United States
Environmental Protection
Agency

Office of Research and
Development
Washington, DC 20460

EPA/600/8-91/038
March 1993

EPA

Selection Criteria for Mathematical Models Used in Exposure Assessments:

Atmospheric Dispersion Models

EPA/600/8-91/038
March 1993

SELECTION CRITERIA FOR MATHEMATICAL MODELS USED IN EXPOSURE ASSESSMENTS: ATMOSPHERIC DISPERSION MODELS

Exposure Assessment Group
Office of Health and Environmental Assessment
U.S. Environmental Protection Agency
Washington, D.C.

Printed on Recycled Paper

DISCLAIMER

This document has been reviewed in accordance with U.S. Environmental Protection Agency policy and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

CONTENTS

List of Tables vii
List of Figures viii
Foreword ix
Preface x
Authors and Reviewers xi

PART I. SELECTION CRITERIA FOR ATMOSPHERIC DISPERSION MODELS

1. LIMITATIONS OF ATMOSPHERIC DISPERSION MODELS 1

2. BACKGROUND INFORMATION 3

2.1. Characterization of Contaminant Concentrations in Air 3

2.1.1. Source Characteristics 3
2.1.2. Meteorological Conditions 5
2.1.3. Geographic Scale 6
2.1.4. Topography 7
2.1.5. Contaminant Properties 8

2.2. Characteristics of Exposure Assessments 9
2.3. Definition of Terms 10

3. GENERAL GUIDELINES AND PRINCIPLES OF MODEL SELECTION 13

3.1. Atmospheric Dispersion Models 13

3.1.1. Buoyant Line and Point Source Dispersion Model (BLP)* 15
3.1.2. CALINE3* 15
3.1.3. Climatological Dispersion Model (CDM 2.0)* 15
3.1.4. Offshore and Coastal Dispersion Model (OCD)* 16
3.1.5. Gaussian Plume Multiple Source Air Quality Algorithm (RAM)* 16
3.1.6. Industrial Source Complex Model (ISC)* 16
3.1.7. Multiple Point Gaussian Dispersion Algorithm with Terrain Adjustment (MPTER)* 17
3.1.8. Single Source Model (CRSTER)* 17
3.1.9. Urban Airshed Model (UAM)* 17
3.1.10. Air Pollution Research Advisory Committee (APRAC-3) 17
3.1.11. Air Quality Display Model (AQDM) 18

3.1.12. Air Resources Regional Pollution Assessment Model (ARRPA) 18
3.1.13. COMPTER 18
3.1.14. ERT Air Quality Model (ERTAQ) 19
3.1.15. HIWAY-2 19
3.1.16. LONGZ 19
3.1.17. Multiple Point Source Diffusion Model (MPSDM) 19
3.1.18. Mesoscale Transport Diffusions and Deposition Model for Industrial Sources (MTDDIS) 20
3.1.19. MULTIMAX 20
3.1.20. Point, Area, Line Source Algorithm (PAL) 20
3.1.21. Pacific Gas and Electric PLUME5 Model (PLUME5) 21
3.1.22. Rough Terrain Diffusion Model (RTDM) 21
3.1.23. Multi-Source Model (SCSTER) 21
3.1.24. SHORTZ 22
3.1.25. Simple Line Source Model (SLSM) 22
3.1.26. Texas Climatological Model (TCM-2) 22
3.1.27. Texas Episodic Model (TEM-8) 22
3.1.28. Models 3141 and 4141 22

3.2. Human Exposure Models 23
3.3. Model Selection Process 23

3.3.1. Geographic Scale 24
3.3.2. Time Scale 24
3.3.3. Land Use 31
3.3.4. Terrain 31
3.3.5. Source Characteristics 31
3.3.6. Reactivity 33
3.3.7. Form of Release 34
3.3.8. Removal Mechanism 34

4. EXAMPLES OF MODEL SELECTION FOR SPECIFIC EXPOSURE ASSESSMENTS 35

4.1. Municipal Waste Combustors 35

4.1.1. Assessment 35
4.1.2. Recommendation 35

4.2. Perchloroethylene Emissions from Dry Cleaning Facilities 37

4.2.1. Assessment 38
4.2.2. Recommendation 38

4.3. Exposure to Dioxin from Soils via Vapor Inhalation 40

4.3.1. Assessment 40
4.3.2. Recommendation 40

REFERENCES FOR PART I 41

PART II. GAUSSIAN PLUME MODELS

1. INTRODUCTION 44

1.1. Assumptions 44
1.2. Limitations 47
1.3. Uncertainties 47

1.3.1. Site Conditions 47
1.3.2. Meteorologic Conditions 50
1.3.3. Release Conditions 51
1.3.4. Source Complexity 51
1.3.5. Plume Depletion Processes 52

2. DISPERSION COEFFICIENTS 54

2.1. Pasquill-Gifford Dispersion Coefficients 54
2.2. Briggs Dispersion Coefficients 54
2.3. Klug Dispersion Coefficients 59
2.4. Brookhaven Dispersion Coefficients 59
2.5. St. Louis Dispersion Coefficients 59
2.6. Jülich Dispersion Coefficients 60

3. INPUT DATA REQUIREMENTS 61

3.1. Source 61

3.1.1. Typical Source Parameters for Hazardous Waste Management Facilities 62

3.2. Meteorologic 64
3.3. Receptor 64

REFERENCES FOR PART II 66

PART III. INDOOR AIR MODELING

1. INTRODUCTION 74

2. CHARACTERIZATION OF INDOOR AIR EXPOSURE 75

2.1. Identification of Emission Sources 75
2.2. Characterization of Emissions 77
2.3. Determination of Ventilation Rates 77
2.4. Relative Impact of Indoor and Outdoor Emissions on Human Exposure . . . 77

3. MODELING INDOOR AIR 80

REFERENCES FOR PART III 82

APPENDIX 85

REFERENCES FOR APPENDIX 95

TABLES

1 Model selection profile 25

2 Characteristics of atmospheric dispersion models 26

3 Site characteristics—atmospheric dispersion models 29

4 Source characteristics—atmospheric dispersion models 30

5 Identification and classification of land use types found in Metropolitan St. Louis 32

6 Model selection criteria for sample sites 36

7 Estimated ratios of predicted to observed air concentrations using Gaussian plume atmospheric dispersion models 48

8 Definition of the Pasquill atmospheric stability categories 55

9 Parameters used to compute dispersion coefficients 58

10 Air contaminants by source locations 76

11 Summary of I/O ratios of selected airborne contaminants 79

FIGURES

1 Horizontal dispersion coefficient as a function of downwind distance from the source 56

2 Vertical dispersion coefficient as a function of downwind distance from the source 57

FOREWORD

When performing exposure assessments using predictive methods, assessors frequently ask the following questions: "How do I select the best fate model to use in my assessment," "How can I tell if the model someone else used in an assessment is appropriate," and "What are the strengths and weaknesses of these models?" This document is a first step in addressing these questions as they apply to the dispersion of contaminants in air.

One of the functions of the Exposure Assessment Group is to develop guidelines for exposure assessments. On September 24, 1986, the U.S. Environmental Protection Agency published *Guidelines for Estimating Exposures.* During the development of the guidelines and subsequent review and comment, four areas were identified that required further research. One of these areas was selection criteria for mathematical models. This document, which is the third selection criteria document in the series, deals with atmospheric dispersion models. The first two dealt with surface water and ground-water models. On May 29, 1992, the Guidelines for Exposure Assessment were published in the Federal Register as an update to the original Guidelines. Also, the computer-based Integrated Model Evaluation System (IMES) was developed to incorporate the information within these criteria documents. IMES provides assessors with a simple and up to date mechanism for selecting appropriate models and obtaining details about them and their validation.

This document, as a foundation of the IMES, is designed to help the exposure assessor evaluate the appropriateness of models for various situations. The report defines the terms and discusses the general approaches that modelers take to a problem so that exposure assessors may more readily evaluate the appropriateness of both new and existing models. In addition, step-by-step criteria are provided to enable the assessor to answer the questions posed above.

Michael A. Callahan
Director
Exposure Assessment Group

PREFACE

This is the third of three documents produced by the Exposure Assessment Group of the Office of Health and Environmental Assessment addressing selection criteria for mathematical models used in exposure assessments. These documents serve as technical support documents for the *Guidelines for Estimating Exposures*, (first published in 1986 and replaced by the *Guidelines for Exposure Assessment* published by the U.S. EPA in 1992) and the PC-based *Integrated Model Evaluation System* (IMES) issued by the U.S. EPA in 1991 as a prototype.

The purpose of this document is to present criteria that provide a means for selecting the most appropriate mathematical model(s) for conducting an exposure assessment involving the dispersion of contaminants in air.

The literature search to support the models discussed in this report is current to January 29, 1989. More recent and additional information is contained in the IMES. It must be recognized that the Agency is continually improving its models and approaches to exposure assessment. For example, the Agency is currently re-evaluating air deposition models. This class of air models was not addressed in this document, but information from the re-evaluation will be incorporated into IMES as it becomes available.

AUTHORS AND REVIEWERS

The Exposure Assessment Group within the U.S. Environmental Protection Agency's Office of Health and Environmental Assessment was responsible for the preparation of this document and provided overall direction and coordination during the production effort. The information in this document has been funded, wholly or in part, by the U.S. Environmental Protection Agency under Interagency Agreement No. DW89931434-01-0. Richard Walentowicz, Exposure Assessment Group, served as Project Officer.

AUTHORS

D.E. Fields
Health and Safety Research Division
Oak Ridge National Laboratory
Oak Ridge, TN

J.K. Garrett
Office of Risk Analysis
Health and Safety Research Division
Oak Ridge National Laboratory
Oak Ridge, TN

L.M. Hively
Health and Safety Research Division
Oak Ridge National Laboratory
Oak Ridge, TN

C.W. Miller
Illinois Department of Nuclear Safety
Springfield, IL

F.R. O'Donnell
Environmental and Health Protection Division
Oak Ridge National Laboratory
Oak Ridge, TN

C.C. Travis
Office of Risk Analysis
Health and Safety Research Division
Oak Ridge National Laboratory
Oak Ridge, TN

REVIEWERS

C.F. Baes, III
Environmental Sciences Division
Oak Ridge National Laboratory
Oak Ridge, TN

Randall Bruins
Environmental Criteria and Assessment Office
Office of Health and Environmental Assessment
U.S. Environmental Protection Agency
Cincinnati, OH

Mike Dusetzina
Emission Standards Division
Office of Air Quality Planning and Standards
U.S. Environmental Protection Agency
Research Triangle Park, NC

F.C. Kornegay
Environmental and Health Protection Division
Oak Ridge National Laboratory
Oak Ridge, TN

Norman Kowal
Environmental Criteria and Assessment Office
Office of Health and Environmental Assessment
U.S. Environmental Protection Agency
Cincinnati, OH

John Schaum
Exposure Assessement Group
Office of Health and Environmental Assessment
U.S. Environmental Protection Agency
Washington, DC

John Segna
Environmental Resources Management, Inc.
McLean, VA

PART I.

SELECTION CRITERIA FOR ATMOSPHERIC DISPERSION MODELS

Part I of this document gives risk analysts the basic techniques and guidance they need to select site-appropriate atmospheric dispersion models. Exposure assessment, a critical component of the risk assessment process, determines the extent of human contact with the released contaminant during a specified time. Specifically, the dose from which human risk is calculated must be determined. To determine exposure, or "administered dose," the risk analyst must be able to quantitate (1) the contaminant concentration in a particular medium with which humans may have contact, (2) the contact rate (the rates of inhalation, ingestion, and dermal contact depending on the route of exposure), and (3) the exposure duration (the length of time that contact with the contaminant lasts).

1. LIMITATIONS OF ATMOSPHERIC DISPERSION MODELS

Mathematical modeling is often used in exposure assessments to provide quantitative estimates of contaminant concentrations when site measurements do not exist. Atmospheric dispersion models, designed specifically for regulatory compliance with ambient air quality standards, are often used to estimate contaminant concentrations in air. Some of these models are better suited than others for exposure assessment use.

Regulatory atmospheric dispersion models may be formatted to estimate worst-case *concentrations;* however, these estimates may represent worst-case *exposure*, since exposure is dependent not only on concentration but also on the rate and duration of human contact. Furthermore, regulatory atmospheric dispersion models were designed to consider only those contaminants under regulation for air quality; however, analysts conducting an exposure assessment must consider a much broader range of contaminants and their fates, including the transfer of the contaminants to water, soil, and food. Most existing regulatory atmospheric dispersion models, for example, do not account for deposition.

With these caveats in mind, the risk analyst must select an appropriate model for a particular exposure situation from the existing atmospheric dispersion models. The U.S. Environmental Protection Agency's *Guideline on Air Quality Models (Revised)* (USEPA, 1986a) and the EPA's *Supplement A to the Guideline on Air Quality Models (Revised)*

(USEPA, 1987a) provide extensive information on selecting atmospheric dispersion models for regulatory and compliance uses. In this guideline, EPA's Office of Air Quality Planning and Standards recommends air quality models, data bases, and requirements for concentration estimates to use in air pollution control strategy evaluations and new source reviews. Although the information was not provided for exposure assessment purposes, the risk analyst will find the *Guideline* an excellent companion to the present document for identifying key features of the most often selected air dispersion models. Analysts are not limited to using the models recommended for regulatory uses, and several of the atmospheric dispersion models discussed in the *Guideline* are included in this document.

The remainder of Part I contains background information on air dispersion processes and characteristics of exposure assessments (Section 2); provides general guidelines and principles of model selection criteria, including the model selection process and brief descriptions of representative atmospheric dispersion models (Section 3); and furnishes examples of model selection for three specific exposure assessments (Section 4).

2. BACKGROUND INFORMATION

To select an appropriate dispersion model, an analyst must be able to characterize the factors that affect dispersion of air contaminants. In addition, the route and duration of exposure as well as the location of the exposed population affect model selection. This section provides the background information needed to characterize contaminant concentrations in air and the exposure factors that must be considered when choosing a model.

2.1. CHARACTERIZATION OF CONTAMINANT CONCENTRATIONS IN AIR

The processes or factors that significantly influence contaminant concentration in the air, and hence affect human exposure, must be sufficiently characterized so that they can be described quantitatively by the model. These characterizations may be grouped according to source characteristics, meteorological conditions, geographic scale, topography, and contaminant properties.

2.1.1. Source Characteristics

Source characteristics include the type of source, the rate of contaminant release, the effective plume height, and site-specific parameters.

2.1.1.1. *Type of Source*

A source can be characterized as point, nonpoint, or multiple.

- A *point source* is a single specific emission point that can be defined with geographic coordinates plus height above ground, stack diameter, gas velocity, and temperature.

- A *nonpoint source*, or area source, is either several (usually small) emission points distributed over a specified surface area or one large area (e.g., a seepage zone) that is treated as one source. When many small sources release overlapping emissions along a specified surface area (e.g., urban traffic), they are referred to as a *line source* (Anderson et al., 1983).

- A *multiple source* is a combination of several emission points that includes both point and nonpoint sources. Multiple sources are typically found in urban or industrial settings.

Analysts should note that the way in which a source is typed may depend on the purpose of a particular exposure assessment. For example, if the assessment is concerned with exposure of on-site workers to a contaminant being released near ground level, the emissions would probably be calculated as an area source. However, if we wanted to assess exposure of a population living a distance from the same release, the emissions could be calculated as a point source.

2.1.1.2. *Rate of Release*

The rate of release, or emission rate, is the mass of a contaminant emitted per unit of time (mass/time). Contaminant mass is expressed in various ways, depending on the type of source that has been identified. For point sources, the rate of emissions is expressed as mass per unit of time (e.g., grams/second) or as volume per unit of time (e.g., parts per million/second). Volume rates are typically used in analyses involving chemical reactions (Anderson et al., 1983). For nonpoint sources, both mass per unit of time and spatial distribution of the release must be measured. The latter factor is typically expressed as micrograms per square mile per second, ($\mu g/mi^2$)/s. For line sources such as urban traffic, the rate of emissions is expressed in units such as grams per second per kilometer. For multiple sources, the rate of emissions must incorporate all time and spatial distributions of emissions from all the relevant sources (Anderson et al., 1983).

2.1.1.3. *Effective Plume Height*

The height and temperature of the released contaminant affect the dispersion of the contaminant plume. Effective plume height is the physical height of the stack adjusted by factors that raise the plume (as a result of buoyancy or momentum) or lower it (as a result of downwash or deflection). Higher elevation allows more time for released contaminants to be dispersed before reaching ground level. Thus peak ground-level contaminant concentrations are not normally found close to an elevated emission source (USEPA, 1987b). Contaminants that are hotter than the ambient air are buoyant and will rise above stack height for some time after release (Anderson et al., 1983). Effective plume height can be reduced by stack-tip downwash, a phenomenon that occurs when the velocity of the contaminant emitted from the stack is low compared to windspeed. Aerodynamic downwash, caused by structures near the stack, can also reduce plume height (USEPA, 1986a). The effective plume height for a given

modeling situation is generally estimated by the atmospheric dispersion model. Most near-field atmospheric dispersion models incorporate the plume rise methods of Briggs (1975) and can account for stack-tip downwash. The Industrial Source Complex model (ISC), an often-used near-field model, also contains algorithms to account for aerodynamic downwash (USEPA, 1986a).

2.1.1.4. *Other Site-Specific Factors*

The source characterization is influenced by several other site-specific factors. The analyst must determine the extent of influence these factors have on the source characterization.

- *Variations in emissions and/or meteorological conditions over time.* The emission rate for a continuous source may vary over time because of operational variables. Changes in meteorological conditions can also affect ambient concentrations and dispersion patterns.

- *Use of emission controls.* Emission controls at a facility can reduce emission rates. Facilities that apply emission controls should be identified. The analyst may need to differentiate between exposure to baseline emissions and post-control emissions for some exposure assessment situations.

- *Other source emissions.* Some emissions can escape through leaks or from open processes and not be vented to stacks. These fugitive emissions may be significant at ground level near the emission source. Storage emissions (e.g., losses from holding or storage tanks, or from loading and handling) may also occur. If available, mass balance calculations of a given facility should provide estimates of contaminant concentrations from all emissions.

2.1.2. Meteorological Conditions

Wind speed, wind direction, precipitation, and turbulence affect dispersion and ground-level concentrations. Increased wind speed can reduce ground-level concentrations by increasing the volume of air into which the contaminant is emitted, enhancing dispersion by immediately diluting the contaminant concentration. Increased wind speed generally decreases concentrations of contaminants emitted at ground level, but it can also prevent stack emissions from being dispersed. Precipitation can wash contaminants from the air,

increasing concentrations and ground deposition nearer the source. Many models do not account for precipitation scavenging and washout. The intensity of atmospheric turbulence has profound effects on dispersion and ground-level concentrations of contaminants. Atmospheric turbulence is generated by kinetic and thermal energy transfers between the air and the terrain. Turbulence enhances dispersion of the contaminant plume in the lower atmospheric levels. In the higher atmospheric levels, however, long-range transport of a contaminant plume without reduced concentration often occurs under stable atmospheric conditions and high wind speed (Anderson et al., 1983). Sets of empirically-determined dispersion coefficients for classes of wind speed and atmospheric stability are used for modeling purposes. Factors such as averaging time, urban or rural land use, and type of source may prescribe the choice of specific coefficients used in different models (USEPA, 1986a). Dispersion coefficients used in most atmospheric dispersion models are identical to, or based on, the Pasquill-Gifford dispersion coefficients for rural areas and the McElroy-Pooler (St. Louis) dispersion coefficients for urban areas (USEPA, 1986a; see also Part II of this document).

2.1.3. Geographic Scale

Geographic scale refers to the range of contaminant dispersion that is applicable to the assessment. Dispersion ranges are described as near-field or far-field (long-range). Most exposure assessments are conducted in the near-field range.

2.1.3.1. *Near-Field Dispersion*

Near-field dispersion of a contaminant occurs within 50 km of the source of the contaminant release. In addition to the emission rate, concentration patterns in the near-field range are dependent on effective plume height and meteorological conditions. Atmospheric chemical reactions do not significantly affect concentration patterns in the near-field range.

Most atmospheric dispersion models are designed to estimate concentrations in the near-field. *Gaussian plume models*, a class of atmospheric dispersion models made up of several individual models similar in design and performance, are commonly used to represent plume dispersion in the near-field and are based on the assumption that the plume will spread both laterally and vertically in accordance with a Gaussian statistical distribution under steady-state atmospheric conditions (e.g., constant wind speed) and spatial homogeneity (flat terrain).

Although such conditions rarely exist, average annual atmospheric concentrations computed with Gaussian plume models generally are expected to agree with values measured over flat terrain within a factor of two (National Council on Radiation Protection and Measurement [NCRP], 1984).

2.1.3.2. *Far-Field Dispersion*

Far-field dispersion refers to transport of the contaminant more than 50 km from the emission source(s). As travel time increases, diurnal variations in meteorological conditions, movement of weather systems, mesoscale terrain effects, and transformation and intermedia transfer processes also increase. These increasing numbers of variables and changes in the contaminant plume increase the complexity and uncertainty of an analysis. Although there is some uncertainty in assuming steady-state conditions and spatial homogeneity for near-field dispersion, the variables encountered in far-field dispersion make such assumptions unsound. The objectives of a far-field study influence the level of complexity which must be reflected in the atmospheric dispersion models. Although techniques are available to analyze these effects (Miller et al., 1981), few analysts are experienced in their use. The complexity, time, and cost of applying the techniques pose further limitations. Since it is difficult to channel many complex variables into simplified characterizations appropriate for model application, near-field models are sometimes used as an admittedly poor substitute until more appropriate techniques can be determined. Miller et al. suggest that a simple Gaussian plume model may be adequate to describe intermediate range (50 to 250 km) transport in some situations. A long-range trajectory model has been developed under EPA sponsorship for use in radiological assessments. This model could be adapted for use in nonradiological assessments (Murphy et al., 1984).

2.1.4. Topography

The area surrounding an emission point is characterized as either flat or complex terrain (USEPA, 1986a). Typically, terrain is defined as being flat where land and building elevations are below the stack height of the emission source and where steady-state conditions and uniformity in patterns of air movement can be reasonably assumed. Terrain is defined as complex where land and building elevations are above the stack height of the emission source, where there is a wide diversity in terrain features (e.g., mountains, valleys,

tall buildings, large bodies of water), and where terrain deflects or alters patterns in air movement. Complex terrain can affect dispersion in ways not encountered in flat terrain. Effects include: (1) channeling of flows along valleys, (2) trapping of pollutants within basins, (3) enhanced vertical dispersion through mechanically induced turbulence, (4) large vertical gradients in wind speed and direction, and (5) flow changes resulting from heating and cooling of sloping terrain. These complicated atmospheric dispersion patterns and distributions in areas of complex terrain are difficult to simulate and, therefore, adequate complex terrain dispersion models have not been developed.

2.1.5. Contaminant Properties

Chemical-specific factors and physical processes influence the contaminant's environmental fate and transport and affect contaminant concentration. During long-range transport, in particular, these processes of transformation and intermedia transfer significantly alter contaminant concentrations in air. When a contaminant has undergone some chemical reaction or transformation or has been partially removed from the atmosphere, its concentration in air is reduced. During near-field dispersion, the rates of these processes may not be sufficient to cause appreciable differences in concentrations. For this reason, most near-field atmospheric dispersion models account only for simple exponential decay.

Contaminants are characterized as reactive or nonreactive. Reactivity refers to the potential for chemical change of the contaminant following emission. Although most contaminants undergo some reactions or transformations after release to the atmosphere, some react more readily than others. Transformation processes, such as photolysis and oxidation, may involve multiple contaminants and the formation of reactive secondary contaminants. Modeling of reactive contaminants in a complex reacting system is more difficult because of the need to model both the reactive system and the dispersion and fate of all contaminants involved in the reactive system. Some secondary contaminants resulting from transformation processes may have different properties, and may be more hazardous, than the primary contaminants of concern. The best-known example of such a reactive system is the formation of photochemical smog in which nitrogen oxides, reactive hydrocarbons, and sunlight interact to create ozone and other reactive secondary contaminants (Anderson et al., 1983). Intricate models that require involvement by expert

modelers are available to represent these chemical kinetic mechanisms (e.g., the Urban Airshed Model [UAM]).

Intermedia transfer processes also reduce the contaminant concentrations remaining airborne at any given time. Dissolution, adsorption, gravitational settling, and precipitation affect the removal of contaminants from the air and their transfer to other environmental media. These removal processes are defined in Section 2.3. Definition of Terms. Many near-field atmospheric dispersion models do not account for these removal mechanisms.

2.2. CHARACTERISTICS OF EXPOSURE ASSESSMENTS

The exposure assessment is often the most critical and complex step in determining human risk. Such an assessment is often undertaken for a variety of purposes and for various types of exposures. In most cases, however, this step requires the selection of appropriate mathematical models that can be used to provide quantitative estimates of contaminant concentration, population distribution, and exposure. The results from these models must be able to provide the quantitative data needed to support the intended purpose(s) of the exposure assessment. The objectives of the exposure assessment should be explicitly stated so that appropriate models can be selected.

Three key factors of an exposure assessment directly affect model selection: (1) the duration of exposure, i.e., the time scale of both the release of and human contact with the contaminant; (2) the routes of exposure; and (3) the location of the population.

1. The time period over which exposure estimates are to be averaged should be matched with the model's averaging time capability. For long periods of exposure, the model should have the capability to provide long-term averaging, i.e., annual average air concentrations. For short or intense periods of exposure to potentially toxic substances, the model should have the capability to provide short-term averaging, i.e., 1-, 8-, and 24-hour average air concentrations.

2. All routes of exposure needed to complete the exposure assessment should be specified. An exposure assessment that is concerned with exposure to both airborne contaminants and contaminants in the food chain must use models that can provide both atmospheric concentrations and deposition rates.

3. The location of the populations at risk and areas used for growing food must be identified to determine the appropriate number and locations of model receptors (USEPA, 1987b).

2.3. DEFINITION OF TERMS

Key terms that are used in the text to describe the processes of air dispersion, modeling, and exposure assessment are defined below:

ADSORPTION. An intermedia transfer mechanism in which an airborne contaminant in the vapor phase becomes attached to particulate matter suspended in the air or to soil particles at the air/soil interface, thereby removing the adsorbed contaminant from the air (USEPA, 1988a).

ADVECTION. The movement of contaminants with an air mass in a predominantly horizontal direction. The process is dependent upon wind speed and direction.

AIR CONTAMINANT. Any substance released into the atmosphere and present in sufficient quantity to have an adverse effect on human health.

AREA SOURCE. Numerous, usually small, sources of contaminant emissions that are distributed over a specified surface area.

ATMOSPHERIC STABILITY. A meteorological condition that affects dispersion of airborne contaminants. The atmosphere is said to be stable when there is little or no vertical movement of air masses. With little or no vertical mixing of the contaminants with the air, contaminant concentrations accumulate at ground level. Unstable atmospheric conditions result in vertical mixing of the air masses.

BOX MODEL. A model in which the entire modeling region is contained in a single cell (box); it is used to obtain estimates of area source concentrations.

DEPOSITION. The process by which particulates and reactive gases are deposited on the earth's surface from the atmosphere. Both wet and dry deposition occurs. Wet deposition occurs sporadically during specific rain or snow events; dry deposition occurs continuously under dry atmospheric conditions.

DIFFUSION. The dispersion of a contaminant relative to its advective movement. Diffusion reduces the central concentrations in a contaminant mass (plume), increases the concentration at the periphery of the mass, and expands the periphery.

DISSOLUTION. A constant, reversible intermedia transfer mechanism in which contaminants in the gaseous phase are either dissolved into water droplets in the air and distributed to other media by precipitation or are dissolved directly into surface water at the air/water interface (USEPA, 1988a).

EFFECTIVE PLUME HEIGHT. The physical height of the stack adjusted by factors that raise the plume (as a result of buoyancy or momentum) or lower it (as a result of downwash or deflection).

EMPIRICAL MODEL. A model that statistically fits simple mathematical forms to data; sometimes called a statistical model. It is typically used for screening purposes or when the data are not sufficient to use Gaussian or grid models (USEPA, 1986a).

EXPOSURE. Contact of a chemical or physical agent with the outer boundary of an organism.

EXPOSURE ASSESSMENT. The determination of the magnitude, frequency, duration, and route of exposure.

GAUSSIAN PLUME MODEL. A model most commonly used to represent plume dispersion in the near-field range. Simple expressions (Gaussian functions) are assumed to represent the dependence of pollutant concentration on lateral or vertical distance from the plume centerline (i.e., the advective path).

GRAVITATIONAL SETTLING. An intermedia transfer mechanism where particulate contaminants or contaminants adsorbed onto suspended particulates settle to surface media via gravitational attraction. The particulates are normally more than 20 μm in diameter (USEPA, 1988a).

MODEL. A quantitative or mathematical representation or simulation that attempts to describe the characteristics or relationship of physical events.

PASQUILL-GIFFORD DISPERSION COEFFICIENTS. Numerical values of the standard deviations of atmospheric displacements about any point moving with the mean wind. The values are defined as a continuous, empirical function of downwind travel distance (of pollutant from a source) for each discrete stability class.

PASQUILL-TURNER ATMOSPHERIC STABILITY CLASSIFICATION. The most often used inferential method of estimating the turbulent state of the atmosphere, in discrete classes, using solar intensity and wind speed as surrogate indicators.

PHYSICAL MODEL. A model that uses actual physical simulation for situations involving complex terrain and severe or erratic meteorological conditions. Its use is limited because of cost and other resource constraints.

POINT SOURCE. A specific source of contaminant emissions that can be characterized as a single point in three-dimensional space (geographic coordinates plus height above ground) and by the mass rate of its emissions.

PRECIPITATION. An intermedia transfer mechanism that removes particulate and aerosol matter from the atmosphere. Particulate and aerosol matter serve as nuclei for the condensation of raindrops. Raindrops generally remove particulates and aerosols greater than 1.0 μm in diameter from the air (USEPA, 1988a).

REACTIVITY. The potential for change in contaminant identity characteristics following emission.

RECEPTOR. A point in space, generally on the ground, where the ambient air concentration of a pollutant is to be determined. Knowing the number and placement of receptors in relation to expected peak concentrations of the contaminant and the population distribution is essential to obtaining reasonable exposure estimates. An individual exposed at such a point is also known as a receptor.

STAR (STABILITY ARRAY) DATA. Summaries of meteorological data including seasonal or annual joint frequencies for each stability class, wind direction, and wind speed category. STAR data are available from the National Climatic Center (NCC), Asheville, North Carolina, for all National Weather Service (NWS) locations in the United States. STAR data from the NWS Station most representative of the site should be used for modeling purposes.

3. GENERAL GUIDELINES AND PRINCIPLES OF MODEL SELECTION

The analyst who is familiar with a range of available models is better prepared to select the most appropriate model to meet the objectives of a given exposure assessment. To assess exposure to airborne contaminants or contaminants that have entered the food chain through atmospheric deposition, the analyst may use either an atmospheric dispersion model that provides estimates of contaminant concentrations or a human exposure model that incorporates both an atmospheric dispersion model and an exposure model.

3.1. ATMOSPHERIC DISPERSION MODELS

In general, the atmospheric dispersion models most commonly selected for use in exposure assessments are readily available, widely accepted by both the scientific community and governmental regulatory agencies, and simple to use (i.e., they require a minimum of input data and little time or money to run). In addition, they provide information in a form that can be easily used to estimate exposure (e.g., the number and placement of receptors are sufficient to estimate maximum individual exposure).

Most near-field exposure assessment situations involving air modeling can be adequately handled by one of several simple Gaussian plume models. These atmospheric dispersion models are similar in design and performance, generally conform to a limited set of well-accepted physical laws and principles (e.g., conservation of mass, simple diffusion), and do not attempt to account for atmospheric variables that are prevalent in complex situations (e.g., varied terrain, long-range transport, highly reactive chemical emissions). The Gaussian plume models are simple representations of dispersion patterns of nonreactive contaminants within 50 km of the emission source(s), and are generally expected to produce computed results within a factor of two of the measured values over flat terrain (NCRP, 1984). Several near-field models are available from User's Network for Applied Modeling of Air Pollution (UNAMAP) through the National Technical Information Service (NTIS) (USEPA, 1986b). All the models listed in Table 2 are near-field models.

Although Gaussian plume dispersion models apply to near-field situations, they are not applicable immediately at the site of the emissions. For example, they would not provide air concentration estimates over a landfill resulting from vaporization. Gaussian dispersion modeling cannot be applied to on-site conditions because experimental data needed to

calibrate the dispersion coefficients used to calculate short-range (<100 m) dispersion are lacking (Hwang, 1987). Frequently simple mixing models or box models are applied in this situation. These models typically assume that the emissions are uniformly mixed within a box-shaped volume and are diluted by the wind. The box model is typically formulated as:

$$C = Q/(LS)V(MH) \qquad \text{(I-1)}$$

where
- C = amount of air concentration of contaminant
- Q = total emission rate (g/sec)
- LS = length of the site perpendicular to the direction of the wind (m)
- V = average wind speed
- MH = mixing height

An advantage of this model is its simplicity. A disadvantage is the uncertainty arising from assumptions regarding restrictions on mixing volume, uniform mixing, and wind speed and direction. The model fails to account for contaminant dispersion but, as stated above, experimental data are lacking for which to calibrate dispersion coefficients. Thus, despite its utility, it is important to emphasize the uncertainty resulting from these simplifying assumptions.

Based on availability, general acceptance, and ease of use, a few models, especially the Industrial Source Complex model (a Gaussian plume atmospheric dispersion model), are preferred for use in exposure assessments. The ISC has an extensive range of modeling options which increases its applicability to different modeling situations. Other models are also used and may often be more applicable for a given exposure assessment. Regardless of which atmospheric dispersion model is used, the analyst should remember that the output from an atmospheric dispersion model is expressed as concentration, not exposure, and that a model may estimate maximum concentration at a point where there is little or no human contact.

Several atmospheric dispersion models discussed in the EPA's *Guideline on Air Quality Models (Revised)* (USEPA, 1986a) and the EPA's *Supplement A to the Guideline on Air Quality Models (Revised)* (USEPA, 1987a) are summarized in the following pages. Models marked with an asterisk (*) have been designated by the EPA as preferred models for regulatory uses; the other models listed have been designated by the EPA as alternative models for regulatory uses.

3.1.1. Buoyant Line and Point Source Dispersion Model (BLP)*

The BLP is a Gaussian plume dispersion model designed to model aluminum reduction plants and other industrial sources for which plume rise and downwash effects from stationary line sources are important. This model is recommended for modeling aluminum reduction plants that contain buoyant, elevated line sources in rural areas over distances of less than 50 km in simple terrain with averaging times of 1 hour to 1 year.

3.1.2. CALINE3*

CALINE3 is a steady-state Gaussian plume model used to estimate concentrations of nonreactive pollutants from highway traffic. It can be applied to determine air pollutant concentrations at receptor locations downwind of "at grade," "fill," "bridge," and "cut section" highways located in relatively uncomplicated terrain. It is applicable for any wind direction, highway orientation, and receptor location. Other features include the ability to adjust averaging times and surface roughness, the ability to handle up to 20 highway links and 20 receptors, and the availability of an algorithm to account for deposition and settling velocity (i.e., the ability to handle particulate concentrations). This model is recommended for modeling line (highway) sources in rural or urban areas for distances of less than 50 km in simple terrain with averaging times of 1 to 24 hours.

3.1.3. Climatological Dispersion Model (CDM 2.0)*

The CDM 2.0 is a climatological steady-state Gaussian plume model used for determining long-term arithmetic average pollutant concentrations at any ground level receptor in an urban area. This model is recommended for modeling point and area sources in urban areas for distances of less than 50 km in simple terrain with averaging times of 1 month to 1 year, or longer.

The CDMQC, a version of the CDM, can also produce a source contribution list and, using a statistical model, can transform the average concentration data for a limited number of receptors into expected geometric mean and maximum concentration values for several different averaging times.

3.1.4. Offshore and Coastal Dispersion Model (OCD)*

The OCD is a straight-line Gaussian plume model developed to determine the impact of offshore emissions from point sources on the air quality of coastal regions. The OCD incorporates overwater plume transport and dispersion as well as changes that occur as the plume crosses the shoreline. Hourly meteorological data are needed from both offshore and onshore locations. These include water surface temperature, overwater air temperature, and relative humidity. Some of the key features include platform building downwash, partial plume penetration into elevated inversions, direct use of turbulence intensities for plume dispersion, interaction with the overland internal boundary layer, and continuous shoreline fumigation. The Minerals Management Service (U.S. Department of the Interior, 1985) has recommended the OCD for emissions located on the Outer Continental Shelf. The OCD is applicable for overwater sources where onshore receptors are below the lowest source height. Where onshore receptors are above the lowest source height, offshore plume transport and dispersion may be modeled on a case-by-case basis in consultation with the EPA Regional Office.

3.1.5. Gaussian Plume Multiple Source Air Quality Algorithm (RAM)*

RAM is a steady-state Gaussian plume model used to estimate concentrations of relatively stable pollutants. This model is recommended for modeling point and area sources in urban areas for distances of less than 50 km in simple terrain with averaging times of 1 hour to 1 year. Both RAM and the CDM 2.0 are preferred EPA atmospheric dispersion models for long-term, multiple point sources. The EPA recommends that RAM be used for areas having only a few sources to be modeled. A rural version of RAM exists, but it is not recommended for regulatory use.

3.1.6. Industrial Source Complex Model (ISC)*

The ISC is a steady-state Gaussian plume model used to assess pollutant concentrations from the wide variety of sources associated with industrial complexes. It can account for settling and dry deposition of particulates; downwash; area, line, and volume sources; plume rise as a function of downwind distance; separation of point sources; and limited terrain adjustment. This model is recommended for modeling industrial complexes (collections of varied sources, including points, areas, lines, and volumes, associated with one

plant site) in rural or urban areas for distances of less than 50 km in simple terrain. The ISCST, the short-term version, uses an averaging time of 1 hour and can combine hourly results to give 1- or n-day averages. The ISCLT, a long-term version, uses averaging times of 1 month to 1 year.

3.1.7. Multiple Point Gaussian Dispersion Algorithm with Terrain Adjustment (MPTER)*

The MPTER is a steady-state Gaussian plume model used for making hourly estimates of air concentrations of relatively nonreactive pollutants. This model is recommended for modeling point sources in rural or urban areas for distances of less than 50 km in simple terrain with averaging times of 1 hour to 1 year.

3.1.8. Single Source Model (CRSTER)*

The CRSTER is a steady-state Gaussian plume model recommended to estimate single point sources in rural areas for distances of less than 50 km in simple terrain. Highest and second-highest concentrations are calculated at each receptor for 1-, 3-, and 24-hour and 1-year averaging times.

3.1.9. Urban Airshed Model (UAM)*

The UAM is an urban scale, three-dimensional, grid type, numerical simulation model. It incorporates a condensed photochemical kinetics mechanism for urban atmospheres. It is designed for computing ozone concentrations under short-term, episodic conditions lasting 1 or 2 days resulting from emissions of oxides of nitrogen (NO_x) and volatile organic compounds (VOCs). The model treats urban VOC emissions as their carbon-bond surrogates.

The UAM is recommended for modeling single urban areas having significant ozone attainment problems and no interurban emission transport with an averaging time of 1 hour.

3.1.10. Air Pollution Research Advisory Committee (APRAC-3)

APRAC-3 is a Gaussian plume model that computes hourly average carbon monoxide concentrations for any urban location. It calculates concentrations from dispersion on three scales: extraurban (mainly from sources upwind of the city of interest), intraurban (from freeway, arterial, and feeder street sources), and local (from within a street canyon). Its use

requires an extensive traffic inventory for the city of interest. An emissions model, incorporating MOBILE2, is used to compute emission factors. The documentation now contains a revised table (*Inputs for preprocessor program*) for accommodating additional MOBILE2 inputs.

3.1.11. Air Quality Display Model (AQDM)

The AQDM is a climatological, steady-state Gaussian plume model that estimates annual arithmetic average sulfur dioxide and particulate concentrations at ground level in an urban area. A statistical model is used to transform the average concentration data from a limited number of receptors into expected geometric mean and maximum concentration values for several different averaging times.

3.1.12. Air Resources Regional Pollution Assessment Model (ARRPA)

The ARRPA is a medium- to long-range Gaussian segmented-plume model designed to compute air concentrations and surface dry mass deposition of sulfur dioxide and sulfate. The model is unique in its use of prognostic meteorological output from the National Weather Service Boundary Layer Model (BLM), which computes boundary layer conditions on a grid with spatial resolution of 80 km and archives them in intervals of 3 hours. The ARRPA uses the three-dimensional wind field components and potential temperature at 10 height levels, from the surface through 2000 meters above the surface. It is recommended, possibly, for transport distances less than 50 km.

3.1.13. COMPTER

COMPTER is a Gaussian plume model. It is applicable to both urban and rural areas, calculates maximum 24-, 3-, 1-, and variable-hour concentrations for both block and running averages, considers elevated terrain using either the standard plume chopping technique or a stability-dependent plume path trajectory, uses annual hourly meteorological data in the CRSTER preprocessor format, uses Pasquill-Gifford stability curves, and allows for stability class substitution in the stable categories. Typical use is in rural areas with moderate to low terrain features.

3.1.14. ERT Air Quality Model (ERTAQ)

ERTAQ is a multiple point, line, and area source dispersion model based on the univariate form, with multiple reflections, of the Gaussian plume dispersion model. With the fugitive dust option, entrainment of particulates from ground level sources and their subsequent deposition are accounted for. An urban/rural option is available. Long-term or worst-case concentrations due to arbitrarily located sources may be calculated at arbitrarily located receptors, which may be at or above ground level. The user can specify background concentrations and calibration factors at each receptor. Unique flexibility is afforded by a postprocessing storage and manipulation capability.

3.1.15. HIWAY-2

HIWAY-2 is a steady-state Gaussian plume model that can be used to estimate concentrations of nonreactive pollutants from highway traffic. It considers receptors located downwind of "at grade" and "cut section" highways located in relatively uncomplicated terrain. It is applicable for any wind direction, highway orientation, and receptor location. It was developed for situations where horizontal wind flow dominates, but it cannot handle complex terrain or large obstructions to the flow (e.g., buildings or large trees).

3.1.16. LONGZ

LONGZ uses a steady-state, univariate Gaussian plume formula to calculate ground level air concentrations for both urban and rural areas in flat or complex terrain due to emissions from up to 14,000 arbitrarily placed sources (stacks, buildings, and area sources). The output consists of the total concentration at each receptor due to emissions from each user-specified source or group of sources, including all sources. An option that considers losses due to deposition for complex terrain is considered inappropriate by the EPA.

3.1.17. Multiple Point Source Diffusion Model (MPSDM)

The MPSDM is a steady-state Gaussian dispersion model designed to calculate, in sequential mode or in "case-by-case" mode, concentrations of nonreactive pollutants resulting from single or multiple source emissions. It may be used for sources located in flat or complex terrain in a univariate (σ_y, σ_z) mode. Sufficient flexibility is allowed in the specification of model parameters to allow the user to duplicate results that would be obtained

from other Gaussian point source models. A number of features are incorporated to facilitate site-specific validation studies.

3.1.18. Mesoscale Transport Diffusions and Deposition Model for Industrial Sources (MTDDIS)

The MTDDIS is a variable trajectory Gaussian puff model applicable to long-range transport of point source emissions over level or rolling terrain. It can be used to determine 3-hour maximum and 24-hour average concentrations of relatively nonreactive pollutants from up to 10 separate stacks.

3.1.19. MULTIMAX

MULTIMAX is a Gaussian plume model applicable to both urban and rural areas. It can be used to calculate highest and second-highest concentrations for each of several averaging times for up to 100 arbitrarily located sources.

3.1.20. Point, Area, Line Source Algorithm (PAL)

The PAL is a method of estimating short-term dispersion using Gaussian plume steady-state assumptions. It can be used for estimating concentrations of nonreactive pollutants at 99 receptors for averaging times from 1 to 24 hours, and for a limited number of point, area, and line sources (99 of each type). It is not intended for application to entire urban areas, but rather is intended to assess the impact on air quality (on scales of tens to hundreds of meters) in portions of urban areas such as shopping centers, large parking areas, and airports. Level terrain is assumed. Concentrations from point sources are estimated after determining the effective height of emissions and the upwind and crosswind distance from the source to the receptor. Numerical integration of the Gaussian point source equation is used to determine concentrations from the four types of line sources. Subroutines are included that estimate concentrations for multiple land line and curved path sources, special line sources (those with endpoints at different heights above ground), and special curved path sources. Integration over the area source, which includes edge effects from the source region, is done by considering finite line sources perpendicular to the wind at intervals upwind from the receptor. The crosswind integration is done analytically; integration upwind is done numerically by successive approximations.

3.1.21. Pacific Gas and Electric PLUME5 Model (PLUME5)

PLUME5 is a steady-state Gaussian plume model applicable to both urban and rural areas in uneven terrain. It calculates pollutant concentrations at 500 receptors for up to 10 sources with up to 15 stacks each and uses up to 5 meteorological inputs. PLUME5 is similar to the CRSTER and the MPTER but contains several options that may allow for better simulation of atmospheric conditions and improved model outputs. These options allow plume rise into or through a stable layer and crosswind spread of the plume by wind directional shear with height, initial plume expansion, mean (advective) wind speed, terrain considerations, and chemical transformation of pollutants. PLUME5 and the CRSTER differ in the stability class determination, hourly mixing height schemes, hourly stable layer data, randomization of wind direction, extent of data set required for preprocessing, and meteorological data inputs.

3.1.22. Rough Terrain Diffusion Model (RTDM)

Version 3.0 of the RTDM is a sequential Gaussian plume model designed to estimate ground-level concentrations in rough or flat terrain near one or more collocated point sources. It is specifically designed for applications involving chemically stable pollutants and is best suited for evaluation of buoyant plume behavior within about 15 km of the source(s) location. Results for receptors between 15 and 50 km can be used with caution; results beyond 50 km can be used for screening purposes. Special algorithms deal with plume behavior in complex terrain.

Although the RTDM 3.0 is designed for use with sequential data sets, it can be used in a case-study mode. Optional features make it useful for either research/sensitivity applications or routine evaluations of source compliance. It can use hourly, on-site measurements of turbulence intensity, vertical temperature difference, horizontal wind shear, and wind speed profile exponents. However, it is flexible enough in specifying model inputs to let the user obtain results similar to many other Gaussian point source models. Its ability to read hourly emissions data makes it useful for site-specific model evaluation studies.

3.1.23. Multi-Source Model (SCSTER)

The SCSTER is a modified version of the CRSTER model which includes the ability to consider multiple sources that are not necessarily collocated, enhanced receptor

specifications, variable plume height terrain adjustment procedures, and plume distortion from directional wind shear.

3.1.24. SHORTZ

SHORTZ uses the steady-state bivariate Gaussian plume formulation for both urban and rural areas in flat or complex terrain to calculate ground-level ambient air concentrations. It can calculate 1-, 2-, 3-, and n-hour average concentrations due to emissions from stacks, buildings, and area sources for up to 300 arbitrarily placed sources. Output consists of total concentration at each receptor due to emissions from each user-specified source or group of sources, including all sources. If the option for gravitational settling is used, analysis in complex terrain cannot be accomplished without violating mass continuity.

3.1.25. Simple Line Source Model (SLSM)

The SLSM is a simple, steady-state Gaussian plume model that can be used to determine hourly (or half hourly) averages of exhaust concentrations within 100 meters of a roadway on relatively flat terrain. The model allows for plume rise due to heated exhaust, which can be important when the crossroad wind is very low. It also uses a new set of vertical dispersion parameters that reflects the influence of traffic-induced turbulence.

3.1.26. Texas Climatological Model (TCM-2)

The TCM-2 is a climatological, steady-state Gaussian plume model for determining long-term (seasonal and annual arithmetic) average pollutant concentrations of nonreactive pollutants.

3.1.27. Texas Episodic Model (TEM-8)

The TEM-8 is a steady-state Gaussian plume model for determining short-term concentrations of nonreactive pollutants.

3.1.28. Models 3141 and 4141

Models 3141 and 4141 are modifications of the CRSTER that are applicable to complex terrain, particularly where receptor elevation approximately equals or exceeds the stack-tip elevation. It uses intermediate ground displacement procedures and dispersion

enhancements developed from an aerial trace study and ground level concentrations measured for a power plant located in complex terrain.

3.2. HUMAN EXPOSURE MODELS

In conducting exposure assessments, the analyst may decide to use a model designed specifically to estimate human exposure. These models incorporate a population distribution data base with an atmospheric dispersion model and include mechanisms for calculating exposure from paired contaminant concentrations and population location. Two such models are the Human Exposure Model (HEM) and the Inhalation Exposure Methodology (IEM).

The HEM was specifically designed by the EPA to estimate the population exposed to air pollutants emitted from stationary sources and the carcinogenic risk associated with this exposure (USEPA, 1986c). The HEM is comprised of two basic exposure assessment models that differ slightly in purpose and scope. The Systems Applications Human Exposure and Dosage (SHED) model is generally used to model single pollutants from major point sources on a nationwide basis. The Systems Applications Human Exposure and Risk (SHEAR) model is used to model single or multiple pollutants in more restricted geographic areas for major point, prototype, and area sources. The population distribution data base is comprised of the 1980 Census Data Base, which is broken down by block group/enumeration district (BG/ED). The *User's Manual for the Human Exposure Model (HEM)* (USEPA, 1986c) discusses the characteristics of the two basic models and the population data base in detail. Arrangements for use of the HEM can be obtained through the NTIS (USEPA, 1986c).

The IEM uses the Industrial Source Complex Long-Term model to calculate annual average ground level air concentrations of contaminants. These concentrations are entered into a concentration-exposure program that calculates population exposures to the contaminants. The method provides interactive access to selected STAR data, the ISCLT model, and the 1980 census (population) data (USEPA, 1983).

3.3. MODEL SELECTION PROCESS

The atmospheric dispersion model selected, whether used alone or as a component of a human exposure model, must adequately characterize specific characteristics of site, source, and emissions. Several key factors, processes, and assumptions that affect contaminant concentrations were discussed in the previous section and serve as the basis for

model selection. However, the model user need not determine all of these factors, processes, and assumptions. The atmospheric dispersion models incorporate several of these factors in their codes (e.g., dispersion coefficients).

The model selection process can be simplified by developing a profile of the features needed (Table 1) and comparing it with the capabilities of various models (Table 2). In some cases, several models may meet the general criteria, and the reader should consult the appropriate model descriptions in Section 3.1 and supplemental information in Tables 3 and 4. In other cases, the situation may call for a model feature available only in one or a few models. For some modeling situations, such as those involving complex terrain, no one model may be appropriate.

The EPA's *Guideline on Air Quality Models (Revised)* (USEPA, 1986a) and EPA's *Supplement A to the Guideline on Air Quality Models (Revised)* (USEPA, 1987a) provide extensive information on the selection of atmospheric dispersion models for regulatory and compliance uses. Although the information provided is for purposes different from those of an exposure assessment, the risk analyst will find the *Guideline* to be an excellent resource for identifying key features of the most often selected air dispersion models. The *Guideline* should be used in conjunction with this document and should prove useful to persons filling out the Model Selection Profile (Table 1). A brief summary of the items in the profile follows.

3.3.1. Geographic Scale

Most exposure assessments consider only near-field (≤50 km) dispersion, since individual exposures are highest near the emission sources and these areas usually include most of the exposed population. Far-field (>50 km) dispersion is becoming more of a concern because of the potential for widespread emission and long-term accumulation of contaminants at low concentrations. Since far-field dispersion modeling is complex and not extensively tested, analysts wishing to use this method should get professional help in defining the scope of the study and selecting appropriate modeling techniques.

3.3.2. Time Scale

The time period over which exposure estimates are to be averaged should be matched with the model's averaging time capacity. For long-term exposure, models should be able to

Table 1. MODEL SELECTION PROFILE

GEOGRAPHIC SCALE	
Near-field (≤50 km)	_____
Far-field (>50 km)	_____
TIME SCALE	
Long-term exposure	_____
Short-term exposure	_____
LAND USE	
Urban	_____
Rural	_____
TERRAIN	
Flat/rolling	_____
Complex	_____
SOURCE CONFIGURATION	
Point	_____
Elevated point	_____
Nonpoint (e.g., area, line)	_____
Multiple sources treated individually	_____
REACTIVITY	
Low or nonreactive primary contaminant	_____
Reactive primary contaminant	_____
Formation of secondary contaminants	_____
FORM OF RELEASE	
Gaseous	_____
Particulate	_____
REMOVAL MECHANISMS	
Decay	_____
Reaction	_____
Deposition	_____

Table 2. CHARACTERISTICS OF ATMOSPHERIC DISPERSION MODELS

Model	BLP	CALINE3	CDM 2.0
GEOGRAPHIC SCALE			
Near-field (≤50 km)	Yes	Yes	Yes
Far-field (>50 km)	No	No	No
TIME SCALE			
Long-term exposure	Yes	Yes	Yes
Short-term exposure	Yes	No	Yes
LAND USE			
Urban	No	Yes	Yes
Rural	Yes	Yes	No
TERRAIN			
Flat/rolling	Yes/Yes	Yes/No	Yes/No
Complex	No	No	No
SOURCE CONFIGURATION			
Point/Line	Yes/Yes	No/Yes	Yes/No
Elevated point	No	No	No
Nonpoint (e.g., area, line)	No	No	Yes
Multiple sources treated individually	No	No	No
REACTIVITY			
Low or nonreactive primary contaminant	Yes	Yes	Yes
Reactive primary contaminant	Yes	Yes	Yes
Formation of secondary contaminants	No	No	No
FORM OF RELEASE			
Gaseous	Yes	Yes	Yes
Particulate	—	—	—
REMOVAL MECHANISMS			
Decay	Linear	No	Exponential
Reaction	No	No	No
Deposition	No	?	No

Table 2. (continued)

Model	CRSTER	ISCLT	ISCST
GEOGRAPHIC SCALE			
Near-field (≤50 km)	Yes	Yes	Yes
Far-field (>50 km)	No	No	No
TIME SCALE			
Long-term exposure	Yes	Yes	No
Short-term exposure	Yes	Yes	Yes
LAND USE			
Urban	Yes	Yes	Yes
Rural	Yes	Yes	Yes
TERRAIN			
Flat/rolling	Yes/Yes	Yes/Yes	Yes/Yes
Complex	No	No	No
SOURCE CONFIGURATION			
Point/line	Yes/No	Yes/Yes	Yes/Yes
Elevated point	No	Yes	Yes
Nonpoint (e.g., area, line)	No	No	Yes
Multiple sources treated individually	No	Yes	Yes
REACTIVITY			
Low or nonreactive primary contaminant	Yes	Yes	Yes
Reactive primary contaminant	Yes	Yes	Yes
Formation of secondary contaminants	No	No	No
FORM OF RELEASE			
Gaseous	Yes	Yes	Yes
Particulate	—	Yes	Yes
REMOVAL MECHANISMS			
Decay	Exponential	Exponential	Exponential
Reaction	No	No	No
Deposition	No	Yes	Yes

Table 2. (continued)

Model	MPTER	RAM	UAM
GEOGRAPHIC SCALE			
Near-field (≤50 km)	Yes	Yes	Yes
Far-field (>50 km)	No	No	No
TIME SCALE			
Long-term exposure	No	No	No
Short-term exposure	Yes	Yes	Yes
LAND USE			
Urban	Yes	Yes	Yes
Rural	Yes	No	No
TERRAIN			
Flat/rolling	Yes/Yes	Yes/No	Yes/?
Complex	No	No	No
SOURCE CONFIGURATION			
Point/line	Yes/No	Yes/No	Yes/No
Elevated point	No	No	Yes
Nonpoint (e.g., area, line)	No	Yes	Yes
Multiple sources treated individually	Yes	Yes	Yes
REACTIVITY			
Low or nonreactive primary contaminant	Yes	Yes	NO_x,VO
Reactive primary contaminant	Yes	Yes	Yes
Formation of secondary contaminants	No	No	Ozone
FORM OF RELEASE			
Gaseous	Yes	Yes	Yes
Particulate	—	—	—
REMOVAL MECHANISMS			
Decay	Exponential	Exponential	No
Reaction	No	No	Yes[a]
Deposition	No	No	Yes

[a]USEPA, 1980a

Table 3. SITE CHARACTERISTICS—ATMOSPHERIC DISPERSION MODELS

Model	Reference	Type	Averaging time[a]
BLP	Schulman and Scire, 1980	GP[b]	1H, 3H, 24H to 1Y
CALINE3	Benson, 1979		
	Messina et al., 1983	GP	1H to 24H
CDM 2.0	Irwin et al., 1985	GP	1H to 24H, 1M to 1Y
CRSTER	USEPA, 1977a	GP	1H, 3H 24H, 1Y
ISCLT	USEPA, 1986d; USEPA, 1987c	GP	M, S, Y
ISCST	USEPA, 1986d; USEPA, 1987c	GP	1H to 24H
MPTER	USEPA, 1980b	GP	1H to 24H
RAM	USEPA, 1978	GP	1H to 24H
UAM	Ames et al., 1984	3-D	1H
	USEPA, 1980c	numerical grid	

[a]Averaging times: hourly (H), monthly (M), seasonally (S), yearly (Y)

[b]Gaussian plume

Table 4. SOURCE CHARACTERISTICS—ATMOSPHERIC DISPERSION MODELS

Model	Source configuration	Allowed locations	Plume rise and source-related modifications[a]
BLP	50 points, 10 lines	User-specified	Authors' plume rise and building downwash correction (Schulman and Scire, 1980); line sources use transitional rise, optional for points.
CALINE3	20 lines (highway links)	User-specified	None
CDM 2.0	points, areas	User-specified	Briggs final rise for buoyant plumes under neutral/unstable conditions (Benson, 1979); ISC stack-tip downwash correction (Messina et al., 1983).
CRSTER	19 points	Collocated	Briggs final rise for buoyant plumes under stable/calm (USEPA, 1973), stable/windy (USEPA, 1977a), and unstable or neutral (USEPA, 1977b) conditions; ISC stack-tip downwash correction (Messina et al., 1983).
ISCLT	Unlimited points, lines	User-specified	Briggs final or distance-dependent rise for buoyant and/or momentum plumes depending on areas, volumes value of vertical potential temperature gradient (Benson, 1979; USEPA, 1973); stack-tip downwash correction; Huber and Snyder virtual source treatment of point sources with building wake effects and of volume sources (USEPA, 1979).
ISCST	150 (total) points, lines, areas, volumes	User-specified	Same as ISCLT.
MPTER	Unlimited points	User-specified	Briggs rise for buoyant plumes under stable (USEPA, 1973) and unstable/neutral (Benson, 1979) conditions, and for momentum plumes under stable (USEPA, 1980b) and unstable/neutral (Benson, 1979) conditions; ISC stack-tip downwash correction.
RAM	Unlimited points, areas	User-specified	Briggs rise for buoyant plumes under stable (USEPA, 1977b) and unstable (USEPA, 1973) conditions, momentum plumes under stable (USEPA, 1980c) and unstable/neutral (Benson, 1979) conditions; Briggs stack downwash correction (USEPA, 1973).
UAM	point or area, +500 elevated points	In each grid user-specified	Briggs (Ames et al., 1984; USEPA, 1980a).

[a] Plume rise calculations are applicable only to point sources unless otherwise stated.

provide annual average concentrations. For short-term or brief, intense exposures to potentially toxic substances, the model should be able to provide 1-, 8- and 24-hour average air concentrations.

3.3.3. Land Use

Selecting the type of land use for the modeling area determines the appropriate dispersion coefficients. Use the meteorological land use type scheme (e.g., Table 5) to classify the area within a 3-km radius of the source. If land use types I1, I2, C1, R2, and R3 account for more than 50% of the total area, the area is considered urban. Otherwise, the area is considered rural. For multiple sources, use the parameter that defines the location of most of the sources; that is, if most of the sources are located in urban areas, the entire source is modeled as an urban area (USEPA, 1986a).

3.3.4. Terrain

Many models can be used for flat or rolling terrain, but no dispersion models for complex terrain currently exist. However, for regulatory purposes, the EPA has designated existing models that can be adapted to site-specific complex terrain for screening purposes to calculate concentrations at receptors located at or above plume height (i.e., in complex terrain).

3.3.5. Source Characteristics

Point sources may be elevated or may be located at the site of process vents or near other ground level release points. Models for point sources should account for effective plume rise.

Nonpoint or area sources are evaluated using a simplified box model in which

$$\text{Air Concentration of Contaminant} = \frac{\text{Total Emission Rate (g/s)}}{\text{Area Length X Average Wind Speed X Mixing Height}}$$

Box models assume a well-mixed volume and do not account for contaminant dispersion. The Gifford-Hanna algorithm (Gifford and Hanna, 1973), which contains a

Table 5. IDENTIFICATION AND CLASSIFICATION OF LAND USE TYPES FOUND IN METROPOLITAN ST. LOUIS

	Description	
Type	**Use and structures**	**Vegetation**
I1	**Heavy industrial** Major chemical, steel, and fabrication industries; generally 3-5 story buildings, flat roofs	Grass and tree growth extremely rare; <5% vegetation
I2	**Light-moderate industrial** Rail yards, truck depots, warehouses, industrial parks, minor fabrication; generally 1-3 story buildings, flat roofs	Very limited grass, trees almost totally absent; <5% vegetation
C1	**Commercial** Office and apartment buildings, hotels; >10 story heights, flat roofs	Limited grass and trees; <15% vegetation
R1	**Common residential** Single family dwellings with normal easements; generally one story, pitched roof structures; frequent driveways	Abundant grass lawns and lightly to moderately wooded; >70% vegetation
R2	**Compact residential** Single, some multiple, family dwelling with close spacing; generally <2 story, pitched roof structures; garages (via alley) and ashpits, no driveways	Limited lawn sizes and shade trees; <30% vegetation
R3	**Compact residential** Old multi-family dwellings with close (<2) lateral separation; generally 2 story, flat roof structures; garages (via alley) and ashpits, no driveways	Limited lawn sizes, old established shade trees; <35% vegetation

Table 5. (continued)

Type	Description: Use and structures	Description: Vegetation
R4	**Estate residential** Expansive family dwelling on multi-acre tracts	Abundant grass lawns and lightly wooded; >80% vegetation
A1	**Metropolitan natural** Major municipal, state, or federal parks, golf courses, cemeteries, campuses; occasional single story structures	Nearly total grass and lightly wooded; >95% vegetation
A2	**Agricultural rural**	Local crops (e.g., corn, soybean); >95% vegetation
A3	**Undeveloped** Uncultivated; wasteland	Mostly wild grasses and weeds, lightly wooded; >90% vegetation
A4	**Undeveloped rural**	Heavily wooded; >95% vegetation
A5	**Water surfaces** Rivers, lakes	

SOURCE: Auer, 1978.

coefficient for urban size, is widely used to model area source releases in urban areas. Some models also use the virtual point source concept (e.g., the ISCLT).

3.3.6. Reactivity

Since dispersion of airborne contaminants is affected by their ability to interact with the environment, the analyst must assess the reactivity of the primary contaminant as well as the formation of secondary contaminants. Modeling reactive contaminants in a complex reactive system requires monitoring of both the reactive system and the dispersion and fate of all the contaminants involved.

3.3.7. Form of Release

Although all recommended systems model gases, few can model particulates. Thus the form of the contaminant release may be a significant limiting factor in model selection.

3.3.8. Removal Mechanism

Dissolution, adsorption, gravitational settling, and precipitation affect the removal of contaminants from the air and their environmental fate. Many near-field atmospheric dispersion models do not account for these removal mechanisms. If the exposure assessment is intended to estimate contaminants in the food chain, the model should account for removal mechanisms in the near-field range.

4. EXAMPLES OF MODEL SELECTION FOR SPECIFIC EXPOSURE ASSESSMENTS

This section provides examples of how to select the appropriate air dispersion model for contaminants emitted from various sites. Profiles were developed for three situations by using the Model Selection Profile (Table 1). These profiles (Table 6) were compared to the model characteristics in Table 2 to determine which models were appropriate for each task.

The following sections provide an overview of municipal waste combustors, perchloroethylene emissions from dry cleaning facilities, and exposure to dioxin from soils via vapor inhalation. For each situation, the model requirements and the relative merits of various models are discussed to illustrate the reason for the final model selection.

4.1. MUNICIPAL WASTE COMBUSTORS

Incineration of municipal solid waste releases both metals and organics into the environment. Approximately 100 municipal waste combustors (MWCs) are currently operating in the United States, having the incineration capability of more than 47,000 tons of waste. By the year 2000, that capacity is estimated to reach 250,000 tons (USEPA, 1987d). As the use of municipal waste incineration for a waste management alternative has increased, so has public concern over possible environmental and human health effects. Of particular concern are persons living near incinerators, who are exposed via the inhalation and ingestion routes.

4.1.1. Assessment

Although all recommended models can be used for near-field situations, only the CRSTER and the ISCLT provide long-term averaging and apply to rural and urban settings and stack sources. No models are appropriate for complex terrain, so this need cannot be addressed. Of these two models, only the ISCLT handles both particulate emissions and associated deposition.

4.1.2. Recommendation

Based on these criteria, the ISCLT is the model of choice. The ISC atmospheric dispersion model is well-suited for use in risk assessment at MWCs because it is a point source model and can allow for stack heights, exit velocities, and other source term

Table 6. MODEL SELECTION CRITERIA FOR SAMPLE SITES

	Municipal waste combustors	PCE emissions from dry-cleaning	Dioxin in soils
Site			
Geographic scale	near-field[a]	near-field[a]	on-site and near-field[d]
Time scale	long-term[b]	long-term[b]	long-term[b]
Land use	urban and rural possible	urban for most facilities	rural location for landfills
Terrain	flat or complex possible	flat or complex possible	flat or complex
Source			
Source config.	elevated point source for stacks	single point source and collection of point sources acting as an area	ground level area source (i.e., landfills)
Emissions			
Reactivity	low[c]	low[c]	low[c]
Form of release	particulate and gaseous	gaseous emissions only	gaseous, since vaporization process used
Removal mechanisms	particulate deposition	none[c]	none[c]

[a] Usually where highest exposure occurs.
[b] Since interest is in long-term health effects.
[c] Conservative estimate.
[d] Workers are onsite and residents nearby.

characterization parameters. The ISC is a near-field model, i.e., it can estimate concentrations within 20 to 50 km of a MWC. The ISC computes both short-term (maximum 24-hour concentrations) and long-term (yearly average) atmospheric concentrations around the facility. The ISC also accounts for buoyancy-induced dispersion that is likely to be significant from combustion processes and the aerodynamic effects of building downwash, which is likely to be significant for many MWCs with short stacks.

Although the ISC is often the model selected for estimating concentrations of contaminants from MWCs, it has some limitations in its use for exposure assessments. The ISC is an atmospheric dispersion model, not a human exposure model, and it cannot estimate exposure. As a note, the Human Exposure Model (HEM), developed by the EPA specifically to estimate exposure, combines atmospheric concentration estimates with population statistics for the entire United States. Although HEM currently uses another point source atmospheric dispersion model, the EPA is in the process of incorporating the ISC into the HEM code. Once these modifications have been made, the HEM model will provide a valuable addition to the modeling techniques available for estimating human inhalation exposures around MWCs.

Another limitation of the ISC is that it currently uses reflection coefficients to estimate deposition velocities of pollutants. The use of reflection coefficients is questionable for estimating deposition impacts on the food chain. A more reliable method, employed by the California Air Resources Board (CARB) Model (Sehmel and Hodgson, 1978; CARB, 1986), accounts for particle size deposition velocities.

The ISC is intended for urban or rural situations where the terrain elevations do not exceed stack height; it is not designed to handle complex terrain situations. However, the complex terrain screening models that could be used to model complex terrain, such as LONGZ and COMPLEX I, do not account for particulate deposition and therefore are not useful for estimating food chain impacts in complex terrain situations. In addition, these complex terrain screening models do not account for building downwash.

4.2. PERCHLOROETHYLENE EMISSIONS FROM DRY CLEANING FACILITIES

Perchloroethylene (PCE), a volatile chlorinated hydrocarbon, is used extensively as a solvent in dry cleaning operations; an estimated 40% of all PCE produced annually in the United States is used by the dry-cleaning industry. PCE emissions are almost exclusively

atmospheric and, in vapor form, PCE is readily absorbed through the lungs. PCE is classified as a probable human carcinogen via inhalation.

4.2.1. Assessment

The EPA performed an inhalation risk assessment for PCE emissions from dry-cleaning facilities. The documentation of exposure and cancer risk assessment for the dry cleaning source category was described in an EPA internal memorandum dated December 10, 1987, from J.J. Vandenberg, Pollutant Assessment Branch, to M.L. Meech, Chemicals and Petroleum Branch, Office of Air Quality Planning and Standards. Quantitative estimates for both annual average exposure from a single source and national aggregate exposure from multiple, unspecified sources were needed to adequately assess human exposure nationwide to emissions of PCE from dry-cleaning facilities.

In addition to the requirements outlined in Table 1, the model needs to estimate the aggregated exposure for the United States. This requires a model that can incorporate a population distribution data base with an atmospheric dispersion model and limits selection to the HEM and Inhalation Exposure Model (see Section 3.2).

4.2.2. Recommendation

Of these two models, the HEM specifically addresses the two-point source configuration requirements and is thus the logical choice.

The general HEM model contains an atmospheric dispersion component including meteorological data, a population distribution data file for the entire United States, and an automated method for calculating human exposure and subsequent risk. It includes two basic human exposure models, SHED and SHEAR. To estimate exposures to PCE, SHED was used to model point sources and SHEAR was used to model area sources.

For point source modeling, SHED employs a Gaussian atmospheric dispersion model similar to the Climatological Dispersion Model (CDM) (USEPA, 1986a) to estimate the annual average ground level concentrations resulting from emissions of point sources. It assumes that the terrain is flat. The CDM-type atmospheric model used in SHED also accounts for enhanced dispersion caused by building wake effects; however, as is common for Gaussian plume models, it cannot realistically estimate concentrations at elevated receptors, such as multi-storied apartment buildings.

Input data required by this atmospheric model include source location (specifically, longitude/latitude coordinates); emission rate; source parameter data (e.g., stack height and diameter, gas exhaust velocity and temperature); and the appropriate Stability Array (STAR) station code number. Because PCE has a low rate of reactivity, input for atmospheric reactivity was not required. The STAR data sets for meteorological data and the population data base, which includes the 1980 population of each Block Group/Enumeration District in the United States, are permanent parts of the internal computer data base for the HEM.

To compute exposure, SHED pairs concentration with population at the same location or point. The smallest population "point" is the BG/ED level of census data (1980). Although this is the smallest point that can be determined from census data, each BG/ED contains an average of 800 people. These population points are paired with the concentration array for 160 receptors around the point source (10 receptors along each of the 16 wind directions of STAR). Two interpolation approaches are used to define the best concentration/population relationship and are described in detail in the HEM User's Manual (USEPA, 1986c).

For area source modeling, the SHEAR model was used to estimate national aggregate exposure from multiple, unspecified sources of PCE emissions. Input requirements for area source modeling using SHEAR include location (i.e., defining the area or "box" by determining the specific coordinates of the southwest corner of the box and the length and width of the box), emission rate (determined as emissions/area or emissions/person), and code number of the closest (usually) STAR station. Source parameters and atmospheric reactivity values were not required in this application. The defined boxes were restricted to urban areas, i.e., to areas where sources of PCE emissions are most prevalent.

To model dispersion from area sources, SHEAR incorporates a simplified Gifford-Hanna urban area dispersion algorithm (Gifford and Hanna, 1973). This model was chosen because it is can estimate atmospheric pollutant concentrations caused by area source emissions in urban areas (USEPA, 1986c). The basic Gifford-Hanna equation is given as:

$$X = CQ_0/U \qquad \text{(I-2)}$$

where X is air pollutant concentration, C is the Gifford coefficient, Q_0 is the effective emissions rate per unit area, and U is the wind speed.

Exposure to area emissions is a product of the PCE concentration per area of each BG/ED and the number of people in each BG/ED. National aggregate exposure is a summation of human exposure for each BG/ED (USEPA, 1987b).

4.3. EXPOSURE TO DIOXIN FROM SOILS VIA VAPOR INHALATION

In a recent publication, *Estimating Exposures to 2,3,7,8-TCDD* (USEPA, 1988b), the EPA describes the use of various mathematical modeling approaches to estimate exposure to dioxin, a highly carcinogenic, organic compound, via all probable routes of exposure to contaminated soils and sediments as well as through bioaccumulation of dioxin in fish and cattle. The EPA's modeling treatment of exposure to dioxin from soils via vapor inhalation is used here to represent an area source modeling situation. Dioxin emitted from soil surfaces in the form of vapors or particulates can be an exposure hazard to on-site workers and nearby residents. Estimating average lifetime exposure to dioxin via vapor inhalation is the objective of this particular assessment (USEPA, 1988b).

4.3.1. Assessment

The on-site geographic scale requirement means that Gaussian plume models are not applicable (see Section 3.1.) and that all models except the Urban Airshed Model (UAM) are not appropriate. However, the UAM does not provide long-term averages or apply to rural settings, and thus it is also not appropriate. On-site emission models are not well developed and are usually approached by use of simple box models. These models are well suited to area sources and, accordingly, are the best approach for this situation.

4.3.2. Recommendation

Based on these evaluation factors, the UAM is the best available model. However, the modeler should emphasize the uncertainty caused by its simplifying assumptions.

REFERENCES FOR PART I

Ames, J., T. C. Myers, L. E. Reid, D. C. Whitney, S. H. Golding, S. R. Hayes, and S. D. Reynolds. 1984. The user's manual for the SAI urban airshed model. Systems Applications, Inc., San Rafael, CA. EM 78-89.

Anderson, G. E., R. G. Ireson, and S. M. Greenfield. 1983. Planning atmospheric dispersion modeling programs in support of energy development risk analysis. Final Report. Vol. I and II. Prepared for Health and Environmental Risk Assessment Program, Office of Health and Environmental Research, Office of Energy Research, U.S. Department of Energy. SYSAPP-83/047.

Auer, Jr., A. H. 1978. Correlation of land use and cover with meteorological anomalies. J. Appl. Meteorol. 17:636-643.

Benson, P. E. 1979. CALINE3 - A versatile dispersion model for predicting air pollutant levels near highways and arterial streets. Interim Report. U.S. Department of Transportation, Federal Highway Administration, Washington, DC. FHWA/CA/TL-79/23.

Briggs, G. A. 1975. Plume rise predictions. In Lectures on air pollution and environmental impact analyses, pp. 59-111. American Meteorological Society, Boston, MA.

California Air Resources Board (CARB). 1986. Subroutines for calculating dry deposition velocities using Sehmel's curves. CARB. California.

Gifford, F. A. and S. R. Hanna. 1973. Technical note: Modelling urban air pollution. In Atmospheric environment. Vol. 7. Great Britain: Pergamon Press.

Hwang, S. T. 1987. Methods for estimating on-site ambient air concentrations at disposal sites. Nuclear and Chemical Waste Management 7:95-98.

Irwin, J. S., T. Chico, and J. Catalano. 1985. CDM 2.0 - (climatological dispersion model - version 2.0) user's guide. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA/600/8-85/029. NTIS PB86-136546.

Messina, A. D., J. A. Bullin, J. P. Nelli, and R. D. Moe. 1983. Estimates of air pollution near signalized intersections. U.S. Department of Transportation, Federal Highway Administration, Washington, DC. FHWA/TX-81/541-1.

Miller, C. W., S. J. Cotter, and S. R. Hanna, eds. 1981. Proceedings, Symposium on Intermediate Range Atmospheric Transport Processes and Technology Assessment. October 1-3, 1980, Gatlinburg, TN. CONF-801064. Cosponsored by Department of Energy, National Oceanic and Atmospheric Administration, and Oak Ridge National Laboratory.

Murphy, B. D., S. Y. Ohr, and C. L. Begovich. 1984. RETADD-II: A long range atmospheric trajectory model with consistent treatment of deposition loss and species growth and decay. Oak Ridge National Laboratory, Oak Ridge, TN. ORNL/CSD-99.

National Council on Radiation Protection and Measurement (NCRP). 1984. Radiological assessment: predicting the transport, bioaccumulation and uptake by man of radionuclides released to the environment. NCRP, Washington, DC. Report No. 76.

Schulman, L. L. and J. S. Scire. 1980. Buoyant line and point source (BLP) dispersion model user's guide. Document P-7304B. Environmental Research and Technology, Inc., Concord, MA. NTIS PB81-164642.

Sehmel, G. A. and W. H. Hodgson. 1978. A model for predicting dry deposition particles and gases to environmental surfaces. Pacific Northwest Laboratories, Richland, WA. PNL-SA-67-21.

U.S. Department of the Interior. 1985, Mar. 28. Oil and gas and sulfur operations in the outer continental shelf. Minerals Management Service, Washington, DC. Federal Register 50:12248.

U.S. Environmental Protection Agency (USEPA). 1973. User's guide for the climatological dispersion model. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-R4-73-024. NTIS PB 227346/AS.

USEPA. 1977a. User's manual for single source (CRSTER) model. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-450/2-77-013. NTIS PB 271360.

USEPA. 1977b. Addendum to user's guide for climatological dispersion model. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-450/3-77-015. NTIS PB 274-040.

USEPA. 1978. User's guide for RAM, Vol. A and B. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-600/8-78-016. NTIS PB 294791 and PB 294792.

USEPA. 1979. Industrial source complex (ISC) dispersion model user's guide, Vol. 1. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-450/4-79-030.

USEPA. 1980a. Modeling of simulated photochemical smog with kinetic mechanisms, volume 1, Final Report. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-600/3-80/028a.

USEPA. 1980b. User's guide for MPTER. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-600/8/80-016. NTIS PB80-197361.

USEPA. 1980c. Guidelines for applying the airshed model to urban areas. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-450/4-80-020. NTIS PB81-200529.

USEPA. 1983. User's guide for the automated inhalation exposure methodology (IEM). Prepared for the U.S. Environmental Protection Agency, Washington, DC. EPA-600/2-83-029.

USEPA. 1986a. Guideline on air quality models (Revised). Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-450/2-78-027R. (Supplement A, 1987)

USEPA. 1986b. User's network for applied modeling of air pollution (UNAMAP) (Version 6). U.S. Environmental Protection Agency, Research Triangle Park, NC. NTIS PB86-222 361.

USEPA. 1986c. User's manual for the human exposure model (HEM). Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-450/5-86-001.

USEPA. 1986d. Industrial source complex (ISC) dispersion model user's guide, Second Edition, Vol. 1 and 2. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-450/4-86-005a and 005b. NTIS PB86-234259 and PB86-234267.

USEPA. 1987a. Supplement A to guideline on air quality models (Revised). Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-450/2-78-027R.

USEPA. 1987b. Sensitivity analysis for application of the inhalation exposure methodology (IEM) to studies of hazardous waste management facilities. Prepared for the Hazardous Waste Engineering Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency, Cincinnati, OH. EPA/600/2-87/071.

USEPA. 1987c. Industrial source complex (ISC) dispersion model. Addendum to the User's Guide. U.S. Environmental Protection Agency, Research Triangle Park, NC.

USEPA. 1987d. Characterization of the municipal waste combustion industry. Prepared by Radian Corporation for the Office of Air and Radiation, U.S. Environmental Protection Agency, Washington, DC. EPA Contract No. 68-02-4330.

USEPA. 1988a. Superfund exposure assessment manual. Office of Emergency and Remedial Response, U.S. Environmental Protection Agency, Washington, DC. EPA/540/1-88/001.

USEPA. 1988b. Estimating exposures to 2,3,7,8-TCDD. Office of Health and Environmental Assessment, U.S. Environmental Protection Agency, Washington, DC. EPA/600-6-88/005A. NTIS PB 88-231196/AS.

PART II.
GAUSSIAN PLUME MODELS

1. INTRODUCTION

Part II of this document discusses the assumptions, limitations, and uncertainties associated with Gaussian plume models, several Gaussian plume dispersion coefficients, and typical model input data requirements. The Gaussian plume model is the most widely used method of estimating downwind concentrations of nonreactive pollutants released to the atmosphere within 50 km of the source. This class of models is used frequently because (1) it produces results similar to those produced by other models when comparisons are made to experimental data, (2) its mathematical operations are easily performed, (3) it is appealing conceptually, (4) it is consistent with the random nature of turbulence, (5) it is a solution to the simple diffusion equation for constant diffusion and wind speed, (6) other so-called theoretical formulas also contain large amounts of empiricism in their final stages, and (7) it is the model most often referred to in government guidebooks (Hanna et al., 1982). Specific examples of Gaussian models are the *Industrial Source Complex (ISC) and the Climatological Dispersion Model* (CDM 2.0).

1.1. ASSUMPTIONS

The Gaussian class of models is based on the assumption that the plume will spread both laterally and vertically in accordance with a Gaussian statistical distribution under conditions of constant wind speed, no wind shear, flat terrain, and simple diffusion along the direction of the mean wind. The Gaussian equation for the ground level concentration downwind from a continuously emitting ground-level point source is (Gifford, 1968):

$$X = \frac{Q}{\pi u \sigma_y \sigma_z} \exp\left[-\frac{1}{2}\left(\frac{H^2}{\sigma_z^2} + \frac{y^2}{\sigma_y^2}\right)\right] \qquad \text{(II-1)}$$

where

X = ground level air concentration (units/m^3),
Q = pollutant emission rate (units/s),

σ_y = standard deviation of a Gaussian distribution in the crosswind direction (m),
σ_z = standard deviation of a Gaussian distribution in the vertical direction (m),
u = wind speed (m/s),
H = pollutant plume height (m),
y = crosswind distance (m).

The σ_y and σ_z values are not defined explicitly by the mathematical assumptions and, therefore, must be determined empirically. Thus, a number of different field experiments have been conducted to determine σ_y and σ_z as functions of atmospheric stability and downwind distance. The set of empirically determined atmospheric dispersion values that will yield a predicted value of downwind pollutant concentration from a Gaussian plume model in closest agreement with measured values will vary for differing meteorologic, topographic, or release conditions. A common challenge is choosing the dispersion parameters that most closely suit a poorly characterized emission site. Several empirically determined atmospheric dispersion parameters are discussed in the next section.

Equation (II-1) applies to a release sufficiently long in duration that a plume-like distribution of pollutants results. However, many of the Gaussian models calculate the average concentration around a source for extended periods (e.g., a year). Consequently, Equation (II-1) can be modified to eliminate its σ_y dependence based on long-term historical weather data for most U.S. cities. Usually these data are expressed as joint frequency distributions of wind direction, wind speed class, and atmospheric stability class. Normally, 16 wind directions are reported in U.S. data, allowing a 22.5°-sector average air concentration to be determined.

The crosswind-averaged concentration due to a continuous source is obtained by integrating Equation (II-1) over $-\infty < y < +\infty$. For long-term, continuous exposure, an average concentration is required over the extended period, (i.e., long compared to the period during which the mean wind conditions are predominant). This average is estimated by multiplying crosswind-averaged concentration by the frequency with which the wind blows toward a given sector and dividing by the width of that sector at the downwind distance of interest (Gifford, 1968). The resulting long-term air concentration is

$$X = \frac{2.032Qf}{xu\sigma_z} \exp[-\tfrac{1}{2}(H/\sigma_z)^2] \qquad \text{(II-2)}$$

where

f = time fraction that the wind blows toward a given receptor,
x = distance between release point and receptor (m).

If the vertical dispersion becomes large (e.g., $\sigma_z \rangle K \times L$)

where

K = some numerical factor (on the order of unity),
L = depth of the tropospheric boundary layer,

then vertical distribution of the pollutant is considered to be uniform. Under these conditions, Equation (II-2) becomes

$$X = \frac{2.032Qf}{xu\sigma_z L} \qquad \text{(II-3)}$$

Equations (II-2) and (II-3) are no longer truly Gaussian plume models. Furthermore, an implicit problem in applying these equations is that there is no consideration of wind velocity persistence. That is, in most cases, the wind does not actually blow in one direction at a specific speed for as long a time as assumed here. Hence, there will never be uniform vertical mixing, even at very large distances. Moreover, concentrations at very large distances will be unduly influenced by stable wind classes and low wind speeds.

The height (H) of the release is another sensitive parameter in the Gaussian plume model. The value of H includes not only the physical height of the stack but also any additional height due to the rise of the plume as a result of its buoyancy or momentum. The amount of this plume rise is usually estimated through the use of models such as those suggested by Briggs (1969). For example, nuclear power plants seldom have either large-momentum buoyant plumes or stacks associated with their routine releases; as a result, plume rise is not usually critical for estimating air concentrations resulting from these facilities (Crawford, 1978). However, fossil-fueled power plants often have large plume rises for which

an accurate estimate can be critical in determining the predicted air concentration (Bowne, 1981).

1.2. LIMITATIONS

The Gaussian plume model often is applied when it theoretically should not be, but this practice has been accepted when predicted impacts are so small that the importance of potential errors would not affect the conclusions reached. Conditions for which the Gaussian plume model is not expected to apply include situations involving complex terrain or meteorologic conditions, long-range transport, and short-term releases. As a result, a large number of more complex, seemingly more realistic, dispersion models have been or are being developed for use in these obviously non-Gaussian situations (Miller et al., 1981).

1.3. UNCERTAINTIES

The best overall uncertainty determination for an atmospheric dispersion model (e.g., Gaussian plume) is a comparison of modeling predictions with environmental measurements for conditions similar to those assumed by the model. These comparison studies should include various terrains, release heights, and meteorologic conditions. Unfortunately, not enough model validation studies under varying conditions have been performed to allow reliable statistical analysis of the uncertainties associated with the Gaussian plume model (Fabrick et al., 1977a,b,c; USEPA, 1977; Crawford, 1978; Hilst, 1978). Several validation studies (and other estimates of the Gaussian plume model accuracy) have been reviewed and are summarized in Table 7. The references in Table 7 include individual validation studies as well as reviews of such studies. The range of ratios (predicted air concentration/observed air concentration) is based on all the literature cited for that condition and is not necessarily representative of any one reference. The results of the validation studies indicate that modeling uncertainties depend on site, meteorologic and release conditions, and source complexities. Little data are available to validate plume depletion processes used in atmospheric dispersion models to predict deposition rates.

1.3.1. Site Conditions

The estimate given for a highly instrumented flat-field site (Table 7) assumes that previous data on meteorologic conditions and airborne concentrations are also available.

Table 7. ESTIMATED RATIOS OF PREDICTED TO OBSERVED AIR CONCENTRATIONS USING GAUSSIAN PLUME ATMOSPHERIC DISPERSION MODELS

Conditions	Range	References
Highly instrumented site centerline concentration within 10 km of a continuous point source		
ground level releases	0.8 - 1.2	Pasquill, 1974
elevated releases	0.65 - 1.35	Pasquill, 1974
maximum air concentration for elevated releases	0.5 - 1.5	Pasquill, 1974; Wendell et al., 1976
Annual average for a specific point, flat terrain, within 10 km downwind of the release point	0.5 - 2.0	Gifford and Pack, 1962; Gogolak et al., 1981; Lindeken et al., 1980; Ruff et al., 1980
Annual average for a specific point, flat terrain, 10-150 km downwind of the release point	0.25 - 4.0	Buckner, 1981; Draxler, 1980; Fields et al., 1981a; Fields et al., 1984; Huang, 1980; Pendergast, 1979; Pendergast, 1982; Raridon and Murphy, 1982; Telegadas et al., 1978; Weber et al., 1982; Yildiran and Miller, 1984
Specific hour and receptor point, flat terrain, steady meteorologic conditions		
elevated releases without building wake effects	0.1 - 10.0	Bowne, 1981; Cotter et al., 1985; Fields et al., 1981b; Gogolak, 1973; Guzewich and Pringle, 1977; Lewellen et al., 1985; Miller et al., 1980b; Miller and Cotter, 1982; Nickola, 1979; Partridge et al., 1976; USEPA, 1981; Vankatram and Vet, 1981; Yildiran and Miller, 1983
elevated releases with building wake effects	0.01 - 100.0	Fields et al., 1984; Howroyd and Gutfreund, 1980; Koziar et al., 1980; Miller, 1981; Miller, 1983; Start et al., 1978

Table 7. (continued)

Conditions	Range	References
Short-term, surface-level releases with building wake effects using temperature gradient method of estimating atmospheric stability		
wind speeds over 2 m/s	0.7 - 100.0	Deluca et al., 1981; Fackrell, 1984; Fields et al., 1984; Huber, 1984; Start et al., 1978; Van der Hoven, 1981;
wind speeds under 2 m/s	1.0 - 100.0	Van der Hoven, 1981
Short-term, surface-level releases without building wake effects using temperature gradient method of estimating atmospheric stability		
wind speeds over 2 m/s	0.3 - 10.0	Miller and Little, 1980; Miller et al., 1982; Van der Hoven, 1981;
wind speeds under 2 m/s	1.0 - 100.0	Miller and Little, 1980; Van der Hoven, 1981
Complex terrain or meteorology (e.g., sea breeze regimes)		
annual average concentrations	0.1 - 10.0	Miller and Moore, 1977; Smith and Ruch, 1979; Veilleque et al., 1981; Yildiran and Miller, 1984
short-term releases	0.01 - 100.0	Bendel and Cresswell, 1977; Egan et al., 1979; Elliott et al., 1977; Iwanchuk et al., 1980; Lavery and Schulman, 1977; Lott, 1984; Miller et al., 1980a; Septoff et al., 1977; Veilleque et al., 1981; Weil and Jepsen, 1977; Wilson et al., 1977
Urban releases		
annual average concentrations	0.25 - 4.0	Gifford and Hanna, 1973; Nieuwstadt and van Dop, 1975
≤24 hr concentrations	0.1 - 10.0	Hanna, 1971; Pendergrass and Rao, 1984a; Pendergrass and Rao, 1984b; Turner, 1964

Pasquill (1974) has also estimated an uncertainty of 10%-20% for short downwind distances (<10 km), steady winds, and ground level releases. He suggests that an error of 30%-35% may be more appropriate for elevated releases. A more appropriate value for the uncertainty associated with the maximum air concentration value from elevated sources may be 50% (Pasquill, 1974; USEPA, 1976). The meteorologic and terrain conditions specified in these idealistic estimates seldom occur in the real world. Consequently, these uncertainty estimates represent the best accuracy that can be expected by present atmospheric dispersion models.

1.3.2. Meteorologic Conditions

Vogt (1977) has compared the short-term diffusion factors Xu/Q(x, y = 0, z = 0) computed from six such sets of curves assuming a 100-m release height and using one method of determining atmospheric stability. He found that maxima in Xu/Q generally agreed within a factor of two for each set of curves and each stability category considered. However, the downwind location of the maxima differed by as much as an order of magnitude. Vogt (1977) also calculated annual average diffusion factors for each of the same six sets of dispersion parameters and annual average meteorologic statistics for Jülich, Germany. In this case, the maxima differed by over an order of magnitude and their location by a factor of five, depending upon which set of dispersion parameters was used.

Vogt's comparisons were based on one method of determining the stability of the atmosphere. However, a variety of methods have been proposed for classifying the stability of the atmosphere (Hanna et al., 1977). It has been shown that these different methods can give significantly different results when applied to the same meteorologic data set (Pendergast, 1982; Miller et al., 1978; Miller and Little, 1980; Miller and Cotter, 1982). There are indications that the selection of a stability category alone can result in an order of magnitude or more difference between the lowest and highest annual average air concentration calculated using a given set of dispersion parameters. To avoid these large differences, the dispersion parameters should be chosen on the basis of as much site-specific information (e.g., wind velocity, topography, and release height) as possible (Hanna et al., 1977).

1.3.3. Release Conditions

1.3.3.1. *Long-term Releases Over Flat Terrain*

Data have been obtained in the Savannah River Plant (SRP) for the release of ^{85}Kr; corresponding air concentrations were measured within 150 km of the SRP (Telegadas et al., 1978; Gogolak et al., 1981). These data have been used in a number of Gaussian plume model validation studies, which have included areas within 10 km of the release point (Gogolak et al., 1981) and 30 to 150 km downwind of the release point (Telegadas et al., 1978; Pendergast, 1979; Draxler, 1980; Huang, 1980; Fields et al., 1981a, 1984; Miller et al., 1981; Buckner, 1981; Weber et al., 1982). The results generally support the summaries presented in Table 7 for ensemble averages, especially for the annual average predictions. Ruff et al. (1980) also were able to predict annual average air concentrations within approximately a factor of 2 at 13 SO_2 monitoring stations around St. Louis, Missouri. These and other model validation studies support the continued use of the Gaussian plume model for assessing the impact of long-term releases of pollutants from facilities located in relatively flat terrain (Miller et al., 1981; Buckner, 1981). The main advantage of flat terrain is that the wind direction (and other weather conditions) remain relatively constant with increasing distance.

1.3.3.2. *Short-term Releases Over Flat Terrain*

More comparisons are available for short-term than for long-term releases. As the averaging time for the air concentration calculation decreases, the uncertainty in that concentration increases. The primary factor in predicting short-term air concentrations seems to be an accurate description of the wind field, assuming that the release rate is well measured (Buckner, 1981). While the given references generally support the uncertainty estimates in Table 7, individual comparisons for releases lasting less than one hour show deviations larger than the one order of magnitude (e.g., Miller and Cotter, 1982).

1.3.4. Source Complexity

The basic Gaussian plume model was never intended for use with complex conditions such as mountainous terrain, lake or seashore environments, low wind speed, inversion conditions, and urban environments or within complexes of buildings and other physical structures. However, many facilities with a potential for atmospheric pollutant release are

located in areas that have complex conditions. Therefore, versions of the Gaussian plume model have been applied in these situations. Available data for validating models under complex conditions are very limited. Often, only a small number of monitoring stations are available for comparisons during any given set of releases. Limited tests in complex terrain (Egan et al., 1979; Iwanchuk et al., 1980) and near large bodies of water (Wilson et al., 1977; Lavery and Schulman, 1977; Septoff et al., 1977; Lague et al., 1980) indicate that, under some conditions, Gaussian type model predictions have less uncertainty than the four orders of magnitude shown in Table 7 for short-term releases. Other studies, however, indicate that the uncertainty estimate shown in Table 7 is not too large at all (e.g., Elliott et al., 1977). For annual average comparisons, an uncertainty range of two orders of magnitude may be more appropriate (Wilson et al., 1977; Smith and Ruch, 1979). In general, results of model validation studies under these release conditions are highly dependent on the exact site involved, the meteorologic conditions during the release, and the exact algorithm used in the calculation (Bendel and Cresswell, 1977). For example, Van der Hoven (1981) has shown that the predicted-to-observed ratios can cluster more closely about one for low wind speed with inversion conditions if atmospheric stability is estimated on the basis of more than just temperature gradient information.

Many pollutant sources are located within complexes of buildings and other physical structures. A limited number of field studies indicate that standard Gaussian modeling techniques may overpredict the downwind air concentration near the point of release from short-term releases by as much as a factor of 1000 (Start et al., 1978). This large discrepancy occurs because wind turbulence around buildings increases the diffusion rate as compared to the simple dispersion from isolated release points that is typically used in standard Gaussian-plume modeling. However, it may be possible to reduce this uncertainty by a factor of 10 to 100 using modified procedures, depending upon the complexity of the site, the release height, and meteorologic conditions (Howroyd and Gutfreund, 1980; Koziar et al., 1980; Miller, 1981).

1.3.5. Plume Depletion Processes

Particulates and reactive gases may deposit on the surface of the earth through the processes of dry and wet deposition. Wet deposition occurs sporadically during specific rain or snow events, but dry deposition processes occur continuously. A number of different

measurements of dry deposition processes have been made (McMahon and Denison, 1979; Sehmel, 1980). Also, a number of different models for estimating plume depletion have been proposed (Hosker, 1984). However, during the course of this project no data have been found that are adequate for validating plume depletion processes. For example, recent sodium release tests to the atmosphere (Johnson et al., 1978; Johnson and Nelson, 1979) have shown that sodium aerosols tend to form agglomerates that fall out rapidly. However, more tests are needed to establish quantitatively the effect of this mechanism on subsequent downwind exposure to sodium. Also, calculations have been performed in which inclusion of depositional processes in the model predictions improved agreement with the observed air concentrations of fluorescein particles (Fields et al., 1981b; Little et al., 1982; Piepho, 1981). However, no deposition measurements were taken during the field studies considered in these comparisons. Good agreement also has been reported between three observed and predicted values of ^{131}I concentration on grass, but because of the input data used in the calculation, the authors do not consider their methods to constitute a validation study (Hubschmann and Miller, 1980). Until such data sets become available, one cannot specify the accuracy associated with a calculation of concentration on the ground or with an air concentration involving significant plume depletion.

2. DISPERSION COEFFICIENTS

Changes in dispersion coefficients, σ_y and σ_z, strongly affect the resulting air concentrations calculated by the Gaussian plume model (Pasquill, 1974; USEPA, 1976). Values for σ_y and σ_z in the Gaussian equation are not defined explicitly and must be determined empirically. A number of different field experiments have been conducted to determine σ_y and σ_z as functions of atmospheric stability and downwind distance. The set of empirically determined atmospheric dispersion values that will yield a predicted value of downwind contaminant concentration from a Gaussian plume model in closest agreement with measured values will vary for differing meteorologic, topographic, and release conditions. A description of several empirically determined atmospheric dispersion values follows. Table 8 lists the values used to compute dispersion coefficients by various methods and shows their correspondence to the Pasquill stability classes.

2.1. PASQUILL-GIFFORD DISPERSION COEFFICIENTS

Pasquill (1961, 1962) developed a weather classification scheme that uses surface wind speed, sunshine, and cloud cover as simple measurements of atmospheric stability. Six atmospheric stability classes, ranging from A through F, or most unstable to most stable, were determined (Table 8). Dispersion values for σ_y and σ_z (nomograms) to be associated with each stability classification type were determined based on ground-level emission tracer studies and wind direction fluctuation data (Pasquill, 1961, 1962). The values are approximate for ground-level emissions of low surface roughness (Vogt, 1977) and were devised from small source distances (<1 km). The values for σ_y and σ_z associated with each stability classification type are given in Figures 1 and 2. Various equations and parameter sets are used to replicate the empirical curves in the available models. Some parameterizations are very complicated.

2.2. BRIGGS DISPERSION COEFFICIENTS

Briggs' values for horizontal and vertical dispersion coefficients are available in two forms, one for releases in rural settings and one for releases in urban settings. For each of these forms, the horizontal dispersion coefficient, σ_y, may be computed from the formulas contained in Moore (1977). These values are represented as a different function for

Table 8. DEFINITION OF THE PASQUILL ATMOSPHERIC STABILITY CATEGORIES

Surface wind speed at 10 m (m/s)	Day: Incoming solar radiation			Night	
	Strong	Moderate	Slight	Thinly overcast or ≥4/8 low cloud cover	≤3/8 Cloud cover
<2	A	A-B	B		
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

SOURCE: Pasquill, 1961.

Note: Types a, b, and c are associated with strong, moderate, and slight instability, respectively; type d corresponds to a neutral lapse and should be assumed for overcast conditions during day or night; and types e and f are associated with slight and moderate inversions, respectively.

each stability class corresponding to the six classes defined by Pasquill (1961). The surface roughness is also considered. It is expected that this parameterization is more appropriate than the Pasquill values for distances between 1 and 50 km. The horizontal dispersion coefficient, σy (m), for rural conditions is calculated for the downwind distance, x (m), using the formula

$$\sigma_y = \alpha \, x \, (1 + 0.0001x)^{0.5} \qquad \text{(II-4)}$$

The vertical dispersion coefficient, σz (m), for rural conditions is calculated using the formula

$$\sigma_z = p \, x \, (1 + qx)^r. \qquad \text{(II-5)}$$

The values of α, p, q, and r are defined in Table 9.

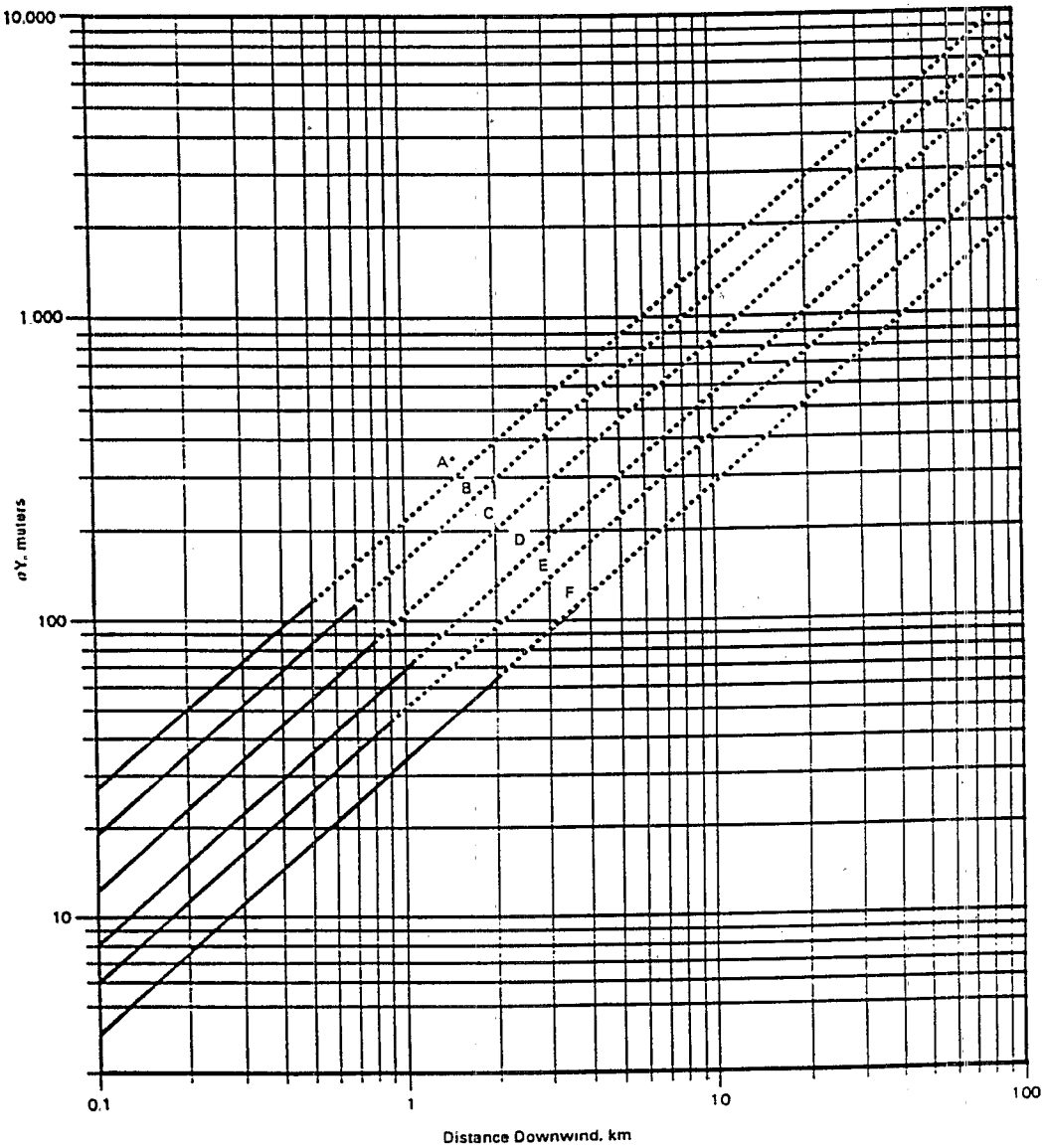

Figure 1. Horizontal dispersion coefficient as a function of downwind distance from the source. Lines A through F represent dispersion coefficient functions for atmospheric stability classes A through F.

SOURCE: Turner, 1970 (as cited in USEPA, 1988).

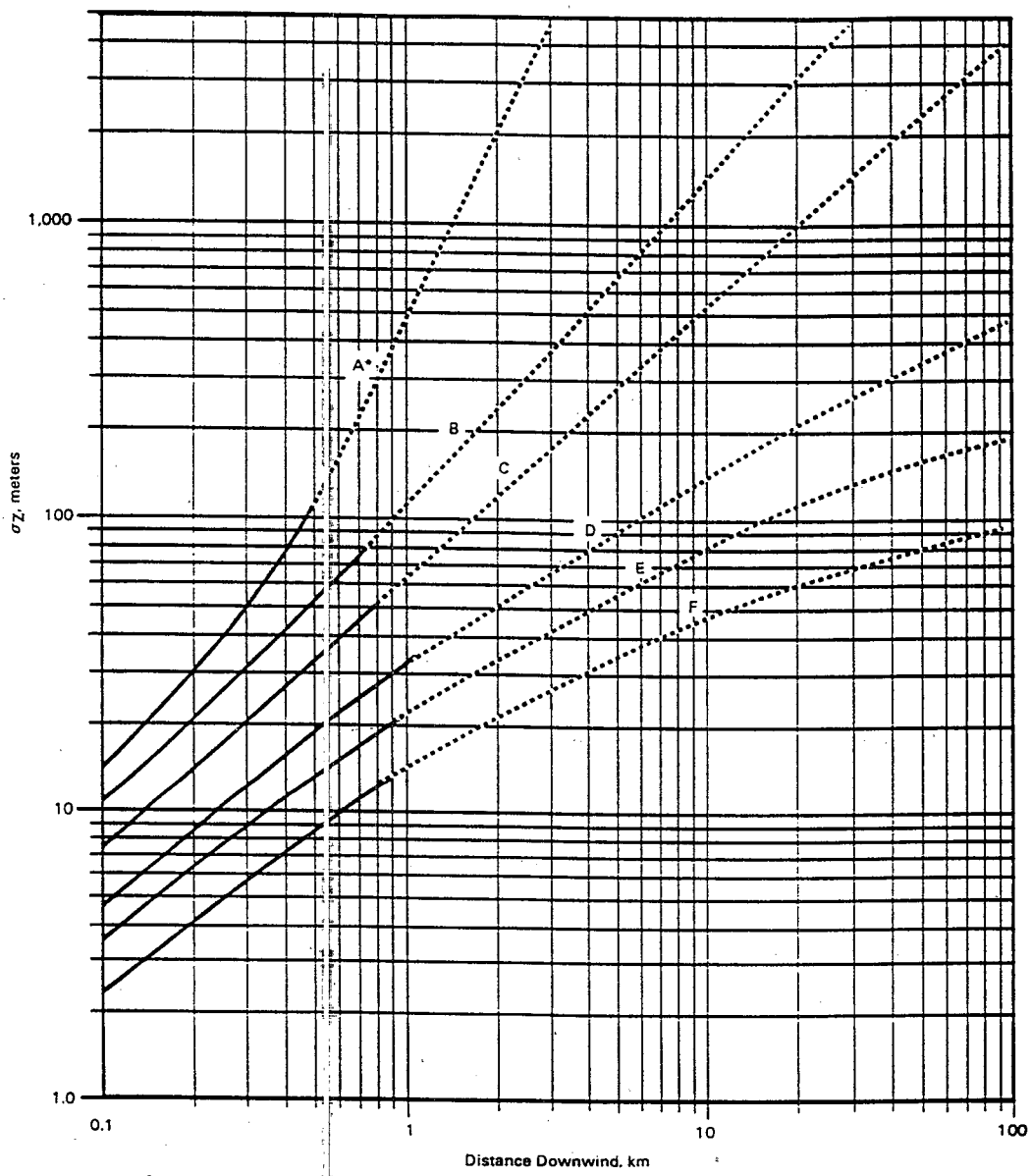

Figure 2. Vertical dispersion coefficient as a function of downwind distance from the source. Curves A through F represent dispersion coefficient functions for atmospheric stability classes A through F.

SOURCE: Turner, 1970 (as cited in USEPA, 1988).

Table 9. PARAMETERS USED TO COMPUTE DISPERSION COEFFICIENTS

Pasquill stability class (see Figures 1 and 2)		A	B	C	D	E	F
Briggs parameterization class		A	B	C	D	E	F
	α	0.22	0.16	0.11	0.08	0.06	0.04
	p	0.20	0.12	0.08	0.06	0.03	0.016
	q	0.00	0.00	0.0002	0.0015	0.0003	0.0003
	r	1.00	1.00	-0.50	-0.50	-1.00	-1.00
Klug parameterization class		V	IV	III2	III1	II	I
	p	0.469	0.306	0.230	0.219	0.237	0.273
	q	0.903	0.885	0.855	0.764	0.691	0.594
	r	0.017	0.072	0.076	0.140	0.217	0.262
	s	1.380	1.021	0.879	0.727	0.610	0.500
Brookhaven gustiness class			B2	B1	C	D	
	p		0.400	0.360	0.320	0.310	
	q		0.910	0.860	0.780	0.710	
	r		0.411	0.326	0.223	0.062	
	s		0.907	0.859	0.776	0.709	
St. Louis parameterization class			B	C	D	E	
	p		1.700	1.440	0.910	1.020	
	q		0.717	0.710	0.729	0.648	
	r		0.079	0.131	0.910	1.930	
	s		1.200	1.046	0.702	0.465	
Jülich parameterization class		A	B	C	D	E	F
(50 meter)	p	0.87	0.87	0.72	0.62	1.69	5.38
	q	0.81	0.81	0.78	0.76	0.62	0.58
	r	0.22	0.22	0.21	0.20	0.16	0.40
	s	0.97	0.97	0.94	0.94	0.81	0.62
(100 meter)	p	0.23	0.23	0.22	0.22	1.69	5.38
	q	1.00	0.97	0.94	0.90	0.62	0.58
	r	0.097	0.16	0.25	0.40	0.16	0.40
	s	1.15	1.02	0.89	0.71	0.81	0.62

SOURCE: Vogt, 1977.

2.3. KLUG DISPERSION COEFFICIENTS

The Klug (1969) dispersion coefficients are intended primarily for short-term ground-level releases over terrain having low surface roughness. Klug dispersion coefficients are normally determined by considering several observables, such as insolation, sun altitude angle, wind velocity, and site-specific equation coefficients. Vogt (1977) infers a correspondence between Klug and Pasquill stability classes and defines parameters used in the dispersion coefficients functions

$$\sigma_y = px^q \,, \qquad \text{(II-6)}$$

$$\sigma_z = rx^s \,. \qquad \text{(II-7)}$$

These results are summarized in Table 9.

2.4. BROOKHAVEN DISPERSION COEFFICIENTS

The Brookhaven dispersion coefficients as formulated by Singer and Smith (1966) were derived from experiments made using a 108-m stack height and one-hour emission period over terrain of "medium" roughness. Vogt fitted these values to Equations (II-6) and (II-7) with the values shown in Table 9; correspondences between the Brookhaven gustiness classes and the Pasquill dispersion categories are also shown.

2.5. ST. LOUIS DISPERSION COEFFICIENTS

The St. Louis dispersion coefficients, described by McElroy and Pooler (1968), were compiled under urban experimental conditions including one-hour emission duration, source near ground level, and relatively flat terrain of high surface roughness. One may use Vogt's correspondences between McElroy and Pooler along with Pasquill's dispersion classes to compute the St. Louis dispersion coefficients using Equations (II-6) and (II-7) with Vogt's parameters listed in Table 9.

2.6. JŰLICH DISPERSION COEFFICIENTS

Experiments performed near the Jülich Nuclear Research Center with emission heights of 50 m and 100 m have been evaluated by Geiss et al. (1979). They considered wind velocity, sun angle and insolation, and the vertical temperature gradient and derived two dispersion classifications that correspond closely to the Pasquill categories. Jülich parameterizations are expected to be appropriate for "medium to higher" surface roughness. This scheme uses Equations (II-6) and (II-7) of the above form with parameters as given in Table 9 to compute the dispersion coefficients.

3. INPUT DATA REQUIREMENTS

Data input requirements for Gaussian plume models typically fall into one of three categories: source data (i.e., stack parameters for point sources, dimensional characteristics for area sources), meteorologic data, and receptor data.

3.1. SOURCE

Input requirements of Gaussian plume models are dependent on source type. For point sources, input requirements typically include stack location, physical stack height, stack inside diameter, stack gas exit velocity, stack gas exit temperature, and pollutant emission rate. Optional input may include source elevation, building dimensions such as average building width and average spacing between buildings, particle size distribution with corresponding settling velocities, or surface reflection coefficients.

Input requirements for area sources typically include location, size, average emission rates, and heights of emissions. For line sources, input requirements typically include coordinates of the end points of the line, release height, emission rate, average line source width, and average line source buoyancy parameter.

Values for input parameters can be determined by direct measurement, sampling, estimates based on sound engineering principles, or calculation, and may be found in a variety of sources. Values for typical source parameters at hazardous waste management facilities are compiled below. Values for emission rates for sources under specific operating conditions, a major source input parameter, can be found in published literature by the EPA (Godish, 1985). Emission controls and operational variations may affect actual emissions from a source and should be taken into consideration when selecting values for emission rates. Most models use the time-weighted average value as the source emission rate. This value is appropriate for long-term assessment of cumulative risk but may not be appropriate to use in assessment of significant short-term emissions where the maximum risk high population areas need to be identified.

3.1.1. Typical Source Parameters for Hazardous Waste Management Facilities

Typical hazardous waste management facilities include landfills, land treatment areas, surface impoundments, treatment plants (wastewater and other), and incinerators. The following sources may be found either singly or in various combinations at these facilities and may be modeled using one or more stack, point, area, or line source configurations. It also may be necessary to model some of the sources using a combination of the above source representations. Some typical source parameters for these hazardous waste management facilities are provided below (USEPA, 1987).

Drum Piles

Typical parameters:
Area covered, m^2: 1300 (typical)
Release height, m: 6.1 (typical)

Comments:
Releases may be from specific locations within the pile or from the pile in general.

Incinerator Stacks

Typical stack parameters:
Diameter, m: 0.7 to 2.0 (range); 1.1 (average)
Height, m: 9.0 to 30.4 (range); 22.0 (average)
Gas exit velocity, m/s: 3.0 to 7.0 (range); 4.0 (average)
Gas exit temperature, °K: 290 to 1000 (range); 500 (average)

Comments:
Stack emissions could be affected by wake effects due to adjacent or nearby buildings.

Landfills

Typical parameters:
Area covered, m^2: 900 to 100,000,000 (range); 7000 (average)
Release height, m: 0 (ground level)

Comments:
Releases may occur at/or below ground level. Part of the area may be undisturbed, part may be active (wastes being deposited), and part may be inactive (wastes deposited and covered). Characteristics of undisturbed, active, and inactive areas will be different.

Land Treatment Areas

Typical parameters:

Area covered, m^2: 4000 to 400,000,000 (range); 3,300,000 (avg)
Release height, m: 0 (ground level)

Comments:

Emission rates may vary over the area. Waste application operations could produce emissions at slightly above ground level.

Process Commercial Buildings

Typical parameters:

Area covered, m^2: 70 to 300 (range); 150 (average)
Release height, m: 3.0 to 18 (range); 9.0 (average)

Comments:

Emissions could come from vents or openings in the roof or in the walls of the building. The building likely will influence emission characteristics. Commercial buildings might also have small stacks with somewhat higher release heights.

Stack Structures (Other Than Incinerators)

Typical parameters:

Area covered, m^2: 100 to 300 (range); 200 (average)
Release height, m: 4.0 to 20 (range); 12.0 (average)

Comments:

Emissions likely come from discrete sources (e.g., valves and vents) within the structure. Many structures have no walls.

Storage Tanks

Typical parameters:

Area covered, m^2: 50 to 1400 (range); 300 (average)
Release height, m: 2.0 to 10.0 (range); 7.0 (average)
Stack diameter, m: 0.02 to 0.1 (range); 0.06 (average)
Stack gas exit velocity, m/s: 0.103 to 1.65 (range); 0.878 (avg)
Stack gas exit temperature, °K: 280.0 (typical ambient)
Adjacent building height, m: 2.0 to 10.0 (range); 7.0 (average)
Adjacent building width, m: 3.0 (typical)

Comments:

Emissions likely come from process and emergency valves. Individual tanks or entire tank farms can be involved. Adjacent or nearby structures could affect emission behavior. May be modeled as stacks, areas, or volumes.

Surface Impoundments

Typical parameters:

Area covered, m^2: 20 to 75,000 (range); 2000 (average)
Release height, m: 0 (ground level) or height of spray

Comments:

Releases may occur below ground level for static impoundments. Releases may occur above ground level for dynamic impoundments (e.g., for spray ponds).

Waste Piles

Typical parameters:

Area covered, m^2: 30 to 400,000 (range); 300 (average)
Release height, m: 3.0 (typical)

Comments:

Part of the area may be undisturbed, part may be active (wastes being deposited), and part may be inactive (wastes deposited and covered). Emission characteristics of undisturbed, active, and inactive areas will be different.

3.2. METEOROLOGIC

Meteorologic parameters are required in Gaussian plume models to reasonably predict the transport, dispersion, and depletion characteristics of the pollutant plume. Some models may accept hourly surface weather data from a preprocessor program (RAMMET) that provides hourly stability class, wind direction, wind speed, temperature, and mixing height. In addition, the actual height of the anemometer may be required for some models. For models using long-term averages, STAR (Stability Array) summaries provide necessary meteorologic data.

3.3. RECEPTOR

Typical atmospheric dispersion models provide estimates of maximum or annual-average ground-level concentrations at individual receptor sectors. The number and placement of receptors will vary depending on risk assessment needs (see USEPA, 1987 for a

discussion of optimal receptor placement). All receptor locations relevant to an exposure assessment should be identified, i.e., areas of high population *and* expected maximum ground-level concentrations. Receptor input requirements for most Gaussian plume models include location (coordinates) and elevation data for individual receptors (although most models assume the receptors to be located at ground level) or the location and size of a receptor grid. Some models have options for automatic placement of receptors near expected maximum concentrations. Models that use a grid system to identify the relationship between the source and receptor use either a polar coordinate or a Cartesian coordinate system. The grid can consist of a sector (22.5° angle and 5-mile width) or areas with square, rectangular, or hexagonal shapes.

REFERENCES FOR PART II

Bendel, W. B. and G. A. Cresswell. 1977. A comparison of predicted EPA VALLEY model concentrations to measured ground level tracer gas concentrations obtained in complex terrain. In Preprints, Joint Conference on Applications of Air Pollution Meteorology, pp. 176-181. American Meteorological Society, Boston, MA.

Bowne, N. E. 1981, April. Preliminary results from the EPRI plume model validation project-plains site. Electric Power Research Institute, Palo Alto, CA. EPRI-1788-SY.

Briggs, G. A. 1969. Plume rise. U. S. Atomic Energy Commission Critical Review Series. Oak Ridge National Laboratory, Oak Ridge, TN.

Buckner, M. R. 1981. Proceedings of the First SRL Model Validation Workshop, November 19-20, 1980. Hilton Head, SC. Department of Energy, Aiken, SC. DP-1597.

Cotter, S. J., C. W. Miller, and W. C-T. Lin. 1985. A comparison of observed and predicted short-term tracer gas concentrations in the atmosphere. In Proceedings of 18th Midyear Topical Symposium of Health Physics Society, Colorado Springs, CO.

Crawford, T. V. (Chairperson). 1978. Atmospheric transport of radionuclides. In Hoffman, P. O., D. L. Shaeffer, C. W. Miller, C. T. Garten, Jr., eds. Proceedings of a Workshop on the Evaluation of Models Used for the Environmental Assessment of Radionuclide Releases, pp. 5-32. CONF-770901.

Deluca, P. J., Jr., J. A. Bauhs, and D. W. Pearson. 1981. Calculated and measured HTO atmospheric dispersion rates within meters of a release site. Health Phys. 41:191-195.

Draxler, R. R. 1980. An improved gaussian model for long-term average concentration estimates. Atmos. Environ. 14:597-601.

Egan, B. A., R. D'Errico, and C. Vando. 1979. Estimating air quality levels in regions of high terrain under stable atmospheric conditions. In Preprints, Joint Conference of Applications of Air Pollution Meteorology, pp. 177-181. American Meteorological Society, Boston, MA.

Elliott, R. D., E. L. Hovind, and M. W. Edelstein. 1977. Observations and model calculations of plume impaction on rising terrain. In Preprints, Joint Conference on Applications of Air Pollution Meteorology, pp. 182-187. American Meteorological Society, Boston, MA.

Fabrick, A., R. Sklarew, and J. Wilson. 1977a. Point source model evaluation and development study: Appendixes A and B. Science Applications, Inc., Westlake Village, CA.

Fabrick, A., R. Sklarew, and J. Wilson. 1977b. Point source modeling. Form and Substance, Inc., Westlake Village, CA.

Fabrick, A., R. Sklarew, and J. Wilson. 1977c. User guide to IMPACT. Science Applications, Inc., Westlake Village, CA.

Fackrell, J. E. 1984. An examination of simple models for building influenced dispersion. Atmos. Environ. 18:89-98.

Fields, D. E., C. W. Miller, and S. J. Cotter. 1981a. The AIRDOSE-EPA computer code and its application to intermediate range transport of ^{85}Kr from the Savannah River plant. In Miller, C.W., S.J. Cotter, and S.R. Hanna, eds. Proceedings, Symposium on Intermediate Range Atmospheric Transport Processes and Technology Assessment, pp. 49-60. CONF-801064.

Fields, D. E., C. W. Miller, and S. J. Cotter. 1981b. Comparison of observed and predicted sector-averaged air concentrations for elevated releases of fluorescein particles. J. Air Poll. Control Assoc. 31(8):871-876.

Fields, D. E., C. W. Miller, and S. J. Cotter. 1984. Validation of the AIRDOSE-EPA computer code by simulating intermediate range transport of KR-85 from the Savannah River plant. Atmos. Environ. 18:2029-2036.

Geiss, H., K. J. Vogt, H. S. Ehrlich, and G. Polston. 1979. Recent results of dispersion experiments at emission heights of 50 and 100 m. In Proceedings of the 12th Annual Symposium of the German-Swiss Fachverband fur Strahlenschultz, October 2-6, 1978, Norderney, Federal Republic of Germany (in German), translated in OLS-79-43, Oak Ridge National Laboratory, Oak Ridge, TN.

Gifford, F. A., Jr. 1968. An outline of theories of diffusion in the lower layers of the atmosphere. In Slade, D., ed. Meteorology and Atomic Energy - 1968 (Chapter 3). U.S. Atomic Energy Commission Report TID-24190.

Gifford, F. A. and S. R. Hanna. 1973. Modeling urban air pollution. Atmos. Environ. 7:131-136.

Gifford, F. A., Jr. and D. H. Pack. 1962. Surface deposition of airbourne material. Nucl. Saf. 3(4):76.

Godish, T. 1985. Air quality. Chelsea, MI: Lewis Publishers.

Gogolak, C. V. 1973. Comparison of measured and calculated radiation exposure from a boiling water reactor plume. HASL-277.

Gogolak, C. V., H. L. Beck, and M. M. Pendergast. 1981. Calculated and observed ^{85}Kr concentrations within 10 km of the Savannah River plant chemical separation facilities. Atmos. Environ. 15:497-507.

Guzewich, D. C. and W. J. B. Pringle. 1977. Validation of the EPA-PTMTP short-term gaussian dispersion model. J. Air Poll. Control Assoc. 27(6):540-542.

Hanna, S. R. 1971. A simple method of calculating dispersion from urban area sources. J. Air Pollution Control Assoc. 21:774-777.

Hanna, S. R., G. A. Briggs, J. Deardorff, B. A. Egan, G. A. Gifford, and F. Pasquill. 1977. AMS workshop on stability classification schemes and sigma curves—summary of recommendations. Bulletin of the American Meteorological Society 58:1305-1309.

Hanna, S. R., G. A. Briggs, and R. P. Hosker, Jr. 1982. Handbook on atmospheric diffusion. U. S. Department of Energy Report DOE/TIC-11223.

Hilst, G. R. 1978. Plume model validation. Electric Power Research Institute, Palo Alto, CA. Report EA-917-SY.

Hosker, R. P., Jr. 1984. Flow and diffusion near obstacles. In Randerson, D., ed. Atmospheric Sciences and Power Production, U.S. Department of Energy Report DOE/TIC-27601.

Howroyd, G. C., and P. D. Gutfreund. 1980. An evaluation of the Briggs downwash formulation. In Conference Papers, Second Joint Conference on Application of Air Pollution Meteorology, pp. 185-192. American Meteorological Society, Boston, MA.

Huang, J. C. 1980. Evaluation of a modified Gaussian plume model for travel distances 25-150 km. In Conference Papers, Second Joint Conference on Applications of Air Pollution Meteorology. American Meteorological Society, Boston, MA.

Huber, A. H. 1984. Evaluation of a method for estimating pollution concentrations downwind of influencing buildings. Atmos. Environ. 18:2313-2338.

Hubschmann, W. and C. W. Miller. 1980. Final report of the working group atmospheric transport. In Proceedings of a Workshop on Accuracy in Dose Calculations for Radionuclides Released to the Environment. GUW Gesellschaft fur Umweltuberwachung mbH, Aldenhoven, Federal Republic of Germany.

Iwanchuk, R. M., G. F. Hoffnagle, C. J. Vaudo, D. M. Shear, and J. T. Ferrill. 1980. Model comparisons for the high terrain monitoring program. In Conference Papers, Second Joint Conference on Applications of Air Pollution Meteorology, pp. 600-607. American Meteorological Society, Boston, MA.

Johnson, R. P. and C. T. Nelson. 1979. Interim test report for the characterization of released particle tests conducted at INEL during FY1979. Rockwell International, Atomic International Div., Canaga Park, CA. N707TR130028.

Johnson, R. P., K. Hardcastle, C. T. Nelson, B. Perez, C. Guderjohn, and C. R. Dickson. 1978. Test report for the characterization of released particle tests conducted at INEL during FY1978. Rockwell International, Atomic International Div., Canaga Park, CA. N707TR130025.

Klug, W. 1969. Ein Vertahren zur Bestimmurg der Ausbreitnugsbedingungen aus Synoptischen. Straub 29:143.

Koziar, R., B. Adamski, and B. Anderson. 1980. A sensitivity analysis of three downwash models under neutral atmospheric stability. In Conference Papers, Second Joint Conference on Applications of Air Pollution Meteorology, pp. 121-128. American Meteorological Society, Boston, MA.

Lague, J. S., E. M. Irvine, and T. F. Lavery. 1980. Validation of alternate turbulence typing models for estimating air quality effects of coastal sources near rough terrain. In Conference Papers, Second Joint Conference on Applications of Air Pollution Meteorology, pp. 586-592. American Meteorological Society, Boston, MA.

Lavery, T. F. and L. L. Schulman. 1977. The validity of a gaussian plume point source diffusion model for predicting short-term SO_2 levels in the vicinity of electric generating plants in New York State. In Preprints, Joint Conference on Applications of Air Pollution Meteorology, pp. 291-298. American Meteorological Society, Boston, MA.

Lewellen, W. S., R. I Sykes, and S. F. Parker. 1985, May. Comparison of the 1981 INEL dispersion data with results from a number of different models. Nuclear Regulatory Commission. NUREG/CR-4159.

Lindeken, C. L., W. J. Silver, A. J. Toy, and J. H. White. 1980. Correlation between predicted and observed levels of airborne tritium at Lawrence Livermore laboratory site boundary. ANS National Topical Meeting, April 29-May 1, Dayton, Ohio. CONF-800427.

Little, C. A., C. W. Miller, and S. J. Cotter. 1982. Comparison of observed and predicted air concentrations for 18.6 micro fluorescein particles. Health Phys. 43(3):355.

Lott, R. A. 1984. A case study of plume dispersion over elevated terrain. Atmos. Environ. 18:125-134.

McElroy, J. L. and R. Pooler, Jr. 1968. St. Louis Dispersion Study, Vol. II, Analysis. U. S. Department of Health, Education, and Welfare, National Air Pollution Control Administration, Arlington, VA.

McMahon, T. A. and P. J. Denison. 1979. Empirical atmospheric deposition parameters a survey. Atmos. Environ. 13:571-585.

Miller, C. W. 1981. Comparison of gaussian plume model air concentration predictions using Huber's building wake effects adjustment with Rancho Seco observations. In Extended Abstracts, Fifth Symposium on Turbulence, Diffusion, and Air Pollution, pp. 248-249. American Meteorological Society, Boston, MA.

Miller, C. W. 1983. Comparison of observed and predicted air concentrations downwind of the EOCR reactor complex. Sixth Symposium on Turbulence and Diffusion, pp. 348-351. March 22-25, Boston, MA.

Miller, C. W. and R. E. Moore. 1977. Verification of a methodology for computing ground-level air concentration of SO_2 and suspended particulates for both point and dispersed sources, pp. 321-326. In Joint Conference on Applications on Air Pollution Meteorology. American Meteorological Society, Boston, MA.

Miller, C. W. and C. A. Little. 1980. Accuracy of gaussian plume dispersion model predictions as a function of three atmospheric stability classification calculations. Health Phys. 39:773-782.

Miller, C. W. and S. J. Cotter. 1982. Comparison of observed and predicted normalized air concentrations for particles released from a height of 111 meters. In Preprint Volume, Third Joint Conference on Applications of Air Pollution Meteorology, pp. 271-274. American Meteorological Society, Boston, MA.

Miller, C. W., F. O. Hoffman, and D. L. Shaeffer. 1978. The importance of variations in the deposition velocity assumed for the assessment of airborne radionuclide releases. Health Phys. 34:730.

Miller, C. W., S. J. Cotter, et al. 1980a. Estimates of dose to the population within fifty miles due to noble gas releases from the three mile island accident. In Proceedings of ANS/European Nuclear Sox. Topical Mtg. on Thermal Reactor Safety, pp. 1336-1343. April 6-9, Knoxville, TN. CONF-800403/V-II.

Miller, C. W., C. A. Little, and S. J. Cotter. 1980b. A comparison of observed and predicted normalized air concentrations for 56-m releases of fluorescein particles. In Second Joint Conference on Applications of Air Pollution Meteorology and Second Conference on Industrial Meteorology, pp. 634-641. March 24-28, New Orleans, LA.

Miller, C. W., S. J. Cotter, and S. R. Hanna, eds. 1981. Proceedings, Symposium on Intermediate Range Atmospheric Transport Processes and Technology Assessment. October 1-3, 1980, Gatlinburg, TN. Cosponsored by Department of Energy, National Oceanic and Atmospheric Administration, and Oak Ridge National Laboratory. CONF-801064.

Miller, C. W., D. E. Fields, and P. J. Wiseman. 1982. Comparison of observed and predicted air and ground concentrations. Trans. ANS 43:81-82.

Moore, R. E. 1977. The airdose-II computer code for estimating radiation dose to man from airborne radionuclides in areas surrounding nuclear facilities. Oak Ridge National Laboratory, Oak Ridge, TN. ORNL-5245.

Nickola, P. W. 1979. Field measurements of the benefits of increased stack height. J. Appl. Meteorol. 18:1296-1303.

Nieuwstadt, F. T. M. and H. van Dop. 1975. Validation of a multiple source diffusion model based on the gaussian plume model. 6th NATO/CCMS International Technical Meeting on Air Pollution Modeling, September 24-26. Frankfurt, Germany.

Partridge, J. E., J. A. Broadway, C. R. Phillips, S. T. Windham, and C. B. Nelson. 1976. Air pathway exposure model validation study at the Monticello Nuclear Generating Plant. EPA-520/5-76-015.

Pasquill, F. 1961. The estimation of the dispersion of wind-borne material. Meteorol. Mag. 90:33.

Pasquill, F. 1962. Atmospheric diffusion; the dispersion of windborne materials from industrial and other sources. Princeton, NJ: Van Nostrand.

Pasquill, F. 1974. Atmospheric diffusion, 2nd ed. New York, NY: John Wiley and Sons.

Pendergast, M. M. 1979. Model evaluation for travel distances 30-140 km. In Proceedings, Fourth Symposium on Turbulence, Diffusion, and Air Pollution. American Meteorological Society, Boston, MA.

Pendergast, M. M. 1982. The effect of spatial variability of meteorological data on annual average air concentrations predicted by wind-rose model. Atmos. Environ. 16:267-271.

Pendergrass, W. R. and K. S. Rao. 1984a, Sept. Evaluation of the pollution episodic model using the RAPS Data. NOAA Technical Memorandum ERL ARL-128. September.

Pendergrass, W. R. and K. S. Rao. 1984b. Evaluation of the pollution episodic model using the RAPS data. 4th Joint Conference on Applications of Air Pollution Meteorology, pp. 75-78. October 16-19, Portland, OR.

Piepho, M. G. 1981. Gaussian model predictions of elevated particle releases using tilted plume and deposition model features. In Miller, C.W., S.J. Cotter, S.R., Hanna, eds. Proceedings, Symposium on Intermediate Range Atmospheric Transport Processes and Technology Assessment, pp. 343-349. CONF-801064.

Raridon, R. J. and B. D. Murphy. 1982. Validation of the atmospheric transport model: comparison of observed Krypton-85 concentrations with those computed using a gaussian plume model. Proceedings of Summer Computer Simulation Conference, pp. 219-223. July 19-21, Denver, CO.

Ruff, R. E., H. S. Javitz, and J. S. Irwin. 1980. Development and application of a statistical methodology to evaluate the realtime air quality model (RAM). In Conference on Applications of Air Pollution Meteorology, pp. 663-669. American Meteorological Society, Boston, MA.

Sehmel, G. A. 1980. Particle and gas dry deposition: A review. Atmos. Environ. 14:983-1011.

Septoff, M., L. J. Brunton, and L. H. Teuscher. 1977. Results of an offshore dispersion program conducted at the San Onfre Nuclear Generating Station. In Preprints, Joint Conference on Applications of Air Pollution Meteorology, pp. 5-8. American Meteorological Society, Boston, MA.

Singer, I. A. and M. E. Smith. 1966. Atmospheric dispersion at Brookhaven National Laboratory. Int. J. Air Water Poll. 10:125.

Smith, D. B. and R. B. Ruch, Jr. 1979. Comparative performance in complex terrain of several air quality impact assessment models based on aerometric program data. In Preprints, Fourth Symposium on Turbulence, Diffusion, and Air Pollution, pp. 225-228. American Meteorological Society, Boston, MA

Start, G. E., J. H. Cate, et al. 1978, December. Rancho Seco Building Wake Effects on Atmospheric Diffusion. Nuclear Regulatory Commission. NUREG/CR-0456.

Telegadas, K., G. J. Ferber, J. L. Heffter, and R. R. Draxler. 1978. Calculated and observed seasonal and annual krypton-85 concentrations at 30-150 km from a point source. Atmos. Environ. 12:1769-1775.

Turner, D. B. 1964. A diffusion model for an urban area. J. Appl. Meteorol. 3:83-91.

Turner, D. B. 1970. Workbook of atmospheric disperison estimates. Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC. AP-26.

USEPA. 1976. Atmospheric dispersion parameters in gaussian plume modeling part I, review of current systems and possible future developments. Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC. EPA-600/4-76-030a.

USEPA. 1977. Addendum to user's guide for climatological dispersion model. Office of Air Quality Planning and Standards, U. S. Environmental Protection Agency, Research Triangle Park, NC. EPA-450/3-77-015. NTIS PB 274-040.

USEPA. 1981. User's guide to MOBILE2 (mobile source emissions model). U. S. Environmental Protection Agency, Research Triangle Park, NC. EPA-600/8/81/009. NTIS PB 81-201410.

USEPA. 1987. Sensitivity analysis for application of the inhalation exposure methodology (IEM) to studies of hazardous waste management facilities. Hazardous Waste Engineering Research Laboratory, Office of Research and Development, U. S. Environmental Protection Agency, Cincinnati, OH. EPA/600/2-87/071.

USEPA. 1988. Superfund exposure assessment manual. Office of Emergency and Remedial Response, U. S. Environmental Protection Agency, Washington, DC. EPA/540/1-88/001.

Van der Hoven, I. 1981. A comparison of measured versus model-predicted effluent diffusion for ground releases. NOAA Technical Memorandum. ERL ARL-105.

Vankatram, A. and R. Vet. 1981. Modeling of dispersion from tall stacks. Atmos. Environ. 15:1531-1538.

Veilleque, P. G., B. Kahn, et al. 1981. Evaluation of the air-vegetation-milk pathway for I-131 at quad cities nuclear power station. NUREG/CR-1600

Vogt, K. J. 1977. Empirical investigations of the diffusion of waste air plumes in the atmosphere. Nucl. Technol. 34(6):43-57.

Weber, A. H., M. R. Buckner, and J. H. Weber. 1982. Statistical performance of several mesoscale atmospheric dispersion models. J. Appl. Meteorol. 21:1633-1644.

Wendell, L. L., D. C. Powell, and R. L. Drake. 1976. A regional scale model for computing deposition and ground level concentrations of SO_2 and sulfates from elevated and ground sources. Third Symposium on Atmospheric Turbulence, Diffusion, and Air Quality (Preprint Volume). American Meteorological Society, Boston, MA.

Weil, J. C. and A. F. Jepsen. 1977. Evaluation of the gaussian plume model at the Dickerson power plant. Atmos. Environ. 11:901-910.

Wilson, D. A., H. E. Cramer, J. F. Bowers, Jr., and H. V. Geary, Jr. 1977. Detailed diffusion modeling as a method of interpreting and supplementing air quality data. In Preprints, Joint Conference on Applications of Air Pollution Meteorology, pp. 315-320. American Meteorological Society, Boston, MA.

Yildiran, M. and C. W. Miller. 1983. Comparison of observed and predicted normalized particulate air concentrations. pp. 54-56. Trans. of ANS 45.

Yildiran, M. and C. W. Miller. 1984. Comparison of observed and predicted Kr-85 air concentrations. International Symposium on the Biosphere, Miami Beach, FL, April 16.

PART III.
INDOOR AIR MODELING

1. INTRODUCTION

Contaminants in residential indoor air have been identified as a major source of human exposure. Two significant factors indicate indoor air as a major exposure pathway: (1) residences contain numerous sources of airborne contaminants, and (2) people spend a high percentage of time each day at home (approximately 67%). Recent studies (Mølhave and Moller, 1979; Repace and Lowrey, 1980; Committee on Aldehydes, 1981; Committee on Indoor Pollutants, 1981; Leaderer, 1982; Seifert and Abraham, 1982; Spengler and Sexton, 1983; Spengler et al., 1983, 1985; Lebret et al., 1984; Gammage et al., 1984; Monteith et al., 1984; Leaderer et al., 1986; Wallace et al., 1985) show that residential indoor air concentrations of several contaminants (e.g., NO_2, CO, SO_2, respirable particles, radon, formaldehyde, volatile organics, bioaerosols) are higher than, sometimes as much as 10 times, concentrations found in outdoor air. These studies show that some residential indoor air contaminant concentrations exceed limits set by ambient air quality standards and, in some cases, limits set by occupational standards (Leaderer, 1987). While these standards may be violated by indoor air concentrations, the standards are nonenforceable because exposure occurs inside residences (Sexton, 1986).

The use of source modeling to predict indoor air concentrations of contaminants is a relatively new research topic (Sexton and Hayward, 1987). While some work has been done in this area, no particular model or modeling technique has emerged to adequately address indoor air modeling. A brief overview of the current work being undertaken to determine human exposure to contaminant concentrations in indoor air is included in this document to emphasize the importance of indoor contaminant concentrations on human exposure.

2. CHARACTERIZATION OF INDOOR AIR EXPOSURE

Four major factors are necessary to determine the extent of human exposure to contaminants in indoor air: (1) identification of home-generated emission sources, (2) characterization of emissions, including estimation of emission rates (Wallace et al., 1985; Leaderer, 1987; Sexton and Hayward, 1987), (3) determination of ventilation rates, and (4) determination of the relative impact of indoor and outdoor emissions on human exposure (Sexton and Hayward, 1987).

2.1. IDENTIFICATION OF EMISSION SOURCES

Contaminants found in indoor air comprise a broad spectrum of organic and inorganic chemicals in gaseous and particulate forms, as well as a range of viable particulates. Indoor emission sources can be characterized as point (e.g., space heaters) or area sources (e.g., use of aerosols) (Leaderer, 1987). Typical sources of contaminants in indoor air include migrating outdoor air, occupant activity-related sources (e.g., tobacco smoking, cooking, space heating, use of propellants, showering), environmental control sources (e.g., heating, cooling), and the building itself (e.g., construction materials such as concrete, chipped board, insulation) or its contents (e.g., furnishings, dry-cleaned clothes, moth crystals, printed materials). Table 10 lists specific air contaminants by common source locations.

Because thousands of consumer products and building materials are in use in private and public buildings and may be used differently in each household, the sources of indoor contaminants have only been partially characterized. A complete characterization of emission sources is needed to better estimate possible risks to public health from all potential sources of human exposure (Wallace et al., 1985; Leaderer, 1987).

Table 10. AIR CONTAMINANTS BY SOURCE LOCATIONS

Contaminants	Sources
Group I—Predominantly Outdoor Sources	
Sulfur oxides (gases, particles)	Fuel combustion, nonferrous smelters
Ozone	Photochemical reactions
Pollens	Trees, grass, weeds, plants
Lead, manganese	Automobiles
Calcium, chlorine; silicon, cadmium	Soil suspension, industrial emission
Organic substances	Solvents, nature, fuel vaporization
Group II—Both Indoor and Outdoor Sources	
Nitric oxide, nitrogen dioxide	Fuel burning
Carbon monoxide	Fuel burning
Carbon dioxide	Combustion, metabolic activity
Particles	Resuspension, vapor condensation, and combustion products
Water vapor	Biological activity, combustion, and evaporation
Organic substances	Volatilization, combustion, paint, metabolic action, pesticides, insecticides, fungicides
Spores	Fungi, molds
Group III—Predominantly Indoor Sources	
Radon	Building construction materials (e.g., concrete, stone), water, soil
Formaldehyde	Particleboard, insulation, gas stoves, tobacco smoke, furnishings
Asbestos, mineral/synthetic fibers	Fire-retardant, insulation (acoustic, thermal, electrical)
Organic substances	Adhesives, solvents, cooking, cosmetics
Ammonia	Metabolic activity, cleaning products
Polycyclic hydrocarbons, arsenic, nicotine, acrolein	Tobacco smoke
Mercury	Fungicides in paints, thermometer breakage, spills (labs and dental)
Aerosols	Consumer products
Viable organisms	Infections
Allergens	House dust, animal dander

SOURCE: National Academy of Sciences, 1981.

2.2. CHARACTERIZATION OF EMISSIONS

The emission rate of any emission source is a crucial factor for determining the extent of human exposure. Emission rates must be determined for the various indoor air contaminants before modeling can be used to predict contaminant concentrations. However, emission rates for only a relatively small number of identified indoor emission sources have been determined (Leaderer, 1987). Indoor contaminant concentrations tend to be both building- and occupant-specific (Sexton and Hayward, 1987). Contaminant concentrations from indoor sources can vary from home to home because of variables in building construction, air exchange rates, and occupant activities and use patterns. Because of the complexities involved in determining the actual emission rates for each indoor contaminant from each identified source in each indoor setting, modelers must rely on measurements from controlled laboratory studies. Some of these studies have measured emissions from gas ranges (Himmel and DeWerth, 1974; Yamanaka et al., 1979; Traynor et al., 1982; Moschandreas et al., 1985) and from unvented gas or kerosene-fired heaters (Girman et al., 1982; Porter, 1984). Emission rates determined in a controlled laboratory setting can only be assumed to be equivalent to actual emission rates in a home. Field studies conducted to measure actual emission rates are needed to corroborate laboratory results.

2.3. DETERMINATION OF VENTILATION RATES

Ventilation rates, or air exchange rates, are determined by the amount of mechanical or natural ventilation, the building tightness, the indoor/outdoor temperature differences, and the wind speed and direction (Sexton and Hayward, 1987). Specific air exchange rates are usually unknown, but can be estimated using tracer gas decay methods (Borrazzo et al., 1987). In turn, the ventilation pattern, the size and layout of rooms, and temperature stratification affect the mixing conditions of inside air (Sexton and Hayward, 1987).

2.4. RELATIVE IMPACT OF INDOOR AND OUTDOOR EMISSIONS ON HUMAN EXPOSURE

Airborne contaminants from outdoor sources may penetrate the indoors and adversely affect the quality of indoor air. The combined effects of outdoor and indoor sources determine air contaminant exposures inside buildings. The relationship of indoor and outdoor emissions to contaminant concentrations in indoor air is generally described in terms of indoor/outdoor

(I/O) ratios. Use of I/O ratios indicates the relationship of indoor and outdoor emissions on the quality of indoor air when concentrations are averaged over a long period of time. If the I/O ratio is greater than 1, the excess is assumed to be due to indoor emissions. If the I/O ratio is less than 1, it is assumed that the penetration of outdoor-generated contaminants is primarily responsible for the measured indoor levels (Sexton and Hayward, 1987). Yocum (1982) provides a discussion of I/O relationships for several airborne contaminants. A summary of typical I/O ratios is provided in Table 11.

Table 11. SUMMARY OF I/O RATIOS OF SELECTED AIRBORNE CONTAMINANTS

Contaminant	Usual range	Typical I/O ratio	Comments
Carbon dioxide	1.0 - 4.0	3	I/O >10 without ventilation
Carbon monoxide	1.0 - 2.0	1	I/O >2 during unvented combustion
Hydrocarbons	1.5 - 2.0	1.5	Numerous indoor sources
Lead	0.3 - 1.0	0.7	No significant indoor sources
Nitrates	0.6 - 1.0	0.8	I/O >7 near gas stoves
Nitrogen dioxide	0.5 - 2.0	0.5	I/O >2 near unvented combustion sources
Ozone	0.1 - 1.0	0.2	
Particulates respirable	0.4 - 5.0	<1	Smoking can raise I/O to >5
Particulates (total)	0.1 - 1.2	--	Little I/O relationship
Sulfates	0.5 - 1.0	0.7	
Sulfur dioxide	0.1 - 1.0	0.5	

SOURCE: Yocum, 1982; Dudney and Hawthorne, 1985; Gammage and Kaye, 1985.

3. MODELING INDOOR AIR

Atmospheric dispersion models and other model types (i.e., the proportional rollback model and receptor models), designed to model contaminant concentrations in ambient air, may be used as modeling tools for indoor air. Sexton and Hayward (1987) provide a detailed analysis of the advantages and disadvantages of each model type and possible applications of these techniques to indoor modeling practices. However, the use of models to determine indoor contaminant concentrations is a relatively new research topic (Sexton and Hayward, 1987) and modeling methodologies are not well established.

One potential drawback to the use of models to predict indoor air concentrations of contaminants is the lack of quantitative data for site parameters. Quantitative data are needed for source strengths of the contaminant, ventilation rates, and penetration factors of contaminants from outdoor sources. Little actual site-specific data exist for these parameters. The modeler must, therefore, rely on measurements conducted in testing chambers that may not be equivalent to actual values.

Specifically, five major parameters of indoor contaminant concentrations must be included in any indoor air quality model: (1) outdoor pollutant concentration; (2) ventilation rate; (3) indoor source strength(s) (i.e., types of sources and use patterns and resulting emission rate); (4) inside mixing conditions; and (5) contaminant decay rate (i.e., chemical transformations, physical deposition). An indoor air quality model should be capable of incorporating these five major parameters of indoor contaminant levels into a mass-balance equation. The equation is expressed

$$V\frac{dC_{in}}{dt} = R(C_{out} - C_{in}) - KC_{in} + S \qquad \text{(III-1)}$$

where

V	=	volume of the indoor space
C_{in}	=	indoor contaminant concentration
R	=	ventilation rate
C_{out}	=	outdoor contaminant concentration
K	=	contaminant decay rate
S	=	source emission rate

Use of this equation for modeling employs the following assumptions: the contaminants are well-mixed; they do not undergo significant chemical reactions; they are not lost from the system; all sources are known and their emission rates are quantified; and quantification of outdoor contaminant concentration is applicable to the indoor modeling site.

Because the use of models to predict indoor air concentrations of contaminants is relatively new, no specific indoor modeling selection criteria can be provided. It is still questionable if currently used atmospheric dispersion models, which have been validated for use in outdoor environments, can be effectively used to predict indoor air concentrations. Risk analysts should seek the assistance of expert modelers and indoor air specialists when conducting exposure assessments involving contaminant sources in an indoor environment.

REFERENCES FOR PART III

Borrazzo, J. E., J. F. Osborn, R. C. Fortmann, R. L. Keefer, and C. I. Davidson. 1987. Modeling and monitoring of CO, NO and NO_2 in a modern townhouse. Atmos. Environ. 21(2):299-311.

Committee on Aldehydes. 1981. Formaldehyde and Other Aldehydes. Washington, DC: National Academy Press.

Committee on Indoor Pollutants. 1981. Indoor Pollutants. Washington, DC: National Academy Press.

Dudney, C. S. and A. R. Hawthorne. 1985. Analysis of Indoor Air Quality Data from East Tennessee Field Studies. Oak Ridge National Laboratory, Oakridge, TN. ORNL/TM-9588.

Gammage, R. B. and S. V. Kaye, eds. 1985. Indoor Air and Human Health. Chelsea, MI: Lewis Publishers.

Gammage, R. B., D. A. White, and K. C. Gupta. 1984. Residential measurements of high volatility organics and their sources. In Indoor Air, Vol. 4, pp. 157-162. Swedish Council for Building Research, Stockholm, Sweden.

Girman, J. R., M. G. Apte, G. W. Traynor, J. R. Allen, and C. D. Hollowell. 1982. Pollutant emission rates from indoor combustion and sidestream cigarette smoke. Environ. Int. 8:213-221.

Himmel, R. L. and D. W. DeWerth. 1974. Evaluation of the pollutant emissions from gas-fired ranges. American Gas Association Laboratories, Report No. 1492.

Leaderer, B. P. 1982. Air pollutant emissions from kerosene space heaters. Science 218:1113-1115.

Leaderer, B. P. 1987. Forward. Atmos. Environ. 21(2):279-280.

Leaderer, B. P., R. T. Zagraniski, M. Berwick, and J. A. J. Stolwijk. 1986. Assessment of exposure to indoor air contaminants from combustion sources: Methodology and application. Am. J. Epidemiol. 124:275-289.

Lebret, E., H. J. Van de Wiel, H. P. Bos, D. Noij, and J. S. M. Boleij. 1984. Volatile hydrocarbons in Dutch homes. In Indoor Air, Vol. 4, pp. 169-174. Swedish Council for Building Research, Stockholm, Sweden.

Mølhave, L. and J. Moller. 1979. The atmospheric environment in modern Danish dwellings: Measurements in 39 flats. In Indoor Climate, pp. 171-186. Danish Building Research Institute, Copenhagen, Denmark.

Monteith, D. K., T. H. Stock, and W. E. Seifert, Jr. 1984. Sources and characterization of organic air contaminants inside manufactured housing. In Indoor Air, Vol. 4, pp. 285-290. Swedish Council for Building Research, Stockholm, Sweden.

Moschandreas, D. J., S. M. Relwani, H. J. O'Neill, J. T. Cole, R. H. Elkins, and R. A. Macriss. 1985. Characterization of emission rates from indoor combustion sources. Gas Research Institute, Report GRI-85/0075.

National Academy of Sciences. 1981. Indoor Pollutants. Washington, DC: National Academy Press.

Porter, W. K. 1984. Pollutant emissions from kerosene heaters and unvented gas space heaters. In Indoor Air, Vol. 4, pp. 265-270. Swedish Council for Building Research, Stockholm, Sweden.

Repace, J. L. and A. H. Lowry. 1980. Indoor air pollution, tobacco smoke, and public health. Science 208:464-472.

Seifert, B. and H. J. Abraham. 1982. Indoor air concentrations of benzene and some other aromatic hydrocarbons. Ecotoxicol. Environ. Safety 6:190-192.

Sexton, K. 1986. Indoor air quality: An overview of policy and regulatory issues. Science Technol. Human Values 11:53-67.

Sexton, K. and S. B. Hayward. 1987. Source apportionment of indoor air pollution. Atmos. Environ. 21(2):407-418.

Spengler, J. D. and K. Sexton. 1983. Indoor air pollution: A public health perspective. Science 221:8-17.

Spengler, J. D., C. Duffy, R. Letz, T. W. Tibbitts, and B. G. Ferris, Jr. 1983. Nitrogen dioxide inside and outside 137 homes and implications for ambient air quality standards and health effects research. Environ. Sci. Technol. 17:164-168.

Spengler, J. D., R. D. Treitman, T. D. Tosteson, D. T. Mage, and M. L. Soczek. 1985. Personal exposures to respirable particulates and implications for air pollution epidemiology. Environ. Sci. Technol. 19:700-706.

Traynor, G. W., M. G. Apte, J. F. Dillworth, C. D. Hollowell, and E. M. Sterling. 1982. The effects of ventilation on residential air pollution from a gas-fired range. *Atmos. Environ.* 16:2979-2987.

Wallace, L., E. E. Pellizzari, T. D. Hartwell, C. M. Sparacino, L. S. Sheldon, and H. Zelon. 1985. Personal exposures, indoor-outdoor relationships, and breath levels of toxic air pollutants measured for 355 persons in New Jersey. Atmos. Environ. 19:1651-1661.

Yamanaka, S., H. Hirose, and S. Takada. 1979. Nitrogen oxides emissions from domestic kerosene-fired and gas-fired appliances. Atmos. Environ. 13:407-412.

Yocum, J. E. 1982. Indoor-outdoor air quality relationships. A critical review. J. Air Pollut. Control Assoc. 32:500-520.

APPENDIX

ADDITIONAL INFORMATION ON AIR MODEL SELECTION

This appendix, consisting of five tables and one figure from other documents, provides alternative presentations of air model selection criteria. Readers may find these tables useful as both additional information and as a supplement or second opinion to the decision-making process described in the main text of the document. The tables are basically self-explanatory and are briefly described below:

Table A-1. Capabilities of Selected Models—This chart compares the technical features of 11 common air models.

Figure A-1. Decision Tree for Selection of Air Transport Models—A flow diagram which leads to a quick initial selection of models on the basis of averaging time, urban/rural setting, and point/area source.

Table A-2. Preferred Models for Selected Application in Simple Terrain—Recommends models on the basis of averaging time, source configuration, and land use.

Table A-3. Resource Requirements and Information Sources: Atmospheric Fate Models—Summarizes capabilities and assumptions, resource requirements in terms of computing equipment and input data, and references for 11 atmospheric fate models.

Table A-4. Features of Atmospheric Models—Compares technical features/capabilities and output forms of nine models.

Table A-5. Data Requirements for Atmospheric Models—Compares various data requirements for the nine models in Table A-4.

Table A-1. Capabilities of Selected Models

MODEL FUNCTION	ISCLT	ISCST	CRSTER	MPTER	RAM	PT MODELS[a]	VALLEY	LONGZ	SHORTZ	COMPLEX I	RTDM
Point Source	•	•	•	•	•	•	•	•	•	•	•
Area Source	•	•			•		•	•	•		
Volume Source	•	•						•	•		
Short-Term		•	•	•	•	•	•		•	•	•
Long-Term	•		•	•	•		•	•		•	
Hourly Meteorological Data		•	•	•	•	•			•	•	•
Annual Meteorological Data	•	•					•	•			•
Plume Trapping	•	•	•		•	•	•	•	•	•	
Half-Life	•	•	•	•	•		•	•	•	•	
Gravitational Settling	•	•						•	•		
Building Wake Effects	•	•									
Buoyant Plume Rise	•	•	•	•	•	•	•	•	•	•	•
Momentum Plume Rise	•	•	•	•	•			•	•	•	
Stack-Tip Downwash	•	•	•	•	•	•		•	•	•	
Terrain Adjustment	•	•	•	•			•	•	•	•	•
Complex Terrain							•	•	•	•	•
Urban/Rural Dispersion	•	•	•	•	•	•	•	•	•		
Rural Dispersion Only										•	
Windspeed Extrapolation	•	•	•	•	•	•		•	•	•	•
Em. Rates Funct. of Met Condit'ns	•	•								•	•
Em. Rates Funct. Of Time of Day		•		•	•					•	•
Buoyancy Induced Dispersion	•	•	•	•	•	•		•	•	•	•
Deposition	•	•						•	•		
Discrete Receptors	•	•	•	•	•	•		•	•	•	•
STAR Data	•						•	•			
Maximum Number of Sources	100[b]	100[b]	19	250P	250P100A	25(PTMTP)	50	14,000	300	250	35
Maximum Number of Receptors	400[b]	400[b]	180	180	150	30(PTMTP)	112	1,800	1,800	180	400

[a] PTMAX, PTDIS, PTMP, PTPLU

[b] THE MAXIMUM NUMBER OF SOURCES AND RECEPTORS ARE INTERRELATED
THESE VALUES ARE REASONABLE ESTIMATES

P — Point Sources
A — Area Sources

SOURCE: Versar, 1988.

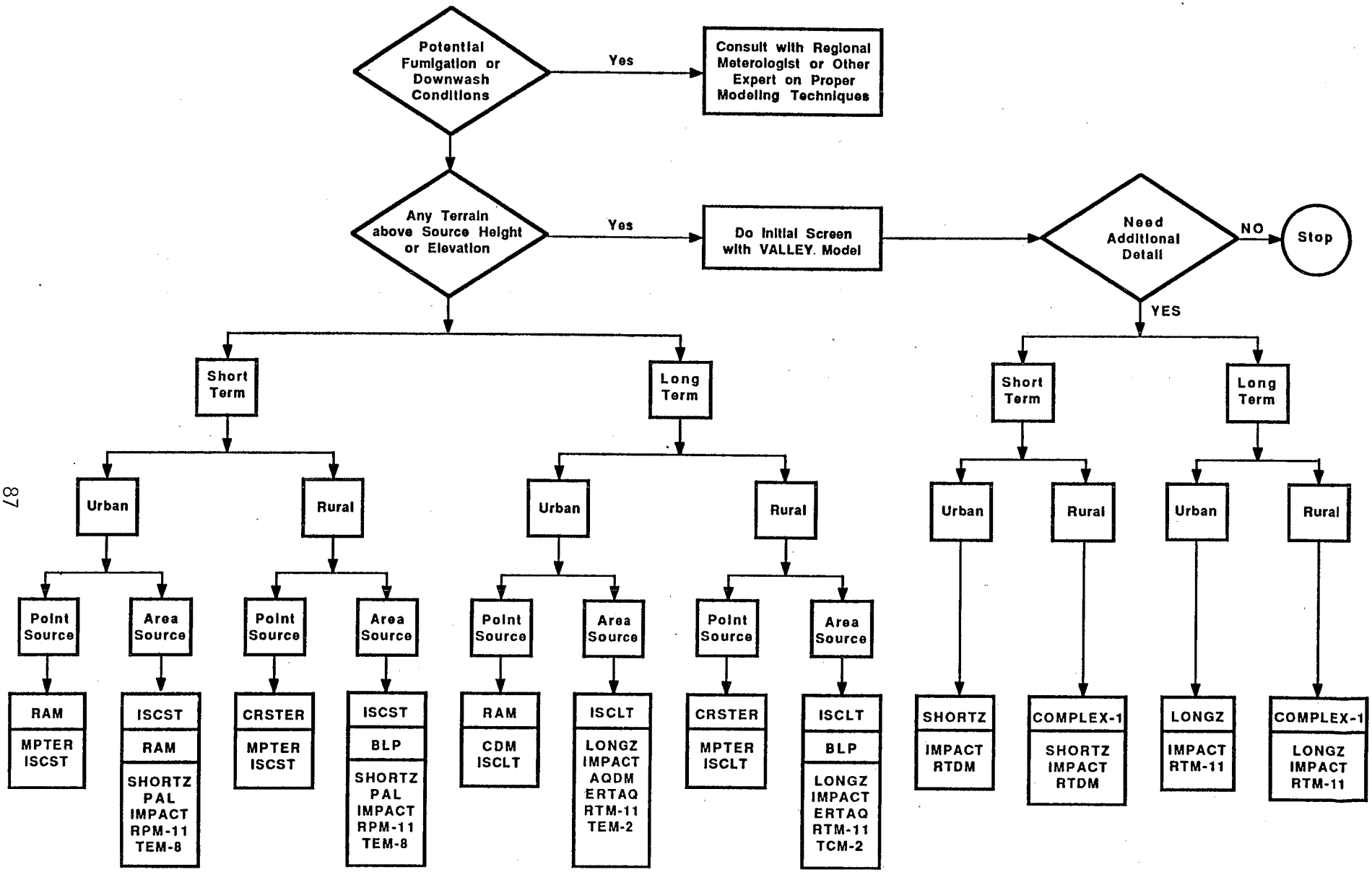

Figure A-1. Decision Tree for Selection of Air Transport Models

SOURCE: Versar, 1988.

Table A-2. Preferred Models for Selected Applications in Simple Terrain

Short-Term (1-24 hours)	Land Use	Model[a]
Single Source	Rural	CRSTER
	Urban	RAM
Multiple Source	Rural	MPTER
	Urban	RAM
Complicated Sources[b]	Rural/Urban	ISCST
Buoyant Industrial Line Sources	Rural	BLP
Long-Term (monthly, seasonal, or annual)		
Single Source	Rural	CRSTER
	Urban	RAM
Multiple Source	Rural	MPTER
	Urban	CDM 2.0 or RAM[c]
Complicated Sources[b]	Rural/Urban	ISCLT
Buoyant Industrial Line Sources	Rural	BLP

[a] Several of these models contain options that allow them to be interchanged. For example, ISCST can be substituted for CRSTER, and equivalent, if not identical, concentration estimates can be obtained. Similarly, for a point source application, MPTER with an urban option can be substituted for RAM. Where a substitution is convenient to the user and equivalent estimates are assured, it can be made. The models as listed here reflect the applications for which they were originally intended.

[b] Complicated sources are sources with special problems such as aerodynamic downwash, particle deposition, volume and area sources, etc.

[c] If only a few sources in an urban area are to be modeled.

SOURCE: Versar, 1988.

Table A-3. Resource Requirements and Information Sources: Atmospheric Fate Models

Model	Description	Resource requirements	References, sources of document, software
PTMAX	• Steady-state Gaussian plume model • Point source • Short-term • Assumes conservative pollutant • Produces maximum hourly concentrations for each stability and wind speed location of maximum concentration	• Available through GEMS • FORTRAN IV Program, applicable to wide range of computers; has been implemented on UNIVAC 1110 • Approximately 12 K bytes memory required • Software available as part of UNAMAP package for $420	Reference: GSC, 1982 Software: Computer Products, National Technical Information Service (NTIS), Springfield, VA 22161
PTDIS	• Steady-state Gaussian plume model • Point source • Accommodates limit to upward vertical mixing • Short-term • Assumes conservative pollutant • Produces estimates of hourly concentrations at a user-selected downwind distance	• Available through GEMS • FORTRAN IV Program, applicable to wide range of computers; has been implemented on UNIVAC 1110 • Approximately 12 K bytes memory required • Software available as part of UNAMAP package for $420	Reference: GSC, 1982 Software: Computer Products, NTIS, Springfield, VA 22161
Texas Episodic Model (TEM)[a]	• Steady-state model • Point or area sources • Short-term - 10 minutes to 24 hours • Produces maximum and average concentrations over time periods selected by user • User can select up to 2500 downwind receptor points, according to an automatic or specified grid array • Handles nonconservative pollutants • Up to 24 meteorologic scenarios can be input for a single run	• FORTRAN program applicable to a wide range of computer types; has been implemented on Burroughs 6810/11 • Requires approximately 26 K bytes memory • Engineering, meteorology, atmospheric transport background useful	Reference: USEPA, 1976a

Table A-3. (continued)

Model	Description	Resource requirements	References, sources of document, software
Box Model	• Area Source • Vertical dispersion or no vertical dispersion option • Basic box model	• Available through GEMS	
Texas Climatological Model Control (TCM)[a]	• Long-term (seasonal or annual) • Gaussian dispersion • Two pollutants per run • Includes option for simulation of urban area turbulence classes • Handles nonconservative pollutants • Point or area sources • Up to 2500 receptor locations on downwind user-specific grid • Outputs average concentration data	• Requires stability array data • FORTRAN program language; has been implemented on Burroughs 6810/11 • Batch mode • 17 K bytes memory required • Technical background in meteorology, air pollution useful	Documentation: USEPA, 1979b
Climatological Dispersion Model (CDM)	• Long-term seasonal or annual • Point or area sources • Gaussian plume model • Simulates nonconservative pollutants • Can simulate turbulence over urban areas • Outputs long-term average concentrations at user-specified receptors	• Requires stability array data • FORTRAN V program language; has been implemented on the UNIVAC 1110 • 22 K bytes storage required • Software available as part of UNAMAP package.	Documentation: USEPA, 1976b Software: Computer Products, NTIS, Springfield, VA 22161
VALLEY[b]	• Short- or long-term • Simulates plume impact in complex terrain • Provides screening estimates of worst-case short-term concentrations • Provides annual average concentrations • 12-receptor grid	• May require careful analysis of output by experienced air quality modeler • FORTRAN V program, applicable to wide range of computers • Approximately 13 K bytes memory required	Reference: USEPA, 1977a Software: Computer Products, NTIS, Springfield, VA 22161

Table A-3. (continued)

Model	Description	Resource requirements	References, sources of document, software
	• Accommodates nonconservative pollutants • Requires stability array data for long-term option • Requires user-input worst-case meteorological data for short-term screening option	• Software available as part of UNAMAP	
Industrial Source Complex (ISC)	• Operates in both long-term and short-term modes • Accounts for settling and dry deposition of particles; downwash, area, line, and volume sources; plume rise as a function of downwind distance; separation of point sources; and limited terrain adjustments. • Appropriate for industrial source complexes, rural or urban areas, flat or rolling terrain, transport distances less than 50 kilometers, and one hour to annual averaging times.	• Integrated into GEMS • Source data: location, emisison rate, physical stack height, stack gas exit velocity, stack inside diameter, and stack gas temperature. Optional inputs include source elevation, building dimensions, particle size, distribution with corresponding settling velocities, and surface reflection. • Meteorological data: includes stability wind rose (STAR deck), average afternoon mixing height, average morning mixing height, and average air temperature.	Documentation: USEPA, 1979a Software: Computer Products, NTIS, Springfield, VA 22161
Ram	• Steady-state Gaussian plume model. • Appropriate for point and area sources, urban areas, flat terrain transport distances less than 50 kilometers, and one hour to one year averaging times. • May be used to model primary pollutants, however settling and deposition are not treated.	• Available code on UNIMAP (Version 6) • Source data: point sources require location, emission rate, physical stack height, stack gas exit velocity, stack inside diameter and stack gas temperature. Area sources require location, size, emission rate, and height of emission.	Reference: USEPA, 1978

Table A-3. (continued)

Model	Description	Resource requirements	References, sources of document, software
		• Meteorological data: hourly surface weather data from the preprocessor RAMMET. Actual anemometer height is also required.	
CRSTER	• Steady-state Gaussian dispersion model. • Designed to calculate concentrations from point sources at a single location. • Highest and second highest concentrations are calculated at each receptor. • Appropriate for single point sources, rural or urban areas, transport distances less than 50 kilometers, and flat or rolling terrain.	• Available on UNIMAP (Version 6). • Source data: emission rate, physical stack height, stack exit velocity, stack inside diameter and stack gas temperature. • Meteorological data: hourly surface weather data from the preprocessor RAMMET. Actual anemometer height is also required.	Reference: USEPA, 1977b
MPTER	• Multiple point source algorithm useful for estimating air quality concentration of relatively nonreactive pollutants. • Appropriate for point sources, rural or urban areas, flat or rolling terrain, transport distances less than 50 kilometers, and one hour to one year averaging times.	• Source data: location, emission rate, physical stack height, stack gas exit velocity, stack inside diameter, stack gas temperature, and optional ground level elevation. • Meteorological data: hourly surface weather data from the preprocessor RAMMET. Actual anemometer height is also required.	Documentation: USEPA, 1980, 1986

[a] These models are not EPA-preferred models. They can, however, be used if it can be demonstrated that they estimate concentrations equivalent to those provided by the preferred models (e.g., CDM, RAM, ISC, MPTER, CRSTER, for a given application).

[b] This model is recommended for screening applications only.

SOURCE: Bonazountas et al., 1982; USEPA, 1979b, 1982.

Table A-4. Features of Atmospheric Models

	HANDLES PARTICULATE RELEASES	HANDLES VOLATILIZATION RELEASES	POINT SOURCE	AREA SOURCE	MULTIPLE SOURCE	ACCOUNTS FOR HORIZONTAL DISPERSION	ACCOUNTS FOR VERTICAL DISPERSION	ACCOUNTS FOR DEGRADATION	ACCOUNTS FOR DISSOLUTION/RAINOUT	ACCOUNTS FOR ADSORPTION/SETTLEOUT	HANDLES ROUGH TERRAIN/URBAN SIMULATION	ACCEPTS TIME-VARIANT RELEASE TERMS	PRODUCES 24-HOUR MAXIMUM AMBIENT CONCENTRATION DATA	PRODUCES ANNUAL AVERAGE CONCENTRATION DATA	PRODUCES RATE OF DEPOSITION (FOR PARTICULATE RELEASES)	OUTPUT IN FORM OF ISOPLETHS OR DATA SUFFICIENT FOR ISOPLETH CHARTING	OUTPUT IN FORM OF CONCENTRATIONS AT RECEPTOR POINTS
TEM		●	●	●	●	●	●	●					●	●		●	●
TCM[a]		●	●	●	●	●	●	●			●			●		●	●
CDM		●	●	●		●	●	●	●	●				●		●	●
VALLEY[b]		●	●	●	●	●	●	●	●	●			●	●			
ISC	●	●	●	●	●	●	●	●		●		●	●	●	●	●	●
BOXMOD	●	●		●			●	●	●	●				●			●
RAM	●	●	●	●	●	●	●	●				●	●	●		●	●
CRSTER	●	●	●			●	●	●			●		●	●		●	●
MPTER	●	●	●		●	●	●	●				●	●	●		●	●

[a]This model is recommended for screening applications only.
[b]These models are not EPA preferred models. These models can be used if they can be demonstrated to estimate concentrations equivalent to those provided by the preferred models, e.g. CPM, ISC, MPTER, CRSTER, for a given application.

SOURCE: Bonazountas et al., 1982; USEPA, 1979b, 1982.

Table A-5. Data Requirements for Atmospheric Models

	SITE LOCATION (USES STORED CLIMATOLOGICAL DATA)	WIND ROSE (OR WIND SPEED FREQUENCIES IN SINGLE DIRECTION)	STABILITY ARRAY (STAR) DATA	PRECIPITATION	AMBIENT TEMPERATURE	WORST-CASE CLIMATOLOGICAL DATA ASSUMPTIONS	RECEPTOR ELEVATIONS	RECEPTOR LOCATION GRID OR POINT	TOPOGRAPHIC/VEGETATIVE COVER/ URBAN BUILDING FEATURES	EMISSION STATE (GASEOUS/PARTICULATE)	PARTICLE SIZE AND DENSITY	POLLUTANT MOLECULAR WEIGHT	ATMOSPHERIC HALF-LIFE (OVERALL DECAY) COEFFICIENT	EMISSION RATE (EXPRESSED AS STEADY STATE)	TIME-VARIANT EMISSION RATE	SOURCE DESCRIPTION (POINT OR AREA SIZE)
TEM[a]		●			●			●						●	●		●
TCM[a]		●			●			●	●					●	●		●
CDM		●	●					●	●						●		●
VALLEY[b]		●	●			●	●	●	●						●		
ISC		●	●							●	●					●	●
BOXMOD	●			●						●		●	●	●			●
RAM		●						●		●			●	●	●	●
CRSTER		●					●	●		●			●	●		●
MPTER		●			●		●	●		●			●		●	

[a]This model is recommended for screening applications only.
[b]These models are not EPA preferred models. These models can be used if they can be demonstrated to estimate concentrations equivalent to those provided by the preferred models, e.g. CPM, ISC, MPTER, CRSTER, for a given application.

SOURCE: Bonazountas et al., 1982; USEPA, 1979b, 1982.

REFERENCES FOR APPENDIX

Bonazountas M., J. Fiksel, et al. 1982. Environmental Mathematical Pollutant Fate Modeling Handbook/Catalogue. Draft. Prepared for the Office of Policy and Resource Management, U.S. Environmental Protection Agency, Washington, DC, Contract No. 68-01-5146. As cited in USEPA (1988).

General Software Corporation (GSC). 1982. Graphical Exposure Modeling System (GEMS) User's Guide. Prepared for the Office of Pesticides and Toxic Substances, U.S. Environmental Protection Agency, Washington, DC, Contract No. 68-01-6618. As cited in USEPA (1988).

Texas Air Control Board. 1980. User's Guide to the Texas Climatological Model. Texas Air Control Board, Austin, TX. As cited in USEPA (1988).

USEPA. 1976a. Design and application of the Texas episodic model. Proceedings of the Conference on Environmental Modeling and Simulation. U.S. Environmental Protection Agency, Washington, DC. EPA-600/9-76-016. As cited in USEPA (1988).

USEPA. 1976b. User's Guide for the Climatological Dispersion Model. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-R4-73-024. As cited in USEPA (1988).

USEPA. 1977a. VALLEY Model User's Guide. U.S. Environmental Protection Agency, Washington, DC. EPA-450/2-77-018. As cited in USEPA (1988).

USEPA. 1977b. User's Manual for Single Source (CRSTER) Model. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-4502-77-013. As cited in USEPA (1988).

USEPA. 1978. User's Guide for RAM. *Vols. a and b.* U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-600/8-78-016. As cited in USEPA (1988).

USEPA. 1979a. Industrial Source Complex (ISC) Dispersion Model User's Guide. Vols. 1 and 2. Office of Air Quality Planning and Standards, U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA 450/4-79-030. As cited in USEPA (1988).

USEPA. 1979b. Environmental Modeling Catalogue. Prepared for the Management Information and Data Systems Division, U.S. Environmental Protection Agency, Washington, DC, Contract No. 68-01-4723. As cited in USEPA (1988).

USEPA. 1980. User's Guide for MPTER. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-600/8-80-016. NTIS PB80-176361. As cited in USEPA (1988).

USEPA. 1982. Chemical Fate Test Guidelines. Test Guideline CG-1700. U.S. Environmental Protection Agency, Washington, DC. EPA 560/6-82-003. NTIS PB82-233008. As quoted in Leifer et al. (1983).

USEPA. 1986. Addendum to the User's Guide for MPTER. U.S. Environmental Protection Agency, Research Triangle Park, NC. EPA-600/8-86/021. NTIS PB86-217163. As cited in USEPA (1988).

USEPA. 1988. Technical Support Document. Incineration of Sewage Sludge. Office of Water Regulations and Standards, U.S. Environmental Protection Agency, Washington, DC. NTIS PB89-136592.

Versar, Inc. 1988. Air Dispersion Modeling as Applied to Hazardous Waste Incinerator Evaluations: An Introduction for the Permit Writer. Prepared for the Office of Solid Waste, U.S. Environmental Protection Agency, Washington, DC.

☆ U.S. GOVERNMENT PRINTING OFFICE: 1993—750-002/60,180

United States
Environmental Protection Agency
Center for Environmental Research Information
Cincinnati, OH 45268

Official Business
Penalty for Private Use
$300

EPA/600/8-91/038

Please make all necessary changes on the below label, detach or copy, and return to the address in the upper left-hand corner.

If you do not wish to receive these reports CHECK HERE ☐; detach, or copy this cover, and return to the address in the upper left-hand corner.

BULK RATE
POSTAGE & FEES PAID
EPA
PERMIT No. G-35