unstable. Under

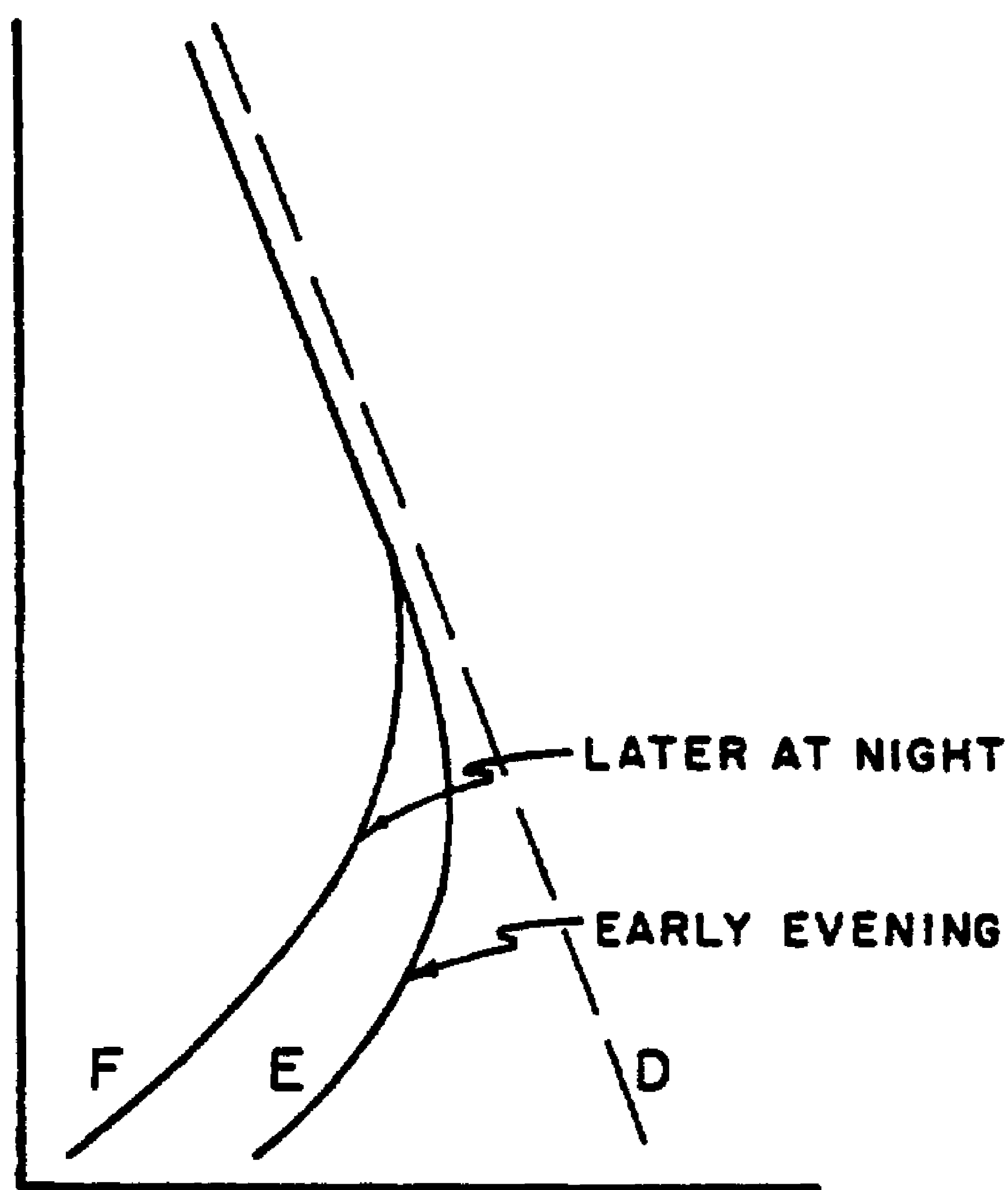
these conditions, the lapse rate is called "superadiabatic," "overturning," "unstable," or "advecting".

Since about 1972 a number of studies have been conducted to help in understanding convective turbulence better. Briggs enumerates these in a 1975 review. During the day, convective turbulence strongly mixes the lower atmosphere, but this mixing ends abruptly at the top of the mixing layer. Nearly all of the time there is a stable air (a lapse rate with a positive slope) layer aloft that acts as a lid on mixing. In rural areas on clear mornings the mixing zone starts as a shallow layer near the ground at sunrise and continues to increase during the day as long as the radiation input from the sun exceeds the earth's outward radiation. The lower boundary of the upper air stable layer increases in height as more of this stable air becomes involved in the convective turbulent layer.

The temperature gradient is superadiabatic only in the lowest tenth or so of the mixing depth and just slightly less than adiabatic above this. The mixing layer consists of upward thermals carrying heated air from the surface and of compensating downdrafts. The turbulence is much greater inside the thermals than in the subsiding downdrafts. Extremely unstable conditions

can only exist during periods of light winds. Moderately unstable conditions can exist with winds up to moderate speeds.

As night comes and solar radiation ceases, the earth cools as it radiates heat. The earth, like the sun, radiates heat in proportion to the fourth power of the absolute temperature. In the absence of wind, the cooling air near the surface shrinks in volume and tends to settle. This results in cool air tending to "drain" downhill. For example, in the fall, frost will most often first occur in the valleys rather than on the tops of the hills.



This condition is typical of relatively cloudless nights with light winds. The elevation at which the actual lapse rate reverses is the depth of the "inversion layer".

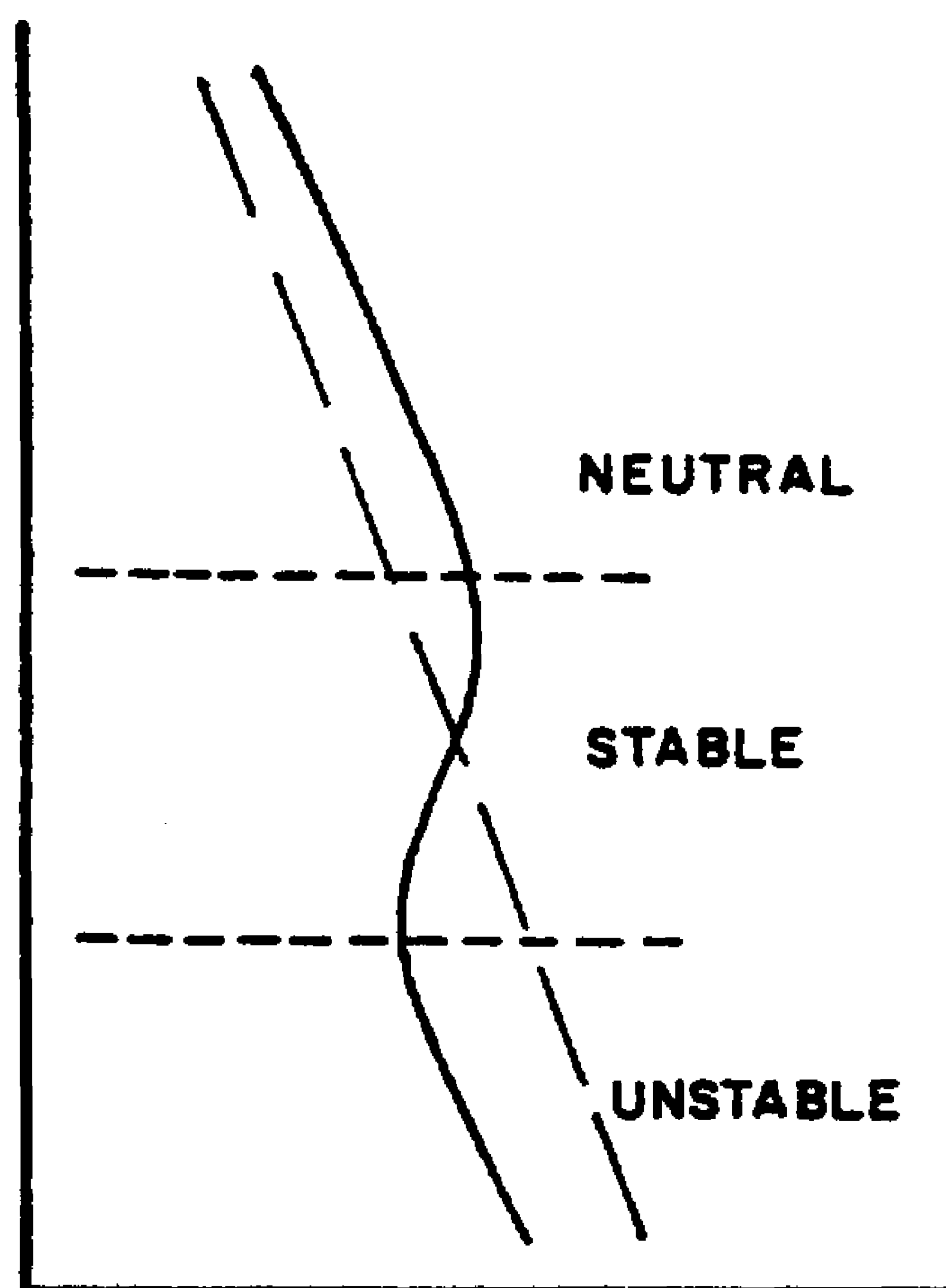
This condition is called "stable".

Pasquill divided the stable conditions into two categories.

Stability E applies with clear nights and moderate winds or partly cloudy nights and light winds. Stability F applies to calm clear nights in rural areas. The United States Environmental Protection Agency uses a potential lapse rate of $0.02^{\circ}\text{C}/\text{m}$ for E and $0.035^{\circ}\text{C}/\text{m}$ for F stability or actual lapse rates of $0.01^{\circ}\text{C}/\text{m}$ and $0.025^{\circ}\text{C}/\text{m}$ respectively for E and F.

During the Arctic winter, rather severe inversions can occur. During extended periods of cloudless still days with virtually no sun, lapse rates of .036 to .055 degrees per meter are not uncommon in places such as Fairbanks, Alaska. Strong inversions can also occur at the surface as warm winds blow across cold bodies of water. This is typical of spring conditions on the Great Lakes. It can also occur as cold winds are drawn in across land such as in the Los Angeles basin. Stabilities stronger than E or F are sometimes referred to as G and H.

After sunrise on clear mornings, the sun starts to heat the surface. The layer of thermally induced turbulence starts at the surface and gradually increases in depth as it erodes the stable layer from beneath. The inversion layer generally disappears within 5 to 7 hours after sunrise.



This condition is typical of the period after sunrise when the sun starts to warm the surface and the night-time inversion starts to disappear.

Mixing takes place only within layers in the atmosphere, not between the layers. Thus in the morning situation just described, the layer closest to the ground will be very well mixed due to the vertical motions typical of superadiabatic conditions. The start of the stable layer forms a lid. If pollutants were emitted into the stable layer during the night, they would remain in this layer until the unstable layer erodes the stable layer and reaches a depth equal to the centerline of the plume. At this point, the pollutants will be mixed rapidly in the unstable layer. Meteorologists call this condition "Inversion Breakup Fumigation".

Under typical daytime conditions, after disappearance of the nocturnal inversion layer, the surface boundary layer continues to have a reasonably well-defined upper limit that is usually between 500 and 2000 meters deep. At night the surface layer is stable in nature and is not nearly as deep as the daytime layer because of the absence of ground thermals.

The diurnal changes in the atmosphere are illustrated in Figure 1. It shows average wind speeds by hour for the 27 days of June at an Alabama location at a 10-meter elevation and at a nearby 150-meter elevation. It is apparent that there is a strong inversion at night. The surface wind speed is a small fraction of the wind aloft. By about 0900 the surface has become warmed so that good vertical mixing is occurring and the winds at the surface are equal to those aloft. This condition continues past mid-day when the cumulus clouds start to increase. By evening the winds subside. At night only the aloft winds increase, suggesting a surface-based inversion.

B. Categories of Atmospheric Turbulence

Figure 2 is the description of Atmospheric Stability Categories taken from Turner's "Workbook of Atmospheric Dispersion Estimates". This table is similar to that on page 368 in F. Pasquill, "Atmo-

FIGURE 1
 AVERAGE WIND SPEED AT
 ANNISTON AIRPORT (SURFACE) AND
 PLANT (500' ELEVATION)
 JUNE 3-29, 1975

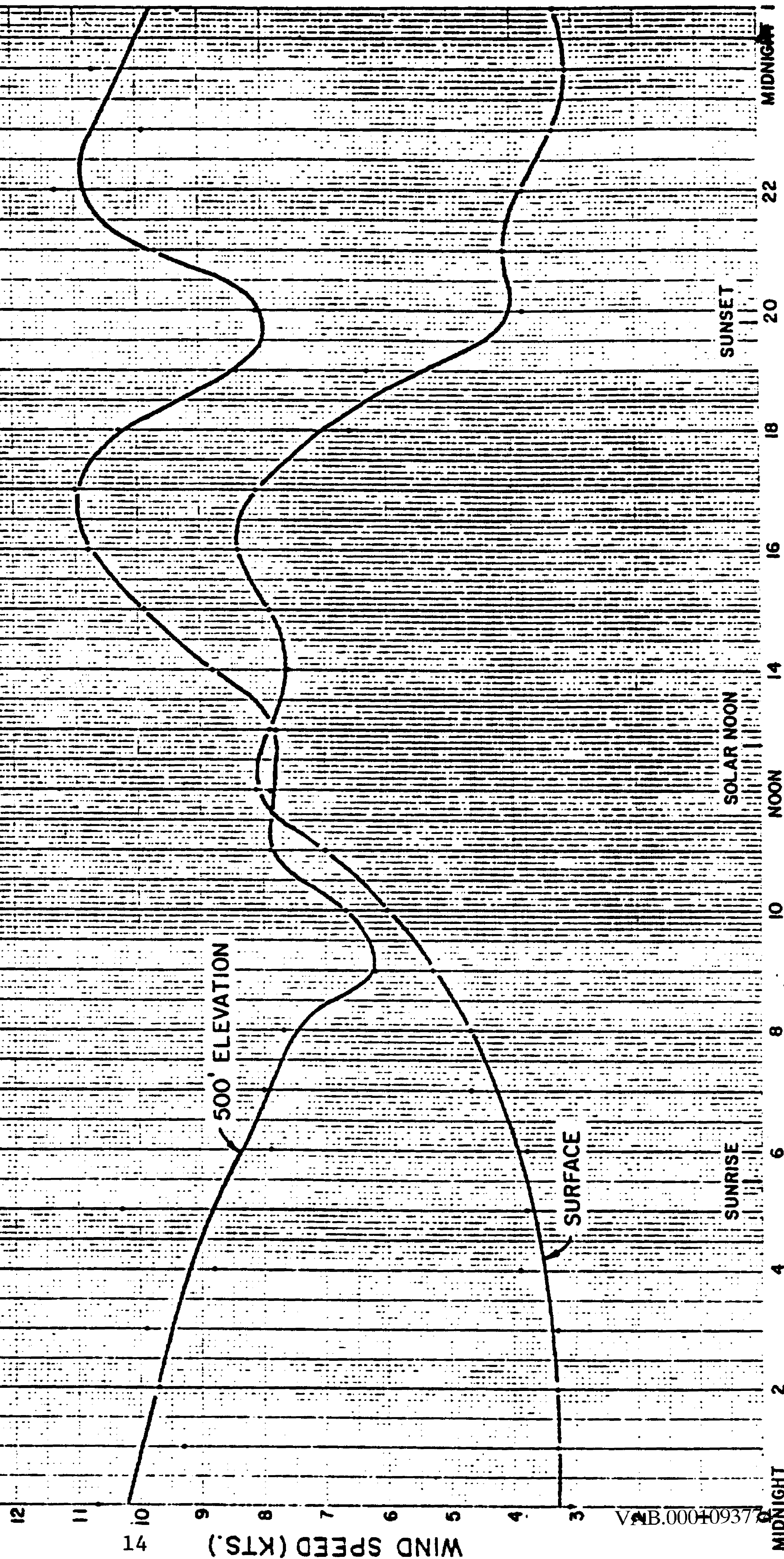


FIGURE 2

DESCRIPTION OF ATMOSPHERIC STABILITY CATEGORIESKEY TO STABILITY CATEGORIES*

Surface Wind Speed at 10 m. Altitude 2.24 MPH = 1.95 Knots = 3.6 KPH = 1.0 m/sec			Day Incoming Solar Radiation			Night Thinly Overcast or >4/8 Low Cloud	
			Strong	Moderate	Slight		<3/8 Cloud
MPH	Knots	m/sec					
<4.5	<3.9	<2	A	A-B	B		
4.5-6.7	3.9-5.8	2-3	A-B	B	C	E	F
6.7-11.2	5.8-9.7	3-5	B	B-C	C	D	E
11.2-13.4	9.7-11.7	5-6	C	C-D	D	D	D
>13.4	>11.7	>6	C	D	D	D	D

The neutral category, D, should be assumed for overcast conditions during day or night. Night refers to a period from 1 hour before sunset to 1 hour after sunrise. For purposes of the computer program Stability Category A=1, B=2, etc.

"Strong" incoming solar radiation corresponds to a solar altitude greater than 60° with clear skies in midsummer; "slight" insolation corresponds to similar conditions in midwinter or to a solar altitude from 15° to 35° with clear skies in midsummer. Cloudiness will decrease incoming solar radiation and should be considered along with solar altitude in determining solar radiation. Incoming radiation that would be strong with clear skies can be expected to be reduced to moderate with broken (5/8 to 7/8 cloud cover) middle clouds and to slight with broken low clouds.

Caution should be used when forecasting to result in ambient concentrations with wind velocities of less than 2 meters per second (4.5 MPH or 3.9 knots). At low velocities the winds tend to meander widely. In addition, surface wind speeds at low velocities are rarely indicative of aloft velocities or of upper air stability categories.

Stability categories are reliable in open, rural areas. In urban and heavily wooded areas, the surface roughness and heat islands have an effect on the category, particularly on still nights. On calm clear nights stability E or F night occurs in rural areas where D is likely to occur over urban areas.

*D. Bruce Turner, Workbook of Atmospheric Dispersion Estimates, U.S. Department of Health, Education, and Welfare, Revised 1970.

spheric Diffusion" (second edition). Turner defined stabilities in terms of solar insolation angles and cloud cover instead of such terms as "sunny midday in summer in England" used by Pasquill. Turner also omitted a notation Pasquill used in his table which reads "for A-B take average of values for A and B etc." The Appendix contains the description of a computer algorithm that determines stability category from routine surface meteorological observations that is used in the "STAR" program.

Figure 3 illustrates the Combinations of Wind Speed and Stability analyzed by PTMAX, a computer program by Turner that analyzes a single stack. This matrix of stabilities and wind speed in PTMAX contains some inconsistencies with Figure 2. According to Figure 2, stability A can't exist with winds in excess of 2 or 2.5 meters per second. Low wind speeds can exist for both C- and F-stabilities. PTMAX also analyzes wind speeds of 4 and 5 meters per second for F-stability that, according to Pasquill's definition, cannot occur. It is also questionable that any sort of modeling will be very accurate with winds of 1 meter per second or less.

The National Climatic Center produces a "STAR" listing of the frequency of stability, wind speed, and wind direction based on historical meteorological data. The degree of atmospheric tur-

FIGURE 3

COMBINATIONS OF WIND SPEED AND STABILITY
ANALYZED BY PTMAX

WIND SPEED (M/SEC.)	STABILITY (PASQUILL)					
	A=1	B=2	C=3	D=4	E=5	F=6
.5	Shaded	Shaded		Shaded		
.8	Shaded	Shaded		Shaded		
1.0	Shaded	Shaded		Shaded		
1.5	Shaded	Shaded		Shaded		
2.0	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
2.5	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
3.0	Shaded	Shaded	Shaded	Shaded	Shaded	Shaded
4.0		Shaded	Shaded	Shaded	Shaded	Shaded
5.0		Shaded	Shaded	Shaded	Shaded	Shaded
7.0			Shaded	Shaded		
10.0			Shaded	Shaded		
12.0			Shaded	Shaded		
15.0			Shaded	Shaded		
20.0				Shaded		

Shaded area indicates 49 combinations of wind speed and stability analyzed by PTMAX Computer Program. This program was developed by D. B. Turner of the Environmental Protection Agency to analyze single stacks following the method described in his "Workbook of Atmospheric Dispersion Estimates."

4

bulence is inferred from the surface observations. Figure 4 illustrates the frequency distributions of wind speed and stability for New Orleans, Louisiana and Williston, North Dakota. It provides an idea of the relative frequency of the occurrence of various stability and wind speed combinations.

New Orleans generally has less cloudiness so it has a higher frequency of both A-, B-, and F-stability than North Dakota. For these two locations, unstable conditions exist between 14 and 25 percent of the time while stable conditions exist between 29 and 39 percent of the time. Neutral conditions occur between 38 and 57 percent of the time. Extremely unstable conditions, Category A, occur relatively rarely.

There are two other methods used by some scientists to determine stability. One relates stability to variation in wind direction. The other method physically measures the vertical lapse rate on a tower or with a balloon.

"Stability" used to go to stability

The standard deviation of wind direction in the horizontal direction is termed "horizontal sigma". It can be determined by analyzing the directional trace of anemometer either manually or by use of computer averaging techniques. Below are two schemes for

FIGURE 4

FREQUENCY OF OCCURRENCE OF WIND
SPEED AND STABILITY COMBINATIONS

Data derived from STAP data
STAPDEX - Max
Commuter data
Center-Phillips
400 locations
Trinity for sale

Stability	Wind Speed		New Orleans Inter- national Airport		Williston, North Dakota	
	(Kts)	(m/sec)	Frequency (percent)	Hours per Year	Frequency (percent)	Hours per Year
A	calm		0.09	8		
	1 - 3	.5 - 1.5	.20	18	} 0.26	} 23
	4 - 6	2.1 - 3.1	<u>1.02</u>	<u>89</u>	<u>0.14</u>	<u>12</u>
	TOTAL		1.31	115	0.40	35
B	calm		0.34	30		
	1 - 3	0.5 - 1.5	1.24	109	} 1.00	} 88
	4 - 6	2.1 - 3.1	4.09	358	1.73	152
	7 - 10	3.6 - 5.1	<u>3.82</u>	<u>335</u>	<u>1.09</u>	<u>95</u>
	TOTAL		9.50	832	3.82	335
C	calm		0.32	28		
	1 - 3	0.5 - 1.5	0.57	50	} 1.09	} 95
	4 - 6	2.1 - 3.1	3.57	313	2.80	245
	7 - 10	3.6 - 5.1	8.02	703	5.08	445
	11 - 16	5.6 - 8.2	1.43	125	1.07	94
	17 - 21	8.7 - 10.8	0.05	4	0.12	11
	> 21	> 10.8			<u>0.04</u>	<u>4</u>
	TOTAL		13.95	1223	10.19	893
D	calm		0.27	24		
	1 - 3	0.5 - 1.5	0.87	76	} 1.05	} 92
	4 - 6	2.1 - 3.1	5.84	512	8.15	714
	7 - 10	3.6 - 5.1	14.21	1245	17.43	1527
	11 - 16	5.6 - 8.2	13.23	1159	23.24	2036
	17 - 21	8.7 - 10.8	1.47	129	5.63	493
	> 21	> 10.8	<u>0.19</u>	<u>17</u>	<u>1.34</u>	<u>117</u>
	TOTAL		36.08	3162	56.84	4979
E	4 - 6	2.1 - 3.1	6.83	598	5.55	486
	7 - 10	3.6 - 5.1	<u>5.54</u>	<u>485</u>	<u>6.87</u>	<u>602</u>
	TOTAL		12.37	1083	12.43	1089
F	calm		7.58	664		
	1 - 3	0.5 - 1.5	9.04	792	} 5.70	} 499
	4 - 6	2.1 - 3.1	<u>10.18</u>	<u>892</u>	<u>10.63</u>	<u>931</u>
	TOTAL		26.80	2348	16.33	1430

Period of Record: New Orleans, January, 1960 - December, 1964
Sloulin Field, January, 1967 - December, 1971

classifying stability, one from Meteorology and Atomic Energy, page 102, and one from the Brookhaven National Laboratory Studies as quoted "Recommended Guide for the Prediction of the Dispersion of Airborne Effluents", published by the American Society of Mechanical Engineers (ASME).⁴

<u>Meteorology and Atomic Energy</u>		<u>A S M E</u>	
<u>Stability</u>	<u>Standard Deviation Horizontal Direction (Degrees)</u>	<u>Stability</u>	<u>Standard Deviation Horizontal Direction (Degrees)</u>
A	25	Unstable	10.5
B	20		
C	15		
D	10	Stable	2
E	5		
F	2.5		
G	1.7		

As indicated in the table, significant wind meander is expected in unstable air. Minimal meander is typical of stable conditions.

The Nuclear Regulatory Commission (NRC) uses a third method to determine stability. It is specified in NRC Guide 1.23.⁵ Applicants for nuclear power plants are required to erect a tower and measure temperature at two different elevations. Most towers are 50 meters high and, therefore, measure the lapse rate only in the lowest portion of the atmosphere. This is satisfactory for nuclear

applications where accidental discharges have no plume rise and disperse within 100 meters of the ground. But such a technique may be misleading for discharges from tall stacks or from stacks having significant plume rises. Below is data taken by Louisiana Power and Light from a tower located within 13 miles across flat terrain from the New Orleans Airport.

Stability Classifications, NRC 1.23

<u>Stability Category</u>	<u>Lapse Rates °C/m</u>	<u>Frequency of Occurrence (percent per year)</u>	
		<u>LP&L* 1.23 Method 7/72 - 7/75</u>	<u>N.O. Airport Pasquill's Method (from Table 4)</u>
A	> -.019	14.9	1.3
B	-.019 to -.017	1.7	9.5
C	-.017 to -.015	2.1	14.0
D	-.015 to -.005	24.1	36.0
E	-.005 to .015	31.9	12.4
F	.015 to .040	14.5	}26.8
G	> .040	10.8	

*Temperature measured at 9 and 40 meter elevations

One notable aspect of the NRC system is the rather narrow range of values assigned B- and C-stabilities. It appears that this was the result of an arbitrary decision by meteorologists at the NRC who incorrectly assigned lapse rates for these categories. In the opinion of many USEPA meteorologists, it is incorrect to assess stability based on measured lapse rates because it is only one of

the turbulence producing mechanisms. In addition, lapse rates are typically measured in the first 50 meters of the atmosphere while most industrial plumes disperse at elevations ranging from 100 to 500 meters.

CHAPTER II: REFERENCES

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2. F. Pasquill, Atmospheric Diffusion, 2nd Edition, John Wiley & Sons Inc., New York, 1974.
3. D. Bruce Turner, Workbook of Atmospheric Dispersion Estimates, U. S. Environmental Protection Agency, Research Triangle Park, North Carolina, 1970. pp. 1-2.
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5. Nuclear Regulatory Commission Guide 1.23.

III. PLUME DISPERSION

Plume dispersion is a problem involving fluid turbulence. Up to now the fluid turbulence problem has resisted all attempts at a general solution. Therefore, the best present solution contains both hypothetical and empirical elements. In the final analysis, the results can only be judged by comparison with data.

A. Gaussian Models

Numerous experiments have been conducted to study the shape of plumes. The publication Meteorology and Atomic Energy lists over twenty experiments, many of which have been conducted by the Atomic Energy Commission (now the U. S. Department of Energy).¹ In general, most investigators have been satisfied that a Gaussian distribution is a good mathematical approximation of plume behavior for periods on the order of five minutes to one hour.

Although Gaussian models, properly applied, are peerless as a practical diffusion modeling tool in terms of simplicity, of flexibility and of correlations between predicted and measured values, they contain some definite shortcomings.

The Gaussian distribution assumes uniform conditions in the vertical direction. In reality, the lapse rate shows changes with elevation as does wind speed. In addition, the dispersing plume will deposit material on the surface.

Accuracy:
+100% - 50%

Rule:

use puff model when

Threat time to the receptor

is longer than the

duration of the release.

For Continuous Models:

EPA models

within 5 km (3 mi)

good at identifying accurate.

but not so good at predicting where maximum

or when.

There is, of course, much more uniformity in the horizontal direction. Strictly speaking, the Gaussian equation implies an infinite speed of propagation of pollutants which is physically unrealistic. Pasquill, however, has pointed out that the exact form of the tails of the distribution is not important as a practical matter.

Accuracy of Models

Despite these objections, Gaussian models provide reasonable estimates in flat or gently rolling terrain. Gently rolling is generally described as terrain elevations of less than twenty percent of effective stack height. Turner states that the estimates provided are generally accurate by a factor of 2 (plus 100, minus 50 percent).² This is significantly less accurate than most engineering calculations or work done with computers. An American Meteorological Society Committee evaluated the accuracy of models and quoted Pasquill in saying that under ideal conditions, the error can be as little as 10 to 20 percent, but "Factor of 2 accuracy is perhaps the best that can be expected in most applications of urban-scale dispersion models".³

This estimate of accuracy also underscores the need for a monitoring program should calculated values start to approach the ambient air standards. It has been the experience of Trinity Consultants that most of the computer models used by EPA tend to over-predict, rather than under-predict concentrations.

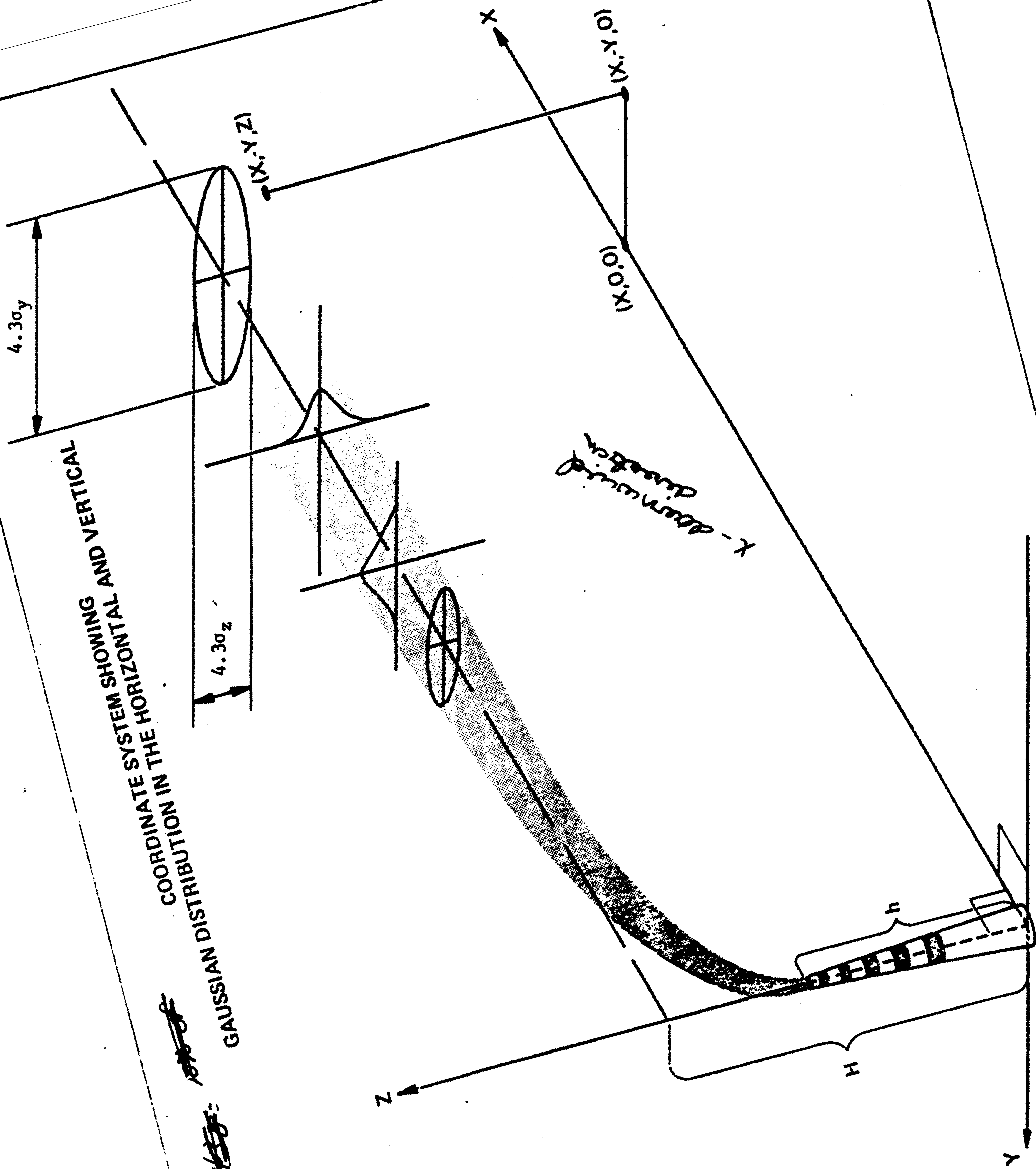
C. Pasquill-Gifford Coefficients

Figure 5 illustrates the coordinate system of a typical plume. The downwind direction is "x," the horizontal crosswind is "y," and the vertical is "z." As a result of field studies, coefficients of dispersion in the y and z direction have been developed. Figures 6 through 9 show the Pasquill-Gifford dispersion coefficients as a function of distance from the stack, both in graphical form from Turner and in formulas used in several EPA models. Although these coefficients have many shortcomings, they are those in widest current use. As discussed previously, mixing - and therefore diffusion - is more rapid in unstable air. The plot also shows that diffusion in both the y and z direction is accentuated when the air is unstable and minimized when the air is stable.

D. Continuous Release Equations

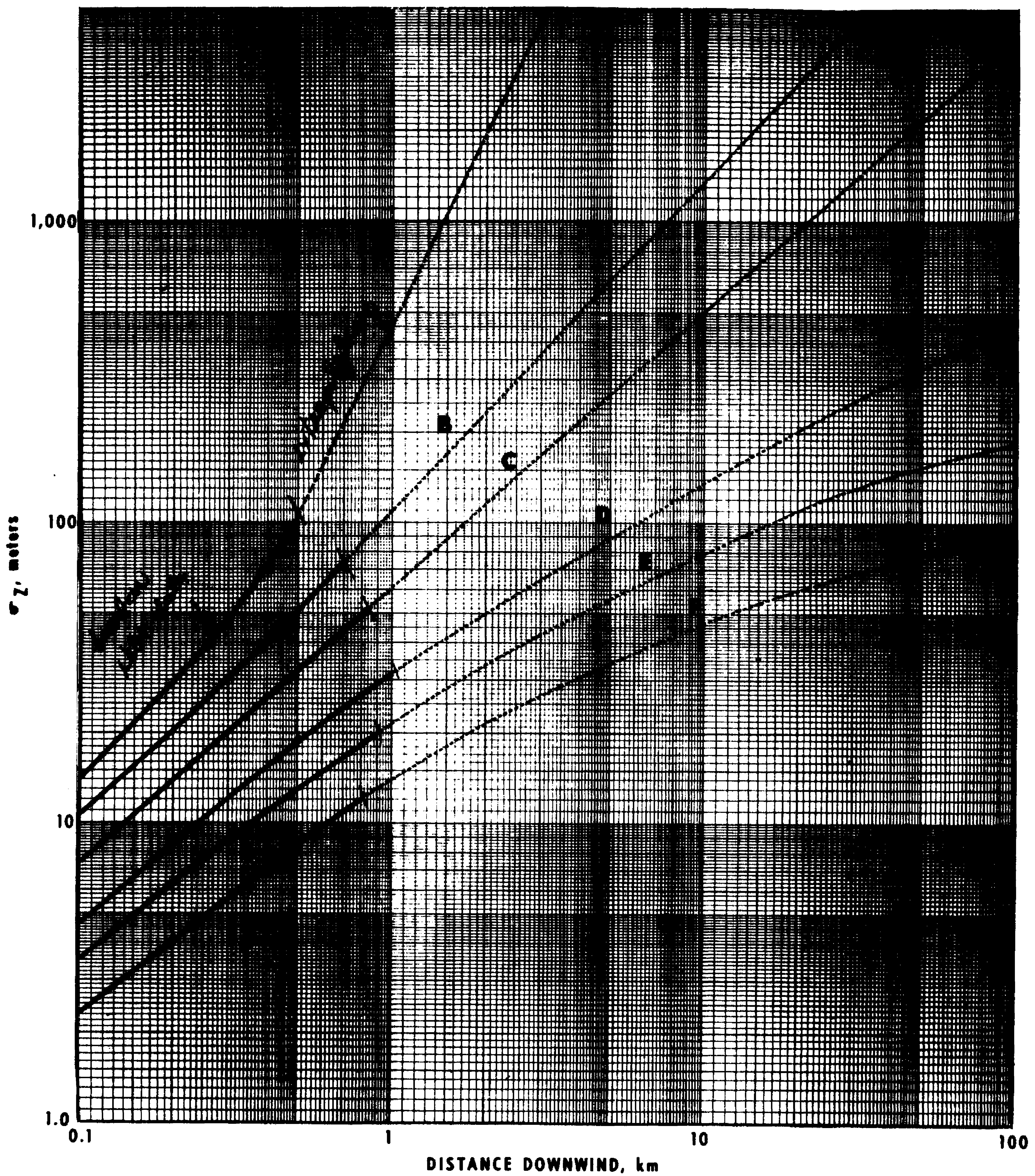
There are four equations that are useful for estimated ground-level concentrations.

FIGURE 1



COORDINATE SYSTEM SHOWING
HORIZONTAL AND VERTICAL
GAUSSIAN DISTRIBUTION IN THE HORIZONTAL AND VERTICAL

PASQUILL-GIFFORD
Dispersion Coefficients



Vertical dispersion coefficient as a function of downwind distance from the source.

FIGURE 7

Constants Used to Calculate σ_z
in EPA Developed Programs

*Std. Dev. of
wind direction
in vert. direction*

$$\sigma_z = ax^b$$

Stability (Pasquill)	DBTSIG (used in PTMTP, ISC, CRSTER, RAM)				CDM ⁵ , TEM, TCM		
	Downwind Distance (x) (kilometers)		Values for σ_z (meters)		Downwind Distance (x) (meters)		
			a	b		a	b
A	< .1		122.8	.9447			
	.1 - .15		158.08	1.0542			
	.15 - .2		170.22	1.0932			
	.2 - .25		179.52	1.1262	100 - 500	.0383	1.2812
	.25 - .3		217.41	1.2644			
	.3 - .4		258.89	1.4094			
	.4 - .5		346.75	1.7283	500 - 5000	.000254	2.0886
	.5 - 3.11		453.85	2.1166			
	> 3.11			*			
B	< .2		90.673	.93198			
	.2 - .4		98.483	.98332	100 - 500	.1393	.9467
	.4 - 35.0		109.30	1.0971	500 - 5000	.04936	1.1137
	> 35.0			*			
C					100 - 500	.1120	.9100
	> 123.0 -		61.141	.91465	500 - 5000	.1014	.9260
	< 123.0			*	5000 - 123000	.1154	.9109
D	< .3		34.459	.86974	DAY		
	.3 - 1.0		32.093	.81066	100 - 500	.0856	.8650
	1.0 - 3.0		32.093	.64403	500 - 5000	.2591	.6869
	> 3.0 - 10.0		33.504	.60486	5000 - 50000	.7368	.5642
					NIGHT		
	10.0 - 30.0		36.650	.56589			
	30.0 -		44.053	.51179	100 - 500	.0818	.8155
					500 - 5000	.2527	.6341
					5000 - 50000	1.2969	.4421

*The maximum calculated value for σ_z is 5000 meters.

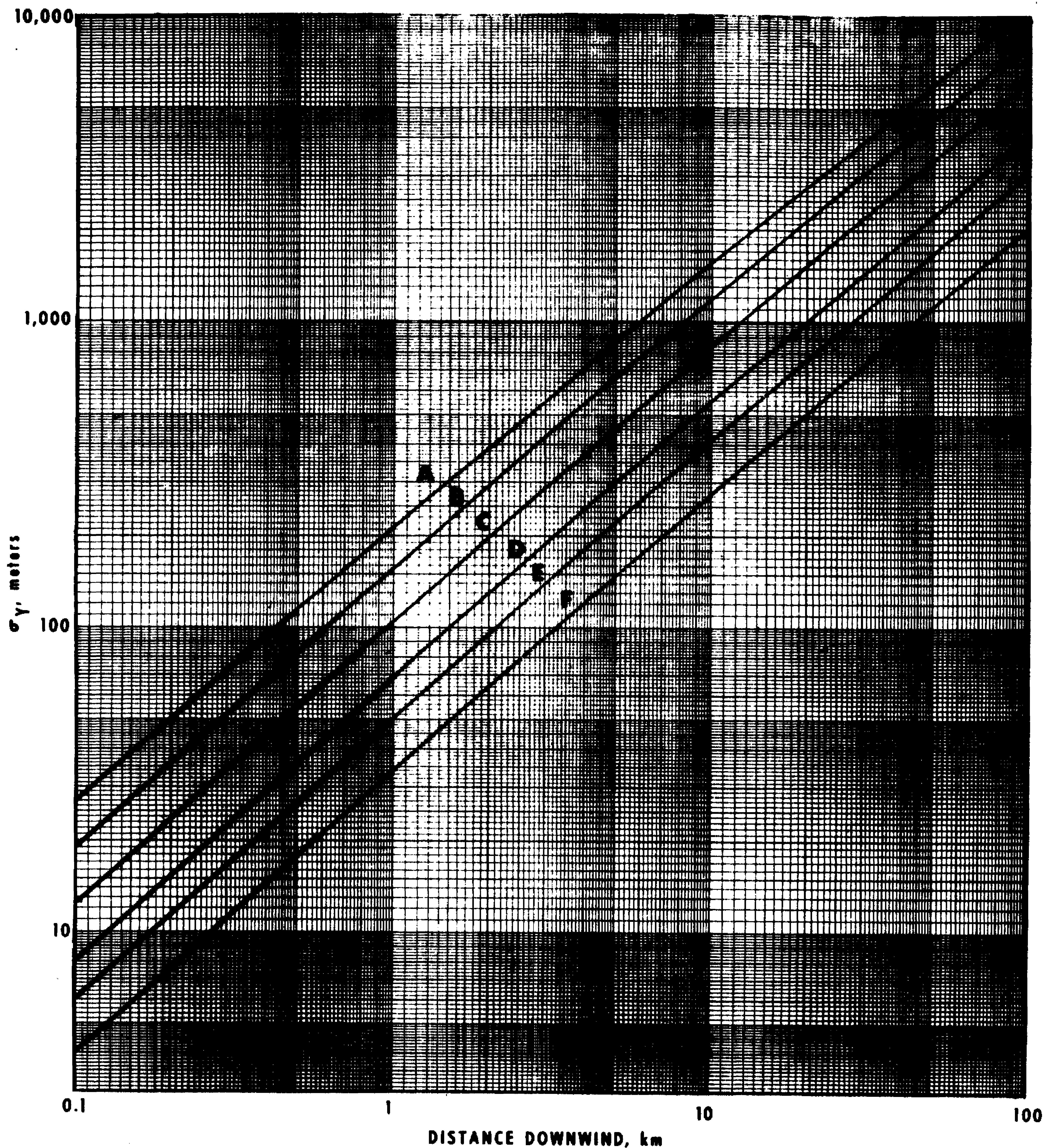
**FIGURE 7
(Continued)**

$$\sigma_z = ax^b$$

DBTSIG (used in PTMTP, ISC, CRSTER, RAM)				CDM⁴, TEM, TCM		
Stability (Pasquill)	Downwind Distance (x) (kilometers)	Values for σ_z (meters)		Downwind Distance (x) (meters)		
		a	b		a	b
E	< .1	24.260	.83660	E & F (CDM & TCM)		
	.1 - .3	23.331	.81956	100 - 500	.0545	.8124
	.3 - 1.0	21.628	.75660	500 - 5000	.2017	.6020
	1.0 - 2.0	21.628	.63077	5000 - 50000	1.5763	.3606
	2.0 - 4.0	22.534	.57154	E (TEM)		
	4.0 - 10.0	24.703	.50527	100 - 500	.1094	.7657
	10.0 - 20.0	26.970	.46714	500 - 5000	.2452	.6358
	20.0 - 40.0	35.420	.37615	5000 - 50000	.9204	.4805
	>40.0	47.618	.29592			
F	< .2	15.209	.81558	F (TEM)		
	.2 - .7	14.457	.78407	100 - 500	.05645	.8050
	.7 - 1.0	13.953	.68465	500 - 5000	.1930	.6072
	1.0 - 2.0	13.953	.63227	5000 - 50000	1.505	.3662
	2.0 - 3.0	14.823	.54503			
	3.0 - 7.0	16.187	.46490			
	7.0 - 15.0	17.836	.41507			
	15.0 - 30.0	22.651	.32681			
	30.0 - 60.0	27.074	.27436			
	>60.0	34.219	.21716			

Example Calculation:

C-Stability 3000 meters			
PTMTP	σ_z	$= 61.141(3.0)^{.91465}$	$= 167.0$
CDM	σ_z	$= .1014(3000)^{.9260}$	$= 168.2$



Horizontal dispersion coefficient as a function of downwind distance from the source.

FIGURE 9

Constants Used to Calculate
in EPA Developed Subroutine DBTSIG

$$= \frac{1000 \ xk \ \sin \theta}{2.15 \ \cos \theta} = 465.12 \ xk \ \tan \theta$$

xk = downwind distance in Kilometers

<u>Stability (Pasquill)</u>	<u>Value of θ (radians)</u>
A	$\frac{24.167 - 2.5334 \log_e xk}{57.2958}$
B	$\frac{18.333 - 1.8096 \log_e xk}{57.2958}$
C	$\frac{12.5 - 1.0857 \log_e xk}{57.2958}$
D	$\frac{8.333 - .72382 \log_e xk}{57.2958}$
E	$\frac{6.25 - .54287 \log_e xk}{57.2958}$
F	$\frac{4.1667 - .36191 \log_e xk}{57.2958}$

(Continued on next page)

FIGURE 9
(continued)

Example calculation:

C-Stability 3000 meters

$$= \frac{12.5 - 1.0857 \ln 3.}{57.2958} = \frac{12.5 - 1.0857 \bullet 1.099}{57.2958} = \frac{11.307}{57.2958} = .19735$$

$$= (465.12)(3.)(\tan .19735) = (465.12)(3.)(.19995) = 279.0$$

Constants Used to Calculate σ_y in TEM

Stability (Pasquill)	Downwind Distance (x) (meters)	$\sigma_y = cx^d$ Values for σ_y (meters)	
		c	d
A	<10,000	.495	.873
	>10,000	.606	.851
B	<10,000	.310	.897
	>10,000	.523	.840
C	<10,000	.197	.908
	>10,000	.285	.867
D	<10,000	.122	.916
	>10,000	.193	.865
E	<10,000	.0934	.912
	>10,000	.141	.868
F	<10,000	.0625	.911
	>10,000	.0800	.884

Example calculation: C stability 3000 meters $\sigma_y = (.197)3000^{.908} = 282.9$

Workbook of ATUW Disp. Coefficients: WAVE - Turner's Workbook.

The basic dispersion equation is:

$$(1) \quad \chi(x, y, z; H) = \frac{Q}{2\pi\sigma_y\sigma_z u} \exp\left\{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right\} \left[\exp\left\{-\frac{1}{2}\left(\frac{H+z}{\sigma_z}\right)^2\right\} + \exp\left\{-\frac{1}{2}\left(\frac{H-z}{\sigma_z}\right)^2\right\} \right]$$

where the term $\exp\left\{-\frac{a}{b}\right\} = e^{-\frac{a}{b}}$

This equation is valid if the source emits at a continuous rate.

If only ground level concentrations are of interest then

$z = 0$ and the equation becomes

$$(2) \quad \chi(x, y, 0; H) = \frac{Q}{\pi\sigma_y\sigma_z u} \exp\left\{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right\} \exp\left\{-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right\}$$

And if only center line concentrations are of interest then the equation can be further simplified.

$$(3) \quad \chi(x, 0, 0; H) = \frac{Q}{\pi\sigma_y\sigma_z u} \exp\left\{-\frac{1}{2}\left(\frac{H}{\sigma_z}\right)^2\right\}$$

tells what fraction is occurring at the ground in the centerline

If the point of release is at ground level and there is no effective plume rise ($H = 0$) then the centerline concentration is:

$$(4) \quad \chi(x, 0, 0; 0) = \frac{Q}{\pi\sigma_y\sigma_z u}$$

where χ = ground level concentration (grams per cubic meter)
 Q = source strength (grams per second)
 π = 3.1416
 σ_y = horizontal dispersion coefficient (meters) (Figure 10)
 σ_z = vertical dispersion coefficient (meters) (Figure 8)
 u = wind speed (meters per second)
 H = effective stack height (meters)

PROBLEM A:

1. It is estimated that 80 grams per second of hydrogen sulfide is being emitted from an extinguished flare at a petroleum refinery at an average effective height of 60 meters. At 8 a.m. on an overcast winter morning with the surface wind of 6 meters per second, what is the ground level concentration directly downwind from the refinery at a distance of 500 meters?

∴ D stability

SOLUTION:

Use equation 3

H = 60 m
Q = 80 gm/sec. = 80 x 10⁶ microgm/sec.
500 m downwind
σ_y = 36.15 m
σ_z = 18.3 m
u = 6 m/sec.

$$\begin{aligned}
 X &= \frac{80}{\pi (36.1)^2 (18.3)^2} \exp \left[-\frac{1}{2} \left(\frac{60}{18.3} \right)^2 \right] \\
 &= 6.42 \times 10^{-3} \exp \left[-\frac{1}{2} (3.28)^2 \right] \\
 &= \frac{e^{-\frac{1}{2} (3.28)^2}}{e^{-\frac{1}{2} (10.75)}} = \frac{e^{-5.37}}{e^{-5.37}} = \frac{1}{216} \\
 X &= \frac{6.42}{216} \times 10^{-3} = 29.7 \times 10^{-6} \text{ grams/meter}^3 = 30 \mu\text{g/m}^3
 \end{aligned}$$

PROBLEM B

2. Under the conditions of problem 1 what is the concentration at the same distance downwind but at a distance 50 meters from the x-axis? That is:
- $$\chi(500, 50, 0: 60) =$$

SOLUTION:

Use equation 2 and calculation made for Problem 1.

$$\chi = 33 \times 10^{-6} \exp \left[-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 \right]$$

$$\exp \left[-\frac{1}{2} \left(\frac{50}{36.1} \right)^2 \right] = \exp \left[-\frac{1}{2} (1.385)^2 \right] = \frac{1}{e^{.959}} = \frac{1}{2.61}$$

$$\chi = 29.7 \times .3835 = 11.4 \mu\text{g}/\text{m}^3$$

E. Description of Puff Release

The dispersion of a puff can be described in Gaussian terms just as the continuous release. In a continuous model the plume disperses in the vertical (z) and horizontal cross wind (y) direction. In a puff model the dispersion takes place in the z,y and downwind (x) direction. The calculated concentration is the peak instantaneous concentration and it is independent of wind speed.

When a release occurs the gas forms a spherically-shaped cloud just above the point of release. The concentration in the cloud is highest at the center. The cloud then is transported by the wind growing in size as it entrains ambient air. The growth of the cloud and its movement can be compared to a balloon that gradually inflates as it is moved by the wind. The mass of the gas in the cloud does not change as the cloud moves downwind, but its concentration does, as more ambient air is entrained.

Sometimes the release is not instantaneous but takes place over a period of several minutes such as when gas in a cylinder leaks out or during the interval between the time a leak in a valve is discovered and it can be stopped. In cases such as these the cloud may become somewhat elongated and look like a blimp or a hot dog. By assuming an instantaneous release a puff model will overestimate peak concentrations, but it will have virtually no effect on average concentrations provided the averaging time is long enough.

F. Puff Model Dispersion Coefficients

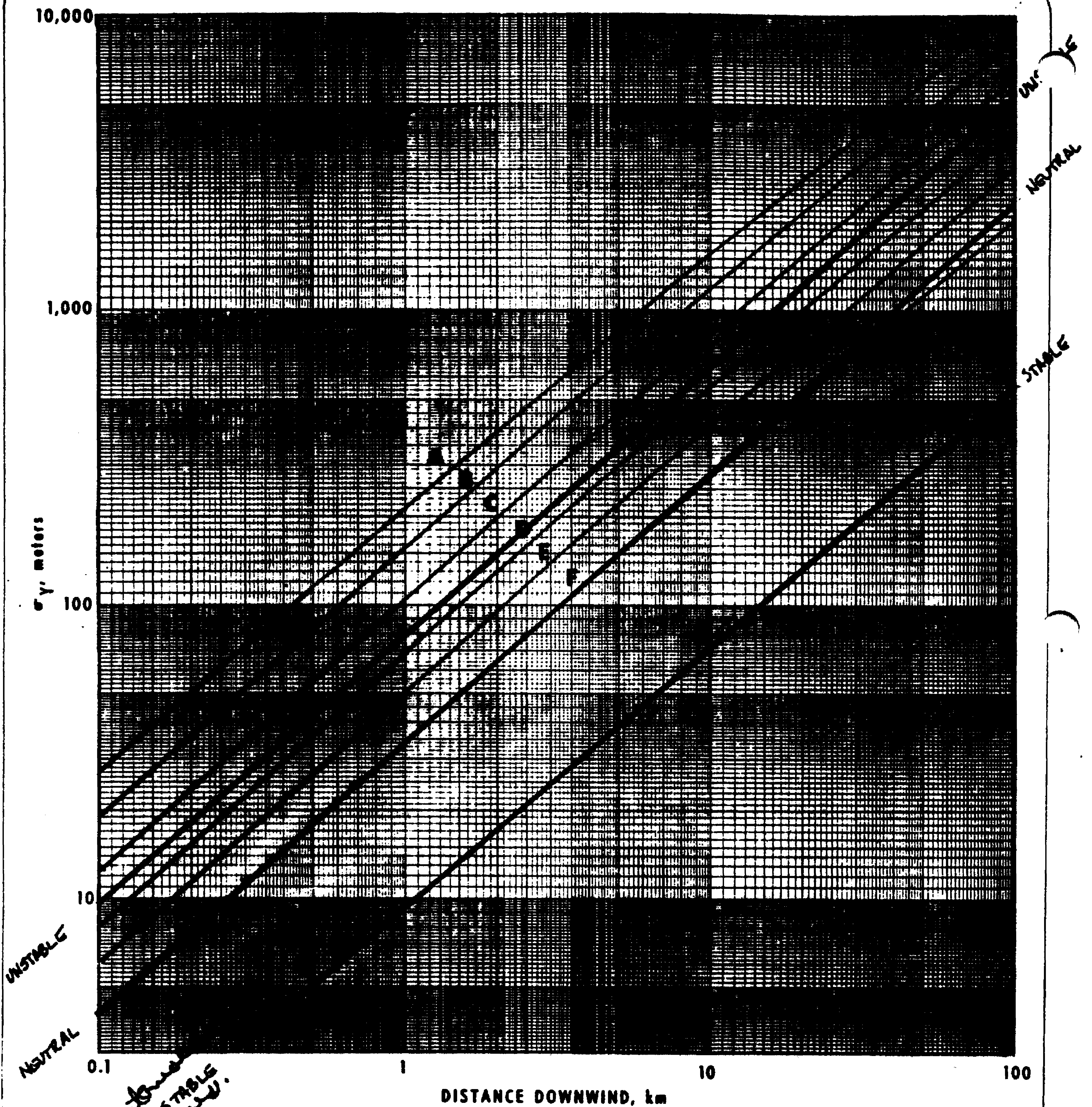
The EPA puff model uses dispersion coefficients developed by studying instantaneous release.⁶ These coefficients generally provide for less plume dilution than the familiar Pasquill-Gifford coefficients. The table shows the dispersion coefficients. Figures 1 and 2 plot the coefficients on a diagram of the Pasquill-Gifford coefficients.

Coefficient = ax^b where x is downwind distance in meters

<u>Stability</u>	<u>Horizontal (x and y)</u>		<u>Vertical (z)</u>	
	<u>a</u>	<u>b</u>	<u>a</u>	<u>b</u>
Unstable	.14	.92	.53	.73
Neutral	.06	.92	.15	.70
Very Stable	.02	.89	.05	.61

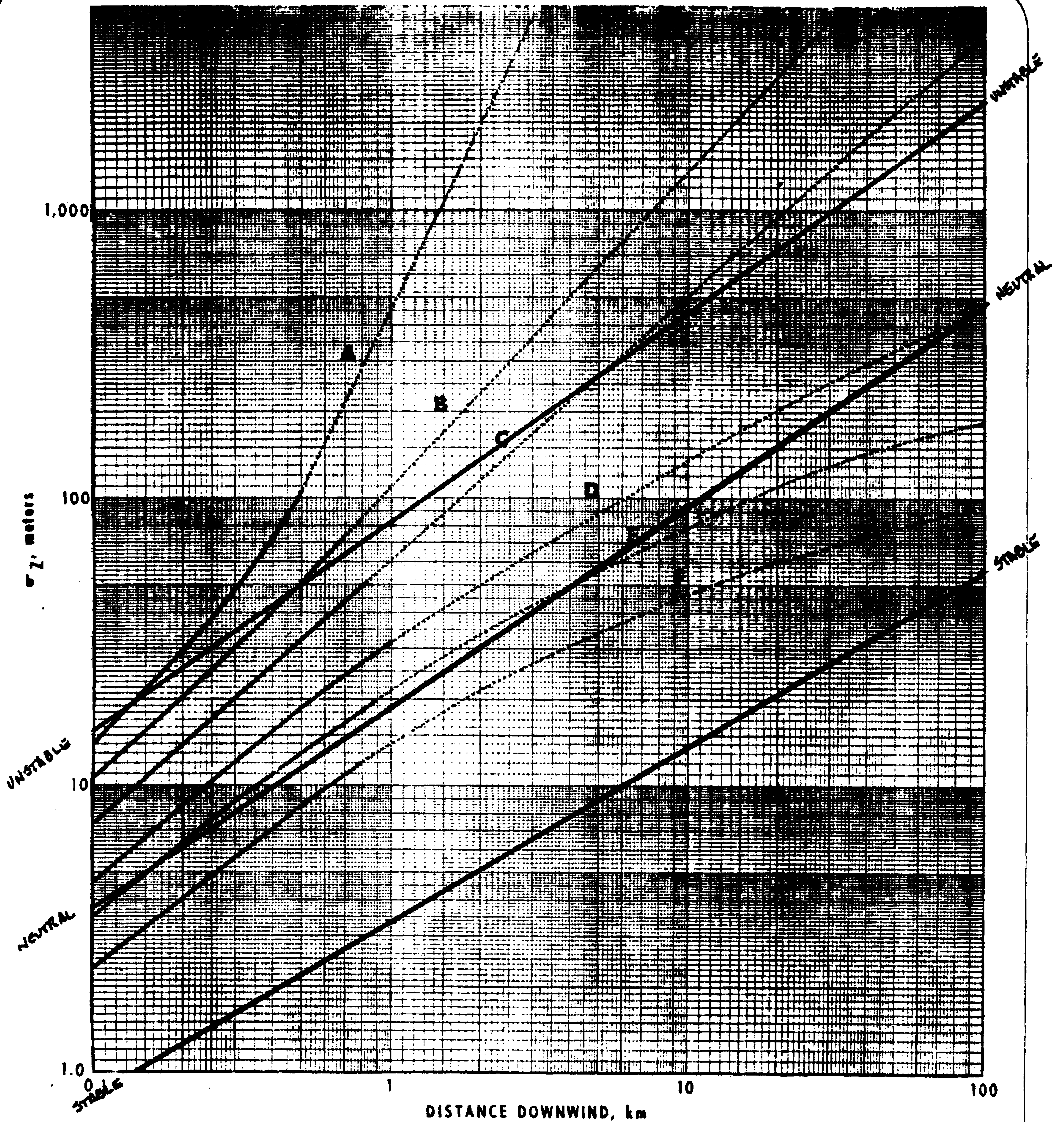
Since the dispersion in the x and y direction are generally considered to be equal, some authors refer to the standard deviation in the horizontal as σ_r (r for radius).

Figure 4.0



*Quasi-Stationary
Dispersion Curves
in bold lines*

Horizontal dispersion coefficient as a function of downwind distance from the source.



Vertical dispersion coefficient as a function of downwind distance from the source.

G. Average Concentrations from Puff Releases

The average concentration is a function of wind speed. For example, a wind of 10 knots will transport twice as much air past a site as wind of 5 knots. The average concentration is a function of the number of standard deviations in the horizontal direction (σ_x or σ_r) that pass a given point for the averaging time in question. At long downwind distances and low wind speeds the average concentration will not be much less than the peak instantaneous concentration. The puff has become so dilute that possibly less than one sigma passes a point for the averaging time specified.

At the other extreme, there is a significant difference between average and peak instantaneous close to the release point. This is because the puff is small in dimension and most of the material passing a point is air except for the very concentrated puff. Figure 12 illustrates how a puff would disperse from a pipeline break.

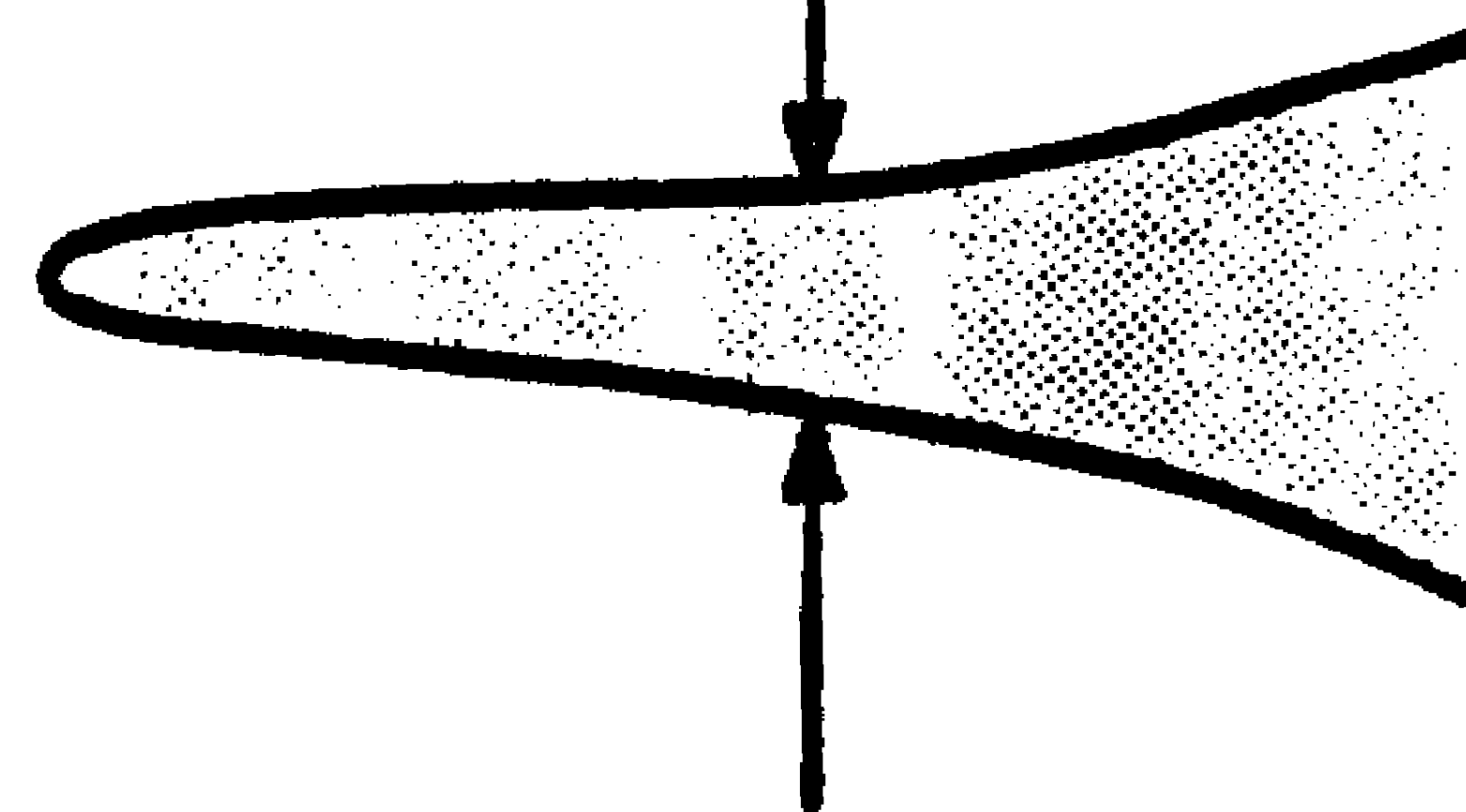
Figure 12

TIME OF RELEASE

WIND



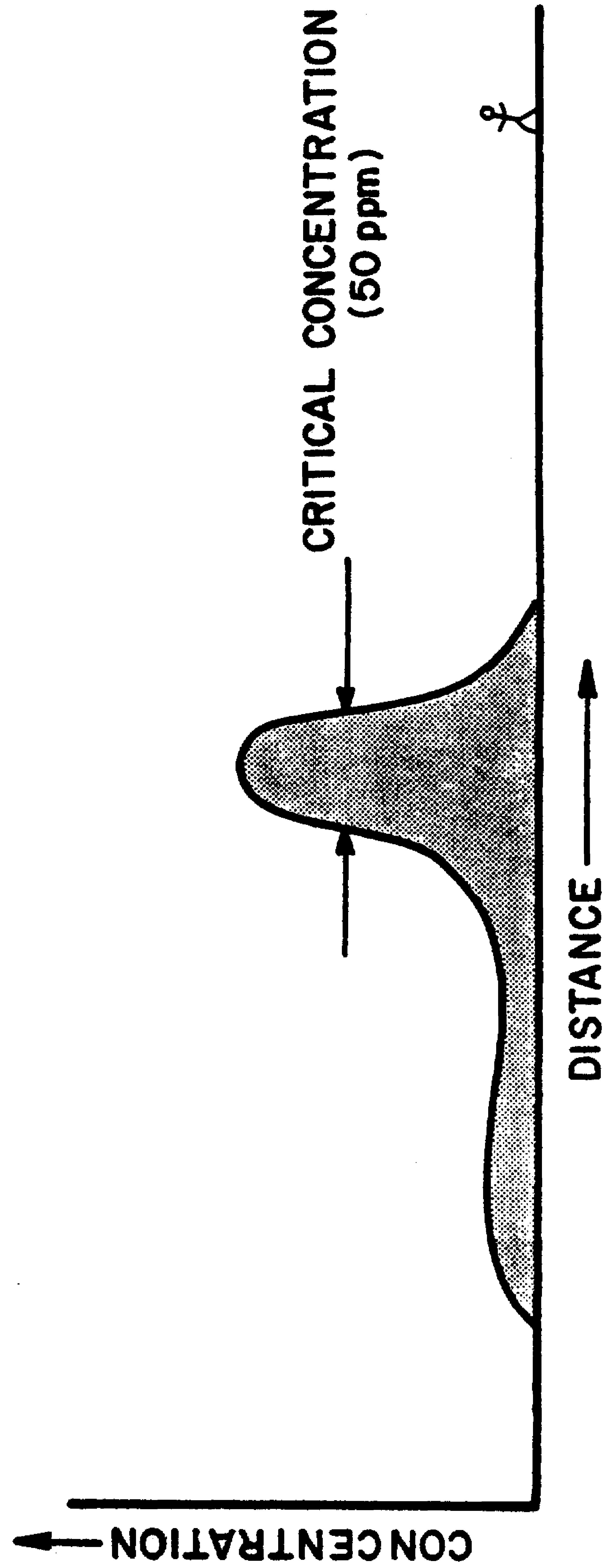
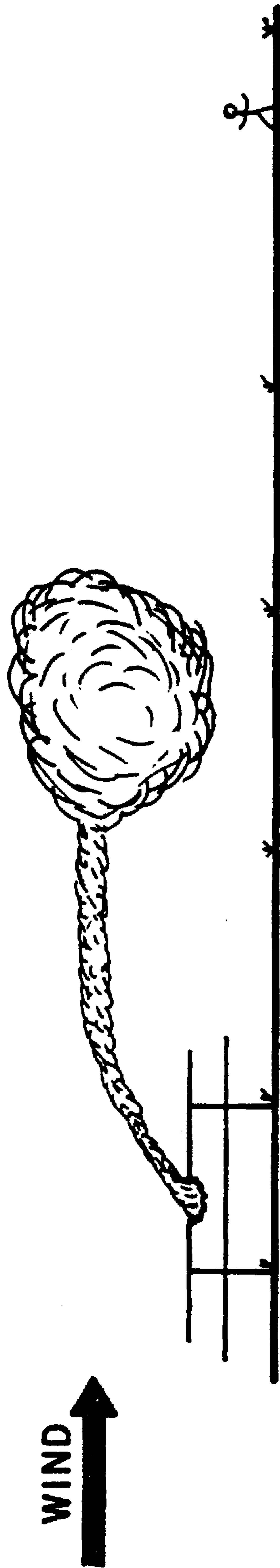
CONCENTRATION



CRITICAL CONCENTRATION
(50 ppm)

DISTANCE

5 MINUTES AFTER RELEASE



10 MINUTES AFTER RELEASE

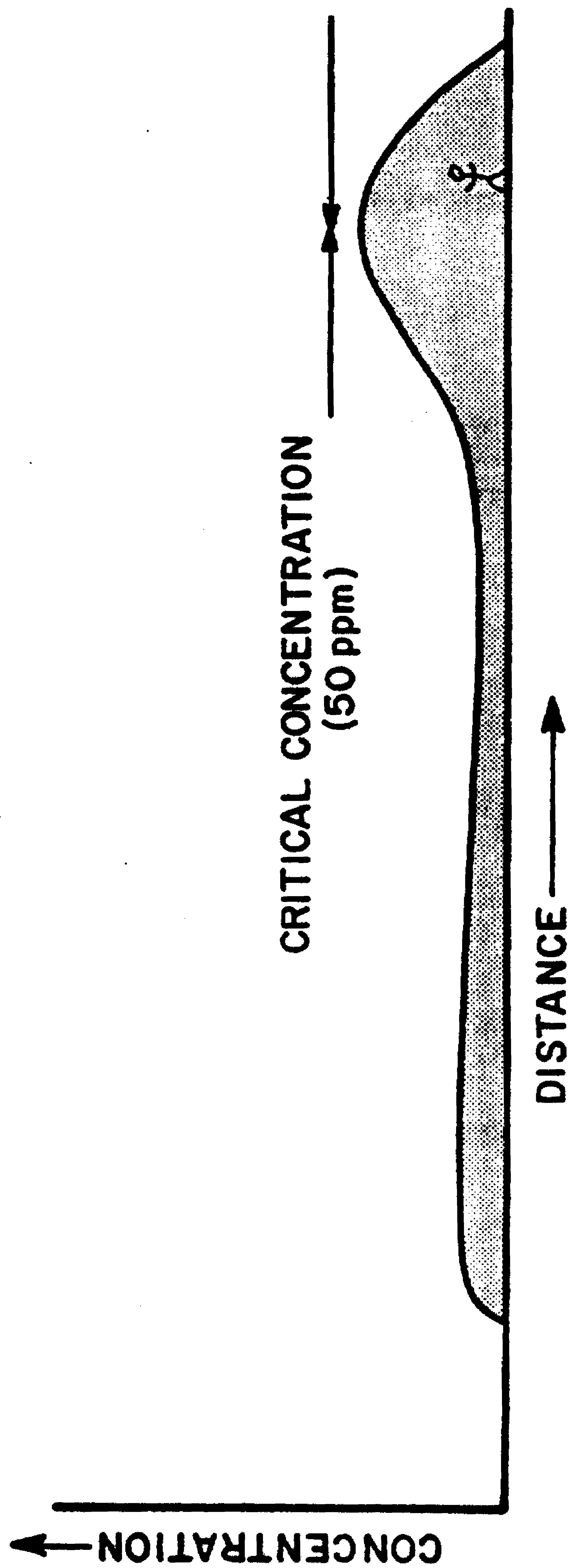
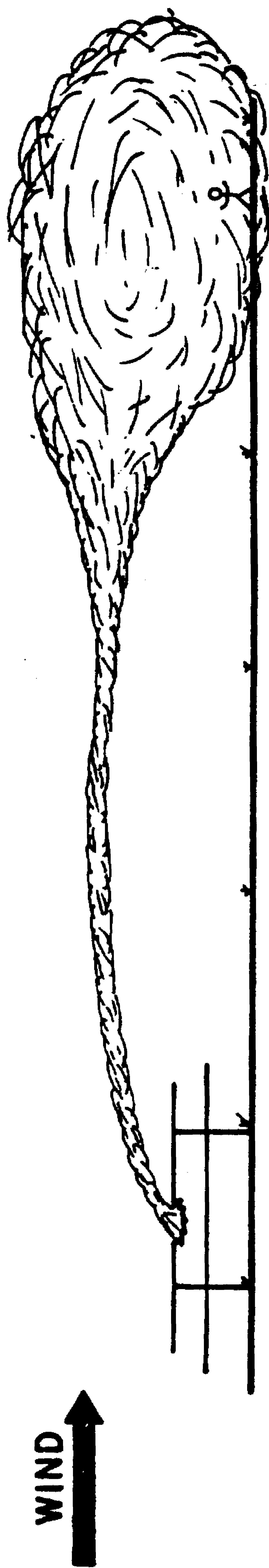


Figure 12 (cont'd)

H. Puff Equations

The basic equation is:

at $H=0$
 $e^0 = 1$ $1+1=2$

$$X = \frac{Q}{(2\pi)^{1.5} \sigma_x \sigma_y \sigma_z} \exp\left\{-\frac{1}{2}\left(\frac{y}{\sigma_y}\right)^2\right\} \left\{ \exp\left\{-\frac{1}{2}\left(\frac{H+z}{\sigma_z}\right)^2\right\} + \exp\left\{-\frac{1}{2}\left(\frac{H-z}{\sigma_z}\right)^2\right\} \right\}$$

Note that Q is a release quantity in this equation, not a release rate. X is a peak instantaneous concentration, not the average concentration.

X = peak instantaneous concentration
 (grams per cubic meter)

Q = Source strength (grams)

$\pi = 3.1416$

σ_x = horizontal downwind dispersion coefficient (meters)
 (This value is often set equal to)

σ_y = horizontal crosswind dispersion coefficient (meters)

σ_z = vertical dispersion coefficient (meters)

H = effective stack height (meters)

no wind speed because this equation calculates max. mix moves with wind, so wind is not a factor.

at $H=0$

$$X = \frac{2Q}{(2\pi)^{1.5} \sigma_x \sigma_y \sigma_z}$$

σ_x & σ_y are usually equal.

I. When to use Puff or Continuous Release Models

The puff model should be used when the release interval of the cloud is less than the travel time of the cloud. For example, if the release took place over a period of 10 minutes, then it would be appropriate to calculate concentrations at receptors beyond a 10-minute travel time using a puff model. For receptors within a 10-minute travel time distance it would be appropriate to use a puff model based on the release of a series of puffs at intervals of, say, one minute or use a continuous release model such as PAL or ISCST.

Answer Sheet

Problem C

It is estimated that 4800 grams of hydrogen sulfide is emitted from an extinguished flare at a petroleum refinery from at an effective stack height of 60 meters. At 8 a.m. on an overcast winter morning with a surface wind of 6 meters per second, what is the peak instantaneous concentration at a distance of 500 meters from the flare and how long does it take to reach that distance?

1. Time of travel: $500\text{m}/6\text{m/sec} = 83.3 \text{ seconds} = 1 \text{ minute}, 23.3 \text{ seconds}$

2. Peak concentration:

$$Q = 4800$$

$$\sigma_y = .06(500)^{.92} = 18.25$$

$$\sigma_z = .15(500)^{.70} = 11.62$$

$$X = \frac{2Q}{(2\pi)^{1.5} \sigma_y^2 \sigma_z} \exp -\frac{1}{2} \left\{ \frac{H}{\sigma_z} \right\}^2$$

$$X = \frac{2 \times 4800 \times 10^6}{(15.75)(18.25)^2(11.62)} \exp -\frac{1}{2} \left\{ \frac{60}{11.62} \right\}^2$$

$$X = (157492) \exp -13.331$$

$$X = 0.256 \text{ } \mu\text{g}/\text{m}^3$$

CHAPTER III: REFERENCES

1. Slade, op. cit. pp. 117-188.
2. Turner, op. cit. pp. 5-10.
3. "Accuracy of Dispersion Models," Bulletin of the American Meteorological Society, Volume 59, Number 8 (August, 1978) p. 1025.
4. U. S. Environmental Protection Agency, UNAMAP Series of Dispersion Models. Data derived by examination of coded data in program.
5. Adrian D. Busse and John R. Zimmerman, "User's Guide for the Climatological Dispersion Model," U. S. Environmental Protection Agency publication number EPA-R4-73-024, Research Triangle Park, North Carolina, 1973, p. 8.
6. Slade, op. cit. p. 120, p. 173-175.

1984
Emergency
Response
DOT
Guidelines

IV. Initial Cloud Size and Building Wake Effects.

A. Accounting for Initial Cloud Size

Rarely is the source a point. Instead a cloud of finite dimensions is formed. For example, a cylinder in a gas cabinet may break. The cylinder contains 165 cubic feet of 90 percent hydrogen and 10 percent arsine. The ventilated gas cabinet has a volume of 83 feet. Thus a cloud containing the arsine will have a volume before dilution in the atmosphere of 248 cubic feet of which 16.5 cubic feet will be arsine. The initial concentration of arsine is 66,500 ppm and 248 cubic feet would occupy a sphere with a diameter of 2.38 meters at 68°F.

The cloud is already 2.38 meters in the x, y and z direction before it leaves the point of release. The standard deviation is calculated by dividing the horizontal extent of the cloud by 4.3 and the vertical extent of the cloud by 2.15. The appropriate way to adjust the dispersion coefficient for the initial cloud size is to vectorially add the standard deviation of the cloud dimensions to the standard deviation calculated from the dispersion coefficients.

$$\begin{aligned}\sigma_{ya} &= \sqrt{\sigma_y^2 + \sigma_{y0}^2} \\ \sigma_{za} &= \sqrt{\sigma_z^2 + \sigma_{z0}^2}\end{aligned}$$

- a Subscript for adjusted sigma values
- o Subscript for sigma values at origin

In a Gaussian cloud the material is assumed to be distributed in

a Gaussian fashion. In dispersion modeling the concentration at the edge of the cloud is assumed to be 10 percent of the central value. Statistically speaking, the cloud is 4.3 standard deviations wide. Within this area 96.48 percent of material is contained. The average concentration across such a cloud is:

$$\frac{.9648}{(4.3)(.3989)} = 0.5625 \text{ of the value at the center of a two dimensional Gaussian curve}$$

What really happens is that instead of having a sphere of uniformly mixed gas 2.38 meters in diameter, there is a cloud with a gaussian distribution of contaminants. At the center of this cloud the concentration is 66,500 ppm. The mathematics to convert the two dimension values to three dimensions are complex. The equivalent gaussian sphere with a diameter of 4.3 standard deviation is about 2.04 times the diameter of a cloud containing uniformly mixed gas. In the example the diameter of the cloud is 4.86 meters. Sigma y is 1.13 meters and sigma z is 2.26 meters.

When using computer programs that request a user-supplied dimension of the initial cloud size, it is best to estimate the initial sphere size and then adjust it in the manner described above.

The degree of accuracy in estimating the initial cloud size can make a significant difference at receptors close to the source, those within a few hundred meters. At greater distances

A

atmospheric turbulence dominates dispersion and rarely does the initial cloud size have much effect on concentrations at distances beyond one or two kilometers.

B. Virtual Distance Method

Instead of making detailed calculations of initial cloud size, a computer program can be written which will calculate a virtual distance. The virtual distance will be added to the actual downwind distance for the purpose of determining dispersion coefficients.

The virtual distance is the distance a puff would have to travel for atmospheric turbulence to dilute it to a concentration equal to the initial center-of-cloud concentration calculated. Usually a computer program iterates up-wind in 1 or 10 meter increments until the virtual distance is too great then reverses direction and iterates in 0.1 or 1 meter steps to find the correct distance.

The initial concentrations are most often known in terms of parts per million (ppm). If a pure gas escapes the concentration at the center of the cloud is 1,000,000 ppm. But the model is designed to calculate concentrations in grams per cubic meter. A calculation must be made involving molecular weight, temperature and pressure to relate ppm to grams per cubic meter.

In the example in Chapter II, the initial concentration was 66,500 ppm of arsine (molecular weight = 77.9). If this release were to take place at 77°F and at sea level, the concentration would be:

$$\chi = \frac{77.9 \times 1013.2 \times 66,500}{298.16 \times .0831} = 211.8 \text{ grams per cubic meter}$$

Under neutral conditions the virtual distance is calculated to be 29.3 meters. The sigma x and sigma y value is 1.342 meters and the sigma z value is 1.596 meters.

C. Conversion of Concentration Units

Concentrations are usually expressed in a volume ratio such as ppm or in a weight per unit volume such as micrograms per cubic meter.

The equation to convert concentrations is:

$$\chi(\text{ppm}) = \frac{\chi(\mu\text{g}/\text{m}^3) \times T(\text{K}) \times R}{M \times P(\text{mb})}$$

where:

T	Absolute temperature (K)	298.16
R	Gas constant (mb m ³ /gm-mol K)	0.0831
M	Molecular weight (gm-mol)	
P	Atmospheric pressure (mb)	1013.2

Standard conditions are defined in 40 CFR50.3 and are noted to the right of the definitions.

$$\chi(\text{ppm}) = \frac{.02445}{M} \cdot \chi(\mu\text{g}/\text{m}^3)$$

Increases in altitude reduce atmospheric pressure and result in increases in concentrations expressed in ppm. The table below summarizes values for various altitudes:

<u>Altitude (feet)</u>	<u>Atmospheric pressure (mb)</u>	<u>Molecular weight where ppm equals micrograms per cubic meter</u>
0	1013.2	.02445
2,000	942.1	.02630
4,000	875.0	.02832
6,000	812.05	.03051
8,000	752.45	.03293
10,000	696.9	.03555

D. Obstructions

If a cloud or plume is traveling downwind and it encounters an obstruction such as a building the cloud will generally flow around the building. In flowing around the building the cloud grows in size so that it is as large as the building. Other disturbances that can cause the cloud to grow include automobile traffic on a road or a complex open structure such as structural steel supports of process units at a chemical plant.

This phenomenon suggests that as obstructions to wind-driven flow increase, the greater the probability that the cloud will become diluted.

In 1977 and 1979, Alan Huber of the U.S. Environmental Protection Agency published the results of extensive wind tunnel investigations. The conclusions of the study were that the wake^{1,2} could be divided into three areas:

Downwind Distance (x)
Divided by Height of
Building (H_b)

Zone I	3.
Zone II	3. to 10.
Zone III	10.

The building studied was twice as long as it was high, representing a typical type of structure.

The vertical dispersion parameter for stack heights less than the sum of H + 1.5H in Zone II was determined to be:

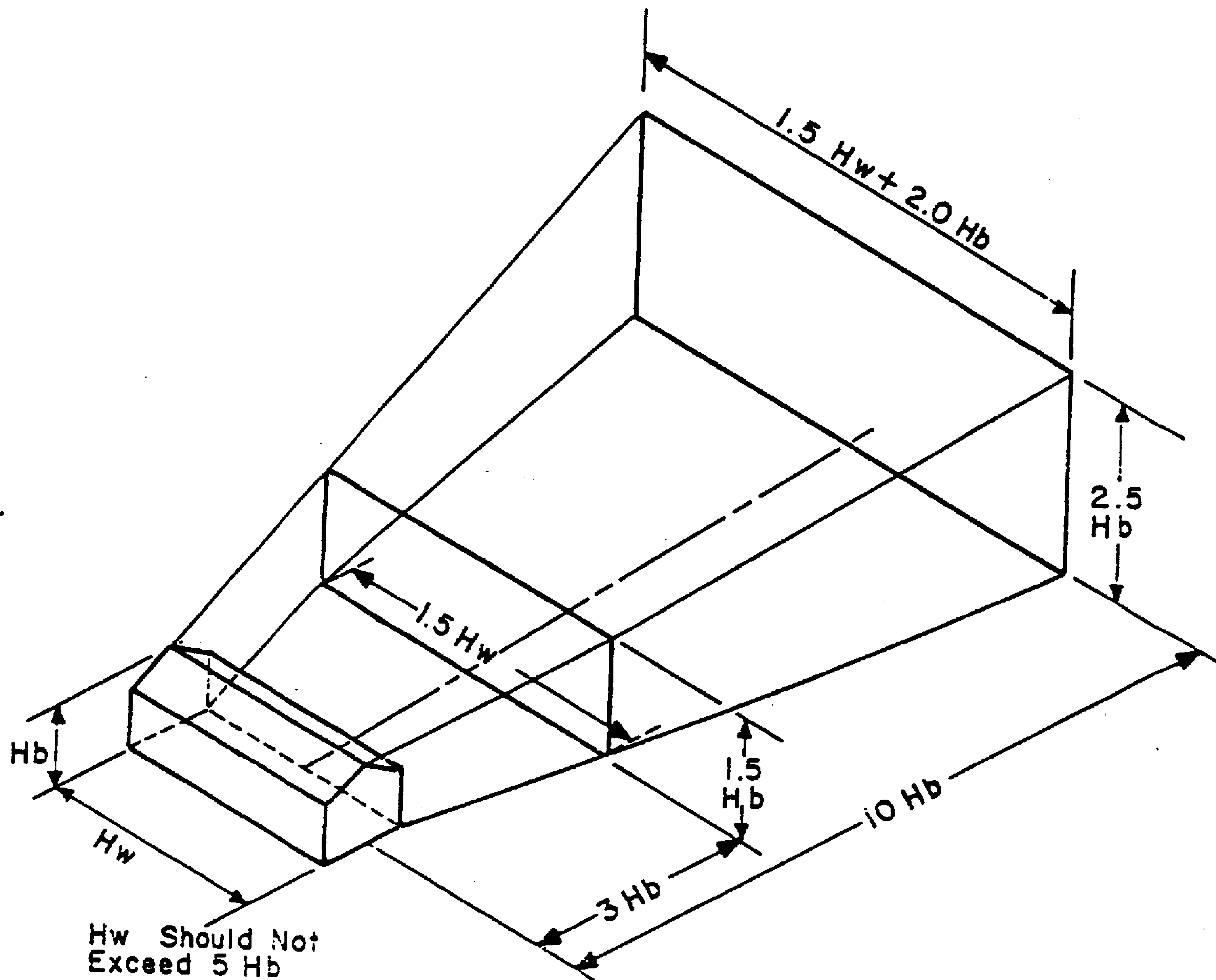
$$\sigma'_z = 0.7H_b + 0.067 (x - 3H_b)$$
$$\sigma'_y = \frac{0.7H_w}{2} + 0.067 (x - 3H_b)$$

where: H_w = width of building perpendicular to the wind

Figure 13 illustrates the growth of the wake. The value for σ'_y is determined by dividing the wake width by 4.3. The value for σ'_z is determined by dividing the half height by 2.15.

For Zone III calculations, an enhanced dispersion parameter can be estimated using a virtual displacement. The plume widths are estimated based on moving the source somewhat further away from its actual location.

Figure 13



GROWTH OF WAKE

$$\sigma_y' = (x + S_y)$$

$$\sigma_z' = (x + S_z)$$

where: S_y is the virtual source distance such that

$$\sigma_y'(10H_b) = 0.7H_w / 2 + 0.46H_b .$$

S_z is the virtual source distance such that

$$\sigma_z'(10H_b) = 1.167H_b .$$

If the building is taller than it is wide, substitute H_w for H_b in the calculations of both σ_y' and σ_z' .

An example will clarify the calculations:

Assume a building 15 meters in height, 50 meters in width, D stability and Pasquill-Gifford dispersion coefficients.

<u>Downwind Distance</u>		<u>Wake Area</u>		<u>Undisturbed Flow</u>	
<u>Meters</u>	<u>Multiple of Building Height</u>	<u>σ_y' (m)</u>	<u>σ_z' (m)</u>	<u>σ_y (m)</u>	<u>σ_z (m)</u>
45	3	17.5	10.5	3.9	2.3
75	5	19.5	12.5	6.3	3.6
150	10	24.6	17.6	11.9	6.6
300	20	34.7	21.9	22.6	12.1
328		36.5	22.8	24.6	13.0
478		46.2	26.8	34.5	17.6
1000	67	79.1	39.4	68.1	32.1

At 150 meters (10 characteristic dimensions) downwind $\sigma_y' = 24.55$ meters which is the same σ_y as undisturbed flow for a downwind distance of 328 meters. The virtual distance for the calculation is σ_y' is 178 meters (328 less 150 meters).

In the wake σ_y' for 300 meters downwind is based on the width of undisturbed flow at 478 meters. For 1000 meters it is based on 1178 meters. The σ_y should not be adjusted if the stack height is greater than $1.2H_b$ according to Huber.

At 150 meters σ_z' is 17.55 meters which is the same width as undisturbed flow for a downwind distance of 475 meters. The virtual distance is 325 meters. The σ_z' for 300 and 1000 meters is determined from the σ_z for 625 and 1325 meters respectively.

Huber recommends ignoring the horizontal dispersion parameter enhancement if the stack height is greater than $1.2H_b$.

This algorithm for wake effects is included in the following computer models: ISCST, ISCLT, TEM8 and TCM2.

CHAPTER IV: REFERENCES

1. Alan H. Huber, "Incorporating Building/Terrain Wake Effects on Stack Effluents", presented at Joint Conference on Applications of Air Pollution Meteorology, November 29 - December 1, 1977, Salt Lake City, Utah.
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V. Effective Stack Heights

In order to calculate ground-level concentrations, the effective height of emission must be known. The diffusion experiments described in the previous chapter all oriented the source of tracer material in the horizontal position and emitted material at ambient temperatures. This sidestepped the practical problem associated with industrial stacks of plume rise due to momentum or thermal effects.

The simplest way to calculate effective stack height is to add physical stack height to the observed or calculated plume rise:

$$H = h + \Delta h$$

Where: H is effective stack height

h is physical stack height

Δh is plume rise

Some confusion centers on the meaning of plume rise. Ideally it is the elevation above the stack top of the centerline of a plume traveling in a horizontal direction. The only difficulty, according to Briggs, is that in more than 90 percent of the recorded observations the plume had not yet become level when it was no longer visible. Measured plume rise is strongly a function of measuring technique. Plumes dispersing in stable or neutral atmospheres are relatively easy to measure. Those under unstable conditions are nearly impossible to measure accurately.

To overcome this problem Briggs suggests that plume rise be defined as the difference between stack height and the effective stack height one would need in the diffusion equation to correctly calculate the maximum ground-level concentration.¹

Plume rise is both a function of momentum and buoyancy. Terms related to one or both factors are included in all plume rise formulas. For cold stacks, those with emissions of less than 5 to 10°C. above ambient, momentum is probably the most important. For hot stacks (those warmer than about 50°C) buoyancy, due to the light weight of hot gases, is the most important.

Caution should be used on stacks where the emissions include moisture droplets. As the water in the plume leaving the stack vaporizes, it requires heat of vaporization which quickly cools the diluting stack gases. Under conditions of low humidity this can cause the plume to fall to the ground rather than rise. This condition is often visible on cooler days.

Over the years more than 100 plume rise formulas have been proposed by over 50 groups of investigators according to Briggs. For the most part, these investigators limited their studies to specific stacks. Many also studied plume rise under a limited range of conditions.

Although there has been widespread disagreement within the environmental community regarding the accuracy and appropriateness

V. Effective Stack Heights

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of dispersion modeling there has been virtually no challenge to the plume rise formulas developed by Briggs. These formulas are incorporated in all EPA models and are appropriate in modeling puff releases.

A. Briggs' Buoyancy Formula

In 1969 Gary A. Briggs, then an employee of the Atomic Energy Commission, made a very thorough study of the available plume rise equations. Figure 14 is taken from Briggs' work³ and it compares calculated and observed values for selected formulas. Briggs went on to study plumes, most of them from coal-fired power plants, in much greater detail than previous investigators. He then proposed his own set of formulas.

Following a detailed evaluation of Briggs' original work and two subsequent modifications, the Environmental Protection Agency adopted his equations.^{4,5} Briggs' equations have been recommended in place of Holland for calculating dispersion following Turner's Workbook of Atmospheric Dispersion Estimates starting with the sixth edition, published in December, 1972.

FIGURE 14

Comparison of Calculated Values with
Observations for Neutral Conditions

Table 5.1 (Continued)

Ratio of calculated to observed values of $u \Delta h$										
Code	Source	Reference	Moses and	Stümke ¹⁰⁸	Holland ⁶	Priestley ^{73,87}	Lucas, Moore, and Spurr ⁹¹	Lucas ¹⁰⁹	Eq. 4.32	Eq. 4.34
			Carson ¹¹⁰			(first phase)			("2/3 law")	
B	Ball	76	1.59		0.04	1.31	1.51	0.78	0.86	0.72
HA	Harwell A	75	0.43	0.74	0.23	2.00	1.70	1.27	1.40	0.95
HIB	Harwell B	75	0.48	0.83	0.25	1.60	1.59	1.19	1.17	0.93
BO	Bosanquet	73	0.92	0.75	0.44	1.19	1.38	1.12	0.98	0.98
DS	Darmstadt	80	0.78	1.04	0.25	1.49	1.69	1.36	1.13	1.09
DB	Duisburg	80	0.74	1.12	0.38	1.47	1.62	1.60	1.17	1.16
T	Tallawarra	87	0.57	1.53	0.30	0.91	1.02	0.87	0.76	0.75
L	Lakeview	88	0.28	0.41	0.31	0.78	0.62	0.68	0.66	0.64
CEGB plants										
E	Earley	91	0.40	0.72	0.18	2.49	1.59	1.30	1.73	1.05
E	Earley	91	0.48	0.57	0.37	2.26	1.44	1.16	1.71	1.25
CD	Castle Donington	91	0.43	0.74	0.44	1.57	1.01	1.01	1.29	1.17
CD	Castle Donington	91	0.39	0.62	0.47	1.34	0.86	0.86	1.13	1.05
N	Northfleet	93	0.47	0.79	0.44	2.24	1.24	1.35	1.75	1.46
N	Northfleet	93	0.56	0.84	0.65	2.43	1.35	1.47	1.96	1.73
TVA plants										
S	Shawnee	99	0.68	0.90	0.54	1.88	1.69	1.36	1.53	1.40
C	Colbert		0.66	0.96	0.55	0.86	0.96	0.82	0.77	0.77
J	Johnsonville		0.59	0.66	0.66	1.37	1.24	1.21	1.19	1.17
WC	Widows Creek		0.94	1.32	1.18	1.94	1.76	1.92	1.73	1.72
G	Gallatin		0.53	0.90	0.64	1.35	1.05	1.15	1.10	1.09
G	Gallatin		0.68	1.53	0.58	1.41	1.37	1.50	1.21	1.20
P	Paradise		0.39	0.65	0.51	1.19	0.80	0.96	1.03	1.00
P	Paradise		0.42	0.70	0.58	1.28	0.85	1.03	1.11	1.09
Median for all data			0.54 ± 34%	0.79 ± 27%	0.44 ± 37%	1.44 ± 26%	1.36 ± 21%	1.18 ± 20%	1.17 ± 23%	1.09 ± 19%
Median for selected data			0.48 ± 19%	0.72 ± 24%	0.47 ± 26%	1.41 ± 18%	1.24 ± 22%	1.16 ± 14%	1.17 ± 12%	1.09 ± 7%

$$\text{Equation 4.32: } \Delta h = \frac{1.8F0.33x0.67}{u}$$

Briggs later substitutes 1.6 for 1.8, a reduction of 11 percent.

BRIGGS' BUOYANCY PLUME RISE EQUATIONS

For neutral and unstable conditions (stability categories A, B, C and D)
at distance x downwind

$$\Delta h = \frac{1.6F^{.333}(x)^{.667}}{u} \quad \text{For final rise:} \quad \Delta h = \frac{21.425F^{.75}}{u} \quad F < 55$$
$$\Delta h = \frac{38.710F^{.6}}{u} \quad F > 55$$

Final plume rise is achieved when the downwind distance x equals $3.5x^*$.
For final plume rise under stable conditions (stability categories E and F)

$$\Delta h = 2.6 \left(\frac{F}{u_s} \right)^{.333}$$

Where $F = \frac{gV_f}{\pi} \left(1 - \frac{T}{T_s} \right)$

$$x^* = 14F^{.625} \quad \text{where } F < 55$$

$$x^* = 34F^{.4} \quad \text{where } F > 55$$

$$s = \frac{g}{T} \left(\frac{\delta\theta}{\delta z} \right)$$

$\delta\theta/\delta z$ = Vertical potential temperature gradient in the atmosphere

E category .02° K/m (stable conditions)

F category .035°K/m (stable conditions)

F = buoyancy flux (m^4/sec^3)

Δh = plume rise above stack top (m)

u = wind speed at stack level (m/sec)

x = horizontal downwind distance (m)

x^* = horizontal distance from the stack at which atmospheric turbulence begins to dominate entrainment

$3.5x^*$ = distance to point of final rise for unstable conditions (m)

g = gravitational acceleration = 9.8 m/sec²

T = ambient air temperature = 293°K (usually)

T_s = stack gas temperature (°K)

V_f = stack gas volume flow (m^3/sec)

In some lectures Gary A. Briggs has commented on the shortcomings of his widely used formula for plume rise.

1. Buoyancy Flux

The Briggs' formula assumes that the stack gases have a molecular weight similar to that of air. For fuel combustion sources this assumption is accurate within five percent. The products of natural gas combustion have a molecular weight of about 27.5 which is slightly lighter than air because of the water vapor formed from the combustion of hydrogen. The products of coal burning have a molecular weight of about 30, which is slightly heavier than air because of the large amount of carbon dioxide. As a practical matter, nitrogen nearly always dominates the composition of stack gases so that molecular weights significantly different from air are rare.

On the other hand, an incinerator burning hydrogen sulfide or one emitting chlorine compounds does not have the same weight as air and some adjustment may be appropriate.

The term $(1 - T/T_g)$ reflects the buoyancy of the heated gases. It is this term in the buoyancy flux, F , that can be modified to account for differences in the molecular weight of the stack gases.

$$F = \frac{gVf}{\pi} \left(1 - \frac{w_m T}{28.9 T_s}\right)$$

where w_m = molecular weight of stack gases

When using computer models which don't allow entry of molecular weight, it is often easier to adjust the stack temperature for the molecular weight difference. Trinity Consultants recommends that this adjustment should only be attempted if the use of routine plume rise formulas produces results which are quite different than observations.

2. Wind Speed

The wind speed in the various formulas should be the centerline of the plume as it rises. Some investigators developed a computer program which adjusted wind speed for the height of the stack top. Then for each incremental plume rise, the wind speed was recalculated until the final plume rise was determined. It turned out that if one made an appropriate adjustment for the wind speed at stack top, then it wasn't necessary to make the incremental adjustments.

The CDM, RAM, TEM, TCM and CRSTER programs make adjustments for higher average wind speed at the top of the stack compared to anemometer height. The PTMAX, PTMTP and VALLEY programs do not make wind speed adjustment, but this may or

may not be a flaw depending on how these programs are used. If the programs are being used to calibrate a model, then it is likely that correction for the higher speed winds aloft than those measured at the surface is appropriate. If the program is being used to forecast worst case, then assuming a uniform vertical wind field may be better.

3. Restoring Acceleration

In the plume rise equation for stable air the "potential lapse rate" represented by the term $\delta\theta/\delta z$ is used. This is assigned a somewhat arbitrary value by EPA in their models.

Briggs suggests that when evaluating a specific site the restoring acceleration value should be the difference between the adiabatic lapse rate ($-0.01^\circ\text{C}/\text{meter}$) and the actual lapse rate from the top of the stack to the plume centerline, not the lapse rate close to the ground. In other words:

$$\delta\theta/\delta z = \Delta T/\Delta h + 0.01$$

Where: ΔT is the air temperature difference between the plume centerline and the top of the stack.

Δh is the plume rise in meters.

In all EPA models z is assumed to be 0.02 and $0.035^\circ\text{C}/\text{m}$ for

E- and F-stabilities respectively. These values are typical

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values in the lowest 50 meters of the atmosphere. At higher elevations it may be more appropriate to use lower values because the lapse rate will tend to become more adiabatic. For tall stacks on a power plant, a value of $0.01^{\circ}\text{C}/\text{meter}$ is probably more appropriate.

4. Size of Plants

The Briggs formulas have generally been validated for plants with an approximate fuel consumption greater than 200×10^6 BTU per hour or roughly 34 cubic meters per second of stack gases at about 300°F (422°K) assuming fuel oil combustion and 30 percent excess air. The use of Briggs formulas for smaller stacks is often done, but there is an absence of validation on these smaller stacks. Among other things, it appears that the coefficient for the stable plume rise is less (about 2.4) for smaller stack and greater (up to 3.1) for larger stacks.

B. Plume Rise of Flares

Flares are incinerators that burn waste gases in the open atmosphere. Typically, a flare is a vertical stack through which waste gas, and sometimes fuel gas, is emitted to the atmosphere. At the top of the stack the mixture burns in the atmosphere. The flare tip is often equipped with an automatic device to keep the flare lit. It is also often equipped with a steam line. The steam acts to make the flare "smokeless."

Most flares at industrial facilities are used for the emergency release of process gases during upsets. Thus emissions from flares are rarely included in emission inventories and are rarely modeled, except for the annual rate of emissions. An exception is the natural gas processing industry which uses a large number of continuous flares for disposing of acid gases (hydrogen sulfide and carbon dioxide) from the amine plants used to "sweeten" the gas.

Flares tend to be very efficient in converting hydrocarbons to products of combustion. A study was performed by Engineering Science, Inc. in 1983 and jointly sponsored by the Chemical Manufacturers Association and the United States Environmental Protection Agency.⁷ This study reports that

"when flares are operated under conditions which are representative of industrial practices, excluding emergency releases, the combustion efficiencies in a flare plume are greater than 98%."

The Briggs' buoyancy plume rise formulas can be easily adapted to forecast the plume rise from flares. These formulas require parameters that are commonly available such as the stack temperature and the volumetric flow rate in the stack. From these values the user calculates buoyancy flux, F , which is equal to the heat release of the stack. If manual calculations are being made, F can be calculated knowing the volume and heat content of the gases being flared. But if a computer is being used, it is often easier to first calculate F , assume a stack temperature and calculate a synthetic volumetric flow rate.

This latter method permits one to use all existing EPA computer programs to analyze flares.

1. Calculating F from Heat Release

Briggs states the following equivalencies in Equations 4.19c and 4.20.

$$F = gvr^2(1 - \frac{\rho_s}{\rho}) = \frac{gQH}{\pi C_p \rho T} = 3.68 \times 10^{-5} Q_H \quad (1)$$

where:

F = buoyancy flux parameter (m⁴/sec³)
g = gravitational constant (9.8 m/sec²)
v = stack velocity (m/sec)
r = stack radius (m)
ρ = density of air (1205 kg/m³)
ρ_s = density of stack gases
Q_H = heat release (low heat value) (calories/sec)
C_p = specific heat of air (0.24 calories/g K)
T = ambient air temperature (usually 68°F = 20°C = 293K)
T_s = stack gas temperature (K)
V = volume of stack gases at standard conditions (m³)
V_f = volume of stack gases at stack conditions

The equation on page 57 of this manual is:

$$F = \frac{gV_f}{\pi} (1 - \frac{T}{T_s}) \quad (2)$$

The equality between equations (1) and (2) can be demonstrated

$\frac{\rho_s}{\rho}$ is proportional to $\frac{T}{T_s}$ and $V_f = \pi r^2 v$.

$$\text{Thus, } F = gvr^2(1 - \frac{\rho_s}{\rho}) = \frac{gV_f}{\pi} (1 - \frac{T}{T_s}) \quad (3)$$

The heat release is the product of the volume of gases, the specific heat per unit volume and the temperature change. The specific heat of gases is given in units per weight so

one must multiply this by the density to get specific heat per unit volume. A value for V can be calculated and substituted in equation (3).

$$Q_H = VC_p \rho (T_s - T) \quad (4)$$

substituting stack conditions: $V = V_f \frac{T}{T_s}$

$$Q_H = V_f \rho \frac{T}{T_s} (T_s - T) \quad (5)$$

rewriting to get an equations for V_f :

$$V_f = \frac{Q_H}{C_p \rho T} \left(\frac{T_s}{T_s - T} \right) \quad (6)$$

substituting this value for V_f in equations (3)

$$F = \frac{g Q_H}{\pi C_p \rho T} \left(\frac{T_s}{T_s - T} \right) \left(\frac{T_s - T}{T_s} \right) = \frac{g Q_H}{\pi C_p \rho T}$$

The usual problem is to intermix flare stacks with conventional stacks. In the usual form of Briggs' plume rise equation, heat release is calculated from stack temperature and the volumetric flow rate of the stack. For a flare, heat release is known, but in order to intermix flares with conventional stacks, a stack temperature is assumed and an equivalent volumetric flow rate determined.

Trinity Consultants usually makes the following assumptions and then substitutes in equation (6).

$$T = 68^{\circ}\text{F} = 20^{\circ}\text{C} = 293^{\circ}\text{K}$$

$$C_p = 0.24 \text{ cal/gram}^{\circ}\text{K}$$

$$\rho = 1205 \text{ gram/m}^3$$

$$T_s = 1000^{\circ}\text{K}$$

$$V_f = \frac{Q_H}{0.24(1205)(293)} \left(\frac{1000}{1000 - 293} \right) = 16.7 \times 10^{-5} Q_H$$

Although the products of combustion usually have a higher specific heat than air and are heated first, these products become rapidly diluted with ambient air. Hence the specific heat of air should be used for calculating plume rise.

At higher altitudes the density of air decreases, as does the density of the plume. Although this increases the absolute plume buoyancy, the buoyancy relative to ambient air remains unchanged. Altitude has no effect on plume rise.

2. Losses Due to Radiation

Most of the heat of combustion is used to heat the products of combustion. A small portion is radiated. The visible and ultraviolet emissions rarely exceed 0.4 percent of the heat of combustion. The infrared emissions are much larger and often range from 2 to 20 percent. The energy lost

through infrared radiation is a function of the surface area and the fourth power of the absolute temperature of the hot gas envelope. If the flame is burning smoothly, and turbulence is at a minimum, then a higher radiation loss will occur. As turbulence increases, due to either the nature of the gas discharge jet or wind, the radiation loss decreases. This is a result of a higher rate of dilution and a smaller hot gas envelope.

Judgment should be used to determine the amount of radiated heat. In order not to underestimate radiation and therefore overstate plume rise, Trinity Consultants assumes a 20 percent loss. This means that 80 percent of the heat of combustion is used to heat the products of combustion.

3. Effect of Addition of Steam

Steam is often used to make a flare "smokeless." High pressure steam is throttled through nozzles into the area of combustion. If the nozzle were perfect, then the flow would be isentropic (constant entropy). Most nozzles have an efficiency of between 87 and 92 percent.

Trinity Consultants assumes that 90 percent of the enthalpy loss at isentropic (constant entropy) conditions occurs and from this calculates the enthalpy at the nozzle outlet. This is compared to the enthalpy of water vapor at standard conditions and the difference subtracted (or added) to the

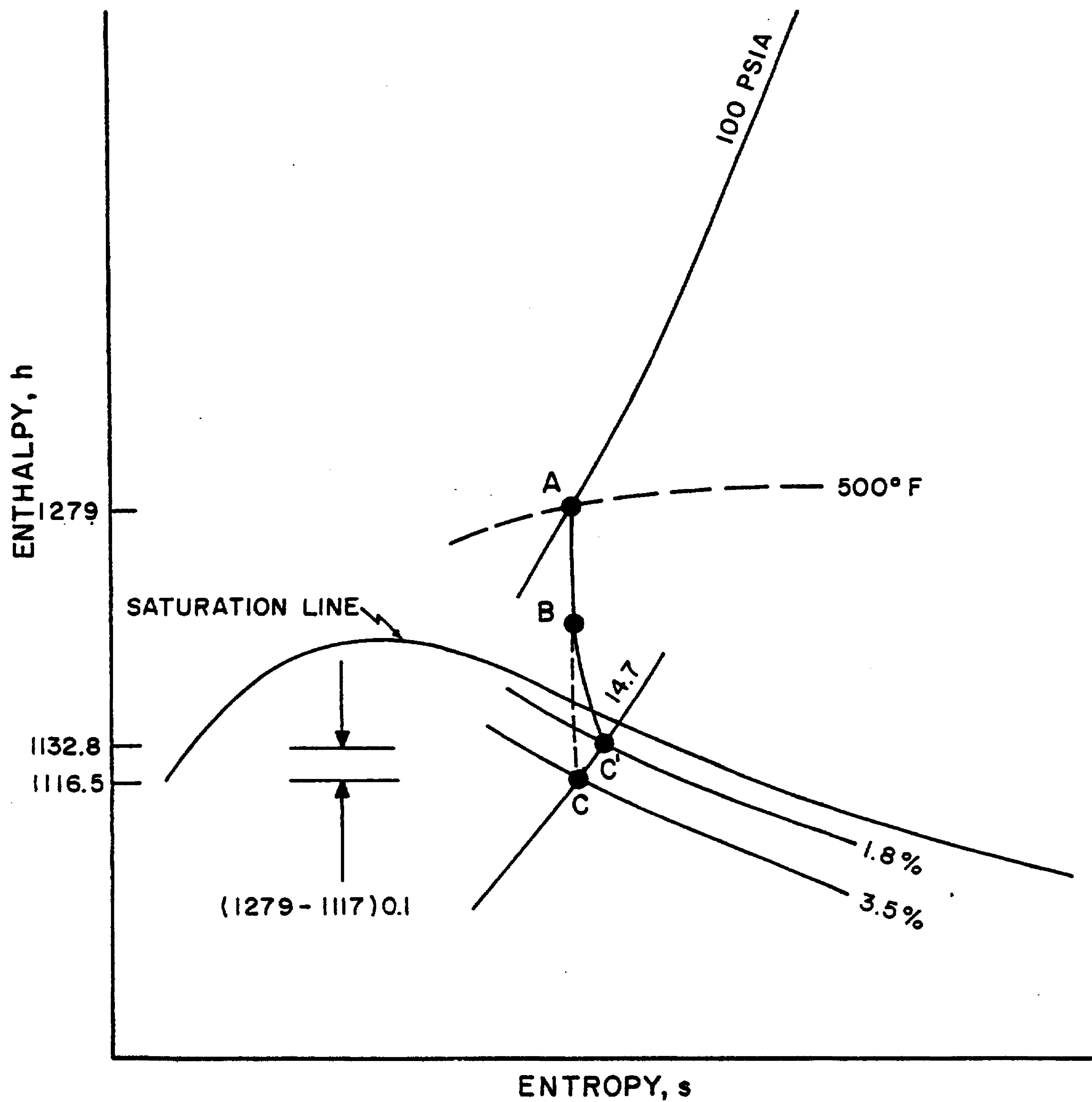
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heat of combustion. This can be illustrated with a schematic Mollier chart.

In the example shown in Figure 15, the steam to the flare has a pressure of 100psia and 500°F. Its initial enthalpy is 1279 BTU per pound. If the nozzle were perfect the change would take place at constant entropy and the final enthalpy would be 1117 BTU per pound. The discharge steam would contain 3.5 percent water vapor. Because of the inefficiency of the nozzle only 90 percent of the enthalpy loss takes place (to 1133), and entropy increases somewhat. The discharge stream contains 1.8 percent water. Since 970 BTU's are required to convert each pound of water to steam, 17 BTU's (970 times .018) must be supplied per pound of steam by the combustion of the flare to vaporize the water formed.

The heat content in fuels is described by two numbers, the high heat value and the low heat value. The difference between the two is that the high heat value includes the heat of vaporization. Low heat is the high heat value less the heat required to vaporize water formed during combustion. Between the point of formation of water vapor to ultimate plume rise of a flare, water is rarely condensed. Therefore, as a matter of being conservative, the use of the low heat value is recommended.

FIGURE 15



PROBLEM E:

An acid gas stream of the following composition is being sent to a flare. No fuel gas is being used:

	<u>% by volume</u>
Methane (CH ₄)	1.97
Ethane (C ₂ H ₆)	.55
Propane (C ₃ H ₈)	.41
Other (C ₄ +)	.68
Hydrogen Sulfide (H ₂ S)	43.40
Carbon Dioxide (CO ₂)	52.84
Nitrogen (N ₂)	.15
	<u>100.00</u>

The measured flow rate is 452,000 cubic feet per day measured at 60°F at 14.65 pounds per square inch pressure. No steam or fuel gas is being used. The first form is used to correct gas flows from measured conditions (which vary widely) to standard conditions. The second form calculates the effective heat release (Q_H) and the equivalent volumetric flow rate for an assumed stack temperature of 1000K. Calculate the equivalent volumetric flow rate assuming an equivalent stack gas temperature of 1000K.

CALCULATION OF VOLUME

WASTE GAS FLOW RATE .3139 10^3 CF/MIN. AT STD. CONDITIONS 60°F 14.65 psia

FUEL GAS FLOW RATE 10^3 CF/MIN. AT STD. CONDITIONS °F psia

COMPONENT	CORRECTED FLOW RATE TO 68°F = 20°C = 293°K, 14.7 psia			
	WASTE GAS		FUEL GAS	
	mol%	10^3 CFM	mol%	10^3 CFM
CH ₄	1.97	.006		
C ₂ H ₆	.55	.002		
C ₃ H ₈	.41	.001		
C ₄ +	.68	.002		
CO				
H ₂ S	43.40	.138		
CO ₂	52.84	.168		
N ₂	.15			
H ₂ O				
TOTAL	100.00	.318	100.00	

TO CORRECT FUEL GAS FLOW RATE:

$$\text{RATE AT } 60^\circ\text{F, } 14.65 \text{ psia} \quad \frac{460 + 68}{460 + 60} \times \frac{14.65}{14.70} = 1.012$$

CALCULATION OF HEAT RELEASE

FUEL	10 ³ CFM BURNED	LOW HEAT VALUE 10 ³ BTU PER CF AT 68°F 14.7 PSIA	HEAT RELEASED 10 ⁶ BTU/MIN
CH ₄	.006	.896	.005
C ₂ H ₆	.002	1.594	.003
C ₃ H ₈	.001	2.282	.002
C ₄ +	.002	~3.000	.006
CO		.316	
H ₂ S	.138	.560	.077
TOTALS			.093

HEAT RELEASE FROM COMBUSTION .093 10⁶ BTU/MIN

PORION OF HEAT USED TO
HEAT PRODUCTS OF COMBUSTION .80 (Usually .80 or greater)

NET HEAT RELEASE (Q_H) .0744 10⁶ BTU/MIN x $\frac{252}{60}$ = .312 10⁶ CAL/SEC

252 Calories = 1 BTU 60 Seconds = 1 Minute

Using an assumed stack temperature of 1000°K (1340°F)

$$V_f = 16.7 \times 10^{-6} Q = \text{5.22} \text{ m}^3/\text{sec}$$

C. Briggs' Momentum Formulas

Since 1967 there has been considerable research done on the plumes from sources where momentum, not buoyancy, is the principal source of rise. Briggs proposed these formulas in 1971 and they are used in most of the newer models. In these models, the plume rises are calculated by adding the buoyant rise to the momentum rise. The greater of the two values is then used for further calculations. The formulas used are as follows:

$$\text{Unstable: } \Delta h = 1.89 \left[\frac{v^2 d}{u(v + 3u)} \right]^{.667} x^{.333}$$

$$\Delta h(\text{max}) = 3 \frac{vd}{u}$$

Stable:

$$\Delta h(\text{max}) = .945(vd)^{.667} u^{-.333} s^{-.167}$$

Where:

x = downwind distance (m)
v = stack exit velocity (m/sec)
u = wind speed (m/sec)
d = stack diameter (m)

$$s = \frac{g}{T} \frac{\partial \theta}{\partial z}$$

g = gravitational acceleration (9.8) m/sec²
T = ambient air temperature (293°K usually)
 $\partial \theta / \partial z$ = vertical temperature gradient in the atmosphere. Both EPA and Texas assume:

E-stability category .02°C/m
F-stability category .035°C/m

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As a practical matter final plume rise with unstable conditions is reached rather rapidly so the use of the final plume rise formula rarely results in an error. It is questionable whether the gases from short vents on buildings enter a stable atmosphere. The atmosphere in the immediate vicinity of buildings, especially in industrial areas is more likely to be neutral than stable.

CHAPTER V: REFERENCES

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VI. Toxicological Considerations

A. Chronic and Acute Toxicity

Chronic toxicity refers to long term effects on the human body. Chronic effects are usually estimated using annual average models.

Acute toxicity refers to short term effects on the human body. Time spans ranging from a few seconds to 30 minutes are generally of interest when studying acute effects.

Section 112 of the Clean Air Act requires EPA to develop regulations for hazardous air pollutants. The term hazardous air pollutant means

"an air pollutant to which no ambient air quality standard is applicable and which in the judgment of the Administrator causes, or contributes to, air pollution which may reasonably be anticipated to result in a increase in mortality or an increase in serious irreversible, or incapacitating reversible, illness."

Under this section EPA has generally limited its studies to the continuous releases of chronic pollutants such as asbestos, vinyl chloride, benzene, acrylonitrile and similar compounds. The EPA has not employed probability estimates for episodic releases of such pollutants. A human can be exposed to a rather large concentration of some of these but if the duration is quite brief the long terms effects will be rather small. Vinyl chloride is a good example of such an air contaminant.

On the other hand some compounds are dangerous in high concentrations for brief periods of time but relatively harmless in lower concentrations for extended periods. Hydrogen sulfide is generally fatal if concentrations exceed 1000 ppm for 5 minutes but the workplace standard allows values of 10 ppm for an 8-hour work day.

Because each chemical compound has different short and long term effects, it is suggested that a toxicologist be consulted to establish safe acute toxicity levels for human exposure. The appendix contains a sample report prepared for arsine.

B. Air Contaminant Limits in the Work Place

The most comprehensive set of suggestions is published annually by the American Conference of Governmental Industrial Hygienists (ACGIH).¹ The 1968 version of this publication forms the basis for the Occupational Safety and Health Administration (OSHA) rules affecting air contaminants 29CFR1910.93.² It also is used by various state agencies. One example is "Airborne Contaminants" published by the State of California, Department of Industrial Relations (CAL/OSHA).

The ACGIH publication contains four columns of data for each substance. The time weighted average (TWA) and The Short Term Exposure Limit (STEL) are shown in terms of ppm and milligrams per cubic meter.

The TWA is defined as follows:

"The time-weighted average concentration for a normal 8-hour work day and a 40-hour work week, to which nearly all workers may be repeatedly exposed, day after day, without adverse effect."

The STEL is defined as follows:

"a 15-minute time-weighted average exposure which should not be exceeded at any time during the work day even if the eight-hour time weighted average is within the TLV. Exposures should not be longer than 15 minutes and should be repeated more than four times per day. There should be at least 60 minutes between successive exposures to the STEL. (It is a) concentration to which workers can be exposed continually for a short period of time without suffering from:
1) irritation, 2) chronic or irreversible tissue change or 3) narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue or materially reduce work efficiency."

For the great majority of substances with a TLV, there is not enough toxicological data available to warrant a STEL. The ACGIH recommends that short term exposures should exceed 3 times the TLV-TWA for no more than 30 minutes during the work day and under no circumstance should they exceed five times the TLV provided the TLV-TWA is not exceeded. Thus this most widely used publication is directed towards the work place environment and provides limited aid in assessing safe levels for a one-time intensive exposure to a toxic gas.

The U.S. Government has two organizations involved in worker safety. Under the Department of Labor, OSHA has general responsibility for developing and enforcing regulations. Under the Department of Health and Human Services, the National Institute for Occupational Safety and Health (NIOSH) is

responsible for research to develop the technical basis for standards. These organizations jointly published a guide that defines acute levels of toxicity.³ It is entitled, "NIOSH/OSHA Pocket Guide to Chemical Hazards". This is probably the most useful publication to establish safe one-time short-term exposure levels for assessing the hazard caused by a toxic gas cloud.

One concept that is commonly used by toxicologists is ppm/min. For example, chlorine may have a value of 1000 meaning that a person can withstand 1000 ppm for one minute, 200 ppm for five minutes, or any other combination of values in which the product of concentration and time in minutes is 1000.

It is improper to apply this technique to the TLV-TWA values without professional advice because the physiological effects of substances differ so widely.

Two other publications provide a rich source of information to help establish tolerable levels of contaminants. N. Irving Sax is the author of "Dangerous Properties of Industrial Materials".⁴ "Patty's Industrial Hygiene and Toxicology"⁵ is a publication consisting of five volumes.

C. Air Contaminant Limits in Ambient Air

Starting with Montreal in 1978 numerous governments in North America

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have adopted procedures for analyzing the continuous emissions of toxic compounds from industrial plants in the ambient air.

According to a recent report, 14 states and 6 local programs have toxics regulatory programs in place.⁶ An even larger number have programs in preparation.

Many states and localities use some form of ambient guideline or standard for the control of toxic air pollutants. Most of these use "factored" occupational values as a basis for developing the ambient limit, at least for some pollutants. A factored occupational value is the use of a constant fractional value to apply to all of a specific set of occupational limits to convert from a workplace guideline (based on exposure to a particular contaminant over an eight-hour day, five days a week) to an ambient guideline.

The occupational limits used most commonly for this purpose are the TLV-TWA, the OSHA limits and the NIOSH recommended criteria for occupational exposures in air. NIOSH recommendations are based primarily on medical science while OSHA considers technical feasibility and economic factors in its role as regulator.

Figure 16 is a summary of the limits adopted or proposed by selected state and local air pollution control programs.⁷

D. Time Averaged Concentrations

As was discussed in Chapter III, the time average concentration

Figure 16

**SAFETY FACTORS USED TO DERIVE ACCEPTABLE AMBIENT
CONCENTRATIONS FROM OCCUPATIONAL LIMITS**

State or Locality	Safety Factor Applied to Occupational Limit	Averaging Time
Alabama	2.5% (1/40)	1 hour
Arkansas	1% (1/100)	24 hour
Connecticut ¹	0.5% (1/200), 1% (1/100), or 2% (1/50), depending on pollutant group	8 hour
Georgia ¹	0.33% (1/300) if known human carcinogen, 1% (1/100) if not known human carcinogen	24 hour
Illinois	0.33% (1/300) for non carcinogens	24 hour
Indiana ¹	1% (1/100)	24 hour
Michigan	1% (1/100) for selected pollutants	8 hour
Minnesota	1% (1/100)	8 hour
Mississippi	3.3% (1/30), usually	NA ²
Montana	2.4% (1/42)	1 year ³
Nevada	10% (1/10)	8 hour
New Hampshire ¹	1% (1/100)	NA ²
New York	0.33% (1/300), 2% (1/50) depending on toxicity category	1 year
Rhode Island ¹	1% (1/100)	24 hour
South Carolina	0.24% (1/420)	NA ²
Texas	1% (1/100), 0.1% (1/1000)	30 minute 1 year

(Continued)

Figure 16 (cont'd)

State or Locality	Safety Factor Applied to Occupational Limit	Averaging Time
Vermont	0.24% (1/420)	24 hour or 1 year depending on pollutant
Virginia	1% (1/100) for carcinogens 1.7% (1/60) for non-carcinogens	24 hour 24 hour
Wisconsin ¹	2.4% (1/42)	NA ²
Wyoming ³	2.4% (1/42), 2% (1/50), 0.33% (1/300)	1 year, 24 hour, 1 hour
SEACME, California	100% for selected pollutants	8 hour
Philadelphia, Pennsylvania	0.24% (1/420) or 2.4% (1/42)	1 year

¹Tentative: program in preparation.

²Not available at the time of this writing.

³As reported in Radian Corporation, "Survey of State and Local Agency Programs for Control of Toxic Air Pollutants," Draft Report, Prepared for U.S. EPA, Office of Air Quality Planning and Standards, State and Territorial Air Pollution Program Administrators, and Association of Local Air Pollution Control Officials, June 8, 1983.

is determined by counting the number of standard deviations of a cloud that pass a certain point. If an observer is located close to a brief (few-second release), then an observer may only be breathing the toxic gas for a few seconds. The rest of the air breathed over, say, five minutes will be fresh air. On the other hand if the observer is several kilometers away the peak instantaneous concentration would be nearly equal to the maximum 30-second average concentration.

The science of establishing safe acute levels for 30-second, 1-minute or even 5-minute periods is not well developed. Therefore, when analyzing possible accidents it may be best to analyze several averaging times.

Most people spend most of their time indoors. There is a significant buffering effect in air movement into a building. Under ideal conditions the occupants of a building could be warned and they would then shut off all ventilation. When the cloud had passed, ventilation should be increased to the maximum extent possible to flush out any toxic gases that might have permeated the building.

E. Method Used by EPA for Chronic Toxicity Studies.

For years EPA has studied the risk of citizens living near chemical plants. These studies are based on the use of the CDM computer model and meteorological data collected at nearby

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airports.

There is some question regarding the effectiveness of this approach. First CDM is an urban model and many plants are located in rural areas. Nearby airport meteorological data may not be representative of conditions near the plant, particularly in mountainous areas. The CDM model does not consider the wake effects of individual structures, rather it adjusts the vertical dispersion coefficient if the release height is less than 50 meters.

CHAPTER VI: REFERENCES

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7. *ibid*, p.28

III. Large Spills and Heavy Gases

A review of the TLV-TWA list shows values ranging from less than 1 ppm up to 5000 ppm. Some "inert" gases such as acetylene, helium and methane act as simple asphyxiants. No TLV is recommended but the suggested minimum oxygen content is 18 percent by volume.¹ Some of these asphyxiants are explosive and care should be exercised to keep concentrations below the lower explosive limit. If oxygen is 18 percent by volume, the inert gas would be 14.3 percent by volume (143,000 ppm). OSHA sets a limit of 19.5 percent oxygen in 29CFR1910.94 (d)(9)(vi) and 16.5 percent oxygen in 29CFR1915.11 (c)(2).

A. Common Dilute Clouds

Since the concentrations of primary concern for most gases is in the range of less than 1 ppm up to 5000 ppm, this means that the cloud contains no less than 99.5 percent air. As such, the molecular weight of the contaminant, or its original temperature, have virtually no effect on dispersion and can be ignored. More complex processes may exist near or at the source, but by the time the gas has been diluted to concentrations of interest, the cloud will be nearly all ambient air. Moreover, the rate of dilution of the cloud will be primarily governed by the prevalent atmospheric turbulence.

B. Descriptions of Spills

Whenever there is an accidental spill of a liquid or gas, some or all of the material volatilizes. As the cloud of volatile material and air moves gradually downwind, the natural process of atmospheric turbulence reduces the concentrations. If the spill is of a hazardous material, the concentrations at some point downwind will fall below the toxic level. Regardless of the nature of the spill, atmospheric turbulence is generally the major factor in diluting the plume as it moves downwind. The initial turbulence of the actual release generally has only a minor effect on concentrations at distances beyond 250 meters or so from the spill.

There are three types of spills: liquids, gases stored as liquids, and gases. In nearly all cases dense gas clouds are created. Buoyant clouds are created only when there is a small hole in a container of gas or when there is evaporation from a liquid pool on the ground. Buoyant plumes are also created when there is a fire. A more detailed description of the three types of spills follows:

1. Liquid spills.

The spill of a material which is normally a liquid at

atmospheric pressure and temperature causes a pool to form. Examples of such liquids include benzene, acrylonitrile, and vinyl chloride. The liquid will evaporate from the pool at a rate that can be calculated based on the vapor pressure of the liquid which governs the rate of liquid to gas transfer, the area of the pool, the heat of evaporation, the air temperature, the ground temperature and the heat transfer of convection and radiation. The viscosity of the liquid will determine the rate of growth of the pool on flat ground. If the material is spilled into a ditch, both the surface exposed to the atmosphere and the surface exposed to the warm earth will be reduced, thus cutting the evaporation rate. In fact one suggestion for minimizing the emissions from spills is to build concrete basins under the potentially leaking vessel. A small deep basin will result in minimum evaporation. By putting a sump in the basin, the spilled material can be quickly recovered.

For most liquids the initial rate of emission will be greater per unit area than the equilibrium rate. As evaporation takes place, the pool will be cooled, reducing the temperature of the adjacent air into which the liquid is evaporating. Wu and Schroy have provided a good summary of the thermodynamics and heat transfer associated with liquid spills.²

If the spill of a liquid occurs on water, then the release rate of the material will be much greater than if the spill occurs on land. On land there is no circulation, only conduction, a much less efficient means of heat transfer. The rate of release of toxic material decreases as the temperature of the underlying surface decreases. If the pool is floating on water, then circulation patterns in the water will help keep the pool relatively warm. The Chlorine Institute suggests that chlorine spilled on water should be assumed to vaporize.³

2. Liquid Gas Spills.

Many materials are stored in pressurized or refrigerated containers. These include ammonia, chlorine and liquefied natural gas (LNG) and liquefied petroleum gas (LPG). The nature of the failure has much to do with how the release disperses.

a. Small Hole in Vapor Space

If the spill is a puncture in the top of the container where liquids do not escape, the material will enter the atmosphere as a gas. If the release rate is slow and if

Storing gas under refrigeration is safer (lower release rate) than under pressure.

the gas has a molecular weight less than air, the release will have buoyant plume rise.⁴ If the molecular weight is greater than air, the plume will rise due to momentum and then sink because of density differences.

b. Large Hole in Vapor Space.

If a large hole should suddenly exist in a tank containing liquified ammonia under pressure, the consequences are quite different than those associated with a small hole. If the hole is small, the escaping vapor can be replenished by evaporation from the liquid surface above which the pressure changes little if at all. If the hole is large, the pressure above the surface is relieved instantaneously. Pressure at and below the liquid surface (which is the sum of atmospheric pressure and static head) is less than the saturation vapor pressure. As a result, bulk boiling occurs and most of the contents of the vessel will be flung into the air. For ammonia at 20°C the heat will be sufficient to vaporize about 20 percent of the vessel contents. The remaining 80 percent becomes an airborne cloud of finely divided boiling liquid droplets at a temperature of -33°C. Experiments confirm that when rapid depressurization occurs, the entire contents of

the container becomes airborne.

c. Hole in Liquid Space.

If the puncture or release occurs below the liquid level, then liquid will enter the atmosphere. If the contents are stored at atmospheric pressure the liquid will form a pool and as it evaporates gas will enter the atmosphere. One conclusion that can be drawn from this observation is that it is safer to store liquified gases refrigerated at atmospheric pressure than in pressurized containers. If the contents are pressurized, then a portion of the liquid will immediately flash to a gas while the liquid portion is rapidly cooled.

d. Dense Gas Cloud.

Because of the turbulence induced by the flashing of gas most of the liquids do not form a pool on the ground but rather form an aerosol of liquid droplets. This cloud, composed of suspended boiling droplets, is called a "dense gas cloud".

A dense gas cloud is also formed when there is a catastrophic failure of an ammonia or chlorine tank.

When all the boiling liquid droplets in a dense gas cloud vaporize, the cloud becomes neutrally buoyant and the usual Gaussian dispersion equation apply. The location, dimensions and concentrations of gases in a dense gas cloud are analyzed using differential equations that are totally different than the familiar Gaussian equations.

A set of six partial differential equations has been proposed to analyze the characteristics of a dense gas cloud⁵including:

<u>Equation</u>	<u>Variables</u>
Width	Horizontal velocity, gravity spread velocity and entrainment velocity.
Lateral Momentum	Hydrostatic force and surface drag.
Mass Conservation	Entrainment velocities.
Mass Fraction Conservation	Boil off from surface pool is added to local flux valves.
Longitudinal Momentum	Entrainment of ambient momentum (wind speed), acceleration from hydrostatic gradients, and surface drag.
Enthalpy Conservation	Surface heat transfer, entrainment of water vapor, ground ource of boiling cryogenic liquid and longitudinal dispersion.

e. Descriptions of Releases

In the case of a sudden release, such as a tank rupture, the dispersion process can be described as four phases according to Griffiths and Kaiser.⁶ First, there is the turbulence, called "flash off", caused by the rapid escape of the liquid or gas. For a 20-ton ammonia tank rupture, tests suggest that about 20 percent becomes vapor while 80 percent remains as a liquid aerosol. A similar fraction of chlorine will flash at an ambient temperature of 85 F according to the Chlorine Institute. The liquid aerosol appears to observers as a cloud in the shape of a column or vertical cylinder. The gases within this cylinder are quite cold due to the evaporation of part of the gas.

Second, this cylinder starts to slump, much in the way a column of water starts to spread out. During slumping, air is entrained fairly slowly and this stage will typically last 30 to 40 seconds for a 20-ton gas spill.

Third, the cloud of liquid droplets now enters the ground-hugging phase in which the entrainment of air takes place at a rate less than that expected for a passively diffuse plume. The area of the top surface is

much greater than the area of the sides and, therefore, most of the entrainment of air takes place through the top surface. Depending on the ambient temperature, the gases in the cloud will reach ambient air density in 3 to 5 minutes after slumping starts from a 20-ton spill.

Fourth, the natural process of atmospheric turbulence takes over and the cloud diffuses like any other gas in the atmosphere.

The boundaries between the phases are rather blurred and indistinct. The description of the four phases, however, is useful when discussing the atmospheric dispersion of dense gases.

In the case of large volume releases, the dense cloud can remain intact for some distance. For example, the cloud of vapor formed from the release of 40 tons of ammonia at Pensacola, Florida, was tracked on a radar for an hour out to a distance of nine miles before it dissipated into a neutrally buoyant phase.

On May 11, 1976, in Houston, an ammonia truck crashed from the elevated structure of the Southwest Freeway - I-610 interchange. The grass was "burned" in a circle

with a radius of about 150 meters from the point of impact and in the downwind distance out to a distance of about 1000 meters. The "burned" grass apparently reflects the initial slumping column followed by a ground-hugging dense gas cloud of liquid droplets that eventually warmed to become a gas.

f. Shape and Characteristics of Dense Gas Clouds

Slumping of a dense gas cloud takes place rapidly and it causes the cloud to spread out radially including movement upwind until arrested by the wind. A raised front is formed with the slumped cloud assuming a doughnut-like shape and eventually decaying to pancake shape. The shape and movement of a dense gas cloud is nearly independent of atmospheric stability.

A dense gas cloud moves more slowly than a buoyant cloud because of surface drag. Tests in the Burro series reported by Meroney show that with a wind speed of 2m/sec the center of the cloud moved at about a third the wind speed. The cloud dimensions for a 10 ton spill of LNG were approximately 200 meters wide and 6 meters deep at a location 140 meters downwind, 200 seconds after the release.

Griffiths and Kaiser report that a 20 ton ammonia spill forms a cloud up to 400 meters in diameter after 50 seconds and up to 600 meters in diameter after 100 seconds.

Another characteristic of a dense gas cloud is that as the cylindrical cloud slumps, concentrations occur upwind of the center of the release. In the case of Burro, they occurred up to 25 meters upwind. In Houston they extended about 150 meters upwind.

The effects of gravity on a dense gas cloud are strong. In an effort to restrict the number and type of variables that require consideration, the significant dense gas tests have been conducted on flat, open uniform terrain. These include Porton Down, Maplin Sands, China Lake (Burro) and the recent Thorney Island experiments.

It is known qualitatively that dense gas clouds do not move uphill except with moderate strong winds and they may even roll down a hill against slight winds. Further research is necessary to qualify the effects of topography.⁷

There has been extensive research conducted on dense gas spills mostly involving liquified petroleum gas. The studies generally are directed at determining the lower flammable limit (LFL) of a gas/air mixture. Depending on the gas, the LFL are in the range of 10,000 to 125,000 ppm, far in excess of a safe level for gases such as chlorine or ammonia.

The dissipation of the dense gas cloud into a neutrally buoyant cloud and the dilution of the buoyant cloud down to levels of 100 to 500 ppm has not been studied. Various assumptions are made by scientists and a more accurate solution to this issue may not occur for some time.

g. Modeling Dense Gas Clouds.

Although many scientists believe that adequate data exists to validate dense gas models, most are awaiting the availability of data from the China Lake and Thorney Island experiments for confirmation.

At the point of transition to a neutrally buoyant cloud, the dense gas cloud may be up to several hundred meters wide but only a few meters deep.

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For highly toxic substances, for which the concentration of concern may be in the ppm range, the behavior during the gravity influenced phase of dispersion may not significantly affect the calculations. Moreover, in most if not all cases, the Gaussian dispersion calculation will tend to overestimate concentrations relative to methods which combine a dense gas dispersion and Gaussian calculations.⁸

3. Gas Spills.

The spill of a material which is normally a gas both at atmospheric conditions and at storage and/or transportation conditions results in the formation of air/gas mixture at a temperature somewhat below ambient temperature. The reduced temperature is the result of the pressure reduction between storage and/or transportation conditions and atmospheric pressure. An analysis of such a release using hydrogen sulfide as an example is provided by Echols.⁹

C. Bursts with Continuing Emissions

When a tank or vessel fails, the release of the gas starts at a high rate but it rapidly decreases as the container becomes depressurized.

*Some materials
could have a
cumulative effect.
HCl e.g.*

Under these conditions it is appropriate to divide the release into a series of individual bursts. The first the largest burst should be analyzed first. This provides a worst case analysis. The following bursts or puffs will contain less contaminants. If a person can survive or avoid the first puff, the person should be able to survive the subsequent puffs.

D. Lower Flammable Limits

All combustible gases have a lower flammable limit. If the concentration is higher than this level, then any spark or flame can cause an explosion. As a result, good engineering practice is to keep storage tanks of combustibles some distance away from open flames or sources of sparks.

CHAPTER VII: REFERENCES

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VIII. Location of Spills and Data Required

In all cases the most difficult part of analyzing a spill is to determine the quantity spilled. This task is particularly difficult in transportation accidents.

A. Transportation

In most transportation accidents the person at the scene in rural areas is usually local firemen, a state policeman or a sheriff. In urban areas, many larger fire departments have a hazard material coordinator.

The U.S. Department of Transportation publishes "Emergency Response Guidebook" (1984). Copies of this guide have been made available to each police, fire, civil defense and rescue squad vehicle in the United States.

The procedure to use this guide is as follows:

1. Identify the material from:
 - a) Data on Shipping papers
 - b) Four digit number on an orange panel
 - c) Material name that may appear on vehicle
2. Look up Material's 2-digit guide.
3. Turn to numbered guide pages.

The on-scene coordinator is encouraged to call CHEMTREC for immediate advice for those at the scene of emergencies. CHEMTREC immediately contacts the shipper of the hazardous materials for more detailed assistance and appropriate follow-up. It is strongly suggested that the on-scene coordinator keep the phone line open. The CHEMTREC facility consists of a teleconferencing bridge which allows experts from the shipper or anyone else to communicate with the on-scene coordinator.

The user of the Guide is advised to purchase U.S/ Geological Survey Maps of the area of responsibility to aid in evacuations where they are necessary. Preplanning and response team training is recommended.

Figure 17 is a reproduction of the Guide 20 which is used for chlorine, nitrogen dioxide, nitrogen tetroxide, and other gases.

The guide also contains tables (Figure 18) specifying evacuation distances during the initial phase of an accident involving hazardous liquids or gases shipped in bulk or multiple-container loads.

If a hazardous material cloud goes between several multi-story

HEALTH HAZARDS

Poisonous; may be fatal if inhaled.
Contact may cause burns to skin and eyes.
Contact with liquid may cause frostbite.
Runoff from fire control or dilution water may cause pollution.

FIRE OR EXPLOSION

May ignite other combustible materials (wood, paper, oil, etc.).
Mixture with fuels may explode.
Container may explode in heat of fire.
Vapor explosion and poison hazard indoors, outdoors or in sewers.

Keep unnecessary people away; isolate hazard area and deny entry.
Stay upwind; keep out of low areas.
Ventilate closed spaces before entering them.
Wear **positive pressure** breathing apparatus and full protective clothing.
Evacuate area endangered by gas. (See Isolation and Evacuation Table in back of guidebook; find the material by name.)
FOR EMERGENCY ASSISTANCE CALL CHEMTREC (800) 424-9300.
If water pollution occurs, notify appropriate authorities.

FIRE

Small Fires: Dry chemical or CO₂.
Large Fires: Water spray, fog or foam.
Move container from fire area if you can do it without risk.
Stay away from ends of tanks.
Cool containers that are exposed to flames with water from the side until well after fire is out.
For massive fire in cargo area, use unmanned hose holder or monitor nozzles; if this is impossible, withdraw from area and let fire burn.

SPILL OR LEAK

Keep combustibles (wood, paper, oil, etc.) away from spilled material.
Stop leak if you can do it without risk.
Use water spray to reduce vapor but do not put water on leak or spill area.
Isolate area until gas has dispersed.

FIRST AID

Move victim to fresh air; call emergency medical care.
If not breathing, give artificial respiration.
If breathing is difficult, give oxygen.
Remove and isolate contaminated clothing and shoes at the site.
In case of contact with material, immediately flush skin or eyes with running water for at least 15 minutes.
Keep victim quiet and maintain normal body temperature.
Effects may be delayed; keep victim under observation.

Figure 18

TABLE OF ISOLATION & EVACUATION DISTANCES

NAME OF MATERIAL SPILLING OR LEAKING (ID No.)	INITIAL ISOLATION	INITIAL EVACUATION		
	SPILL or LEAK FROM (drum, smaller container, or small leak from tank) ISOLATE in all Directions feet	LARGE SPILL FROM A TANK (or from many containers, drums, etc.)		
		FIRST ISOLATE in all Directions feet	THEN EVACUATE IN A DOWNWIND DIRECTION Width miles	Length miles
Acrolein (1092)	300	620	1.5	2.4
Acrylonitrile (1093)	90	180	0.4	0.6
Ammonia, anhydrous liquified (1005)	80	160	0.4	0.6
Ammonia solution, with more than 44% (2073)				
Anhydrous ammonia (1005)				
Boron trifluoride (1008)	320	670	1.7	2.6
Bromine (1744)	170	350	0.8	1.3
Carbon bisulfide (1131)	50	100	0.2	0.3
Carbon disulfide (1131)				
Chloride of phosphorus (1809)	110	220	0.5	0.8
Chlorine (1017)	140	290	0.7	1.0
Dimethylamine, anhydrous (1032)	80	170	0.4	0.6
Dimethyl sulfate (1595)	80	170	1.4	2.2
Epichlorohydrin (2023)	40	80	0.2	0.3
Ethylene imine (1185)	270	570	1.4	2.2
Ethylene oxide (1040)	80	160	0.4	0.5
Fluorine, cryogenic liquid (9192)	460	980	2.5	3.9
Hydrochloric acid, anhydrous (1050)	190	450	1.0	1.4
Hydrogen chloride, anhydrous (1050)				
Hydrogen chloride, liquid (refrigerated) (2186)				
Hydrocyanic acid (1051)	90	190	0.5	0.7
Hydrogen cyanide, anhydrous (1051)				
Hydrofluoric acid, anhydrous (1052)	150	300	0.7	1.1
Hydrogen fluoride, anhydrous (1052)				

Figure 18 (Cont'd)

TABLE OF ISOLATION & EVACUATION DISTANCES

NAME OF MATERIAL SPILLING OR LEAKING (ID No.)	INITIAL ISOLATION	INITIAL EVACUATION		
	SPILL or LEAK FROM (drum, smaller container, or small leak from tank) ISOLATE in all Directions feet	LARGE SPILL FROM A TANK (or from many containers, drums, etc.) FIRST ISOLATE in all Directions feet	THEN EVACUATE IN A DOWNWIND DIRECTION Width miles	Length miles
Hydrogen sulfide (1053)	120	240	0.6	0.9
Methylamine, anhydrous (1061) Monomethylamine, anhydrous (1061)	110	220	0.5	0.8
Methyl bromide (1062)	50	90	0.2	0.3
Methyl chloride (1063)	30	60	0.1	0.2
Methyl mercaptan (1064)	370	770	1.9	3.0
Methyl sulfate (1595)	80	170	1.4	2.2
Nitric acid, fuming (2032) Nitric acid, red fuming (2032)	100	210	0.5	0.7
Nitric oxide (1660) Nitric oxide and Nitrogen tetroxide mixture (1975)	90	180	0.4	0.6
Nitrogen dioxide (1067) Nitrogen peroxide (1067) Nitrogen tetroxide (1067)	110	220	0.5	0.8
Oleum (1831)	280	580	1.5	2.2
Perchloromethyl- mercaptan (1670)	220	450	1.1	1.6
Phosgene (1076)	600	1250	3.3	5.2
Phosphorus trichloride (1809)	110	220	0.5	0.8
Sulfur dioxide (1079)	120	250	0.6	0.9
Sulfuric acid, fuming (1831) Sulfuric anhydride (1829) Sulfur trioxide (1829)	280	580	1.5	2.2
Titanium tetrachloride (1838)	30	60	0.2	0.2
Trimethylamine, anhydrous (1083)	50	90	0.2	0.3

**THIS INFORMATION IS FOR USE IN ADDITION TO THE GUIDE PAGE RECOMMENDATIONS
FOR HANDLING THE TOXIC HAZARDS OF THESE MATERIALS IF THEY ARE NOT ON FIRE**

buildings or down a valley, the cloud could affect people much further away than the distance specified. The guide also notes that occupants on the upper floors of multi-story buildings are likely to be safer remaining where they are if the heating and air-handling equipment in the building can be shut down.

If a fire begins to burn the spilled material, the health hazard may become less important and the evacuation distance may not have to be as great as they were with no fire involvement.

In order to estimate the dispersion of the gas at a spill, the following information is needed:

- Whether it is day or night
- Estimated wind speed
- Wind direction
- Amount of cloud cover (to determine stability)
- Description of topography

Some firms maintain libraries of USGS maps of the transportation corridors most commonly used in shipping dangerous materials.

B. Accidents at Plant Sites

The instrumentation at a plant often provides a good estimate of the amount of gas released. It is recommended that all plants which handle or process toxic gases record meteorological data and have that data available at several locations in the plant. This data should include the following parameters:

- a) Wind speed
- b) Wind direction
- c) Standard deviation of wind direction

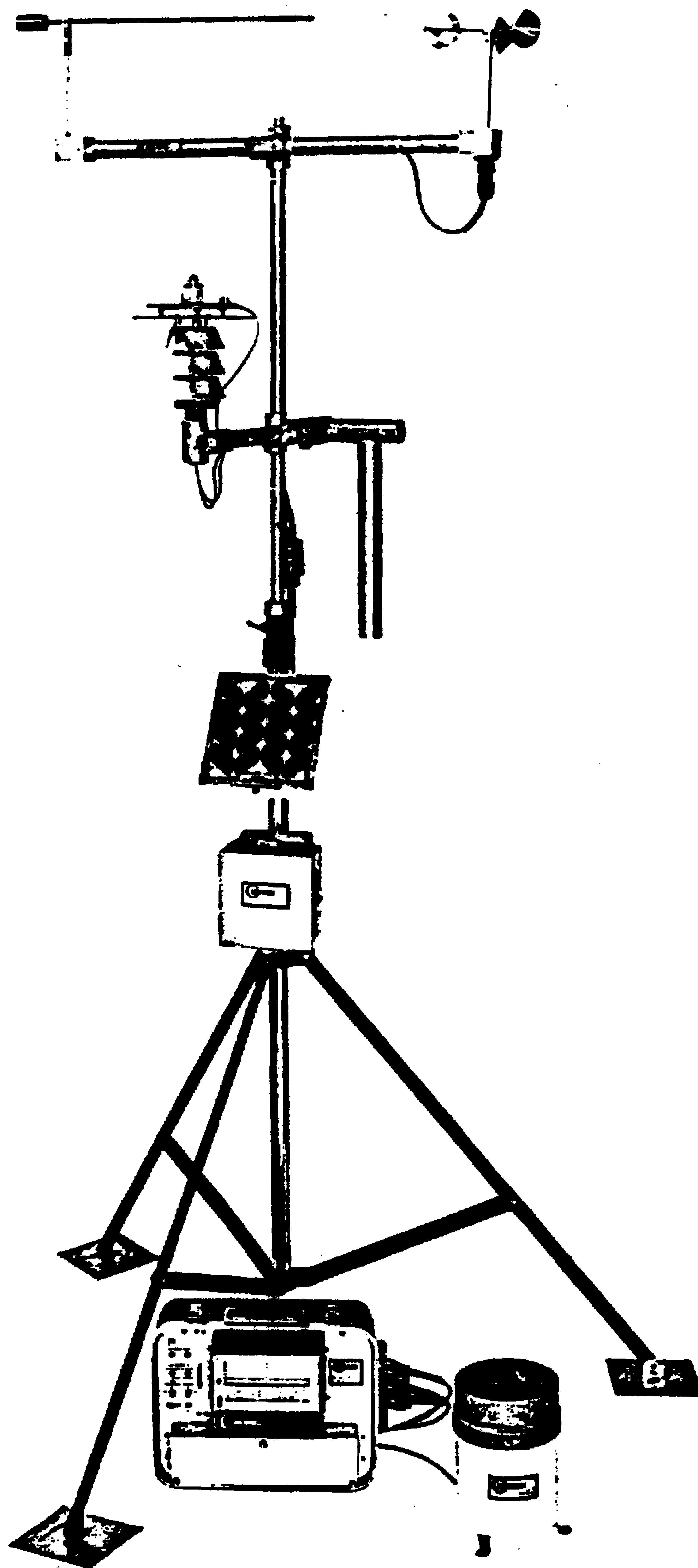
Wind direction should be recorded with a low-mass wind vane, not the type that looks like a wingless, single-engine airplane. The vane should respond quickly to variations in wind direction.

Figure 19 illustrates a typical Weather Station. It is recommended that wind speed and direction be recorded at a 10 meter elevation. The approximate costs are as follows:

<u>Parameter(s)</u>	<u>Cost</u>
Wind speed, wind direction, temperature and strip chart recorder	\$ 3200
Sigma-theta card	600
Cassette recorder	2800
Tripod mast as shown	150
10 meter mast	300
Dew point sensor	675
Solar panel (Solar radiation)	450
Tipping bucket rain guage	475

The availability of real-time meteorological data will aid in forecasting the speed and direction of travel of any released material. Moreover, the recording of the data will be invaluable in determining the validity of any claims for compensation should there be an accident.

Figure 19



A

Some firms that handle toxic gases place monitors along fence lines. An analysis should be made of the width and the vertical dimension of any possible release. This should be compared to the actual or proposed spacing of inlets to the sampler. It is therefore suggested that the inlets to the sampler should be no more than 3 times sigma y apart in the horizontal direction and about one sigma z above grade for releases within 5 meters of the ground.

IX. Techniques for Reducing Risk

There are numerous techniques for reducing the risks.

1. Limit the amount stored at the site. Design a manufacturing process that immediately consumes any toxic gases in further processing. The reduced risk of an accident must be weighed against the reliability of the manufacturing process in which, for example, the failure of a phosgene production unit results in the immediate shutdown of the toluene diisocyanate plant.
2. Construct a building around the plant or loading area. Many chemical plants are built outside with pipes and vessels suspended from a structural steel framework. If the entire process were located in a building, then a monitor could be installed on the forced draft building exhaust vent. Furthermore, the building exhaust vent could be elevated, like a stack, to greatly reduce ground level concentrations.

In some types of facilities there is a fear of an explosion which militates against an enclosed structure. One firm enclosed the process area down to an area about six feet above grade. A large cooling tower fan was installed on the gabled roof. This arrangement overcame possible explosion problems while insuring that most gases from any release would occur at

a significant elevation.

3. Conduct hazardous operations when dispersion is best. Bright, sunny days with moderate to strong winds are indicative of a great deal of atmospheric turbulence and the conditions which will most rapidly dilute a cloud. It may also be possible to select days or times when the winds would not carry any cloud towards populated centers. If a railroad were to attempt to move a punctured tank car of hydrogen fluoride, it should be accomplished on a clear day with strong winds in a direction to affect the fewest people. A semi-conductor manufacturer should choose to move bottles of toxic gases such as arsine during the lunch hour when employees are absent or during the weekend day shift.

4. Properly train people. When a disaster occurs, the reaction of most people is unpredictable. There have been cases where employees have run towards a chlorine cloud and successfully sued their employer. Therefore, it is prudent to develop a detailed plan and to rehearse it.

Nearly everyone recalls the fire drills that took place when they went to grammar school. The fire bell would ring and students and teacher would proceed quickly and orderly outdoors. After a while the fire drill became routine and because it is, deaths from school fires are virtually

non-existent today.

A similar attitude is beneficial at a plant where drills should be conducted not just during the working day, but at all hours. Most of these drills can be announced in advance, but a few can be a surprise.

The drill can test evacuation procedures, evacuation and plant shutdown procedures, evacuation and fire procedures. The drills can be only for plant personnel and on site contractors or they can be held jointly with local public safety officials.

The ideal situation is one in which all personnel involved react out of habit as a result of regular drills.

5. Design unique fittings to avoid misconnections. One of the causes of the Bhopal disaster was the introduction of water instead of nitrogen into a storage tank. One can speculate that the threads on the fittings of the water and nitrogen lines were alike. By making these fittings unique, an error of this type can be avoided.
6. Use existing equipment to increase dispersion. For example, if a vent that could carry a toxic gas release is near a boiler stack, duct the vent to it. The plume rise on the boiler stack will greatly reduce ground level concentrations. If there is an incinerator or burner, supply at least part of the burner

air from the forced draft ventilation of a building in which hazardous gases are used.

7. Provide communications equipment to nearby residents. In at least one location plant safety personnel can broadcast a message directly into homes that could be affected by a release. The residents can be directed to first, close all windows, second, open windows after the cloud has passed or, third, evacuate the area. Some plants are starting to rely on automatically dialed telephone messages. Although some plant managers have been reluctant to share their knowledge of the risks with nearby residents, this will be a requirement of British law effective January 1, 1986.

8. Use water sprays. Tests show that water spray curtains can mitigate the consequences of the release of heavy gases into the atmosphere.^{1,2} The water spray curtain acts to entrain large quantities of air producing a rapid dilution of a dense plume. Several conclusions are drawn from the studies. Location of the barrier makes little difference but by placing it closer to a source, both water use and construction costs are lowered. As wind speeds tripled from 2 to 6 m/sec, the effectiveness of the barrier fell by 50 percent. Increasing the water pressure increased the rate of dilution.

The water spray systems were most effective under stable

conditions. In nearly all cases the resulting dilution was at least a factor of 10 and often could get as large as 50. The barriers are most effective in rapidly decreasing concentrations of flammable gases below the lower explosive limit. The use of water sprays appears to have only limited value where concentrations are less than 10,000ppm or distances are greater than 1000 meters from the source.

9. Construct retention areas. Construct dikes around storage tanks and build basins underneath large process vessels and rail or truck loading facilities. Design the basin to maximize the depth of the liquid and reduce the surface area. Make provision for pumping accumulated liquids to safe storage tank.
10. Ignite flammable gases. The standard procedure in natural gas drilling operations is to ignite a well blow-out if there is significant hydrogen sulfide in the gas. Not only does this convert the hydrogen sulfide to sulfur dioxide (a less hazardous gas) but it adds significantly to plume elevation because of plume buoyancy.
11. Store gases as refrigerated liquids. The catastrophic failure or even a large hole of a pressurized container results in an immediate release of the contents. If the same material were stored in a refrigerated container at atmospheric pressure, the

leak from or failure of the container would result in a boiling pool on the ground. This would extend the period of release reducing the peak concentrations and allowing those in the path of the cloud more time to escape. If a method of containing the leak exists, then it may be possible to recover the product reducing the magnitude of the release.

12. Use pressure relief valves. Many containers have "blow-out" plugs that melt or are forced out under excessive internal pressure. The use of pressure relief valves will reduce the quantity of the material released and distribute the release of the entire contents of a vessel over an extended period.
13. Sample for contaminants. One reason many accidents occur is because of contaminated raw materials. It is wise to sample all incoming raw materials as well as manufactured raw materials to reduce the risk that contamination could cause an unplanned release.
14. Rely on a plan. Real-time systems for forecasting the path of a toxic cloud can be helpful. On the other hand, the use of these systems may reduce managements' interest in frequent, serious drills and thereby impart a false sense of security. Moreover, power to a computer may be lost if the accident is a result of a power failure or the catastrophic release itself causes a power failure. Management may wish to use the

periodic, unplanned power failures at its plants as a means to evaluate shut-down procedures and emergency procedures using computer-based aids.

15. Keep people indoors. The indoor concentrations of pollutants are generally less than those outdoors. The ratio of the two concentrations is:³

$$\frac{X_i}{X_o} = 1 - e^{-ct}$$

X_i = Indoor concentration

X_o = Outdoor concentration

c = Air changes per unit time

t = Time interval

Typically a sealed building will experience between 0.1 and 1.5 air change per hour depending on the make-up air to the ventilation system. A building with open windows on a breezy day will experience 5 to 10 changes per hour. In a typical office building with 1.5 changes per hour the indoor five minute concentration will be only $(1 - e^{-1.5/12})$ or 12 percent of the outdoor concentration.

very leaky office bldg.

CHAPTER IX: REFERENCES

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2. McQuaid, J. and Fitzpatrick, R. D., "Air Entrainment by Water Sprays: Strategies for Application to the Dispersion of Gas Plumes", Journal of Occupational Accidents, 5 (1983) 121-133.
3. Beattie, J. R., "A Quantitative Study of Factors Tending to Reduce the Hazards from Airborne Clouds", Appendix 3 Canvey Report (1978).

X. Computer Models

The first eleven models employ puff algorithms and may also use continuous release algorithms. The next group of models starting with K. PTPLU are continuous release models that are part of the UNAMAP series of programs.

A. SPILLS

This model was developed by Shell Development Company, Houston, Texas, and given to the U.S. Government for public distribution.¹

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 liquefied gases and 3) stacks, where the emission rate is assumed to be known. This model does not analyze concentrations from dense gas clouds. For options 1 and 2, thermophysical properties (available as a subroutine in the computer program) 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 first option is for a small continuous leak of a liquid. Two key variables are unknown, the area of the pool and the emission rate into the atmosphere. Since the area of the pool is difficult to determine, the model makes the simplifying assumption that the emission rate from the leak is equal to the emission rate to the atmosphere. The model calculates the spill area based on convective mass transfer (evaporation). The model also assumes that the liquid spilled is at ambient temperature and pressure so that there is no heat transfer between the pool and the earth.

The second option considers instantaneously formed pools. The mechanism by which the evaporation will take place depends on the nature of the chemical spilled. Chemicals with a normal boiling point below ambient temperature will first flash off due to the pressure drop between the storage pressure (the storage temperature has to be specified by the user) and atmospheric pressure. The evaporation rate due to this adiabatic flash calculation is assumed to occur during the first minute after the spill. The chemical will then form a pool of liquefied gas at its normal boiling point. In reality the remaining liquid after rapid depressurization is often an aerosol rather than a boiling pool. The difference between the temperature of the boiling pool and the ambient temperature will cause heat to be transferred from the ground (the soil is assumed to be at

A

ambient temperature) to the pool by conduction, and from the atmosphere to the pool by convection. Mass transfer, due to the wind blowing over the pool, takes over when the heat transfer evaporation rate becomes equal to the mass transfer evaporation rate. Note that this occurs because the heat transfer rate decreases as time increases whereas, the mass transfer rate is independent of time. The emission rate is set to zero when all the chemical is evaporated. With this option the user must specify, both the amount spilled and the area of the pool.

The third option provides for dispersion of gases from stacks, vents, leaks or other point sources. The user supplies up to 100 emission rates for each time interval from the initiation of the phenomenon. If only one rate is supplied, the program considers the case to be steady state. This option incorporates the Briggs plume rise formulas.

This Pasquill-Gifford dispersion coefficients are used in this model. Total calculated concentrations at a receptor are determined by integrating the contributions from puff centers within four standard deviations from the receptor. For area sources the initial plume width is set equal to the area width divided by 4.3.

The output of the program contains a printer-plot of the

isopleths of concentrations from a release. Typically, the TLV-TWA and the STEL are displayed for the 36 chemicals analyzed by the program.

This program is designed for use on an IBM mainframe computer. Although it is user-friendly, the user must have some type of communications link to the host computer.

B. SAFER

This system is the most widely used real-time toxic gas response system today. It is a sophisticated product that has been marketed very effectively. There are over 30 installations including some overseas. The manufacturer is SAFER Emergency Systems, Inc., 756 Lakefield Road, Westlake Village, CA 91361.

The system is designed around a 32-bit microprocessor employing a Motorola 68000 CPU. It includes a high-resolution 19-inch color graphics screen, a monochrome CRT and a printer. Meteorological information is recorded on site and directly entered into the system. Monitored information on chemicals can also be entered directly.

In its usual operating mode the programs are activated by a light pen. The color graphics terminal typically displays

diagrams of the plant so the operator can pinpoint a leak and maps of the area around the plant on which the projected path of a gas cloud is displayed.

The monochrome screen provides instructions to the operator such as persons to be notified and their telephone numbers. The printer is useful to print out the meteorological record for the previous day as well as a list of landmarks, phone numbers, time of arrival of cloud, direction it is coming from, distance from the plant and the proper message to give the authorities. Also reported is the type of chemical, release time, spill size, maximum downwind distance the cloud will travel and a table of critical concentrations at various downwind distances.

The system can also place telephone calls automatically, send messages over the telephone lines, and keep track of which calls were made and which calls were completed.

The system answers critical questions often asked by plant officials during a release of a hazardous chemical. These include: 1) which direction the vapor cloud is moving, 2) will the concentrations downwind of the plant site exceed critical toxicity levels or explosive limits, 3) how soon will the cloud arrive at population center, 4) when will the cloud disperse to a safe level.

In the case of a leak, sensors tied directly into the system automatically detect the ambient concentrations of the escaping vapors and sound an alarm at the central station, thus alerting the plant operator to the release. The plant operator then enters information into the system regarding type of chemical released and size of leakage ("default" amounts are pre-stored for each plant equipment). Wind direction, speed, temperature and stability data, measured from a tower and sensors located on the plant site, are continuously fed into the system and automatically updated.

The system then quickly calculates the projected path of the vapor cloud and atmospheric dispersion rate of a specific chemical. This calculation of the cloud is displayed in different colors and superimposed over base maps of the plant and surrounding community. Should the wind direction change, the system will automatically shift the projection of the cloud to the new direction. Properties of the plant's chemicals are already pre-programmed into the system so that density, dilution and evaporation effects are taken into account in the on-going calculations.

Print-outs of the emergency actions to be taken are tailored to the severity of the situation, thus eliminating the problem of

over-reacting and causing an unnecessary evacuation.

However, should the release be a severe one, the print-out provides pre-planned instructions on whom to call and what to say. This includes telephone number, areas affected, evacuation routes, emergency procedures and health effects from exposure to the vapors.

The dispersion model is a multiple Lagrangian Wall and can consider both puffs and continuous sources. Complex terrain and wind channeling can be incorporated. No information was provided on the dispersion coefficients or on the mechanics for determining liquid evaporation or buoyancy effects.

The basic price of this system is in the \$70,000 range. The most common use of SAFER is in postulating scenarios and in conducting drills.

C. CHARM

This model was developed by Radian Corporation, 8501 Mo-Pac Boulevard, Austin, TX 78766. CHARM is an acronym for Complex Hazardous Air Release Model and it has been implemented on an IBM-PC with a color graphics screen. Data on 57 compounds are stored. Algorithms for continuous liquid release, continuous

*The release source frequency; 20% in
Sci. content
is unknown.*

gas release, instantaneous liquid or gas releases and fires are included.

use for planning; is not real-time met data input.

The dispersion model has been validated against actual tracer studies of gas release experiments and can simulate the transport and dispersion of buoyant, neutral or heavier-than-air releases.

Meteorological data can be input automatically or by the user. All event data and inputs are archived for documentation and data analysis. The software is priced at about \$10,000 and there are about 40 purchases. Not all purchasers have been able to implement CHARM.

Developer of Software has left Ladian. Ladian has rehired him as a consultant. Members of Houston Regional Monitoring Network have copies.

D. CARE

This system was developed by Environmental Systems Corporation, 200 Tech Center Drive, Knoxville, TN 37912. CARE is an acronym for Computerized Airborne Release Evaluation System. The software can be implemented on an IBM-PC or HP200 personal computer.

The system consists of 5 modules. The source module contains an inventory of chemicals and their properties. It includes a gravitational slumping model for use with dense gas clouds. The meteorological module relies on observed data or it modifies

observed data via a three dimensional wind-field model for use in complex terrain.

The dispersion module is based on a puff-advection model that has a variable trajectory. The display shows the location and concentration of the hazardous chemical. An effects module provides information on the hazard posed to health and welfare by the materials in the plume. It includes dose calculations for nuclear releases as well as data on the TLV and IDLH for chemicals. The fifth module provides the user with recommended response actions.

E. HASTE

*A sale
state of La.*

This system was developed by Environmental Research and Technology, Inc., 696 Virginia Road, Concord, MA 01742. HASTE is an acronym for Hazard Assessment System for Toxic Emissions. The system can be implemented on an IBM-PC or on an NEC APC. There is one known installation. The system sell for about \$40,000.

The system features include a menu driven decision assistance program supported by color graphics, computerized inventories of hazardous chemicals and their properties, pre-programmed release scenarios, dispersion models for dense gas and neutrally buoyant

plumes, real-time or user-input meteorological data, archiving capability for input data and results and automated emerging protocols.

F. EPCHEMS II

This system was developed by Enviroplan, 59 Main Street, West Orange, NJ 07052. EPCHEMS II consists of Enviroplan's Chemical Emergency Mitigation System and a Continuous Emissions Monitoring Data Acquisition System.

*Data General
Computer
new
no sales.*

The system bases its source term on the continuous monitoring of pressure, flow and level for any number of storage tanks and pipes to determine whether parameters are in accepted safe ranges. It alerts control room personnel and aids personnel to respond to the emergency. It calculates and displays concentrations from the release on maps of the area. The system is implemented on a small Data General minicomputer.

G. MESOCHEM, JR.

no sales

This system was developed by Impell Corporation (a subsidiary of Combustion Engineering, Inc.) 350 Lennon Lane, Walnut Creek, CA 94598.

A

This system was originally developed on a main frame computer for clients in the nuclear industry. It uses color graphics and has many if not all the features common to SAFER, HASTE, CARE and EPCHEMS II.

H. Other Systems

Both NUS (Gaithersburg, MD) and Dames & Moore (Chicago, IL) have been prominent in developing systems for emergency response in the nuclear industry on large main frame computers. Both firms offer similar systems to chemical firms for toxic gas releases.

Two other systems under development include CEES, Energy Impact Associates, Pittsburgh, PA and MARRS, Ensco, Indian Harbor, FL.

I. EPA Puff

In 1982, EPA published "Estimating Concentrations Downwind from an Instantaneous Puff Release".² A copy of this publication is included in the Appendix. This model is based on a summary of experiments on the dispersion of clouds from quasi-instantaneous releases contained in Meteorology and Atomic Energy.³ Turner refers to this work in the Workbook of Atmospheric Dispersion Estimates.⁴ Although it is difficult to make direct comparisons between the puff model and continuous models, the concentrations calculated using the quasi-instantaneous dispersion coefficients

are several times those using Pasquill-Gifford coefficients.

user friendly

The EPA program calculates peak instantaneous values and time-averaged values for times selected by the user. It assumes steady state wind conditions. The user supplies the initial height of the release, and the standard deviations of the initial cloud size. The three stability categories analyzed are unstable, neutral and stable.

Concentrations are calculated for 12 downwind distances ranging from 10 meters to 30 kilometers. This model is not particularly user-friendly in terms of both the calculations required by the user before creating an input and in the input format. The model does represent EPA's thinking regarding the analysis of quasi-instantaneous spills.

J. TRPUF

15-20 out in field

\$100.00

This model is based on the EPA puff model and was developed by Trinity Consultants, Inc. Its input is much more user-friendly and the output is significantly more useful than EPA puff. The model is executable on an IBM-PC and includes a graphics capability in which plots are produced on the PC printer. Figure 20 summarizes the differences between TRPUF and the EPA puff model. Figure 21 is a copy of the output of TRPUF and Figure 22 is a plot of the output produced on an IBM-PC printer. This model is used primarily to help management analyze various

Figure 20

Major Differences Between TRPUF and EPA Puff Models

	<u>TRPUF</u>	<u>EPA Model</u>
Concentration at release point and farther downwind	Calculates a virtual distance so that the calculated concentration at release point is equal to the concentration used as input. The user can also specify the distance downwind for which cloud dimensions are known.	Vectorially adds initial sigma values to sigma values for downwind distances.
Average Concentrations	Calculates peak instantaneous as well as average concentrations for all receptors.	Calculates peak instantaneous at all receptors and average concentrations only at discrete receptors.
Receptors	Receptor grid consists of 70 downwind distances selected easily by the user.	Receptor grid consists of 12 downwind distances from 10 meters to 30 kilometers downwind.
Plume Rise	Uses Briggs' unstable/neutral momentum plume rise for all stability classes.	User inputs a fixed value independent of wind speed.
Concentration Units	User selects ppm, mg/m ³ or ug/m ³	grams/m ³
Other Information	Displays travel time and sigma values	—

Figure 21

TRPUF - R005
 COPYRIGHT 1985 TRINITY CONSULTANTS, INC.
 A PUFF MODEL DEVELOPED BY TRINITY CONSULTANTS, RICHARDSON, TEXAS 214/234-8567

EXAMPLE OF TRPUF5

RELEASE AMOUNT (POUNDS) = 2.20500 RECEPTOR HEIGHT ABOVE GRADE (FEET) = 5. INITIAL CONCENTRATION (PPM) = 5.00E+05
 MOLECULAR WEIGHT = 64.00 EXIT VELOCITY (FEET PER SECOND) = 5.000 INITIAL HORIZONTAL SIGMA (FEET) = .00
 AMBIENT TEMPERATURE (DEG F) = 88.00 STACK DIAMETER (FEET) = 1.50 INITIAL VERTICAL SIGMA (FT) = .00
 AMBIENT PRESSURE (MB) = 1013.00 WIND SPEED (MPH) = 5.0 DOWNWIND DISTANCE (FT) = 0.
 STACK HEIGHT (FEET) = 60.00

COMPUTED VIRTUAL DISTANCES (FT) HORIZONTAL VERTICAL
 UNSTABLE 3.3 3.3
 NEUTRAL 16.4 16.4
 STABLE 85.3 85.3

DOWNWIND DISTANCE (FEET)	PEAK INSTANTANEOUS CONCENTRATIONS (UG/M3)				AVERAGE CONCENTRATIONS FOR 300. SECONDS (UG/M3)				TRAVEL (MINUTES)	--- SIGMAS (FEET) ---					
	UNSTABLE	NEUTRAL	STABLE	MAXIMUM	UNSTABLE	NEUTRAL	STABLE	MAXIMUM		UNSTABLE HOR VER	NEUTRAL HOR VER	STABLE HOR VER			
20	5.5409E-07	2.2128E-09	6.7703E-09	5.5409E-07	1.7591E-09	4.5425E-12	1.1093E-11	1.7591E-09	.045	3 7	2 3	1 1			
40	2.0281E+01	7.2767E-10	4.4680E-09	2.0281E+01	1.1391E-01	2.2348E-12	8.5457E-12	1.1391E-01	.091	5 11	3 4	2 2			
60	1.9562E+03	3.3662E-10	3.1362E-09	1.9562E+03	1.5583E+01	1.3668E-12	6.8435E-12	1.5583E+01	.136	7 15	4 4	2 2			
80	1.2150E+04	1.8649E-10	2.3043E-09	1.2150E+04	1.2461E+02	9.3783E-13	5.6399E-12	1.2461E+02	.182	9 18	4 5	2 2			
100	2.8975E+04	1.1553E-10	1.7539E-09	2.8975E+04	3.6224E+02	6.9102E-13	4.7519E-12	3.6224E+02	.227	11 22	5 6	2 2			
120	4.5077E+04	4.2469E-10	1.3728E-09	4.5077E+04	6.6321E+02	2.9391E-12	4.0747E-12	6.6321E+02	.273	13 25	6 7	3 2			
140	5.6339E+04	1.9488E-07	1.0993E-09	5.6339E+04	9.5187E+02	1.5296E-09	3.5444E-12	9.5187E+02	.318	15 27	7 7	3 2			
160	6.2312E+04	1.7899E-05	8.9711E-10	6.2312E+04	1.1873E+03	1.5694E-07	3.1199E-12	1.1873E+03	.364	17 30	8 8	3 2			
180	6.4114E+04	5.3571E-04	7.4386E-10	6.4114E+04	1.3586E+03	5.1847E-06	2.7738E-12	1.3586E+03	.409	19 33	8 9	3 2			
200	6.3107E+04	7.4087E-03	6.2525E-10	6.3107E+04	1.4710E+03	7.8394E-05	2.4873E-12	1.4710E+03	.455	20 35	9 9	3 2			
220	6.0408E+04	5.9064E-02	5.3177E-10	6.0408E+04	1.5350E+03	6.7793E-04	2.2469E-12	1.5350E+03	.500	22 38	10 10	4 3			
240	5.6808E+04	3.1416E-01	4.5695E-10	5.6808E+04	1.5621E+03	3.8856E-03	2.0429E-12	1.5621E+03	.545	24 40	11 10	4 3			
260	5.2623E+04	1.2322E+00	3.9622E-10	5.2623E+04	1.5620E+03	1.6331E-02	1.8680E-12	1.5620E+03	.591	26 43	12 11	4 3			
280	4.8773E+04	3.8245E+00	3.4633E-10	4.8773E+04	1.5427E+03	5.4052E-02	1.7168E-12	1.5427E+03	.636	28 45	12 12	4 3			
300	4.4843E+04	9.8854E+00	3.0491E-10	4.4843E+04	1.5103E+03	1.4836E-01	1.5848E-12	1.5103E+03	.682	30 47	13 12	5 3			
320	4.1134E+04	2.2095E+01	2.7017E-10	4.1134E+04	1.4692E+03	3.5084E-01	1.4690E-12	1.4692E+03	.727	31 50	14 13	5 3			
340	3.7693E+04	4.3934E+01	2.4079E-10	3.7693E+04	1.4228E+03	7.3567E-01	1.3666E-12	1.4228E+03	.773	33 52	15 13	5 3			
360	3.4536E+04	7.9416E+01	2.1575E-10	3.4536E+04	1.3733E+03	1.3963E+00	1.2756E-12	1.3733E+03	.818	35 54	15 14	5 3			
380	3.1659E+04	1.3271E+02	1.9424E-10	3.1659E+04	1.3225E+03	2.4508E+00	1.1942E-12	1.3225E+03	.864	37 56	16 14	5 3			
400	2.9050E+04	2.0776E+02	1.7566E-10	2.9050E+04	1.2717E+03	4.0143E+00	1.1212E-12	1.2717E+03	.909	39 58	17 15	6 3			
420	2.6688E+04	3.0788E+02	1.5949E-10	2.6688E+04	1.2215E+03	6.2112E+00	1.0553E-12	1.2215E+03	.955	40 60	18 15	6 4			
440	2.4554E+04	4.3556E+02	1.4536E-10	2.4554E+04	1.1726E+03	9.1568E+00	9.9557E-13	1.1726E+03	1.000	42 62	18 16	6 4			
460	2.2625E+04	5.9227E+02	1.3294E-10	2.2625E+04	1.1252E+03	1.2952E+01	9.4130E-13	1.1252E+03	1.045	44 65	19 16	6 4			
480	2.0882E+04	7.7844E+02	1.2198E-10	2.0882E+04	1.0797E+03	1.7680E+01	8.9179E-13	1.0797E+03	1.091	45 67	20 17	6 4			
500	1.9305E+04	9.9350E+02	1.1225E-10	1.9305E+04	1.0361E+03	2.3400E+01	8.4648E-13	1.0361E+03	1.136	47 69	21 17	7 4			
520	1.7877E+04	1.2360E+03	1.0359E-10	1.7877E+04	9.9452E+02	3.0148E+01	8.0487E-13	9.9452E+02	1.182	49 71	21 17	7 4			
540	1.6583E+04	1.5038E+03	9.5846E-11	1.6583E+04	9.5490E+02	3.7935E+01	7.6657E-13	9.5490E+02	1.227	51 72	22 18	7 4			
560	1.5408E+04	1.7940E+03	8.8899E-11	1.5408E+04	9.1724E+02	4.6751E+01	7.3121E-13	9.1724E+02	1.273	52 74	23 18	7 4			
580	1.4339E+04	2.1035E+03	8.2645E-11	1.4339E+04	8.8147E+02	5.6565E+01	6.9849E-13	8.8147E+02	1.318	54 76	24 19	7 4			
600	1.3366E+04	2.4290E+03	7.6997E-11	1.3366E+04	8.4753E+02	6.7328E+01	6.6813E-13	8.4753E+02	1.364	56 78	24 19	8 4			
620	1.2478E+04	2.7668E+03	7.1881E-11	1.2478E+04	8.1534E+02	7.8978E+01	6.3992E-13	8.1534E+02	1.409	57 80	25 20	8 4			
640	1.1667E+04	3.1135E+03	6.7234E-11	1.1667E+04	7.8480E+02	9.1440E+01	6.1363E-13	7.8480E+02	1.455	59 82	26 20	8 4			
660	1.0924E+04	3.4656E+03	6.3002E-11	1.0924E+04	7.5585E+02	1.0463E+02	5.8910E-13	7.5585E+02	1.500	61 84	26 21	8 4			
680	1.0244E+04	3.8200E+03	5.9138E-11	1.0244E+04	7.2838E+02	1.1847E+02	5.6616E-13	7.2838E+02	1.545	62 86	27 21	8 4			
700	9.6184E+03	4.1736E+03	5.5602E-11	9.6184E+03	7.0232E+02	1.3285E+02	5.4467E-13	7.0232E+02	1.591	64 87	28 21	9 4			

Figure 21 (Cont'd)

A

TRPUF - MOD5
 COPYRIGHT 1985 TRINITY CONSULTANTS, INC.
 A PUFF MODEL DEVELOPED BY TRINITY CONSULTANTS, RICHARDSON, TEXAS 214/234-9567

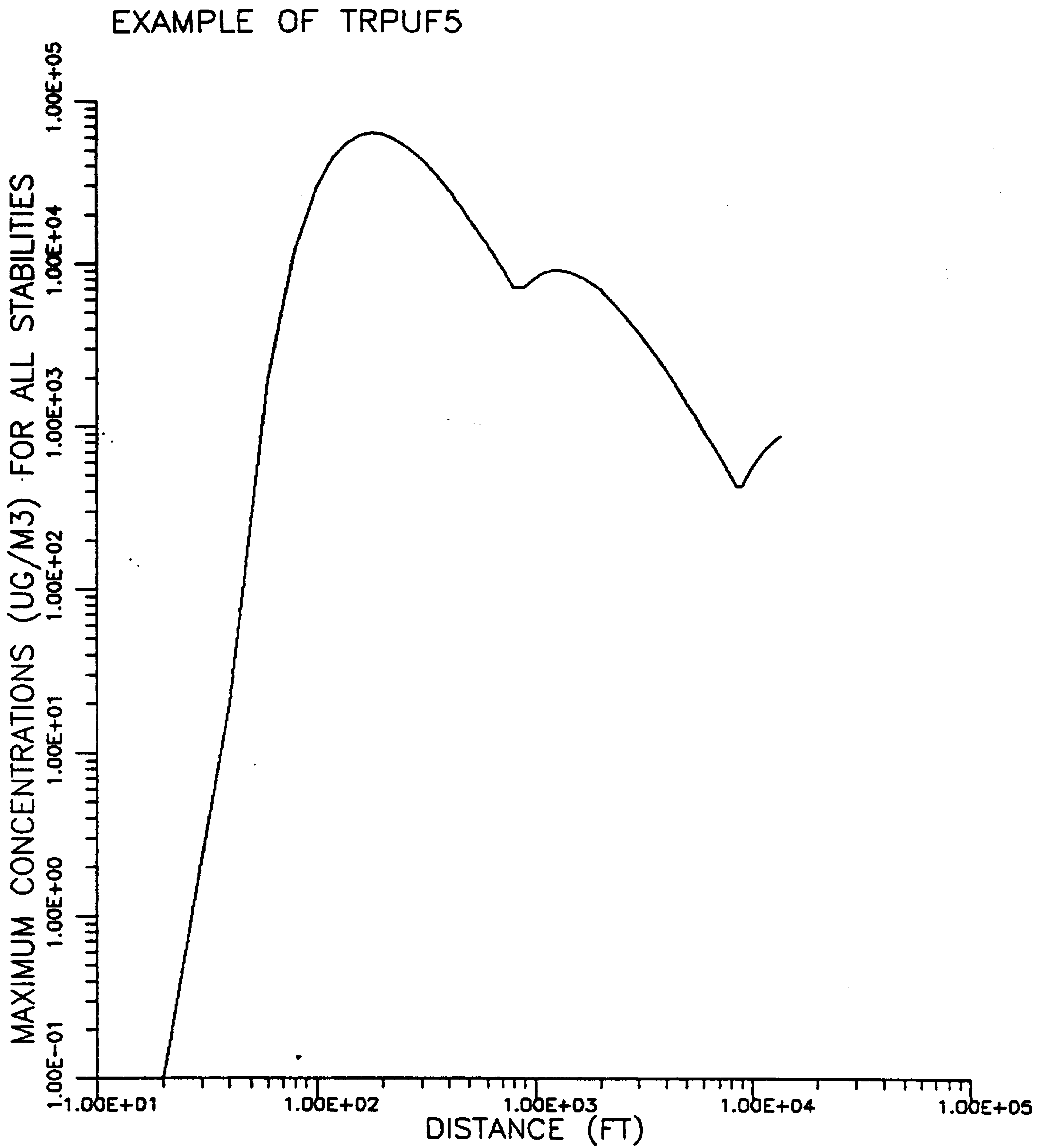
EXAMPLE OF TRPUF5

RELEASE AMOUNT (POUNDS) = 2.20500 RECEPTOR HEIGHT ABOVE GRADE (FEET) = 5. INITIAL CONCENTRATION (PPM) = 5.00E+05
 MOLECULAR WEIGHT = 64.00 EXIT VELOCITY (FEET PER SECOND) = 5.000 INITIAL HORIZONTAL SIGMA (FEET) = .00
 AMBIENT TEMPERATURE (DEG F) = 88.00 STACK DIAMETER (FEET) = 1.50 INITIAL VERTICAL SIGMA (FT) = .00
 AMBIENT PRESSURE (MB) = 1013.00 WIND SPEED (MPH) = 5.0 DOWNWIND DISTANCE (FT) = 0.
 STACK HEIGHT (FEET) = 60.00

COMPUTED VIRTUAL DISTANCES (FT) HORIZONTAL VERTICAL
 UNSTABLE 3.3 3.3
 NEUTRAL 16.4 16.4
 STABLE 85.3 85.3

DOWNWIND DISTANCE (FEET)	PEAK INSTANTANEOUS CONCENTRATIONS (UG/M3)				AVERAGE CONCENTRATIONS FOR 300. SECONDS (UG/M3)				TRAVEL (MINUTES)	--- SIGMAS (FEET) ---					
	UNSTABLE	NEUTRAL	STABLE	MAXIMUM	UNSTABLE	NEUTRAL	STABLE	MAXIMUM		UNSTABLE HOR VER	NEUTRAL HOR VER	STABLE HOR VER			
800	7.1553E+03	5.8462E+03	4.1752E-11	7.1553E+03	5.9044E+02	2.0986E+02	4.5504E-13	5.9044E+02	1.818	72 96	32 23	10 5			
900	5.4742E+03	7.2158E+03	3.2330E-11	7.2158E+03	5.0321E+02	2.6807E+02	3.8735E-13	5.0321E+02	2.045	81 105	35 25	11 5			
1000	4.2882E+03	8.2037E+03	2.5660E-11	8.2037E+03	4.3417E+02	3.6025E+02	3.3524E-13	4.3417E+02	2.273	89 113	39 27	11 6			
1100	3.4273E+03	8.8252E+03	2.0786E-11	8.8252E+03	3.7870E+02	4.2249E+02	2.9373E-13	4.2249E+02	2.500	97 122	42 29	12 6			
1200	2.7867E+03	9.1378E+03	1.7128E-11	9.1378E+03	3.3350E+02	4.7338E+02	2.6012E-13	4.7338E+02	2.727	105 129	45 31	13 6			
1300	2.2997E+03	9.2101E+03	2.2435E-11	9.2101E+03	2.9620E+02	5.1310E+02	3.6422E-13	5.1310E+02	2.955	113 137	49 33	14 7			
1400	1.9225E+03	9.1056E+03	3.2298E-10	9.1056E+03	2.6504E+02	5.4262E+02	5.5789E-12	5.4262E+02	3.182	121 145	52 34	15 7			
1500	1.6255E+03	8.8774E+03	4.2657E-09	8.8774E+03	2.3874E+02	5.6329E+02	7.8031E-11	5.6329E+02	3.409	129 152	56 36	16 7			
1600	1.3832E+03	8.5673E+03	4.0331E-08	8.5673E+03	2.1634E+02	5.7651E+02	7.7955E-10	5.7651E+02	3.636	137 160	59 38	17 7			
1700	1.1962E+03	8.2069E+03	2.8638E-07	8.2069E+03	1.9709E+02	5.8361E+02	5.8267E-09	5.8361E+02	3.864	145 167	62 39	18 8			
1800	1.0390E+03	7.8191E+03	1.6029E-06	7.8191E+03	1.8041E+02	5.8578E+02	3.4233E-08	5.8578E+02	4.091	152 174	66 41	19 8			
1900	9.0896E+02	7.4205E+03	7.3509E-06	7.4205E+03	1.6587E+02	5.8401E+02	1.6438E-07	5.8401E+02	4.318	160 181	69 43	20 8			
2000	8.0039E+02	7.0225E+03	2.8491E-05	7.0225E+03	1.5310E+02	5.7917E+02	6.6531E-07	5.7917E+02	4.545	168 188	72 44	21 8			
2500	4.5860E+02	5.2344E+03	4.1562E-03	5.2344E+03	1.0768E+02	5.2927E+02	1.1757E-04	5.2927E+02	5.682	206 221	89 51	25 10			
3000	2.8996E+02	3.9020E+03	9.5734E-02	3.9020E+03	8.0500E+01	4.3614E+02	3.1695E-03	4.6614E+02	6.818	244 252	105 58	29 11			
3500	1.9643E+02	2.9558E+03	7.9806E-01	2.9558E+03	6.2826E+01	4.0661E+02	3.0201E-02	4.0661E+02	7.955	281 283	121 65	33 12			
4000	1.4003E+02	2.2832E+03	3.6077E+00	2.2832E+03	5.0615E+01	3.5495E+02	1.5335E-01	3.5495E+02	9.091	317 311	136 71	37 13			
4500	1.0392E+02	1.7977E+03	1.1004E+01	1.7977E+03	4.1762E+01	3.1133E+02	5.1837E-01	3.1133E+02	10.227	354 339	152 77	41 14			
5000	7.9402E+01	1.4406E+03	2.5727E+01	1.4406E+03	3.5087E+01	2.7478E+02	1.3238E+00	2.7478E+02	11.364	390 366	167 83	45 14			
5500	6.2281E+01	1.1727E+03	4.9876E+01	1.1727E+03	2.9893E+01	2.4412E+02	2.8004E+00	2.4412E+02	12.500	425 393	183 89	49 15			
6000	4.9885E+01	9.6808E+02	8.4380E+01	9.6808E+02	2.5747E+01	2.1827E+02	5.1133E+00	2.1827E+02	13.636	461 419	198 95	53 16			
6500	4.0665E+01	8.0917E+02	1.2893E+02	8.0917E+02	2.2371E+01	1.9635E+02	8.3816E+00	1.9635E+02	14.773	496 444	213 100	57 17			
7000	3.3651E+01	6.8386E+02	1.8222E+02	6.8386E+02	1.9579E+01	1.7762E+02	1.2643E+01	1.7762E+02	15.909	531 462	228 105	61 18			
7500	2.8210E+01	5.8368E+02	2.4233E+02	5.8368E+02	1.7242E+01	1.6151E+02	1.7637E+01	1.6151E+02	17.045	566 493	243 111	65 18			
8000	2.3913E+01	5.0261E+02	3.0710E+02	5.0261E+02	1.5266E+01	1.4756E+02	2.3965E+01	1.4756E+02	18.182	600 516	258 116	68 19			
8500	2.0482E+01	4.3625E+02	3.7435E+02	4.3625E+02	1.3582E+01	1.3541E+02	3.0816E+01	1.3541E+02	19.318	635 540	272 121	72 20			
9000	1.7694E+01	3.8138E+02	4.4211E+02	4.4211E+02	1.2137E+01	1.2475E+02	3.8274E+01	1.2475E+02	20.455	669 563	287 126	76 21			
10000	1.3510E+01	2.9706E+02	5.7276E+02	5.7276E+02	9.8079E+00	1.0700E+02	5.4414E+01	1.0700E+02	22.727	737 608	316 135	83 22			
10500	1.1923E+01	2.6438E+02	6.3328E+02	6.3328E+02	8.8642E+00	9.9554E+01	6.2811E+01	9.9554E+01	23.864	771 630	331 140	87 23			
11000	1.0583E+01	2.3647E+02	6.8952E+02	6.8952E+02	8.0373E+00	9.2379E+01	7.1257E+01	9.2379E+01	25.000	805 651	345 145	91 23			
11500	9.4439E+00	2.1247E+02	7.4102E+02	7.4102E+02	7.3110E+00	8.6865E+01	7.9645E+01	8.6865E+01	26.136	838 673	360 149	94 24			
12000	8.4680E+00	1.9172E+02	7.8752E+02	7.8752E+02	6.6695E+00	8.1422E+01	8.7837E+01	8.7887E+01	27.273	872 694	374 154	98 25			
12500	7.6266E+00	1.7368E+02	8.2893E+02	8.2893E+02	6.1012E+00	7.6473E+01	9.5908E+01	9.5903E+01	28.409	905 715	388 158	102 25			
13000	6.8971E+00	1.5790E+02	8.6532E+02	8.6532E+02	5.5960E+00	7.1957E+01	1.0365E+02	1.0365E+02	29.545	938 736	402 163	105 26			
13500	6.2609E+00	1.4404E+02	8.9682E+02	8.9682E+02	5.1454E+00	6.7320E+01	1.1107E+02	1.1107E+02	30.682	971 757	417 167	109 26			

Figure 22



A

This model is used primarily to help management analyze various leak scenarios and determine the likely risks.

K. PTPLU

PTPLU is an adapted and improved version of PTMAX for quickly analyzing the approximate location of maximum concentrations and the meteorological conditions under which it occurs for a single point source. Most air quality studies will start by analyzing a representative sample of stacks with this program to guide the receptor placement in more extensive modeling.

PTPLU determines maximum concentrations through a process of iteration. In this process, concentrations are calculated for gradually increasing downwind distances until the peak is passed, then the program decreases the downwind distance until a peak is passed again. After several reversals, the maximum is found. Stack tip downwash and partial plume rise can be considered in the calculations.

L. PAL

*has a good area source
algorithm and as
receptor from center*

PAL requires the user to specify the meteorology. In addition to analyzing point sources, it accepts area sources, two types of line sources and two types of curved path sources. Up to 99

sources of each type can be analyzed. Concentration estimates can be made at 99 user-specified receptor locations. One unique feature is a superior area source algorithm. This makes models particularly useful in analyzing, fugitive dust sources, emissions from waste treatment ponds and land fills, transportation sources, and situations involving sources other than stacks.

M. ISCST

This model is the most versatile of the EPA model for analyzing short term concentrations because of its numerous features that aid the user. If used unwisely, it can be very expensive in terms of computer time.

Sources may be grouped so that average concentrations or deposition from combined sources can be calculated. The ISCST model can analyze point, area and volume sources. Source emission rates may be varied. Receptors may be located in Cartesian or polar coordinates. The effects of stack-tip downwash, building wakes and gravitational settling may also be modeled.

ISCST has one rural and two urban modes. The Rural Mode uses rural mixing heights and Pasquill-Gifford dispersion

coefficients. Urban Mode 1 uses urban mixing heights, Pasquill-Gifford coefficients, and redefines the E and F stability classes as D (neutral) stability. Urban Mode 2 also uses urban mixing heights and Pasquill-Gifford coefficients. Additionally, Urban Mode 2 combines the E and F stability classes, and uses the Pasquill-Gifford dispersion coefficients for the stability class one step more unstable than the indicated category. For example, if the meteorological data indicate C stability, Urban Mode 2 will use the coefficients for B stability.

Urban Mode 2 is recommended for area sources but should not be used for stack sources in modeling studies for regulatory purposes.

If the pollutant is depleted by an exponential time-dependent decay mechanism, the user can specify a decay coefficient. Particulate matter with an appreciable gravitational settling velocity can be modeled by using the gravitational settling option. The user divides particulate emissions into a maximum of 20 settling categories according to particle size. The settling velocity, mass fraction of total particulate emissions, and surface reflection coefficients must be specified for each category.

Emission rates may be varies, 1) by hour of the day, 2) by season or month, 3) by hour of the day and season or 4) by wind speed and stability class.

For point sources the following parameters must be specified: release height, exit velocity, inside diameter and exit temperature. The effect of nearby building wakes on concentrations can be modeled using the Huber-Snyder method by entering the building height, width and length. Entering these dimensions automatically causes the wake effects option to be used.

For area sources, the user enters the location of the southwest corner of each area source square, the length of a side and the effective emission height. For volume sources, the user enters the location and the height of the center of the volume source and the initial horizontal and vertical plume dimensions. The building wake effects option cannot be used with volume or area sources.

The user may select either a Cartesian or polar coordinate system to locate receptors. UTM coordinates can be entered if a Cartesian system is specified. For the polar system a radial distance from a user designated origin and the angle measured clockwise from north are specified. For a single source or a

group of sources in close proximity, the polar system is easiest to use. For widely separated sources, the Cartesian system is usually more convenient. The user may elect to enter a receptor grid and/or discrete receptors. A Cartesian or polar grid can be generated by the program.

Discrete receptors may be located in either Cartesian or polar coordinates. The coordinate system used to specify discrete receptors does not have to be the same as the grid system. The user may find it convenient, for example, to use Cartesian coordinates to locate discrete receptors along a plant fence line and polar coordinates for locating a receptor grid beyond the fence line in the same run.

If the source or sources being modeled are located in gently rolling terrain, the user may input terrain elevations for the base of each source and for each receptor. Receptor heights cannot exceed the lowest stack height or effective emission height.

There are six categories of program output. Any or all of these categories may be output at the user's option. The first category reproduces the input data for the problem run. This category contains all control parameters, meteorological and other constants, receptor data and source data. Additionally,

all hourly meteorological data processed by the program may be output as part of this category. The second category produces an output containing the concentrations at each receptor for each day of meteorological data processed in the problem run. For each day, tables showing concentrations for time periods and groups of sources specified by the user are printed. The third category produces an output containing the concentrations at each receptor for groups of sources specified by the user averaged over the number of days of meteorological data processed in the run. This option allows average concentrations for time periods up to a year to be calculated with ISCST. The fourth category contains tables of the highest and second highest concentrations calculated at each receptor, for sources or groups of sources time periods specified by the user. The fifth category contains a table of the maximum 50 concentrations calculated for the problem run for each time period and source group combination. The sixth category outputs the concentrations to magnetic tape. If deposition is being calculated, deposition values can be output using the above options.

N. VALLEY

This model has two modes of use. It can be used to estimate 24-hour and annual concentrations at receptors located above

stack height. Only VALLEY, COMPLEX I and COMPLEX II can do this. Alternatively, VALLEY can be used to calculate annual averages in flat terrain for rural areas.

The model analyzes 112 receptors located at seven distances on sixteen radial lines. The user can also specify worst-case short-term meteorology for use in complex terrain. Ground-level elevations are subtracted from the effective stack height. In no case, however, is the effective stack height allowed to be less than ten meters. This is illustrated in Figure 23. Short-term calculated concentrations from area and/or point sources are calculated using Briggs' plume rise and Pasquill-Gifford vertical dispersion coefficients. In the horizontal, the plume is assumed to be 22.5 degrees wide. The model assumes that a given type of meteorology will persist for 6 hours out of 24. Thus the short-term calculated values are divided by 4 to produce a 24-hour estimate. The output consists of a print-plot of calculated concentrations along with detailed data. The user can specify a print-plot of each source, the total from all sources and an elevation map. A convenient option permits one to scale the map so that it can be placed directly over standard U.S. Geological Survey maps.

This model has been criticized widely, but EPA continues to use it until a better model is proven. One of the frequent

TERRAIN ADJUSTMENTS FOR SELECTED GAUSSIAN MODELS VALLEY MODEL - STABLE CONDITIONS

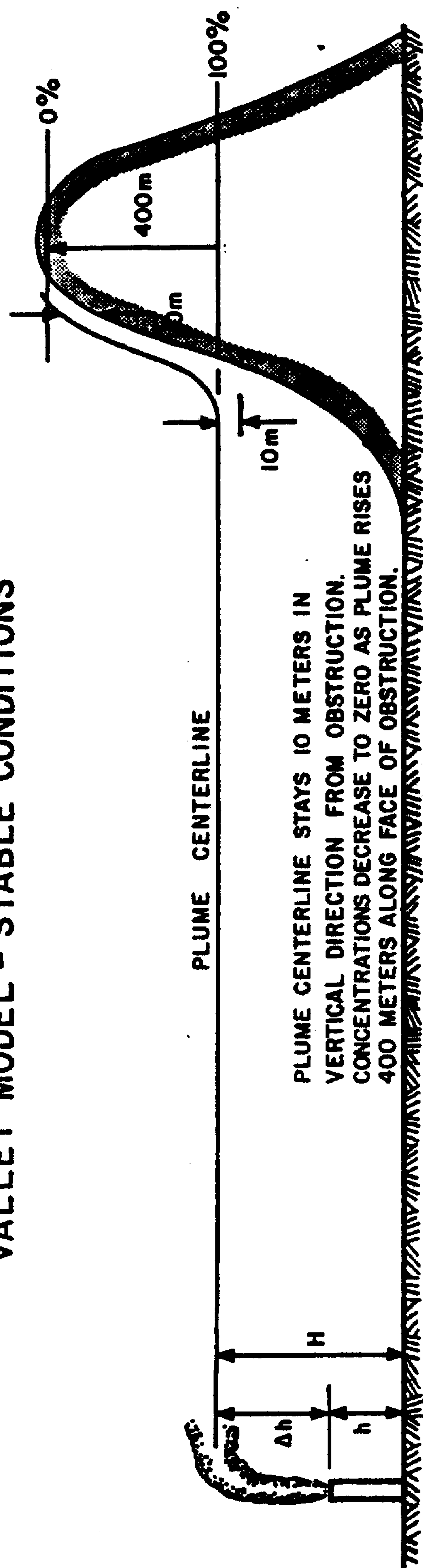
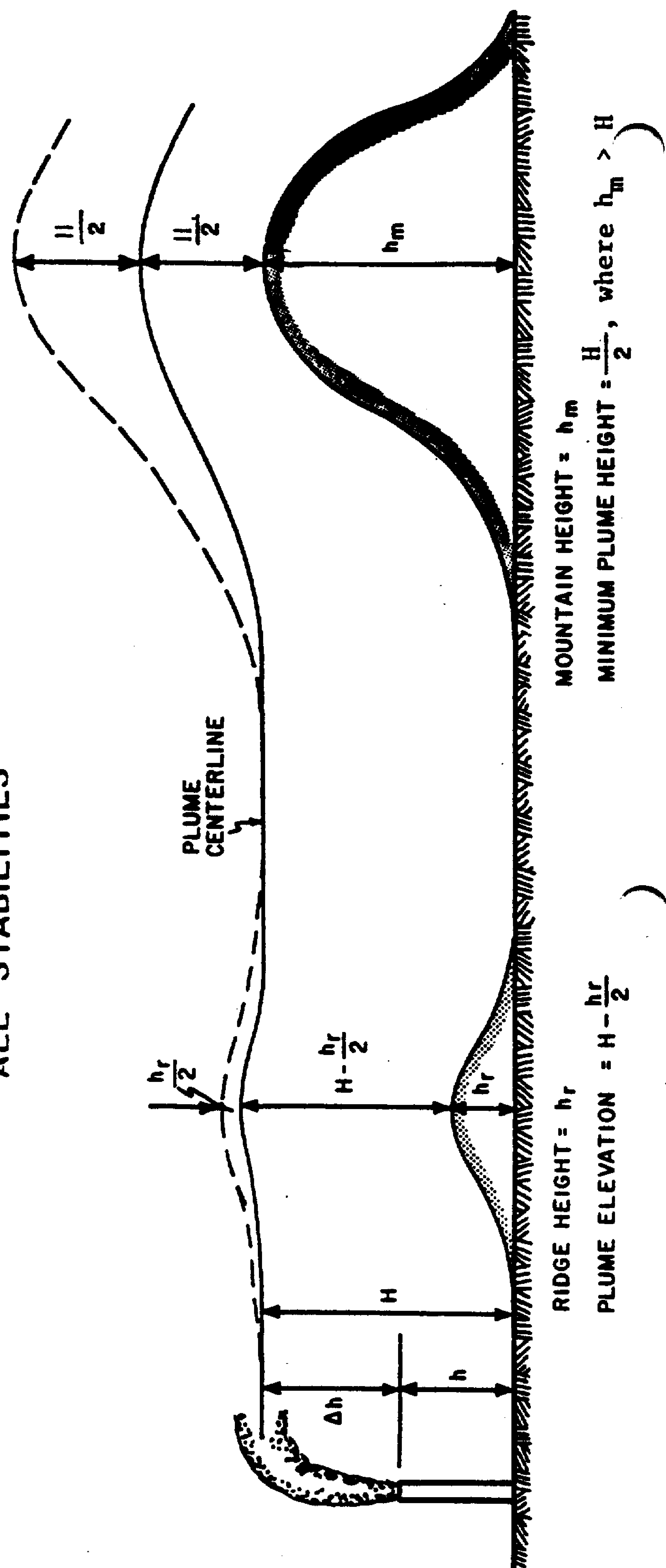


Figure 23

VALLEY PLUME MODEL ALL STABILITIES



questions concerns the 10-meter assumption, but it is relatively unimportant at distances of 2 kilometers or more from a stack. More important is the shape of the terrain. If a plume is carried towards a vertical cliff then plume impingement may occur. On the other hand, if the terrain were rather gently sloping, the air would tend to follow the slope. One study indicated that the overestimate in this case was a factor of 20.

0. TEM8

The TEM (Texas Episodic Model) was developed by the Texas Air Control Board to predict air pollution concentrations for periods up to 24 hours. Since then, it has been revised and modified to increase its flexibility and utility. The current version is TEM-8 (Version 8). The TEM was developed as an alternative to the EPA models, PTMPT and PAL. In developing the TEM, the Texas Air Control Board incorporated a number of enhancements that provided flexibility and speed in the program operation.

PTMPT and PAL were originally developed to provide a method to compare calculated and observed pollutant concentrations. For this comparison, the user input receptor points and meteorological data that would correspond to actual conditions. In contrast, the TEM calculates concentrations for a program generated grid using meteorological data supplied by the user.

By varying the input of meteorological data, the TEM is used primarily to identify worst case conditions over the area covered by the grid. Both PTMPT and PAL could also be used to simulate worst case conditions, but these conditions could only be analyzed for user-specified receptor points.

An additional enhancement made to TEM reduces the program run time. This enhancement creates a data table of precalculated constants. This data table allows the program to go through the concentration calculations only once and interpolate the other values. This enhancement provides accurate concentration predictions with a substantial saving of computer time.

In 1983, TEM was modified to allow the user to input building dimensions so that wake effects can be analyzed as they are in ISCST.

Finally, the TEM uses a time-averaging technique to spread the plume in the crosswind direction. The program takes the calculated sigma-y values for a 10-minute period and adjusts it to a 30-minute, 1-hour or 3-hour value. In this method the mass of the plume cross section is conserved for all averaging times. The 24-hour concentration may be obtained by summing the three-hour values for eight scenarios or 24 1-hour values.

questions concerns the 10-meter assumption, but it is relatively unimportant at distances of 2 kilometers or more from a stack. More important is the shape of the terrain. If a plume is carried towards a vertical cliff then plume impingement may occur. On the other hand, if the terrain were rather gently sloping, the air would tend to follow the slope. One study indicated that the overestimate in this case was a factor of 20.

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ADJUSTED SIGMA-Y RELATED TO SAMPLING TIME

<u>Stability (P-G)</u>	<u>10 Minutes</u>	<u>30 Minutes</u>	<u>1 Hour</u>	<u>3 Hour</u>
A	1.0	2.10	3.35	7.04
B	1.0	1.83	2.68	4.90
C	1.0	1.60	2.14	3.42
D	1.0	1.40	1.71	2.38
E & F	1.0	1.21	1.37	1.66

Sampling time options 1 through 4 correspond to 10-, 30-, 60- and 180-minute averaging times. Sampling time options 5 and 6 are for 24-hour evaluations using either eight 3-hour scenarios or twenty-four 1-hour scenarios. The last two options are for a variable evaluation time depending on the number of scenarios entered. Option 7 assumes the scenarios are for 10 minutes while option 8 assumes one hour. For example, using option 7 with six 10-minute scenarios will produce a 1-hour average.

TEM calculates concentrations at up to 2500 locations in a rectangular grid from up to 300 point sources (stacks) and 50 area sources.

The user has several options for presenting the calculated data: a list of receptors with concentrations, a print plot with concentrations in their correct relative location, a punched card output of concentrations for subsequent use in plotting, a list of the amount of pollutant contributed by the five most important sources to each receptor and a list of maximum concentrations for each scenario.

CHAPTER X: REFERENCES

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2. Petersen, William B. "Estimating Concentrations Downwind from an Instantaneous Puff Release", August 1982. Available from U.S. Environmental Protection Agency as EPA 600/3-82-078 or from NTIS as PB82-261959.
3. Slade, David H. "Meteorology and Atomic Energy", 1968. U.S. Atomic Energy Commission, pp 120, 173-175.
4. Turner, p. 41.

XI. Evaluation of Risks

"Safe" does not mean risk-free. There is no activity or product that does not carry some potential for accidental injury. Often this is related to the misuse of a product or equipment. What "safe" means is that society considers the risk acceptable.

This chapter is concerned with how to identify possible hazardous situations, some typical causes of hazards, how to conduct a hazard and operability survey and briefly how to relate the hazard to risk.

A. Development of Accident Scenarios

Before applying the techniques for analyzing dispersion in the atmosphere, an analysis should be performed to define the possible disaster scenarios. From such an analysis the plant manager can distinguish the accidents which have trivial consequences from those that are significant. Furthermore, the significant possible accidents can be dissected to determine whether improved process design, modification of equipment, improved operator training or other safety measures could be employed to reduce the risk.

This analysis of significant disaster scenarios will aid in the preparation of contingency plans for the plant. Although the computer provides plant managers with the ability to respond in real-time, it would be unwise to not rehearse responses for the

most likely disaster scenarios.

The loss of life from releases or ignition of flammable materials in this century is about equal to the loss of life from hazardous gas releases. Most studies of hazards generally include both ignitable releases as well as toxic gas releases. The property damage from explosions and fires is often much greater than from a toxic gas release alone. The table below summarizes accident statistics.

<u>Substance</u>	<u>Reference</u>	<u>Accidents</u>		<u>Deaths in Fatal Accidents</u>
		<u>Total</u>	<u>Fatal</u>	
Chlorine	1	18	10	112*
Chlorine	2	28	15	120*
Ammonia	1	11	5	41
Flammable gases	1	24	19	306+
Ammonium Nitrate	1	3	3	1132
Ethylene Oxide	1	2	2	5

* Excludes deaths of about 5000 allied troops at Ypres, Belgium in April, 1915.

+ Excludes the LPG incident in Mexico City, 1984 in which 300 lives were lost.

Reference 1 is dated 1979 while Reference 2 is dated 1974.

There have been other releases of toxic gases and compounds:

<u>Year</u>	<u>Location</u>	<u>Substance</u>	<u>Deaths</u>
1928	Hamburg, Germany	Phosgene	10
Late 70's	Lake Charles, LA	Phosgene	1
1976	Seveso, Italy	2,3,7,8 TCDD	none
Early 80's	Palo Alto, CA	Arsine	1
1984	Bhopal, India	Methyl diisocyanate	1600

B. Causes of Failures

On June 1, 1974 a release of 40 tons of cyclohexane was ignited in a large fire ball which largely destroyed a chemical plant at Flixborough, England, killing 28 workers. Several public inquiries were held and one result was a decision to conduct an extensive study of the chemical refinery complex at Canvey near the mouth of the Thames. This study was the first major risk assessment study made for a large refinery/chemical complex.

The British Health and Safety Executive Commissioned a \$600,000 study which was conducted by the Safety and Reliability Directorate of the Atomic Energy Authority. The selection of the contractor was a recognition of the fact that the nuclear industry has pioneered the development of risk analysis procedures.^{3,4}

The principal factors involved in failures include:⁵

- a. Operator errors
- b. Metallurgical fatigue or aging of materials
- c. Internal or external corrosion
- d. Loss of process control, e.q. pressure temperature, flow, etc.
- e. Overfilling
- f. Introduction of Impurities
- g. Fire and/or explosion
- h. Missiles
- i. Flooding

Risk is usually stated in terms of the probability of an event in a year. Thus, an event that can occur once in 100 years has

a probability of $10E-2$ this year. One event in a million years is $10E-6$.

A surprising number of accidents are the result of operator error in which water is introduced to a tank inadvertently, an improper chemical is used to clean a tank or an operator incorrectly pumps caustic soda into a tank of sulfuric acid. It is not enough to examine the obvious sources of a toxic gas release, it is also important to speculate on the reactions of chemicals manufactured, stored or consumed at a site.

C. Hazard and Operability (HAZOP) Studies

One of the first steps to assess potential hazards is a carefully structured hazard and operability (HAZOP) study. It is suggested that a team of three to five members be assembled along with flow sheets of a proposed or an existing process.⁶

The team should meet for no more than three hours at a time and a seasoned study leader should act as chairman. As a general rule, each individual part studied, such as each main pipeline into a vessel, will take about 15 minutes. Another way to estimate time is to allow 2.5 hours per vessel.

The author of the Guide indicates that after several sessions the initial tedium vanishes and the members start to derive satisfaction from such a thorough analysis of a design.

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The purpose of the study is to define the hazards. In some cases solutions for the hazards can readily be identified but in other cases special studies may be necessary to develop solutions.

D. Risk Analysis

It is generally desirable to distinguish between individual risk and societal risk. "Individual Risk" is defined as the risk to an individual of an event. "Societal Risk" is the risk to society of an event in terms of number of fatalities. Thus, individual risk varies from place to place depending on where the person happens to be at the time of a major accident. The societal risk is a measure of a combination of the likelihood and severity of a single event.

Risk is quantified by three factors:

- a. Accident frequency or probability
- b. Accident severity
- c. Exposure - the measure of the opportunity to be involved with an accident.

1. Analyzing Risk

Once hazards are identified it becomes relatively simple to assess probabilities. Consider, for example, a plant with 200 meters of piping. The risk of failure of pipe is 3×10^{-7} per meter per year.⁷ Thus, the likelihood of failure for the network is

$$200 * 3 * 10E-7 = 6 * 10E-5 \text{ per year}$$

Assume that valves exist to limit the quantity released but there is 1 in 100 chance that they will fail to work. The total risk of a large failure is:

$$6 * 10E-5 * 10E-2 = 6 * 10E-7$$

There is also a risk of release of smaller quantities of gas between the values of

$$0.99 * 6 * 10E-5 = 6 * 10E-5$$

If the gas is flammable, the risk of release can be multiplied by the probability that ignition will occur before the released gases are diluted below the lower favorable limit. Finally, meteorological and population location data is used to assess the probability of a gas release affecting nearby residents.

Statistical data is available to assess the probability of many other events. Some of the probabilities used in the second Canvey report include:

Rupture of refinery process vessels from all modes	4.4 * 10E-5 per year
Railroad tank car derailment and puncture	10E-8 per km
Probability of fire after LPG car puncture	0.73 per event
Aircraft crash into process area of a refinery	5 * 10E-6 per year

The Canvey report provides an extensive risk analysis of

ship loading and unloading accidents.

The final result of this work was a series of tables that by the second report had assessed the average individual risk at $35 * 10E-6$ per year for residents living near the Canvey complex. There was also a one in a thousand risk that ten or more lives would be lost in an incident each year.

By way of reference the individual risk of death from motor vehicle accidents in Great Britain is $130 * 10E-6$ and all other accidents about $190 * 10E-6$.

*4000-5000 x 10⁻⁶
Cigarette Smoking
Automotive death.*

2. Computer Model

Needless to say, it is expensive and time consuming to prepare a detailed plan for a plant or for a large complex. A London-based consultant, Technica, Ltd., completed a traditional study in 1981 for selected areas near Rotterdam for the Rijnmond Authority. They then developed a user-friendly computer program for risk analysis of process plants called "SAFETI".⁸ The code sells for about \$70,000, but it is available from timesharing vendors.

The user will typically be trained for about a week and spend an added one or two days collecting data for each process unit such as a group of storage vessels, chlorine plant cell room, or cracking furnace section.

A plant data file is created by an interactive program which prompts the analyst in a logical sequence. Other data needed includes the distribution of population by location, the distribution of ignition sources and meteorological data.

The output consists of individual risk contour plots which are overlaid on a map of the area and so called F-N plots. The frequency of an event (F) is plotted against the number of fatalities (N) for societal risk in a log-log presentation.

3. Value of Risk Analysis

There are many uncertainties involved in any HAZOP and risk analysis survey. First, it is difficult to speculate on all the possible operator errors that could occur. Even if a reasonable method of assessing risk is completed, there is still a great deal of uncertainty as to the consequences given the rather inaccurate nature of dispersion modeling, the number of people that will be affected, the response of individuals to acutely toxic doses and whether the people affected will be outdoors or in buildings with varying ventilation rates.

Perhaps the best that can be accomplished is to use risk assessment to evaluate relative risks. The iteration of

models with different hazard scenarios can tell management how much safer one type of control system is compared to another.

Chapter XI: References

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Publications Dept.
Chem. Ind. Association LTD
Albion House
93 Albert Embankment
London, SE1 7TU

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APPENDIX

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Table 1 Timetable for compliance - manufacturers

Requirement	Category of industrial activity	Date in force	Relevant Regulation
Demonstration of safe operation (Reg 4)	New and existing industrial activities	1.4.85	Reg 1(b)
Reporting major accidents (Reg 5)	New and existing industrial activities	1.4.85	Reg 1(b)
Safety case (Regs 7 to 9)	Existing activity*	Required by 8.7.89 but a limited notification by 1.4.85	Reg 7(3)
	New activity† commenced not more than 6 months after implementation	No later than 8.4.85	Reg 7(2)
	New activity†	At least 3 months before commencement of activity	Reg 7(1)
On-site emergency plan (Reg 10)	Existing activity	1.4.85	Reg 10(3)(b)
	New activity† commenced not more than 3 months after implementation	No later than 8.4.85	Reg 10(3)(a)
	New activity†	Before commencement of activity	Reg 10(3)(a)
Off-site emergency plan (Reg 11)	Existing activity and new activity† commenced before 1.10.85	1.10.85 or within 6 months of the local authority being notified by HSE, whichever is the later	Reg 11(3)
	New activity†	Before commencement of activity or within 6 months of the local authority being notified by HSE, whichever is the later	Reg 11(3)
Informing the public (Reg 12)	Existing activity	1.1.86	Reg 12(3)
	New activity† commenced before 1.1.86	1.1.86	Reg 12(3)
	New activity†	Before commencement of activity	Reg 12(3)

* Pre-existing activities, HSE has the power to exempt manufacturers from the submission of the safety case (Regulation 7(4)). However the safety case must be prepared.
† Regulation 6(2) defines a new industrial activity for the purposes of Regulations 7 to 12 and guidance is given in paragraph 104.

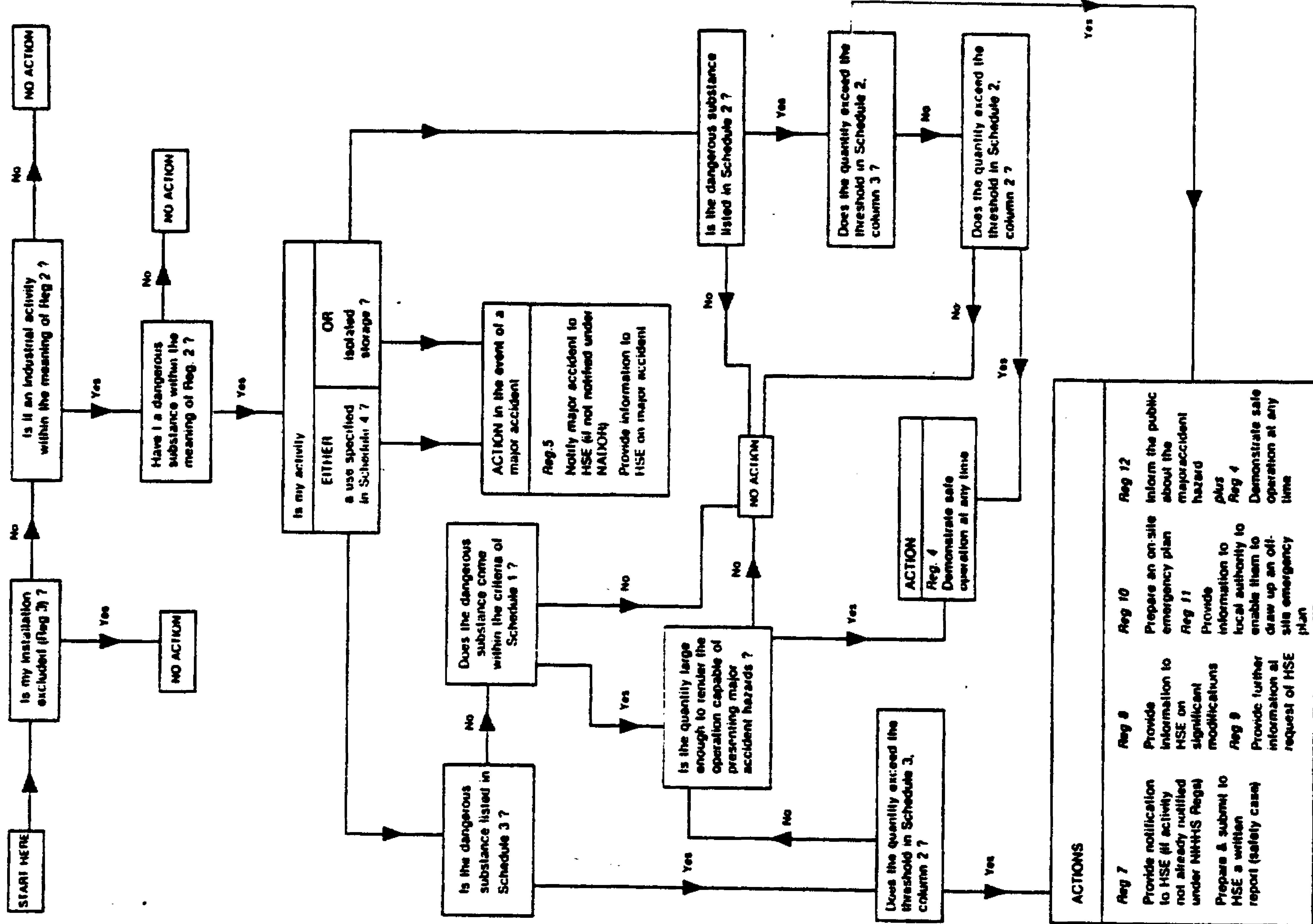


FIGURE A MANUFACTURER'S GUIDE TO THE CIMAH REGULATIONS

RURAL VERTICAL DISPERSION COEFFICIENTS (METERS)

DOWNWIND DIST (KM)	STABILITY					
	A	B	C	D	E	F
0.010	1.58	1.24	0.91	0.63	0.51	0.36
0.020	3.05	2.37	1.71	1.15	0.92	0.63
0.030	4.47	3.45	2.47	1.63	1.29	0.87
0.040	5.87	4.51	3.22	2.10	1.64	1.10
0.050	7.25	5.56	3.95	2.55	1.98	1.32
0.060	8.61	6.59	4.66	2.98	2.31	1.53
0.070	9.96	7.61	5.37	3.41	2.62	1.74
0.080	11.30	8.61	6.07	3.83	2.93	1.94
0.090	12.63	9.61	6.76	4.24	3.24	2.13
0.100	13.95	10.60	7.44	4.65	3.53	2.33
0.110	15.43	11.59	8.12	5.05	3.82	2.51
0.120	16.91	12.57	8.79	5.45	4.10	2.70
0.130	18.40	13.54	9.46	5.84	4.38	2.88
0.140	19.89	14.51	10.12	6.23	4.66	3.06
0.150	21.40	15.47	10.78	6.62	4.93	3.24
0.160	22.96	16.43	11.44	7.00	5.20	3.41
0.170	24.53	17.39	12.09	7.38	5.46	3.58
0.180	26.11	18.34	12.74	7.76	5.72	3.76
0.190	27.70	19.29	13.39	8.13	5.98	3.93
0.200	29.30	20.23	14.03	8.50	6.24	4.09
0.210	30.96	21.23	14.67	8.87	6.49	4.25
0.220	32.62	22.22	15.31	9.23	6.75	4.41
0.230	34.30	23.21	15.94	9.60	7.00	4.57
0.240	35.98	24.21	16.57	9.96	7.24	4.72
0.250	37.67	25.20	17.21	10.32	7.49	4.88
0.260	39.59	26.19	17.83	10.68	7.74	5.03
0.270	41.52	27.18	18.46	11.03	7.98	5.18
0.280	43.48	28.17	19.08	11.39	8.22	5.33
0.290	45.45	29.16	19.71	11.74	8.46	5.48
0.300	47.44	30.14	20.33	12.09	8.70	5.62
0.310	49.69	31.13	20.95	12.42	8.92	5.77
0.320	51.96	32.12	21.56	12.74	9.13	5.92
0.330	54.26	33.11	22.18	13.06	9.35	6.06
0.340	56.60	34.09	22.79	13.38	9.56	6.20
0.350	58.96	35.08	23.41	13.70	9.77	6.35
0.360	61.34	36.06	24.02	14.02	9.98	6.49
0.370	63.76	37.05	24.63	14.33	10.19	6.63
0.380	66.20	38.03	25.23	14.65	10.40	6.77
0.390	68.67	39.02	25.84	14.96	10.61	6.91
0.400	71.16	40.00	26.45	15.27	10.81	7.05
0.410	74.27	41.10	27.05	15.58	11.02	7.19
0.420	77.42	42.20	27.65	15.89	11.22	7.32
0.430	80.64	43.30	28.25	16.19	11.42	7.46
0.440	83.91	44.41	28.85	16.50	11.62	7.59
0.450	87.23	45.52	29.45	16.80	11.82	7.73
0.460	90.61	46.63	30.05	17.10	12.02	7.86
0.470	94.04	47.74	30.65	17.40	12.22	8.00
0.480	97.52	48.86	31.24	17.70	12.41	8.13
0.490	101.06	49.97	31.84	18.00	12.61	8.26
0.500	104.65	51.09	32.43	18.30	12.80	8.40

RURAL VERTICAL DISPERSION COEFFICIENTS (METERS)

DOWNWIND DIST (KM)	STABILITY					
	A	B	C	D	E	F
0.510	109.13	52.22	33.03	18.59	12.99	8.53
0.520	113.71	53.34	33.62	18.89	13.19	8.66
0.530	118.39	54.47	34.21	19.18	13.38	8.79
0.540	123.17	55.59	34.80	19.47	13.57	8.92
0.550	128.05	56.72	35.39	19.77	13.76	9.05
0.560	133.02	57.86	35.98	20.06	13.95	9.18
0.570	138.10	58.99	36.56	20.35	14.14	9.30
0.580	143.28	60.13	37.15	20.64	14.32	9.43
0.590	148.56	61.27	37.73	20.92	14.51	9.56
0.600	153.94	62.41	38.32	21.21	14.69	9.69
0.610	159.42	63.55	38.90	21.50	14.88	9.81
0.620	165.00	64.69	39.49	21.78	15.06	9.94
0.630	170.69	65.84	40.07	22.07	15.25	10.06
0.640	176.47	66.99	40.65	22.35	15.43	10.19
0.650	182.36	68.13	41.23	22.63	15.61	10.31
0.660	188.35	69.29	41.81	22.92	15.79	10.44
0.670	194.44	70.44	42.39	23.20	15.97	10.56
0.680	200.63	71.59	42.97	23.48	16.15	10.68
0.690	206.93	72.75	43.54	23.76	16.33	10.81
0.700	213.33	73.91	44.12	24.03	16.51	10.93
0.710	219.83	75.06	44.70	24.31	16.69	11.04
0.720	226.43	76.23	45.27	24.59	16.87	11.14
0.730	233.14	77.39	45.85	24.87	17.05	11.25
0.740	239.95	78.55	46.42	25.14	17.22	11.35
0.750	246.87	79.72	47.00	25.42	17.40	11.46
0.760	253.89	80.88	47.57	25.69	17.57	11.56
0.770	261.01	82.05	48.14	25.97	17.75	11.67
0.780	268.24	83.22	48.71	26.24	17.92	11.77
0.790	275.57	84.39	49.28	26.51	18.10	11.87
0.800	283.00	85.57	49.85	26.78	18.27	11.98
0.810	290.54	86.74	50.42	27.05	18.44	12.08
0.820	298.19	87.92	50.99	27.32	18.61	12.18
0.830	305.94	89.09	51.56	27.59	18.78	12.28
0.840	313.79	90.27	52.13	27.86	18.96	12.38
0.850	321.75	91.45	52.70	28.13	19.13	12.48
0.860	329.82	92.63	53.26	28.40	19.30	12.58
0.870	337.99	93.81	53.83	28.67	19.47	12.68
0.880	346.26	95.00	54.39	28.93	19.63	12.78
0.890	354.64	96.18	54.96	29.20	19.80	12.88
0.900	363.13	97.37	55.52	29.47	19.97	12.98
0.910	371.72	98.56	56.09	29.73	20.14	13.08
0.920	380.42	99.75	56.65	30.00	20.31	13.18
0.930	389.23	100.94	57.21	30.26	20.47	13.28
0.940	398.14	102.13	57.78	30.52	20.64	13.37
0.950	407.16	103.32	58.34	30.79	20.80	13.47
0.960	416.28	104.51	58.90	31.05	20.97	13.57
0.970	425.51	105.71	59.46	31.31	21.14	13.67
0.980	434.85	106.90	60.02	31.57	21.30	13.76
0.990	444.30	108.10	60.58	31.83	21.46	13.86
1.000	453.85	109.30	61.14	32.09	21.63	13.95

RURAL VERTICAL DISPERSION COEFFICIENTS (METERS)

DOWNWIND DIST (KM)	STABILITY					
	A	B	C	D	E	F
1.050	503.22	115.31	63.93	33.12	22.30	14.39
1.100	555.30	121.35	66.71	34.12	22.97	14.82
1.150	610.08	127.41	69.48	35.12	23.62	15.24
1.200	667.59	133.50	72.24	36.09	24.26	15.66
1.250	727.83	139.62	74.98	37.05	24.90	16.07
1.300	790.83	145.76	77.72	38.00	25.52	16.47
1.350	856.60	151.92	80.45	38.94	26.14	16.87
1.400	925.14	158.10	83.17	39.86	26.74	17.26
1.450	996.47	164.31	85.89	40.77	27.34	17.65
1.500	1070.60	170.53	88.59	41.67	27.93	18.03
1.550	1147.54	176.78	91.29	42.56	28.51	18.41
1.600	1227.31	183.05	93.98	43.44	29.09	18.78
1.650	1309.90	189.33	96.66	44.31	29.66	19.15
1.700	1395.34	195.63	99.34	45.17	30.23	19.52
1.750	1483.63	201.96	102.01	46.02	30.78	19.88
1.800	1574.79	208.30	104.67	46.86	31.34	20.23
1.850	1668.82	214.65	107.33	47.70	31.88	20.59
1.900	1765.72	221.02	109.98	48.52	32.42	20.94
1.950	1865.52	227.41	112.62	49.34	32.96	21.28
2.000	1968.22	233.82	115.26	50.15	33.49	21.63
2.050	2073.82	240.24	117.89	50.96	33.96	21.92
2.100	2182.34	246.68	120.52	51.75	34.43	22.21
2.150	2293.78	253.13	123.14	52.54	34.90	22.50
2.200	2408.15	259.59	125.76	53.33	35.36	22.78
2.250	2525.47	266.07	128.37	54.10	35.82	23.06
2.300	2645.73	272.57	130.97	54.87	36.27	23.34
2.350	2768.95	279.07	133.58	55.64	36.72	23.61
2.400	2895.13	285.59	136.17	56.40	37.17	23.89
2.450	3024.28	292.13	138.77	57.15	37.61	24.16
2.500	3156.40	298.68	141.35	57.90	38.04	24.42
2.550	3291.51	305.24	143.94	58.65	38.48	24.69
2.600	3429.61	311.81	146.52	59.38	38.91	24.95
2.650	3570.71	318.39	149.09	60.12	39.33	25.21
2.700	3714.81	324.99	151.66	60.84	39.75	25.47
2.750	3861.93	331.60	154.23	61.57	40.17	25.73
2.800	4012.06	338.22	156.79	62.29	40.59	25.98
2.850	4165.21	344.85	159.35	63.00	41.00	26.23
2.900	4321.39	351.49	161.91	63.71	41.41	26.48
2.950	4480.62	358.15	164.46	64.42	41.82	26.73
3.000	4642.88	364.81	167.01	65.12	42.22	26.98
3.050	4808.19	371.49	169.55	65.77	42.62	27.18
3.100	4976.55	378.18	172.09	66.42	43.02	27.39
3.150	5000.00	384.87	174.63	67.07	43.42	27.60
3.200	5000.00	391.58	177.16	67.71	43.81	27.80
3.250	5000.00	398.30	179.69	68.35	44.20	28.00
3.300	5000.00	405.03	182.22	68.98	44.59	28.20
3.350	5000.00	411.76	184.74	69.61	44.97	28.40
3.400	5000.00	418.51	187.26	70.24	45.35	28.59
3.450	5000.00	425.27	189.78	70.86	45.73	28.79
3.500	5000.00	432.03	192.29	71.48	46.11	28.98

RURAL VERTICAL DISPERSION COEFFICIENTS (METERS)

DOWNWIND DIST (KM)	STABILITY					
	A	B	C	D	E	F
3.550	5000.00	438.81	194.80	72.10	46.49	29.17
3.600	5000.00	445.59	197.31	72.71	46.86	29.36
3.650	5000.00	452.39	199.82	73.32	47.23	29.55
3.700	5000.00	459.19	202.32	73.92	47.60	29.74
3.750	5000.00	466.00	204.82	74.53	47.96	29.92
3.800	5000.00	472.83	207.32	75.13	48.33	30.11
3.850	5000.00	479.66	209.81	75.72	48.69	30.29
3.900	5000.00	486.49	212.30	76.31	49.05	30.48
3.950	5000.00	493.34	214.79	76.90	49.41	30.66
4.000	5000.00	500.20	217.27	77.49	49.77	30.84
4.050	5000.00	507.06	219.76	78.08	50.08	31.02
4.100	5000.00	513.93	222.24	78.66	50.39	31.19
4.150	5000.00	520.81	224.71	79.24	50.70	31.37
4.200	5000.00	527.70	227.19	79.81	51.01	31.54
4.250	5000.00	534.60	229.66	80.39	51.32	31.72
4.300	5000.00	541.50	232.13	80.96	51.62	31.89
4.350	5000.00	548.41	234.60	81.53	51.92	32.06
4.400	5000.00	555.33	237.06	82.09	52.22	32.23
4.450	5000.00	562.26	239.53	82.65	52.52	32.40
4.500	5000.00	569.19	241.99	83.21	52.82	32.57
4.550	5000.00	576.14	244.45	83.77	53.12	32.74
4.600	5000.00	583.09	246.90	84.33	53.41	32.91
4.650	5000.00	590.04	249.36	84.88	53.70	33.07
4.700	5000.00	597.01	251.81	85.43	53.99	33.24
4.750	5000.00	603.98	254.26	85.98	54.28	33.40
4.800	5000.00	610.96	256.70	86.53	54.57	33.56
4.850	5000.00	617.94	259.15	87.07	54.86	33.73
4.900	5000.00	624.93	261.59	87.61	55.14	33.89
4.950	5000.00	631.93	264.03	88.15	55.43	34.05
5.000	5000.00	638.94	266.47	88.69	55.71	34.21
5.500	5000.00	709.37	290.74	93.95	58.46	35.76
6.000	5000.00	780.42	314.82	99.03	61.08	37.23
6.500	5000.00	852.05	338.74	103.94	63.60	38.64
7.000	5000.00	924.22	362.49	108.71	66.03	40.00
7.500	5000.00	996.90	386.11	113.34	68.37	41.16
8.000	5000.00	1070.04	409.58	117.85	70.64	42.28
8.500	5000.00	1143.63	432.94	122.25	72.84	43.36
9.000	5000.00	1217.64	456.17	126.56	74.97	44.40
9.500	5000.00	1292.05	479.30	130.76	77.05	45.41
10.000	5000.00	1366.85	502.32	134.89	79.07	46.38
10.500	5000.00	1442.01	525.25	138.66	80.89	47.33
11.000	5000.00	1517.51	548.08	142.36	82.67	48.26
11.500	5000.00	1593.35	570.82	145.99	84.40	49.15
12.000	5000.00	1669.51	593.48	149.54	86.10	50.03
12.500	5000.00	1745.98	616.06	153.04	87.76	50.89
13.000	5000.00	1822.75	638.56	156.47	89.38	51.72
13.500	5000.00	1899.81	660.99	159.85	90.97	52.54
14.000	5000.00	1977.14	683.34	163.18	92.53	53.34
14.500	5000.00	2054.74	705.63	166.45	94.06	54.12
15.000	5000.00	2132.60	727.85	169.67	95.56	54.88

RURAL VERTICAL DISPERSION COEFFICIENTS (METERS)

DOWNWIND DIST (KM)	STABILITY					
	A	B	C	D	E	F
15.500	5000.00	2210.72	750.01	172.85	97.03	55.48
16.000	5000.00	2289.08	772.11	175.98	98.48	56.05
16.500	5000.00	2367.68	794.15	179.08	99.91	56.62
17.000	5000.00	2446.50	816.14	182.13	101.31	57.18
17.500	5000.00	2525.56	838.06	185.14	102.69	57.72
18.000	5000.00	2604.84	859.94	188.11	104.05	58.25
18.500	5000.00	2684.32	881.76	191.05	105.39	58.78
19.000	5000.00	2764.02	903.53	193.96	106.71	59.29
19.500	5000.00	2843.92	925.26	196.83	108.02	59.80
20.000	5000.00	2924.02	946.93	199.67	109.30	60.29
21.000	5000.00	3084.80	990.15	205.26	111.33	61.26
22.000	5000.00	3246.33	1033.19	210.74	113.29	62.20
23.000	5000.00	3408.57	1076.06	216.10	115.20	63.11
24.000	5000.00	3571.50	1118.78	221.37	117.06	64.00
25.000	5000.00	3735.09	1161.34	226.54	118.87	64.86
26.000	5000.00	3899.31	1203.76	231.63	120.64	65.69
27.000	5000.00	4064.15	1246.03	236.63	122.36	66.51
28.000	5000.00	4229.59	1288.18	241.55	124.05	67.30
29.000	5000.00	4395.59	1330.19	246.39	125.70	68.08
30.000	5000.00	4562.16	1372.09	251.16	127.31	68.84
31.000	5000.00	4729.26	1413.86	255.41	128.89	69.46
32.000	5000.00	4896.89	1455.52	259.59	130.44	70.07
33.000	5000.00	5000.00	1497.07	263.72	131.96	70.66
34.000	5000.00	5000.00	1538.51	267.78	133.45	71.24
35.000	5000.00	5000.00	1579.85	271.78	134.91	71.81
36.000	5000.00	5000.00	1621.08	275.72	136.35	72.37
37.000	5000.00	5000.00	1662.22	279.62	137.76	72.91
38.000	5000.00	5000.00	1703.26	283.46	139.15	73.45
39.000	5000.00	5000.00	1744.21	287.25	140.52	73.97
40.000	5000.00	5000.00	1785.08	291.00	141.86	74.49
41.000	5000.00	5000.00	1825.85	294.70	142.90	75.00
42.000	5000.00	5000.00	1866.54	298.36	143.92	75.49
43.000	5000.00	5000.00	1907.15	301.97	144.93	75.98
44.000	5000.00	5000.00	1947.68	305.55	145.92	76.46
45.000	5000.00	5000.00	1988.12	309.08	146.89	76.94
46.000	5000.00	5000.00	2028.50	312.58	147.85	77.40
47.000	5000.00	5000.00	2068.79	316.04	148.79	77.86
48.000	5000.00	5000.00	2109.02	319.46	149.72	78.31
49.000	5000.00	5000.00	2149.17	322.85	150.64	78.75
50.000	5000.00	5000.00	2189.25	326.21	151.54	79.19

RURAL HORIZONTAL DISPERSION COEFFICIENTS (METERS)

DOWNWIND	STABILITY					
DIST (KM)	A	B	C	D	E	F
0.010	3.36	2.34	1.47	0.96	0.72	0.48
0.020	6.29	4.42	2.80	1.84	1.37	0.91
0.030	9.08	6.41	4.08	2.68	2.00	1.33
0.040	11.77	8.34	5.33	3.50	2.61	1.74
0.050	14.39	10.23	6.56	4.31	3.22	2.14
0.060	16.96	12.09	7.77	5.11	3.81	2.53
0.070	19.49	13.92	8.96	5.89	4.40	2.92
0.080	21.98	15.72	10.14	6.67	4.98	3.31
0.090	24.43	17.50	11.31	7.44	5.55	3.69
0.100	26.85	19.27	12.46	8.20	6.12	4.07
0.110	29.25	21.01	13.61	8.96	6.69	4.45
0.120	31.63	22.74	14.75	9.71	7.25	4.82
0.130	33.98	24.46	15.88	10.46	7.81	5.19
0.140	36.31	26.16	17.00	11.20	8.36	5.56
0.150	38.63	27.86	18.12	11.93	8.91	5.92
0.160	40.93	29.54	19.23	12.67	9.46	6.29
0.170	43.21	31.21	20.34	13.40	10.01	6.65
0.180	45.48	32.87	21.44	14.12	10.55	7.01
0.190	47.73	34.52	22.53	14.84	11.09	7.37
0.200	49.97	36.17	23.62	15.56	11.63	7.73
0.210	52.20	37.80	24.71	16.28	12.16	8.08
0.220	54.41	39.43	25.79	16.99	12.69	8.44
0.230	56.62	41.05	26.86	17.70	13.23	8.79
0.240	58.81	42.66	27.93	18.41	13.76	9.14
0.250	60.99	44.27	29.00	19.12	14.28	9.50
0.260	63.17	45.87	30.07	19.82	14.81	9.84
0.270	65.33	47.46	31.13	20.52	15.33	10.19
0.280	67.48	49.05	32.19	21.22	15.85	10.54
0.290	69.63	50.63	33.24	21.92	16.38	10.89
0.300	71.76	52.20	34.29	22.61	16.89	11.23
0.310	73.89	53.77	35.34	23.30	17.41	11.58
0.320	76.01	55.34	36.38	23.99	17.93	11.92
0.330	78.12	56.90	37.43	24.68	18.44	12.26
0.340	80.23	58.45	38.47	25.37	18.96	12.60
0.350	82.33	60.00	39.50	26.05	19.47	12.95
0.360	84.42	61.55	40.54	26.74	19.98	13.29
0.370	86.50	63.09	41.57	27.42	20.49	13.62
0.380	88.58	64.62	42.60	28.10	21.00	13.96
0.390	90.65	66.15	43.62	28.78	21.51	14.30
0.400	92.71	67.68	44.65	29.46	22.01	14.64
0.410	94.77	69.21	45.67	30.13	22.52	14.97
0.420	96.82	70.73	46.69	30.80	23.02	15.31
0.430	98.87	72.24	47.71	31.48	23.52	15.64
0.440	100.91	73.75	48.72	32.15	24.03	15.98
0.450	102.94	75.26	49.74	32.82	24.53	16.31
0.460	104.97	76.77	50.75	33.49	25.03	16.64
0.470	107.00	78.27	51.76	34.15	25.52	16.97
0.480	109.02	79.77	52.76	34.82	26.02	17.31
0.490	111.03	81.26	53.77	35.48	26.52	17.64
0.500	113.04	82.75	54.77	36.15	27.02	17.97

RURAL HORIZONTAL DISPERSION COEFFICIENTS (METERS)

DOWNWIND DIST (KM)	STABILITY					
	A	B	C	D	E	F
0.510	115.04	84.24	55.77	36.81	27.51	18.30
0.520	117.04	85.72	56.77	37.47	28.01	18.62
0.530	119.04	87.21	57.77	38.13	28.50	18.95
0.540	121.03	88.69	58.77	38.79	28.99	19.28
0.550	123.01	90.16	59.76	39.45	29.48	19.61
0.560	124.99	91.63	60.75	40.10	29.97	19.93
0.570	126.97	93.10	61.74	40.76	30.46	20.26
0.580	128.94	94.57	62.73	41.41	30.95	20.59
0.590	130.91	96.03	63.72	42.07	31.44	20.91
0.600	132.88	97.50	64.71	42.72	31.93	21.24
0.610	134.84	98.95	65.69	43.37	32.42	21.56
0.620	136.79	100.41	66.68	44.02	32.90	21.88
0.630	138.75	101.86	67.66	44.67	33.39	22.21
0.640	140.69	103.32	68.64	45.32	33.88	22.53
0.650	142.64	104.76	69.62	45.97	34.36	22.85
0.660	144.58	106.21	70.60	46.61	34.84	23.17
0.670	146.52	107.65	71.57	47.26	35.33	23.50
0.680	148.45	109.09	72.55	47.90	35.81	23.82
0.690	150.38	110.53	73.52	48.55	36.29	24.14
0.700	152.31	111.97	74.49	49.19	36.77	24.46
0.710	154.23	113.40	75.46	49.83	37.25	24.78
0.720	156.15	114.84	76.43	50.47	37.73	25.10
0.730	158.07	116.27	77.40	51.11	38.21	25.41
0.740	159.98	117.69	78.37	51.75	38.69	25.73
0.750	161.89	119.12	79.33	52.39	39.17	26.05
0.760	163.80	120.54	80.30	53.03	39.64	26.37
0.770	165.70	121.96	81.26	53.67	40.12	26.69
0.780	167.61	123.38	82.22	54.30	40.60	27.00
0.790	169.50	124.80	83.18	54.94	41.07	27.32
0.800	171.40	126.21	84.14	55.58	41.55	27.63
0.810	173.29	127.63	85.10	56.21	42.02	27.95
0.820	175.18	129.04	86.06	56.84	42.50	28.27
0.830	177.06	130.45	87.02	57.48	42.97	28.58
0.840	178.95	131.85	87.97	58.11	43.44	28.90
0.850	180.83	133.26	88.92	58.74	43.91	29.21
0.860	182.70	134.66	89.88	59.37	44.39	29.52
0.870	184.58	136.06	90.83	60.00	44.86	29.84
0.880	186.45	137.46	91.78	60.63	45.33	30.15
0.890	188.32	138.86	92.73	61.26	45.80	30.46
0.900	190.19	140.26	93.68	61.89	46.27	30.78
0.910	192.05	141.65	94.63	62.51	46.74	31.09
0.920	193.91	143.04	95.57	63.14	47.21	31.40
0.930	195.77	144.43	96.52	63.77	47.67	31.71
0.940	197.63	145.82	97.46	64.39	48.14	32.02
0.950	199.48	147.21	98.41	65.02	48.61	32.33
0.960	201.33	148.59	99.35	65.64	49.08	32.64
0.970	203.18	149.98	100.29	66.26	49.54	32.95
0.980	205.02	151.36	101.23	66.89	50.01	33.26
0.990	206.87	152.74	102.17	67.51	50.47	33.57
1.000	208.71	154.12	103.11	68.13	50.94	33.88

RURAL HORIZONTAL DISPERSION COEFFICIENTS (METERS)

DOWNWIND	STABILITY					
DIST (KM)	A	B	C	D	E	F
1.050	217.88	160.99	107.80	71.23	53.26	35.43
1.100	227.00	167.82	112.46	74.31	55.56	36.96
1.150	236.06	174.62	117.10	77.38	57.86	38.49
1.200	245.07	181.38	121.71	80.44	60.15	40.01
1.250	254.03	188.11	126.32	83.49	62.43	41.53
1.300	262.94	194.81	130.90	86.52	64.70	43.04
1.350	271.81	201.48	135.46	89.54	66.96	44.55
1.400	280.63	208.11	140.01	92.56	69.21	46.05
1.450	289.41	214.72	144.54	95.56	71.46	47.54
1.500	298.16	221.31	149.06	98.55	73.70	49.03
1.550	306.86	227.86	153.56	101.53	75.93	50.51
1.600	315.52	234.39	158.04	104.50	78.15	51.99
1.650	324.15	240.90	162.51	107.46	80.37	53.47
1.700	332.75	247.38	166.97	110.41	82.57	54.94
1.750	341.31	253.83	171.41	113.35	84.78	56.41
1.800	349.83	260.27	175.85	116.29	86.97	57.87
1.850	358.33	266.68	180.26	119.22	89.16	59.33
1.900	366.79	273.08	184.67	122.13	91.35	60.78
1.950	375.22	279.45	189.06	125.05	93.53	62.23
2.000	383.62	285.80	193.45	127.95	95.70	63.68
2.050	392.00	292.13	197.82	130.84	97.87	65.12
2.100	400.34	298.44	202.18	133.73	100.03	66.56
2.150	408.66	304.73	206.52	136.61	102.18	67.99
2.200	416.95	311.01	210.86	139.49	104.33	69.42
2.250	425.21	317.27	215.19	142.36	106.48	70.85
2.300	433.45	323.51	219.51	145.22	108.62	72.28
2.350	441.66	329.73	223.82	148.07	110.76	73.70
2.400	449.85	335.93	228.11	150.92	112.89	75.12
2.450	458.02	342.12	232.40	153.76	115.02	76.53
2.500	466.16	348.30	236.68	156.60	117.14	77.95
2.550	474.28	354.46	240.95	159.43	119.26	79.36
2.600	482.37	360.60	245.21	162.25	121.37	80.76
2.650	490.45	366.73	249.47	165.07	123.48	82.17
2.700	498.50	372.84	253.71	167.88	125.59	83.57
2.750	506.53	378.94	257.94	170.69	127.69	84.97
2.800	514.54	385.02	262.17	173.49	129.78	86.36
2.850	522.53	391.09	266.39	176.29	131.88	87.76
2.900	530.50	397.15	270.60	179.08	133.97	89.15
2.950	538.45	403.19	274.81	181.86	136.05	90.54
3.000	546.38	409.22	279.00	184.65	138.13	91.92
3.050	554.29	415.23	283.19	187.42	140.21	93.31
3.100	562.18	421.24	287.37	190.19	142.29	94.69
3.150	570.05	427.23	291.54	192.96	144.36	96.07
3.200	577.91	433.20	295.71	195.72	146.42	97.44
3.250	585.74	439.17	299.87	198.48	148.49	98.82
3.300	593.56	445.12	304.02	201.23	150.55	100.19
3.350	601.37	451.07	308.16	203.98	152.60	101.56
3.400	609.15	457.00	312.30	206.72	154.66	102.92
3.450	616.92	462.92	316.43	209.46	156.71	104.29
3.500	624.67	468.82	320.56	212.19	158.75	105.65

RURAL HORIZONTAL DISPERSION COEFFICIENTS (METERS)

DOWNWIND DIST (KM)	STABILITY					
	A	B	C	D	E	F
3.550	632.41	474.72	324.68	214.92	160.80	107.01
3.600	640.13	480.61	328.79	217.65	162.84	108.37
3.650	647.83	486.48	332.90	220.37	164.88	109.73
3.700	655.52	492.34	336.99	223.09	166.91	111.08
3.750	663.20	498.20	341.09	225.81	168.94	112.43
3.800	670.85	504.04	345.18	228.52	170.97	113.79
3.850	678.50	509.87	349.26	231.22	173.00	115.13
3.900	686.13	515.70	353.33	233.92	175.02	116.48
3.950	693.74	521.51	357.40	236.62	177.04	117.83
4.000	701.34	527.31	361.47	239.32	179.06	119.17
4.050	708.93	533.11	365.52	242.01	181.07	120.51
4.100	716.50	538.89	369.58	244.69	183.08	121.85
4.150	724.05	544.66	373.62	247.38	185.09	123.19
4.200	731.60	550.43	377.66	250.06	187.10	124.52
4.250	739.13	556.18	381.70	252.74	189.10	125.86
4.300	746.65	561.93	385.73	255.41	191.10	127.19
4.350	754.15	567.67	389.76	258.08	193.10	128.52
4.400	761.64	573.39	393.78	260.74	195.10	129.85
4.450	769.12	579.11	397.79	263.41	197.09	131.18
4.500	776.58	584.82	401.80	266.07	199.08	132.50
4.550	784.03	590.53	405.81	268.72	201.07	133.83
4.600	791.48	596.22	409.81	271.38	203.06	135.15
4.650	798.90	601.90	413.80	274.02	205.04	136.47
4.700	806.32	607.58	417.79	276.67	207.02	137.79
4.750	813.72	613.25	421.78	279.31	209.00	139.11
4.800	821.11	618.91	425.76	281.95	210.98	140.42
4.850	828.49	624.56	429.74	284.59	212.95	141.74
4.900	835.86	630.20	433.71	287.23	214.92	143.05
4.950	843.22	635.84	437.67	289.86	216.89	144.36
5.000	850.56	641.47	441.64	292.48	218.86	145.67
5.500	923.42	697.34	481.01	318.60	238.42	158.69
6.000	995.25	752.50	519.98	344.45	257.77	171.58
6.500	1066.14	807.01	558.57	370.05	276.94	184.34
7.000	1136.17	860.93	596.81	395.43	295.94	196.99
7.500	1205.40	914.30	634.72	420.59	314.78	209.54
8.000	1273.88	967.15	672.34	445.55	333.47	221.98
8.500	1341.67	1019.52	709.67	470.32	352.02	234.34
9.000	1408.80	1071.44	746.74	494.92	370.44	246.61
9.500	1475.32	1122.92	783.55	519.36	388.74	258.79
10.000	1541.25	1174.01	820.13	543.64	406.92	270.90
10.500	1606.63	1224.71	856.48	567.77	424.99	282.94
11.000	1671.48	1275.04	892.62	591.76	442.96	294.90
11.500	1735.83	1325.02	928.55	615.61	460.82	306.80
12.000	1799.70	1374.67	964.29	639.34	478.59	318.63
12.500	1863.11	1424.00	999.84	662.94	496.27	330.41
13.000	1926.08	1473.02	1035.20	686.43	513.86	342.12
13.500	1988.62	1521.75	1070.40	709.79	531.36	353.78
14.000	2050.76	1570.20	1105.42	733.05	548.78	365.38
14.500	2112.50	1618.37	1140.29	756.21	566.12	376.93
15.000	2173.87	1666.28	1175.00	779.26	583.39	388.43

RURAL HORIZONTAL DISPERSION COEFFICIENTS (METERS)

DOWNWIND	STABILITY					
DIST (KM)	A	B	C	D	E	F
15.500	2234.87	1713.93	1209.56	802.21	600.58	399.88
16.000	2295.52	1761.33	1243.98	825.06	617.70	411.28
16.500	2355.82	1808.50	1278.25	847.83	634.75	422.64
17.000	2415.80	1855.44	1312.39	870.50	651.73	433.95
17.500	2475.45	1902.15	1346.40	893.09	668.65	445.22
18.000	2534.78	1948.64	1380.27	915.59	685.50	456.44
18.500	2593.82	1994.92	1414.03	938.01	702.29	467.63
19.000	2652.56	2041.00	1447.66	960.35	719.03	478.77
19.500	2711.01	2086.87	1481.17	982.61	735.70	489.88
20.000	2769.18	2132.55	1514.57	1004.79	752.32	500.95
21.000	2884.72	2223.34	1581.03	1048.94	785.39	522.98
22.000	2999.22	2313.41	1647.06	1092.81	818.25	544.86
23.000	3112.73	2402.78	1712.68	1136.41	850.91	566.62
24.000	3225.29	2491.49	1777.91	1179.75	883.38	588.25
25.000	3336.95	2579.57	1842.77	1222.84	915.66	609.75
26.000	3447.74	2667.04	1907.27	1265.70	947.77	631.14
27.000	3557.70	2753.93	1971.43	1308.33	979.70	652.41
28.000	3666.85	2840.25	2035.24	1350.73	1011.47	673.57
29.000	3775.23	2926.03	2098.75	1392.93	1043.08	694.63
30.000	3882.87	3011.29	2161.94	1434.92	1074.54	715.59
31.000	3989.78	3096.04	2224.83	1476.72	1105.85	736.45
32.000	4096.00	3180.30	2287.43	1518.32	1137.02	757.21
33.000	4201.54	3264.09	2349.75	1559.74	1168.05	777.88
34.000	4306.43	3347.42	2411.80	1600.98	1198.95	798.46
35.000	4410.68	3430.31	2473.59	1642.05	1229.72	818.96
36.000	4514.32	3512.76	2535.12	1682.94	1260.36	839.37
37.000	4617.36	3594.79	2596.40	1723.67	1290.87	859.70
38.000	4719.82	3676.41	2657.44	1764.25	1321.27	879.95
39.000	4821.72	3757.64	2718.24	1804.66	1351.55	900.12
40.000	4923.06	3838.48	2778.81	1844.93	1381.72	920.22
41.000	5023.86	3918.94	2839.16	1885.04	1411.78	940.25
42.000	5124.14	3999.03	2899.29	1925.01	1441.73	960.20
43.000	5223.91	4078.76	2959.21	1964.84	1471.57	980.08
44.000	5323.18	4158.14	3018.92	2004.54	1501.31	999.89
45.000	5421.97	4237.17	3078.43	2044.10	1530.95	1019.64
46.000	5520.27	4315.87	3137.73	2083.52	1560.49	1039.32
47.000	5618.11	4394.25	3196.84	2122.82	1589.94	1058.94
48.000	5715.49	4472.30	3255.77	2162.00	1619.29	1078.49
49.000	5812.43	4550.04	3314.50	2201.05	1648.55	1097.99
50.000	5908.94	4627.46	3373.05	2239.97	1677.72	1117.42

Estimating Concentrations
Downwind from an
Instantaneous Puff Release

**Estimating Concentrations Downwind from an
Instantaneous Puff Release**

**(U.S.) Environmental Sciences Research Lab.
Research Triangle Park, NC**

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National Technical Information Service**

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