2

AD________________________

FIELD MEASUREMENT AND MODEL EVALUATION PROGRAM FOR ASSESSMENT OF THE ENVIRONMENTAL EFFECTS OF MILITARY SMOKES

EVALUATION OF ATMOSPHERIC DISPERSION MODELS FOR SMOKE DISPERSION

prepared by

A. J. Policastro and D. M. Maloney
Environmental Assessment and Information Sciences Division
Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
708-252-3235

and

W. E. Dunn and D. F. Brown
Department of Mechanical and Industrial Engineering
University of Illinois at Urbana-Champaign
Urbana, IL 61801
217-333-3832

OCTOBER 1991

Supported by
U. S. ARMY MEDICAL RESEARCH AND DEVELOPMENT COMMAND
Fort Detrick, Frederick, MD 21702-5012

Contract No. 90PP0819

Project Officer: Major John Young
Health Effects Research Division
U. S. ARMY BIOMEDICAL RESEARCH AND DEVELOPMENT LABORATORY
Fort Detrick, Frederick, MD 21702-5010

The findings in this report are not to be construed as an official Department of the Army position unless so designated by other authorized documents.

10

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION Unclassified

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
Approved for public release;
distribution unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION Argonne National Laboratory

6b. OFFICE SYMBOL *(If applicable)*

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS *(City, State, and ZIP Code)*
9700 South Cass Avenue
Argonne, Illinois 60439

7b. ADDRESS *(City, State, and ZIP Code)*

8a. NAME OF FUNDING / SPONSORING ORGANIZATION U.S. Army Medical Research and Development Command

8b. OFFICE SYMBOL *(If applicable)*

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER 90PP0819

8c. ADDRESS *(City, State, and ZIP Code)*
Fort Detrick
Frederick, Maryland 21702-5012

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
62720A	3E1-62720A835	CA	291

11. TITLE *(Include Security Classification)* (U) Field Measurement and Model Evaluation Program for Assessment of the Environmental Effects of Military Smokes

12. PERSONAL AUTHOR(S) A.J. Policastro, D. M. Maloney, W F. Dunn and D.F. Brown

13a. TYPE OF REPORT Final

13b. TIME COVERED FROM 1990 TO 1991

14. DATE OF REPORT *(Year, Month, Day)* 1991 October

15. PAGE COUNT 66

16. SUPPLEMENTARY NOTATION Subtitle: Evaluation of Atmospheric Dispersion Models for Smoke Dispersion

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
04	01	
07	03	

18. SUBJECT TERMS *(Continue on reverse if neccessary and identify by block number)*
smoke, screening smoke, obscuring smoke, hexachloroethane, dispersion modeling, computer modeling

19. ABSTRACT *(Continue on reverse if neccessary and identify by block number)*

Three Gaussian-puff dispersion models (the BEAR, INPUFF and RIMPUFF Models) are tested with field data from the Atterbury-87 smoke dispersion field study. The BEAR, INPUFF, and RIMPUFF models are similar in their basic treatment of transport and dispersion, but differ in implementation. These three were chosen because they represent the state of the art of models available for general use.

The INPUFF-ON predictions are consistently better than the predictions of the other three models (BEAR, INPUFF-PG and RIMPUFF) and are within a factor of two of the data values 38 % of the time and within a factor of ten 83 % of the time. By contrast, the other three models predict within a factor of two 24 % of the time and within a factor of ten 67 % of the time. The predictions are consistent for the fog-oil and HC trials for the best performing model, INPUFF-ON. However, for the other models, the predictions for the fog-oil trials are somewhat better than for the HC trials. The comparisons also reveal that the models incorrectly predict the decay of concentration with distance from the source, a result which we attribute to the effect of the rising centerline under convective conditions. It is noted that the meteorological and source data which serve as inputs to the models and the concentration data to which the model predictions are compared both contain considerable experimental uncertainty. Thus, although the models can be significantly improved in many respects, their current performance must be viewed in the proper light.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL Mary Frances Bostian

22b. TELEPHONE *(Include Area Code)* 301-619-7325

22c. OFFICE SYMBOL SGRD-RMI-S

DD FORM 1473, JUN 86 *Previous editions are obsolete.*

SECURITY CLASSIFICATION OF THIS PAGE

UN

FOREWORD

Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the U.S. Army.

AJL Where copyrighted material is quoted, permission has been obtained to use such material.

_____Where material from documents designated for limited distribution is quoted, permission has been obtained to use the material.

AJL Citations of commercial organizations and trade names in this report do not constitute an official Department of the Army endorsement or approval of the products or services of these organizations.

_____In conducting research using animals, the investigator(s) adhered to the "Guide for the Care and Use of Laboratory Animals," prepared by the Committee on Care and Use of Laboratory Animals of the Institute of Laboratory Animal Resources, National Research Council (NIH Publication No. 86-23, Revised 1985).

_____For the protection of human subjects, the investigator(s) have adhered to policies of applicable Federal Law 45CFR46.

Anthony J Licastro 10/2/91
PI Signature Date

Accession For
NTIS GRA&I ☒
DTIC TAB ☐
Unannounced ☐
Justification________
By________
Distribution/
Availability Codes
Dist | Avail and/or Special
A-1

EXECUTIVE SUMMARY

Three Gaussian-puff dispersion models (the BEAR, INPUFF and RIMPUFF Models) are tested with field data from the Atterbury-87 smoke dispersion field study. The Atterbury-87 study consists of a total of nine smoke-dispersion experiments conducted in slightly to moderately unstable conditions (stability classes B through D). Five of these trials were carried out using hexachloroethane (HC) smoke pots as the source; the other four were conducted using a fog-oil smoke generator. Although the terrain of the dispersion site is relatively flat, the meteorology is complex owing to the effects of the surrounding hills and vegetation. The field data include average concentration measurements on four or five transects (depending on the trial) out to distances of 575 m. In addition, the data base includes time-dependent source measurements as well as meteorological data from a 10-m instrument tower and a 2-m mast.

The BEAR, INPUFF, and RIMPUFF models are similar in their basic treatment of transport and dispersion, but differ in implementation. These three were chosen because they represent the state of the art of models available for general use. The models treat the release as a series of Gaussian puffs each of which is transported and dispersed downwind with a time-dependent wind speed. An important difference between the models revolves around the way dispersion is handled. The BEAR model uses dispersion coefficients based on stability class which is, in turn, inferred from synoptic meteorological data. The INPUFF model offers two methods for treating dispersion. One method, which we designate "INPUFF-ON", uses on-site measurements of the standard deviation in the horizontal and vertical wind directions. The second method, designated "INPUFF-PG", uses dispersion coefficients based on the Pasquill-Gifford-Turner stability class determined from synoptic data. Although the RIMPUFF model offers the option of using stability class, its predictions were always made with its preferred method which uses on-site measurements of the standard deviation in the horizontal wind direction.

The INPUFF-ON predictions are consistently better than the predictions of the other three models (BEAR, INPUFF-PG and RIMPUFF) and are within a factor of two of the data values 38 % of the time and within a factor of ten 83 % of the time. By contrast, the other three models predict within a factor of two 24 % of the time and within a factor of ten 67 % of the time. The predictions are consistent for the fog-oil and HC trials for the best performing model, INPUFF-ON. However, for the other models, the predictions for the fog-oil trials are somewhat better than for the HC trials. The comparisons also reveal that the models incorrectly predict the decay of concentration with distance from the source, a result which we attribute to the effect of the rising centerline under convective conditions. A second key conclusion involves the sensitivity of predictions to stability class for those models which use that approach. A change of just one class has a pronounced effect on predictions and, in fact, may change the comparison from one of relatively good performance to one of decidedly poor performance. Moreover, we have observed that the D stability class is problematic in that it groups together conditions which are slightly stable with those that are slightly unstable, even though these two conditions have fundamentally different dispersion physics. Lastly, in evaluating model performance, it must be remembered that the meteorological and source data which serve as inputs to the models and the concentration data to which the model predictions are compared both contain considerable experimental uncertainty. Not only is there the uncertainty associated with the experimental procedures which are particularly difficult to carry out under field test conditions, but there is the added fact that each trial represents a single realization of a process which itself has a very large statistical variance. All things considered, a variation of a factor of two between similar data sets is not surprising. Thus, although the models can be significantly improved in many respects, their current performance must be viewed in the proper light.

TABLE OF CONTENTS

Page

EXECUTIVE SUMMARY 1

LIST OF FIGURES 4

LIST OF TABLES 6

1.0 INTRODUCTION 8

2.0 THE DISPERSION MODELS 10

3.0 THE CAMP ATTERBURY FIELD STUDIES 14

- 3.1 Introduction 14
- 3.2 The Site and Sampling Grid Layout 14
- 3.3 Source and Meteorological Measurements 16
- 3.4 Concentration Measurements 23

4.0 COMPARISONS OF MODEL PREDICTIONS WITH THE ATTERBURY-87 FIELD DATA 25

- 4.1 Preparation of Model Inputs 25
- 4.2 Results of Model/data Comparisons 25
  - 4.2.1 Classification of Trials 25
  - 4.2.2 Overview of Model/data Comparisons 26
  - 4.2.3 Discussion of Individual Trials 56
  - 4.2.4 Discussion of Systematic Trends 57

5.0 SUMMARY AND CONCLUSIONS 59

APPENDIX A: COORDINATE INFORMATION 61

REFERENCES 63

LIST OF FIGURES

Figure		Page
3.1	Topological map of the dispersion test site at Camp Atterbury	15
3.2	Sampling grid used for the Atterbury-87 HC Smoke Dispersion Trials	17
3.3	Sampling grid used for the Atterbury-87 HC Smoke Dispersion Trials, with vectors representing average wind directions	18
4.1	Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1109871	27
4.2	Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1110871	28
4.3	Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1110872	29
4.4	Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1112871	30
4.5	Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1113871	31
4.6	Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1103871	32
4.7	Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1104871	33
4.8	Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1104872	34
4.9	Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1106871	35

Figure Page

4.10 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1109871 37

4.11 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1110871 37

4.12 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1110872. 38

4.13 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1112871 38

4.14 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1113871 39

4.15 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1103871 40

4.16 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1104871 40

4.17 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1104872 41

4.18 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1106871 41

LIST OF TABLES

Table Page

2.1 Key Features of the INPUFF, BEAR, and RIMPUFF Models 11

3.1 Source and meteorological data for Atterbury-87 HC Smoke Dispersion Trials 19

3.2 Source and meteorological data for Atterbury-87 Fog-oil Smoke Dispersion Trials 20

3.3 Comparison of the stability classes determined by various methods 22

4.1a Percentages of model predictions within a given factor of the data for the nine trials conducted during the Atterbury-87 Field Study (only observed values within 10% of the transect maximum are considered) 42

4.1b Percentages of model predictions within a given factor of the data for the nine trials conducted during the Atterbury-87 Field Study (only observed values greater than twice the limit of detection are considered) 44

4.1c Percentages of model predictions within a given factor of the data for the nine trials conducted during the Atterbury-87 Field Study - using a log-normal probability distribution (only observed values greater than the limit of detection are considered) 46

4.2a Summary of model/data comparisons for each of the three types of trials conducted during the Atterbury-87 Field Study (only observed values within 10% of the transect maximum are considered) 48

4.2b Summary of model/data comparisons for each of the three types of trials conducted during the Atterbury-87 Field Study (only observed values greater than twice the limit of detection are considered) 49

4.2c Summary of model/data comparisons for each of the three types of trials conducted during the Atterbury-87 Field Study - using a log-normal probability distribution (only observed values greater than the limit of detection are considered) 50

4.3a Summary of model/data comparisons for each of the three stability classes present during the Atterbury-87 Field Study (only observed values within 10% of the transect maximum are considered) 51

Table		Page
4.3b	Summary of model/data comparisons for each of the three stability classes present during the Atterbury-87 Field Study (only observed values greater than twice the limit of detection are considered)	52
4.3c	Summary of model/data comparisons for each of the three stability classes present during the Atterbury-87 Field Study - using a log-normal probability distribution (only observed values greater than the limit of detection are considered)	53
4.4	Summary of the number of model/data pairs used in the various approaches to determining the percentage of values within a given factor	55
A.1	Coordinates of the meteorological tower and the two release points	61
A.2	Coordinates of the sampling masts	61

1. INTRODUCTION

As part of a program to characterize military smokes under actual field conditions, nine smoke dispersion experiments were conducted at Camp Atterbury, Indiana during November, 1987. Five of these nine experiments were carried out using hexachloroethane (HC) smoke pots; the remaining four trials were carried out using a fog-oil smoke generator as the source. This series of field experiments is referred to collectively as the Atterbury-87 Field Studies.

The smoke-dispersion experiments were conducted in slightly to moderately unstable conditions (Stability Classes B through D). Although the terrain of the dispersion site is relatively flat, the meteorology is complex owing to the surrounding hills and vegetation. The field data include average concentration measurements on four or five transects (depending on the trial) out to distances of 575 m. In addition, the data base includes time-dependent source measurements as well as meteorological data from a 10-m instrument tower and 2-m mast.

This report provides an evaluation of three of the more promising dispersion models with the Atterbury-87 field data. A preliminary evaluation of these models with the four fog-oil cases was previously presented (Policastro et al., 1989). Revisions to the original choice of stability classes have been made (see Section 3.3) based on a review of these four fog-oil cases. These fog-oil comparisons have been revised and are presented here in final form.

The purpose of the model evaluation portion of the current research program is to identify the strengths and weaknesses of the existing modeling approaches and to define the level of performance which can be expected given the current state of the art. Based on the experience gained, an improved model can be developed and validated against the field data. Such a validated model can be used in two ways.

(a) A validated model can aid in assessing the potential environmental and health effects associated with smokes used in training exercises. Of greatest interest here is the prediction of dosages (time-integrated concentrations), particle-size distributions, and deposition rates out to several kilometers from the source.

(b) A validated model can also be used in the planning and execution of training exercises at the facilities where smoke is used. In this application, predicting the downwind extent of the visible plume is also an important consideration.

In Section 2 below, we present the key features of the three dispersion models considered for evaluation. Then, in Section 3, we briefly summarize the Atterbury-87 field study. With this groundwork laid, we present the model/data comparisons in Section 4 and, finally, summarize the main conclusions of the work in Section 5.

2. THE DISPERSION MODELS

A Gaussian puff model treats a continuous release as a number of short-duration (typically 1 s) puffs, each of which is advected and dispersed downwind based on time-dependent meteorology. Gaussian puff models differ from each other in the way this basic approach is implemented. Key differences among the various models lay in the dispersion coefficients which are used and in the way the wind field is handled.

For the purposes of this evaluation, three representative Gaussian puff models have been chosen; namely, the BEAR or Ludwig Model (Ludwig, 1977), the RIMPUFF Model (Mikkelsen et al., 1984), and the INPUFF Model (Petersen et al., 1984). These three were chosen because they represent the state of the art of models available for general use. The key features of these models are compared in Table 2.1.

The BEAR Model allows for time-dependent meteorological data at a single spatial location and single height above the ground. The averaging time for the meteorological data is taken to be 3 minutes. This means that the wind speed and direction are averaged over each successive three-minute period, and this average value is used to advect puffs during that interval. To account for the effects of turbulent motions with time-scales smaller than the averaging time, Gaussian dispersion coefficients (σ_y and σ_z) are used. The values of these coefficients are determined from the Pasquill-Gifford-Turner (Turner, 1970) curves which are the *de facto* standard for routine dispersion analysis. The dispersion coefficients depend on the stability class which is first determined from the meteorological data using one of several available methods. The issue of selecting the proper stability class is an important one, and we shall return to this point later when we discuss the Atterbury-87 field data.

As noted in Table 2.1, the BEAR Model assumes a constant release rate from a single location. The failure to allow for a time-dependent source is a potentially important omission since the release rate in the Atterbury-87 field trials was indeed time dependent. A time-dependent source is easy to include in a puff model since the strength of individual puffs can be varied from one puff to the next.

The RIMPUFF Model differs from the BEAR Model in several important respects. First, the RIMPUFF Model allows for meteorological data from several locations, using $1/r^2$ interpolation in space and linear interpolation in time to determine puff advection velocities. In the Atterbury-87 field trials, the meteorological data were acquired at two locations: (a) a 10-m instrument tower near the center of the test site and (b) a 2-m mast located near the source. Only the data from the 10-m instrument tower were used in making RIMPUFF predictions, however. As we shall see later, the wind direc-

Table 2.1 Comparison of key features of INPUFF, BEAR and RIMPUFF models.

	Model		
Feature	INPUFF	BEAR	RIMPUFF
Wind Field	rectangular grid of locations at single height	single location and height	multiple locations and heights
Dispersion Methodology	Gaussian Puff	Gaussian Puff	Gaussian Puff
Dispersion Coefficients	PGT stability classes [a] or on-site scheme [b]	PGT stability classes [a]	PGT stability classes [f] or on-site scheme [c]
Meteorological Averaging Time [d]	2 – 5 minutes	3 minutes	15 seconds
Puff Release Interval [e]	1 second	1 second	1 second
Treatment of Wind Shear on Puff Dispersion [f]	No	No	Yes
Time Dependent Source	Yes	No	Yes
Multiple Sources	Yes	No	Yes

Notes:

(a) PGT refers to Pasquill-Gifford-Turner stability classes A through F.

(b) The INPUFF on-site scheme calculates the dispersion coefficients from measurements of σ_θ and σ_ϕ using expressions derived by Irwin (1983) from a combination of the Draxler (1976) and Cramer (1976) formulas.

(c) The RIMPUFF on-site scheme uses σ_θ and the expressions presented by Smith and Hay (1961) to obtain the dispersion coefficients.

(d) The meteorological averaging times shown here are those recommended by the model developers given the averaging times upon which the dispersion coefficients are based.

(e) The values shown here are the smallest values recommended by the model developers and thus provide the best overall smoothness in the predictions.

(f) The RIMPUFF model uses a non-Gaussian distribution in the vertical direction to account for the effects of wind shear.

tion at the two measurement locations differs by 0 to 20° depending on the test, indicating that significant horizontal wind shear is present for some of the trials. This shear can have a significant effect on plume trajectory and thus predicted concentrations.

A second important difference lies in the fact that the meteorological averaging time for the RIMPUFF Model is 15 s or twelve times smaller than the three minutes used in the BEAR Model. In addition, the RIMPUFF Model handles multiple, time-dependent sources, although only the time-dependency of the source is important in simulating the Atterbury-87 releases.

The RIMPUFF Model provides two alternative methods of determining dispersion coefficients. One method is based on stability class and is similar to the procedure used by the BEAR model, although the coefficients are corrected to account for the shorter meteorological averaging time. The second method is based on direct measurements of σ_θ, the standard deviation in the horizontal wind direction. In this latter so-called "on-site" approach, dispersion coefficients are determined using the work of Smith and Hay (1961). The on-site method is preferred, and thus it was used in preparing all of the RIMPUFF predictions.

Finally, the RIMPUFF Model is somewhat unique in that it does not assume a Gaussian concentration profile in the vertical direction, but rather adjusts the vertical variation of concentration to account for the effects of vertical wind shear. It is presently unknown what effect this difference has on model predictions since the field measurements were all made within 8 m of the ground.

The INPUFF Model is the third Gaussian-puff dispersion model which was tested. With the INPUFF Model, the time-dependent wind speed and direction are specified at a set of grid points in a form such as might be produced by an auxiliary wind-field model. Normally, these values are given as a series of discrete-time values, all at a single height (namely, 10 m). The INPUFF Model then interpolates to obtain puff-advection velocities from these grid values. Since only one 10-m instrument tower was used in the Atterbury-87 Field Studies, the input for the model/data comparisons reduces to a single time series of values averaged over successive 3-min. periods.

Like the RIMPUFF Model, the INPUFF Model provides two schemes for determining dispersion coefficients, an on-site method and a method based on stability class. The method based on stability class is similar to those used by the BEAR and RIMPUFF Models as previously described. The on-site method is based on direct measurements of σ_θ, the standard deviation in the horizontal wind direction, and σ_ϕ, the standard deviation of the vertical wind direction. The on-site scheme is a synthesis of the work performed by Draxler (1976) and Cramer (1976). To examine the effects of using different methods for choosing dispersion coefficients, we prepared INPUFF predictions using both of the available methods. Those prepared using the on-site scheme as designated "INPUFF-ON"; those prepared using the (Pasquill-Gifford-Turner) stability class method are designated "INPUFF-PG".

One difficulty with the application of the above models is the need to specify certain "model" inputs which do not correspond to quantities measured or measurable in the field. An example is the "initial cloud size". Although no quantitative study was made, it is believed that the effect of the uncertainty associated with these choices is rather small compared with major issues such as the choice of dispersion parameters.

3. THE CAMP ATTERBURY FIELD STUDIES

3.1 Introduction

This chapter provides a brief overview of the Atterbury-87 field studies. Detailed discussions of the experimental techniques and the resulting data are given in companion reports by Liljegren et al. (1989) and DeVaull et al. (1989). Here, we restrict ourselves to those aspects of the study which directly impact the model/data comparisons presented in this report.

3.2 The Test Site and Sampling Grid Layout

The Camp Atterbury test site and sampling grid are shown in Fig. 3.1. The test area is a large grassy meadow surrounded on roughly three sides by hills 25 to 50 m high. The test area itself is relatively flat with a moderate downward slope of between 1 and 2 % from northwest to southeast. The ground cover during the period of the study was grass roughly 1 m high. The ground cover was fairly uniform across the test area, although somewhat taller bushes and a few isolated trees were also present. The area surrounding the site is densely forested in all directions with deciduous trees 10 to 20 m tall. The terrain and vegetation features of the surroundings undoubtedly affect the structure of the wind field. Accordingly, we characterize this site as having "simple terrain", but "complex meteorology".

To orient the sampling grid at Camp Atterbury, we analyzed the meteorological data records for 1985 and 1986 from the National Weather Service recording station at Indianapolis, Indiana, 60 miles north of the site. This analysis indicated that the wind is predominantly from the southwest in November. In addition, we logged wind and temperature data near the proposed test area using two portable instrument stations shortly before full-scale operations at the site began. These data confirmed the predominant southwesterly direction of the wind in the daytime.

Based on the results of this analysis, a line of alternative source locations was established in the southwest corner of the test area and sampling transects (designated Transects 1 through 5) were laid out perpendicular to the predominant wind direction at distances roughly 50, 100, 250, 450 and 675 m from this line. With the exception of Transect 5 which consisted of only four sampling masts and which was not used in any of the HC trials for logistical reasons, each transect subtended an arc of at least 90° with respect to the possible source locations. Each sampling location consisted of an 8-m sampling mast with filter cassette samplers mounted at the 2-,

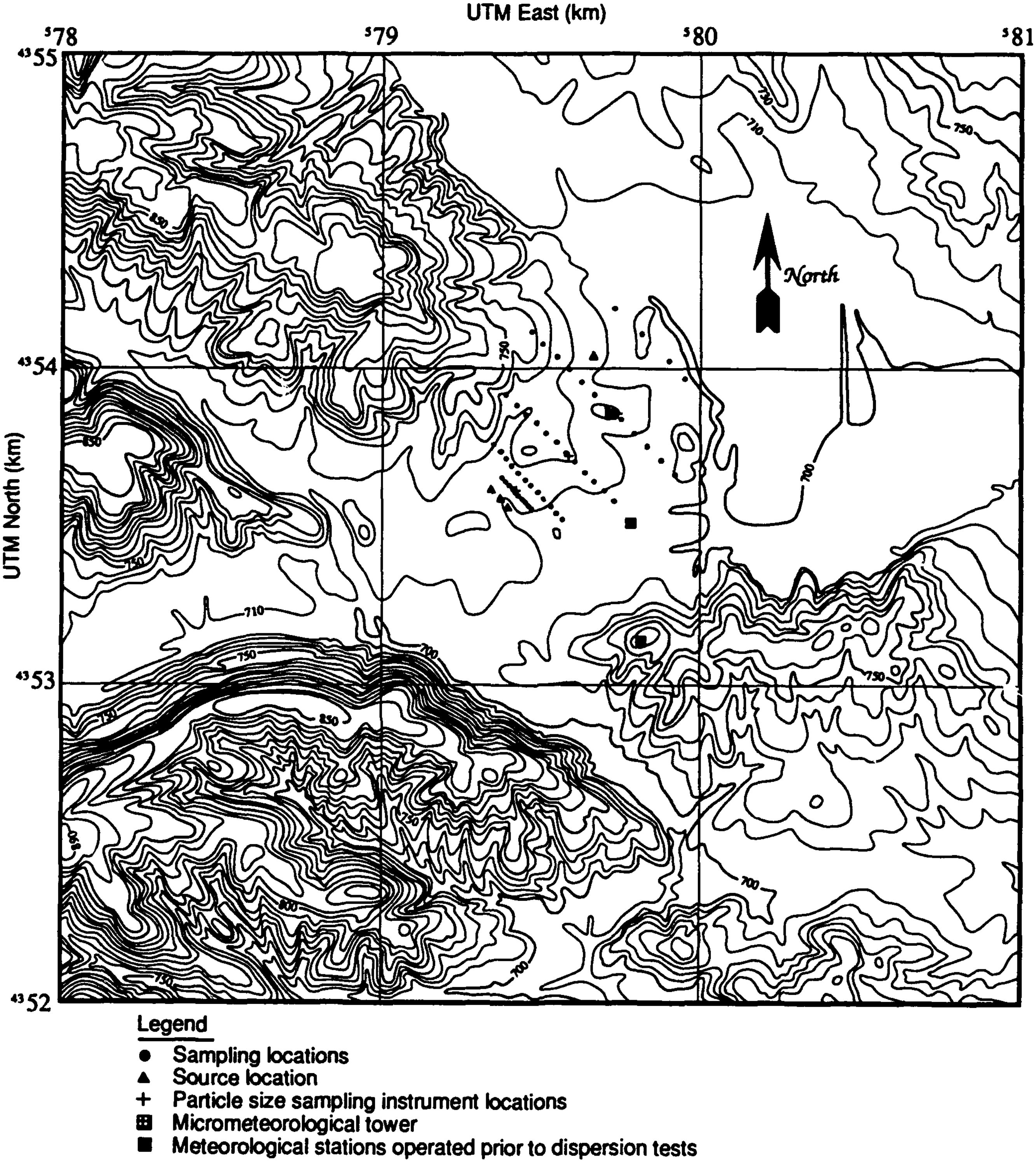

Figure 3.1 Topographical map of the dispersion test site at Camp Atterbury. Elevations are in feet above sea level with isopleths in increments of 10 ft. The horizontal grid is in Universal Tranverse Mercator coordinates with marked increments of 1 km. Topographical data are from a USGS map of Ninevah, Indiana.

4-, 6- and 8-m levels, except on Transect 5 where only the 2- and 8-m levels were used. The separation between masts was 15.2, 30.4, 45.7, 61, and 122 m on Transects 1 through 5, respectively. Detailed coordinate information for the grid is given in Appendix A.

Figure 3.2 shows the sampling grid and illustrates the local coordinate system used to specify the source and sampler locations. Here, the mean wind speed and direction for each of the five HC tests is indicated. A test is identified by a seven-digit code consisting of the date on which the test was conducted in the form MMDDYY followed by a single digit (1 or 2) indicating the number of the test on that particular day. For example, the test designated 1104872 was the second test executed on November 4, 1987. The wind was out of the southwest as planned for two of the five HC trials (Tests 1112871 and 1113871) and out of the north-northeast for the remaining three trials (Tests 1109871,1110871 and 1110872) as the result of a storm front passing through the area. Fortunately, we were able to conduct tests during this period by locating the source northeast of the sampling grid as shown in Fig. 3.2. Figure 3.3 shows the sampling grid once again, but with the mean wind speed and direction for each of the four fog-oil trials identified. Here, we see that the wind was out of the southwest as expected for all four of the trials.

3.3 Source and Meteorological Measurements

A compilation of the relevant source and on-site meteorological data for the HC and fog-oil smoke trials is given in Tables 3.1 and 3.2, respectively. These data represent averages over the period of each test. The mean wind speed and horizontal direction are denoted by $\overline{u}$ and θ, respectively. The vertical wind direction is denoted by ϕ and is assumed to be 0° in the mean. The symbol σ is used to denote a standard deviation with the subscript indicating the variable of interest. The wind-vector components u, v, and w refer to the downwind, crosswind and vertical directions, respectively. The downwind and crosswind components are defined relative to the mean wind direction and thus the average value of u is simply the mean wind speed $\overline{u}$, and the average values of v and w are both zero.

The values of several meteorological scaling variables, derived from the on-site data, are also summarized in Tables 3.1 and 3.2. The wind exponent n is determined by fitting the measured wind speed values to the power-law form $u = a z^n$, where z is height above the ground and a and n are fitting parameters. The friction velocity u_* and the Monin-Obukhov length L are the relevant velocity and length scales in the

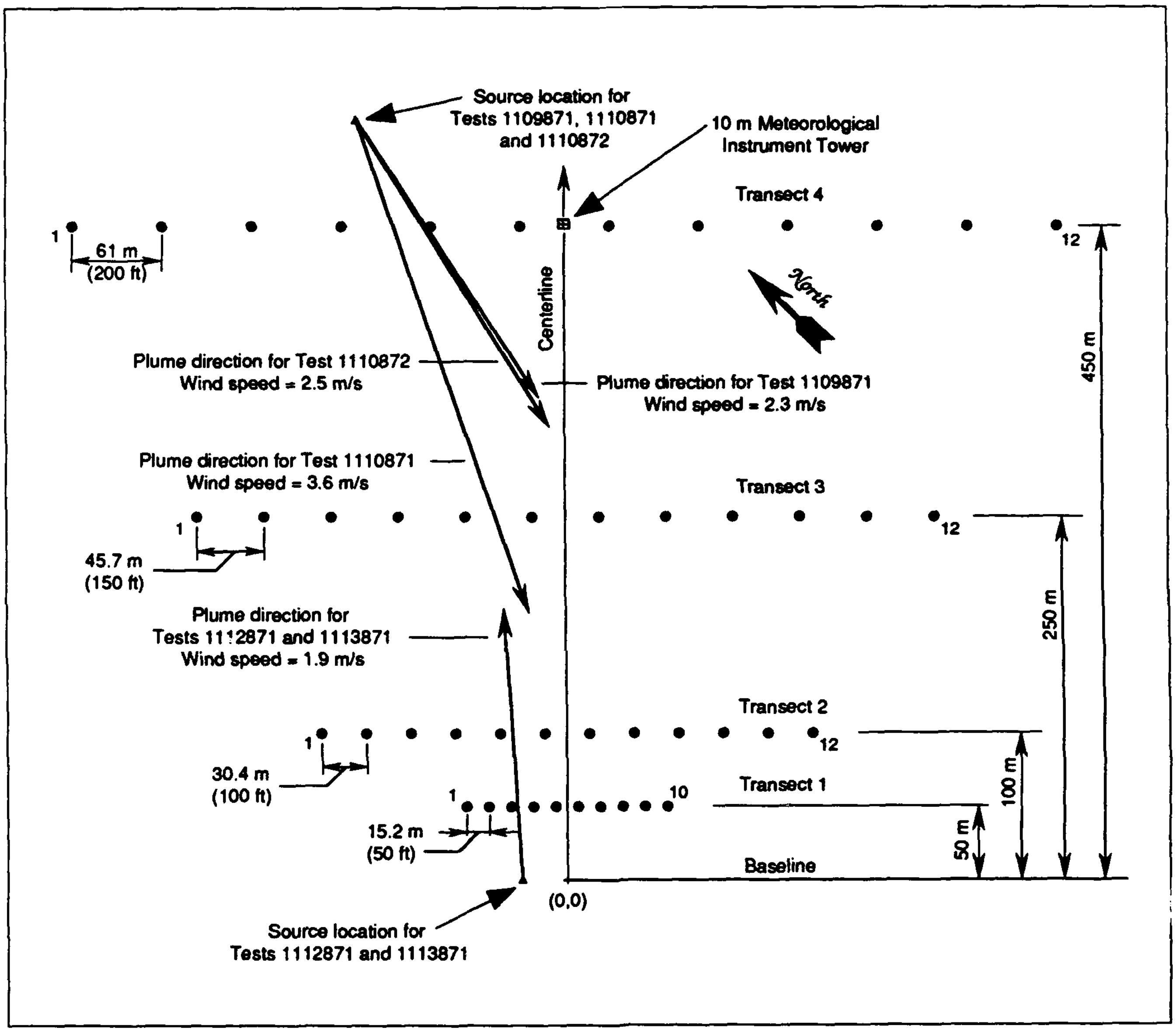

Figure 3.2 Sampling grid used for the Atterbury-87 HC smoke dispersion experiments with vectors indicating the average wind speed and plume direction for each trial.

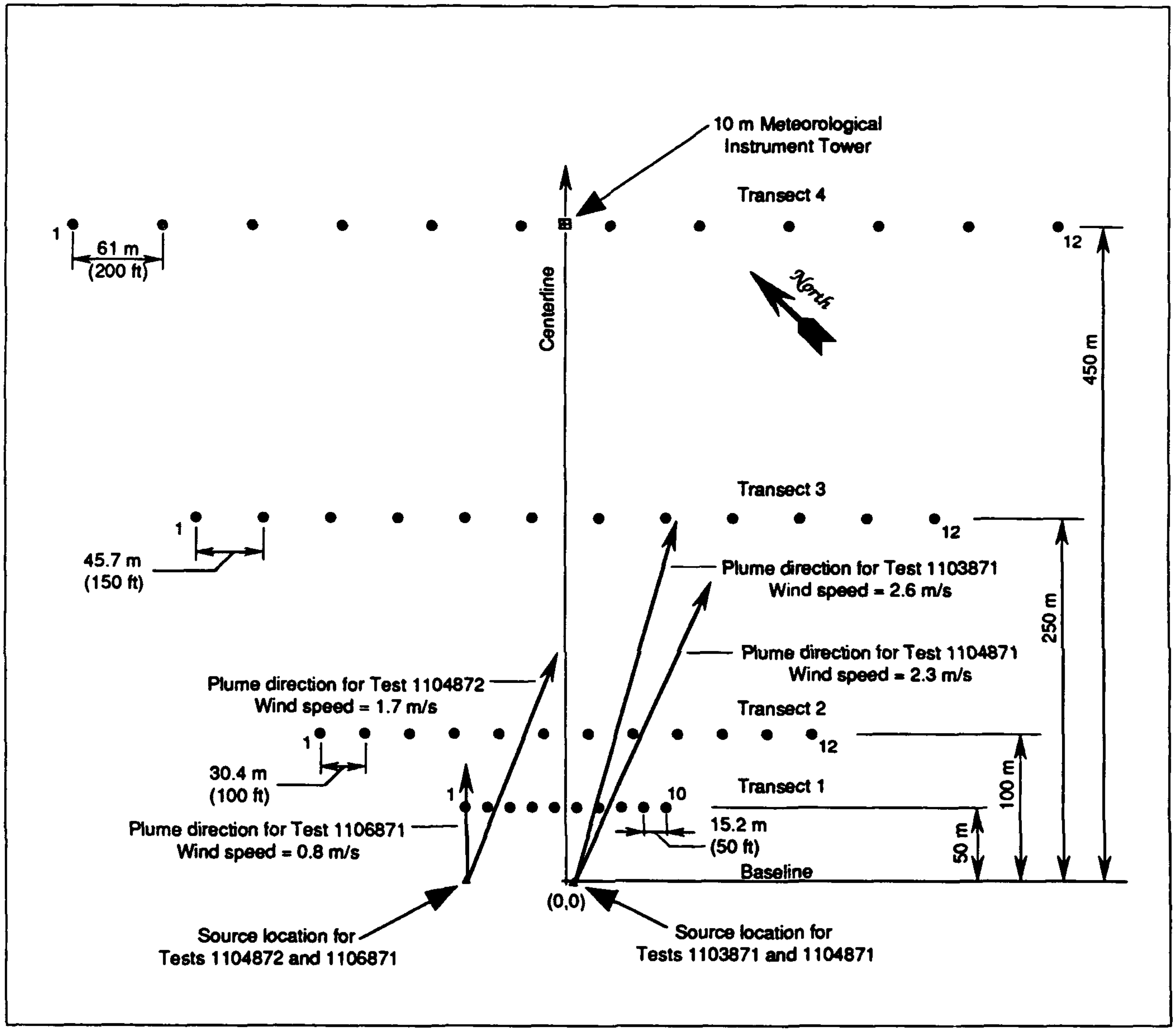

Figure 3.3 Sampling grid used for the Atterbury-87 fog-oil smoke dispersion experiments with vectors indicating average wind speed and plume direction for each trial.

Table 3.1 Source and meteorological data for the HC smoke dispersion trials.

General Information					
Test Designation	1109871	1110871	1110872	1112871	1113871
Date	9 Nov 87	10 Nov 87	10 Nov 87	12 Nov 87	13 Nov 87
Begin Time (CST)	15:45:00	11:27:30	16:37:41	13:31:20	10:21:00
End End (CST)	16:10:00	12:04:00	17:25:00	14:17:00	11:04:00
Duration (MM:SS)	25:00	36:30	47:19	45:40	43:00
Source Location					
Distance east of grid origin (m)	270.3	270.3	270.3	-21.1	-21.1
Distance north of grid origin (m)	470.8	470.8	470.8	21.1	21.1
Summary of Near-source Measurements (2-m height)					
Mean wind speed, $\overline{u}$ (m/s)	2.3	3.6	2.5	1.9	1.9
Mean wind direction, θ (°E of N)	12	26	13	220	221
Std. dev. in hor. wind dir., σ_θ (°)	18.7	19.7	19.9	28.6	31.2
Temperature, T (°C)	5.9	3.2	3.0	13.8	12.9
Relative humidity, RH (%)	69	61	49	35	45
Summary of Instrument Tower Measurements (10-m height)					
Wind speed, $\overline{u}$ (m/s)	4.4	7.1	5.2	4.9	4.3
Wind direction, θ (° E of N)	25	34	24	226	241
Standard deviations:					
σ_θ (°)	11.0	13.2	14.4	15.3	15.5
σ_ϕ (°)	8.0	9.3	8.3	9.8	9.9
σ_u (m/s)	1.03	1.74	1.28	1.32	1.08
σ_v (m/s)	0.80	1.63	1.22	1.34	1.15
σ_w (m/s)	0.75	1.41	0.93	0.94	0.83
ΔT (10 m - 2 m) (°C)	-0.68	-0.95	-0.70	-0.76	-0.74
Cloud cover	heavy overcast	medium overcast	mostly cloudy	clear	clear
Summary of Scaling Parameters					
Wind speed exponent, n	0.130	0.132	0.132	0.121	0.137
Monin-Obukhov Length, L (m)	-46	-110	-68	-63	-53
Friction velocity, u_* (m/s)	0.51	0.72	0.57	0.54	0.49
Roughness height, z_o (m)	0.20	0.20	0.20	0.20	0.20
Inversion height, z_i (m)	649	448	434	816	500
Convection velocity, w_* (m/s)	1.68	1.57	1.42	1.73	1.41
Turner Stability Class	D	D	D	C	C

Table 3.2 Source and meteorological data for the fog-oil smoke dispersion trials.

General Information				
Test Designation	1103871	1104871	1104872	1106871
Date	3 Nov 87	4 Nov 87	4 Nov 87	6 Nov 87
Begin Time (CST)	10:31:06	09:36:33	15:25:50	10:51:50
End End (CST)	11:27:00	10:06:00	16:14:00	12:08:00
Duration (MM:SS)	55:54	27:27	48:10	76:10
Source Locations				
Distance east of grid origin (m)	3.0	3.0	- 47.7	- 47.7
Distance north of grid origin (m)	- 4.7	- 4.7	47.7	47.7
Summary of Near-source Measurements (2-m height)				
Mean wind speed, $\overline{u}$ (m/s)	2.6	2.3	1.7	0.8
Mean wind direction, θ (°E of N)	241	249	247	224
Std. dev. in hor. wind dir., σ_θ (°)	28.6	23.4	26.0	33.8
Temperature, T (°C)	23.4	20.0	25.3	8.0
Relative humidity, RH (%)	41	25	43	40
Summary of Instrument Tower Measurements (10-m height)				
Wind speed, $\overline{u}$ (m/s)	5.5	5.1	4.7	1.6
Wind direction, θ (° E of N)	239	249	261	240
Standard deviations:				
σ_θ (°)	16.2	11.0	18.6	35.4
σ_ϕ (°)	8.8	8.2	8.2	14.9
σ_u (m/s)	1.52	1.17	1.26	0.70
σ_v (m/s)	1.49	0.94	1.54	0.90
σ_w (m/s)	0.94	0.82	0.78	0.49
ΔT (10 m - 2 m) (°C)	-0.41	--	1.89	-.89
Summary of Scaling Parameters				
Wind speed exponent, n	0.143	0.149	0.183	0.103
Monin-Obukhov Length, L (m)	-63	-51	-243	-12
Friction velocity, u_* (m/s)	0.61	0.59	0.44	0.26
Roughness height, z_o (m)	0.20	0.20	0.20	0.20
Inversion height, z_i (m)	668	305	1135	557
Convection velocity, w_* (m/s)	1.83	1.46	1.00	1.30
Turner Stability Class	C	C	D	B

surface layer where mechanical turbulence dominates transport. The roughness height z_o characterizes the roughness elements and is a measure of both the eddy size at the surface and the efficiency of momentum transport at this level.

The EPA publication entitled "On-Site Meteorological Program Guidance for Regulatory Modeling Applications" (1987) recommends two methods for estimating u_* and L. The first is the least-squares profile-fitting method developed by Nieuwstadt (1977) and is favored when wind speed and temperature data are available at three or more heights. In this method, the wind speed and temperature data are fit using profile functions derived from the Kansas and Minnesota boundary-layer experiments. Since these profile functions contain u_* and L as parameters, values of these parameters can be determined, at least in principle, from this fitting procedure. The second method is one proposed by Irwin and Binkowski (1980). This method uses the bulk Richardson number $Ri_b = [\, z_2\, g\, \Delta T / T^2 \,] / u_2^2$ and the roughness height z_o, thus requiring the wind speed at only one height and the temperature at two heights. Here, the subscripts 1 and 2 refer to the two measurement heights, 2 being the upper one and 1 being the lower one. In our early analysis of the data, we attempted to use Nieuwstadt's method, but the fitting procedure failed to give meaningful values for u_* and L. The failure of this method can most likely be attributed to the non-ideal meteorology of the Atterbury-87 site, since the boundary-layer profiles to which fits were attempted were determined using data from very ideal flat-terrain sites. Irwin and Binkowski's method of employing the bulk Richardson number gave reasonable values, however. These values were thus chosen as being representative of our data and are given in Tables 3.1 and 3.2.

For increasingly convective conditions where -L → 0 the relevant scaling parameters are the mixed-layer scales w_* and z_i. These are also the appropriate scales at heights above -L where buoyancy dominates turbulent transport. The mixed-layer scale w_* may be obtained from u_*, L and the inversion height z_i using the basic relationship

$$w_* = u_* \left(\frac{z_i}{-\kappa L} \right)^{1/3} ,$$

where κ is von Kármán's constant which is roughly equal to 0.4. The inversion height, in turn, can be estimated from an early morning sounding and the surface temperature at the time of the test. In this approach, the inversion height is taken as the height at which the potential temperature given by the early morning profile equals the surface potential temperature at the time of the test. We used the early-morning vertical profiles taken by the National Weather Service at the Peoria and Dayton Airports to determine the inversion height.

As previously noted, two of the models being tested (BEAR and INPUFF-PG) require the stability class as input. Because model predictions are very sensitive to the choice made, four approaches for determining atmospheric stability class were examined as shown in Table 3.3. Three of these methods are described and discussed in the EPA report (EPA, 1987); namely, (a) Turner's method which uses on-site values for the solar insolation angle, the cloud cover and the surface wind speed, (b) the "σ_φ method" which uses the wind speed and σ_φ, the standard deviation of the vertical wind angle, and (c) the "σ_θ method" which uses the wind speed and σ_θ, the standard deviation of horizontal wind angle. The fourth method which we considered obtains the stability class from the Monin-Obukhov length and friction velocity using the nomogram presented by Golder (1972).

Table 3.3 Comparison of stability classes determined by various methods.

Test	Turner Method	σ_φ Method	σ_θ Method	Irwin and Binkowski / Golder Method
1103871 (FO)	C	C	C	C
1104871 (FO)	C	C	D	C
1104872 (FO)	D	C	C	D
1106871 (FO)	B	A	A	B
1109871 (HC)	D	C	D	C
1110871 (HC)	C – D	D	D	C - D
1110872 (HC)	D	C	C	C
1112871 (HC)	C	C	C	C
1113871 (HC)	C	C	C	C

The results of these four methods as compared in Table 3.3 indicate that the stability classes determined using Turner's method are consistent with but not always exactly the same as the estimates obtained using the other three methods. Since the EPA recommends Turner's method (EPA, 1987), the Turner stability classes obtained were used in making model prediction and are given in Tables 3.1 and 3.2 which summarize the data for each field trial.

In the preliminary presentation of model/data comparisons for the fog-oil trials (Policastro et al., 1989), stability classes were selected based on preliminary estimates of Monin-Obukhov Lengths. In that report, Trials 1103871, 1104871, and 1104872 were classified as stability class B and Trial 1106871 was classified as stability class A. The results presented in Section 4 (of this report) show the model predictions based on the revised Monin-Obukhov Lengths and stability classes presented in Tables 3.1 and 3.2. The predictions with the INPUFF-PG and BEAR models have been revised since they both rely on stability class information to make predictions. The predictions with the RIMPUFF model have also been revised since the Monin-Obukhov Length is an input parameter to that model. The predictions of the INPUFF-ON model have not changed from the preliminary report. In general, the magnitude of INPUFF-PG and BEAR model predictions have increased due to the change in stability class while the magnitude of the RIMPUFF model predictions has decreased due to the revised Monin-Obukhov Lengths.

3.4 Concentration Measurements

The smoke material was collected on aspirated filter samplers mounted at four heights (two on Transect 5) as explained previously. Chemical analysis was then used to determine the amount of material on each filter, and the average concentration over the duration of the test found by dividing the total mass of material by the product of the aspiration rate and the duration of the release. For the HC smoke pots, zinc was used as a tracer since zinc constitutes roughly 37.4 % of the pot material by mass (Katz et al., 1980). In this way it is possible to eliminate contamination from the ambient particulates collected on the filters during the HC trials. Since the filters collect only oil droplets and not vapors, there is no similar ambient contamination problem in the fog-oil cases. Thus, the fog-oil data are based on the total mass of oil in the proper molecular weight range collected on the filters.

Both the fog-oil and HC data are affected by the realities of field testing as is more fully described in the two companion data reports (Liljegren et. al., 1989 and DeVaull, et al., 1989). Given the limitations of the field and laboratory techniques and, equally important, the fact that each trial represents only a single realization of a process whose variance is many times its mean, we can say that the data are accurate to within roughly a factor of two at the 95 % confidence level. This level of uncertainty in the data must be taken into account in evaluating model performance.

4.0 COMPARISON OF MODEL PREDICTIONS WITH THE ATTERBURY-87 FIELD DATA

4.1 Preparation of Model Inputs

As previously noted, all three models were tested using the meteorological data from the 10-m level of the instrument tower located near the center of the test site. The data were time averaged to conform with the averaging period of each model; namely, 3 min. for the BEAR and INPUFF Models and 15 s for the RIMPUFF Model. In addition, the RIMPUFF Model requires data on σ_θ for use in determining dispersion coefficients, and the on-site scheme of the INPUFF Model (INPUFF-ON) requires data on both σ_θ and σ_ϕ. These values were computed directly from the measured values for the averaging time appropriate to each of these models. Also, the BEAR and INPUFF-PG Models take the stability class as a user input. The values determined by Turner's Method (1970) were used for this purpose as was previously noted.

The release height was chosen to be 2 m above the ground for all of the trials at Camp Atterbury since that was the observed height of the center of the initial smoke plume. The strong initial mixing that takes place and the slight buoyancy of the smoke near the source leads to some uncertainty in the value of this parameter, although the effect of this uncertainty is expected to be quite small.

4.2 Results of Model/data Comparisons

4.2.1 Classification of Trials

A total of nine trials were conducted during the Atterbury-87 field study. These trials can be group together in any of several ways. First, there is the obvious matter of the type of smoke material used. Four of the trials are fog-oil trials, and five are HC trials. It is important for us to determine whether the results depend on smoke type. Passive atmospheric dispersion should not depend on the type of smoke material, although source characteristics such as source buoyancy, differences in the sampling and analysis techniques and possible interactions between the smoke material and the atmosphere (such as evaporation in the case of fog oil or hygroscopic accumulation of liquid water in the case of HC) could all lead to differences between the two materials in terms of observed downwind concentrations.

In addition, the five HC trials can be further subdivided into two groups based on release point and stability class. As shown in Fig. 3.2, the release point for Trials 1110871, 1110872 and 1109871 was located near Transect 4. These trials were all conducted under near-neutral stability (Pasquill-Gifford-Turner Stability Class D), and thus form a natural grouping which we designate HC Group I. An important consideration for the HC Group I trials is that the grid was configured for releases near Transect 1 and not for releases near Transect 4 as is the case here. Hence, the approximately geometric spacing of the transects and sampling masts designed to capture a spreading plume moving from Transect 1 to Transect 4 leads to reduced resolution near the source and reduced coverage far from the source. Even though the grid layout was not ideal, time limitations prevented us from either (a) postponing the trials until more favorable winds were present or (b) reconfiguring the grid to accommodate the true prevailing wind direction. Trials 1112871 and 1113871 were both conducted from a release point just upwind of Transect 1 as shown in Fig. 3.2. Moreover, both of these trials were conducted under slightly unstable atmospheric conditions (Pasquill-Gifford-Turner Stability Class C), and thus we designate these as HC Group II trials. Notably, all four of the fog-oil trials were conducted from release points upwind of Transect 1 as is consistent with the grid layout.

In addition to the three types of releases (Fog-oil, HC Group I and HC Group II), there is also the matter of stability class which from a atmospheric sciences point of view should be significant in affecting dispersion and thus potentially the model/data comparisons. Three stability classes are represented among the nine Atterbury-87 trials as follows: Stability Class B – one fog-oil trial, Stability Class C – two fog-oil trials and two HC Group II trials for a total of four trials, and Stability Class D – one fog-oil trial and three HC Group I trials for again a total of four trials. Because there is a strong correlation between stability class and release type among a limited number of trials, it may well be difficult to confidently determine the controlling factors in a statistically significant manner.

4.2.2 Overview of Model/data Comparisons

The comparisons between model predictions and data take three forms in this report. The first type is a graphical comparison of model predictions and data on a transect-by-transect basis. This is the most natural method of presentation, and provides valuable insight into the models' ability to correctly predict the trajectory and spreading of the plume as well the magnitude of the maximum concentration on each transect. Figures 4.1 – 4.9 present these comparisons for all nine of the Atterbury-87 trials. Figures 4.1 – 4.3 present the results for the three HC Group I Trials, Figs. 4.4

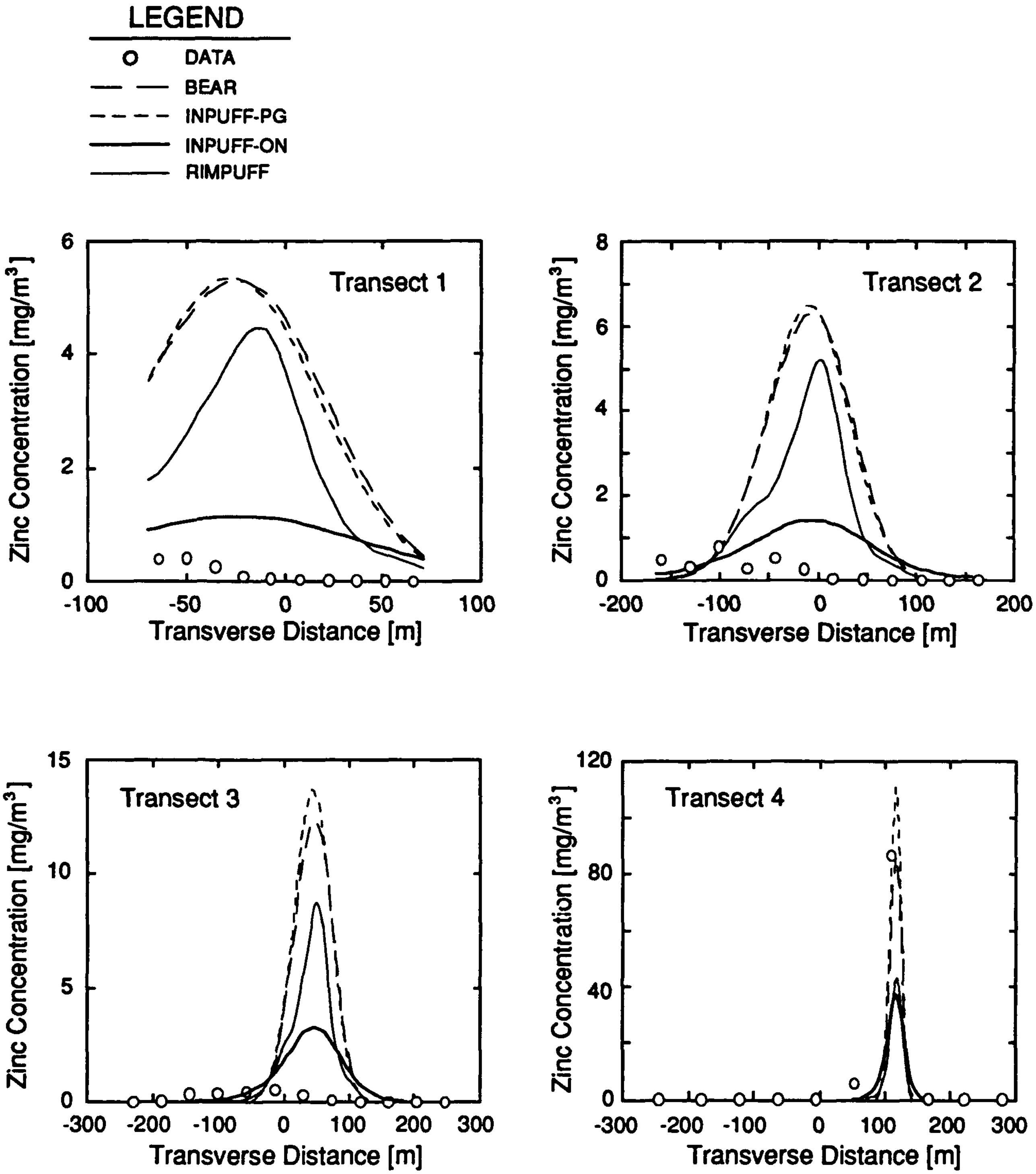

Figure 4.1 Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1109871.

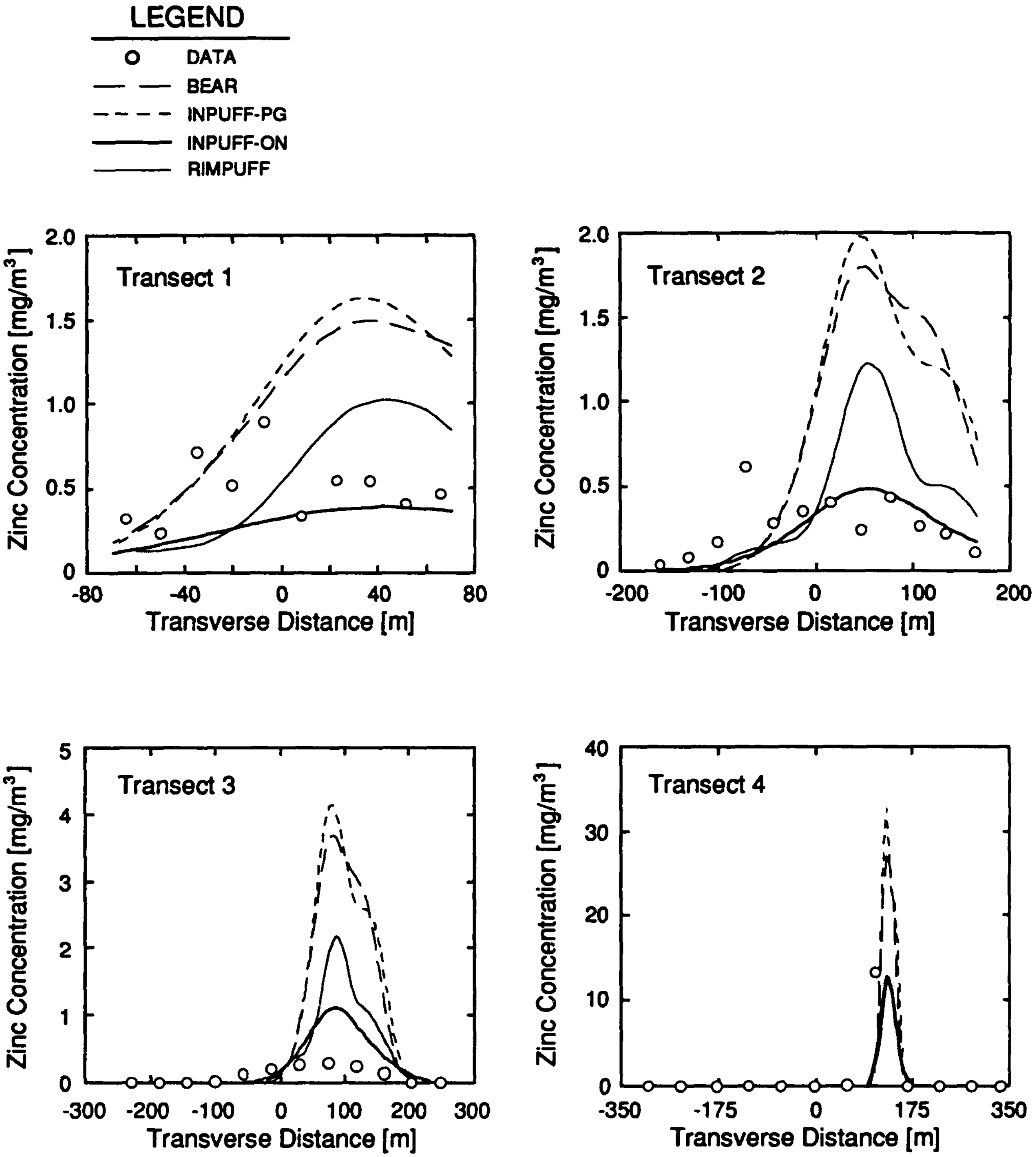

Figure 4.2 Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1110871.

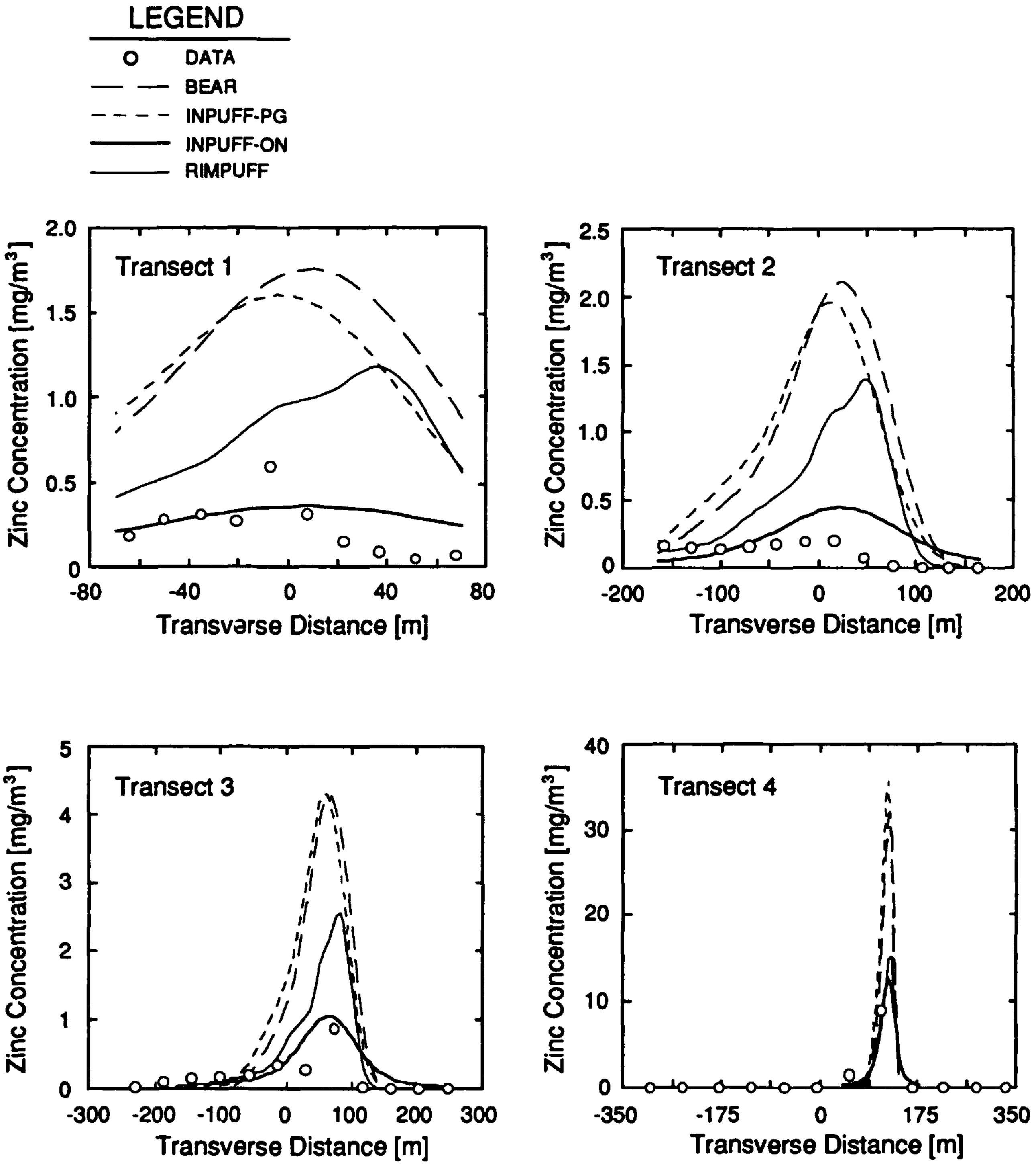

Figure 4.3 Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1110872.

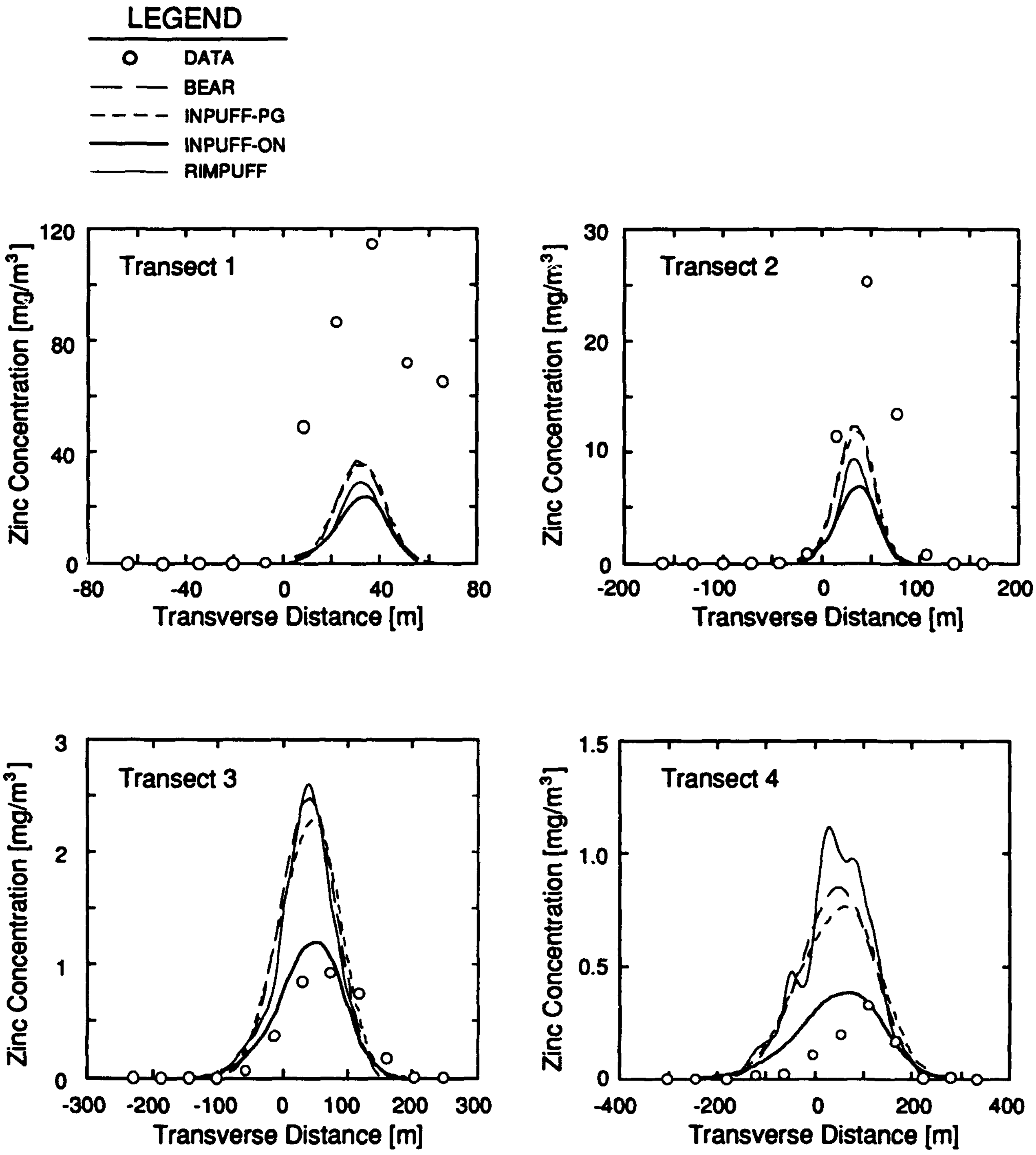

Figure 4.4 Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1112871.

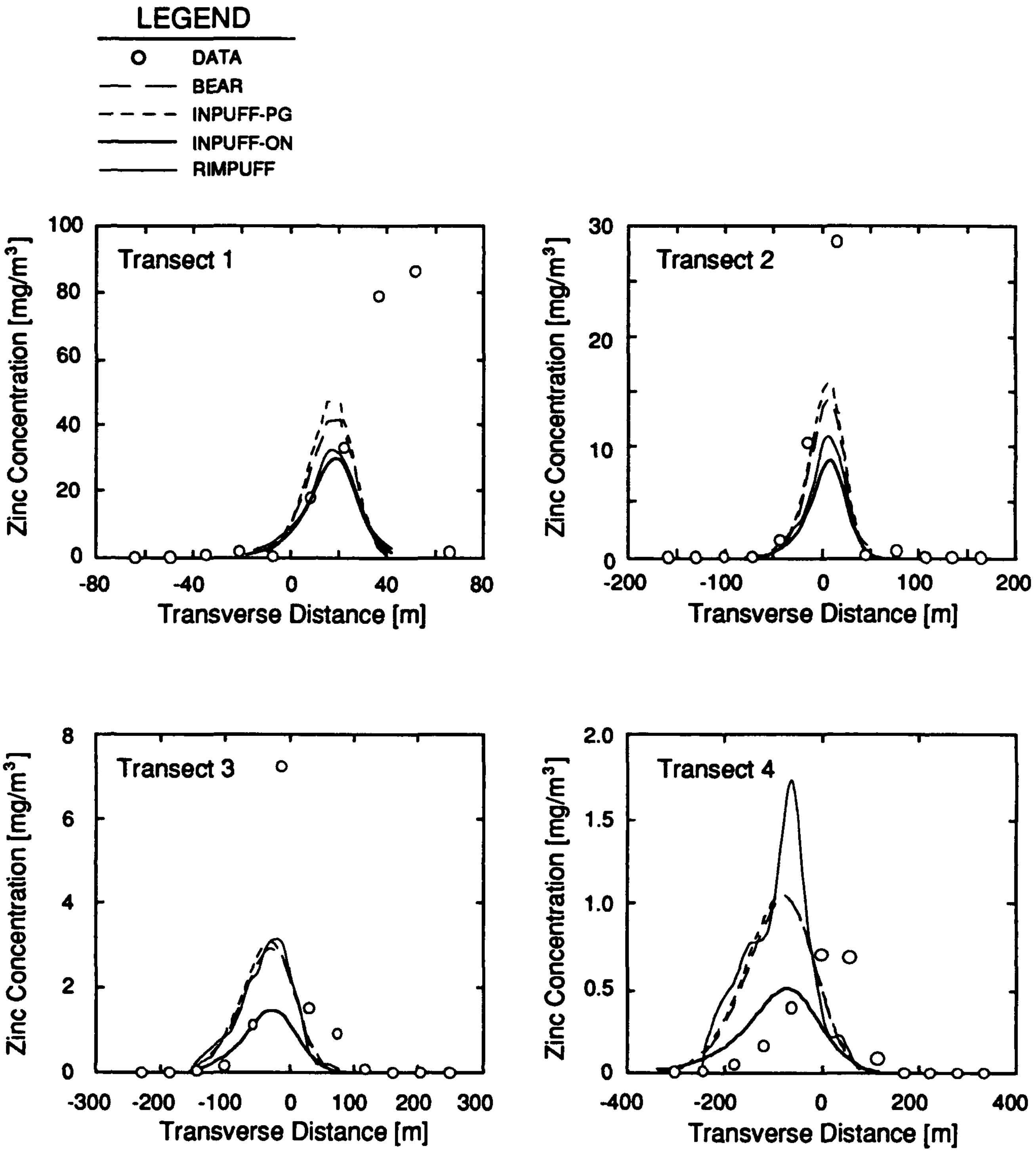

Figure 4.5 Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1113871.

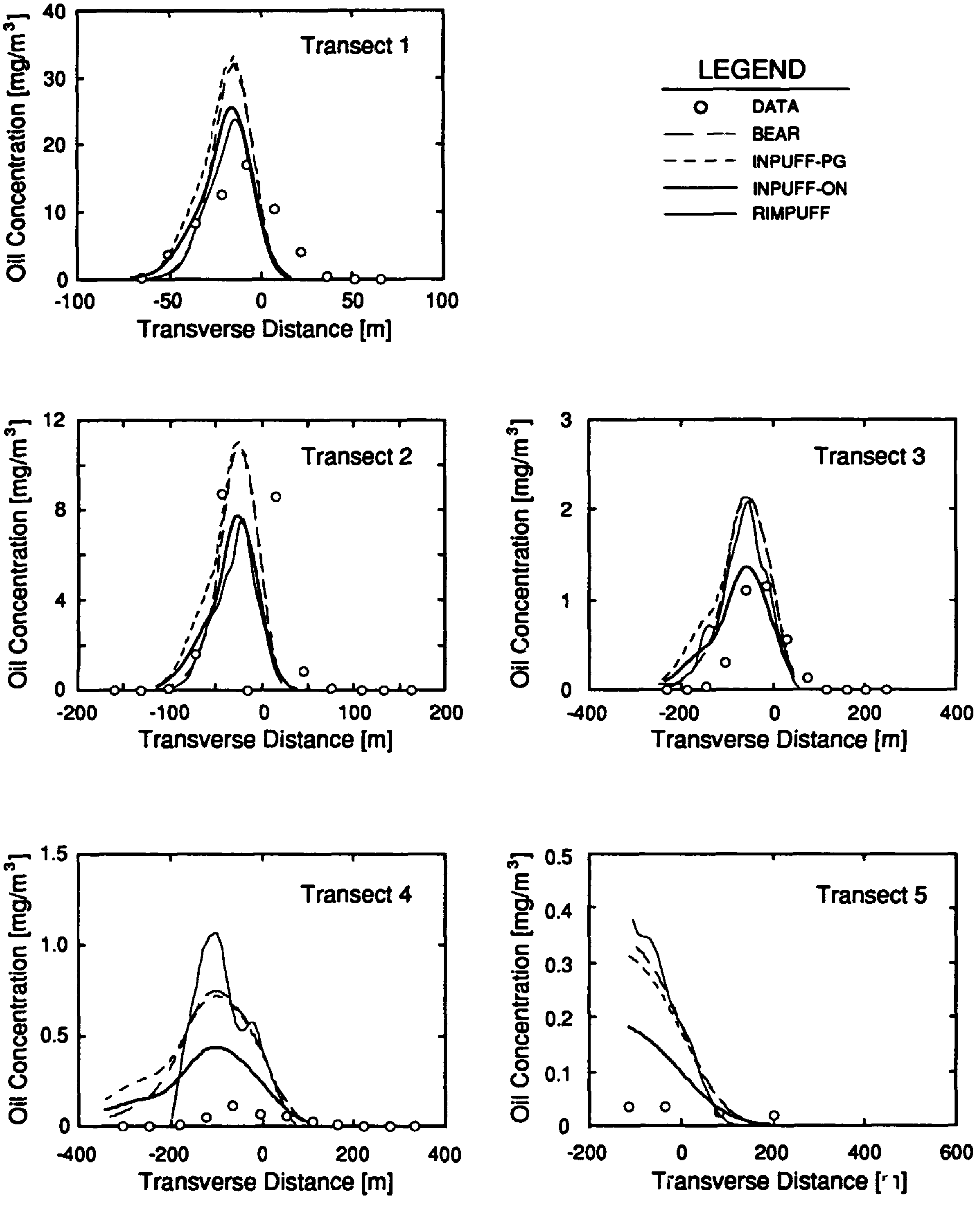

Figure 4.6 Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1103871.

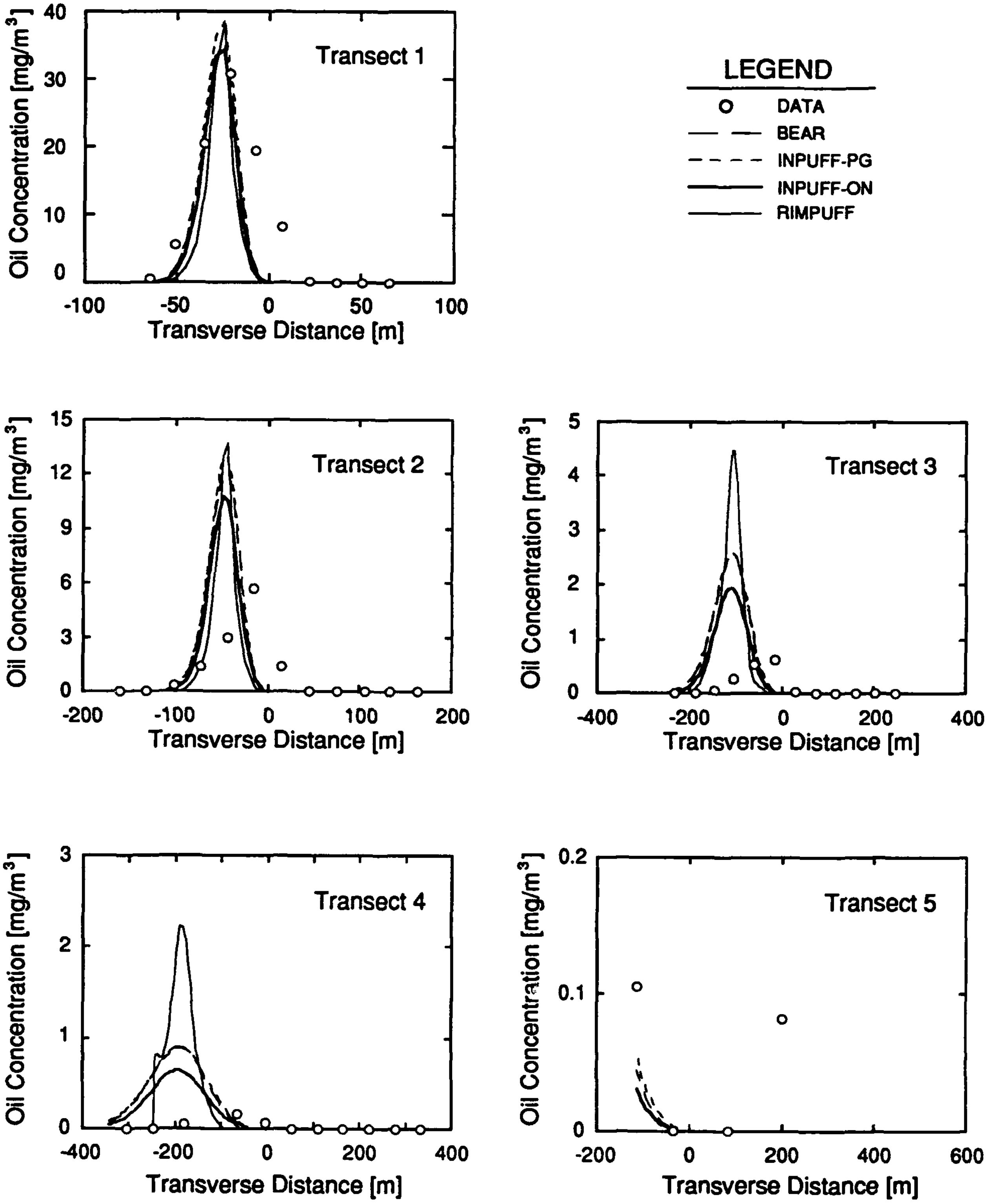

Figure 4.7 Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1104871.

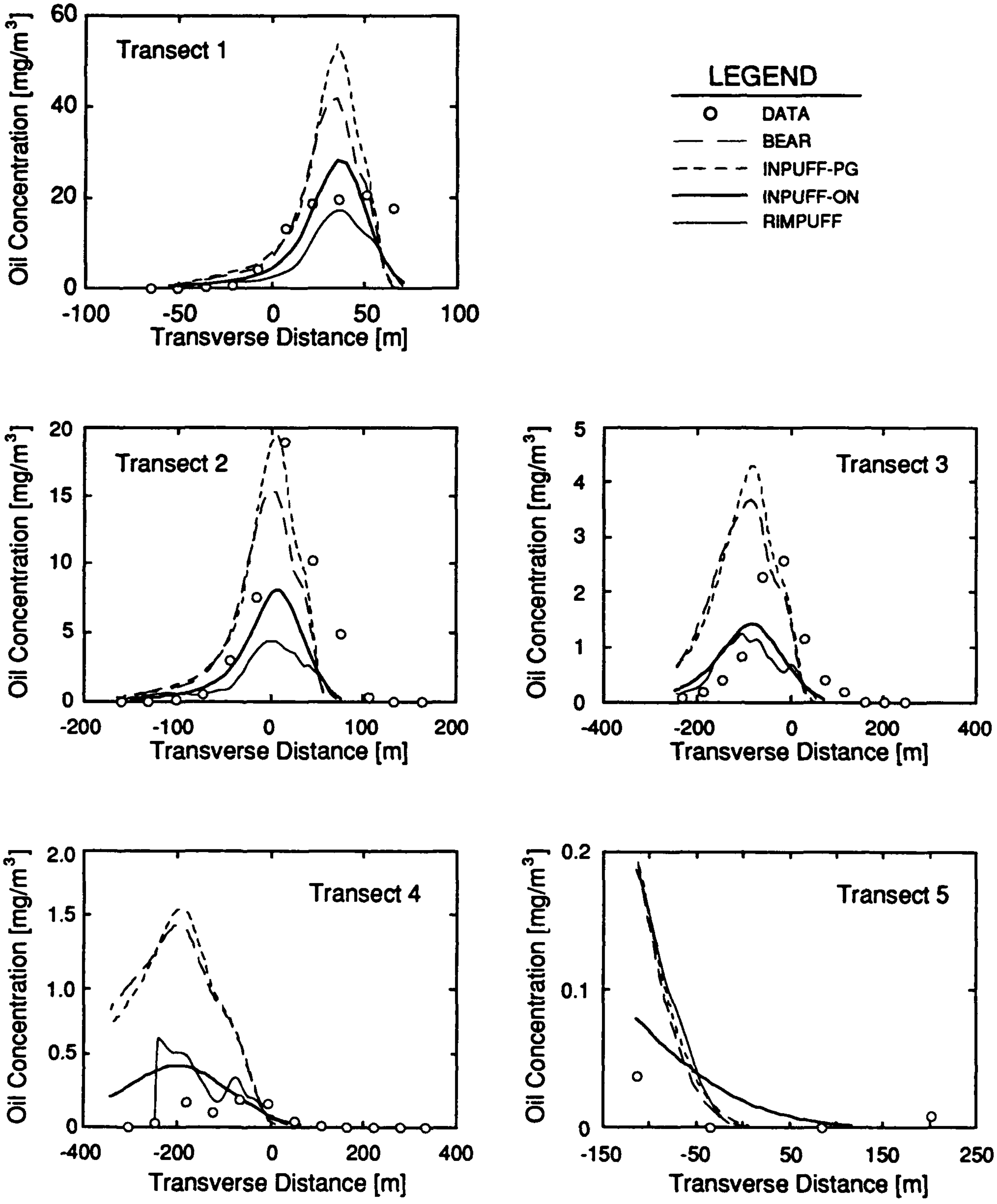

Figure 4.8 Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1104872.

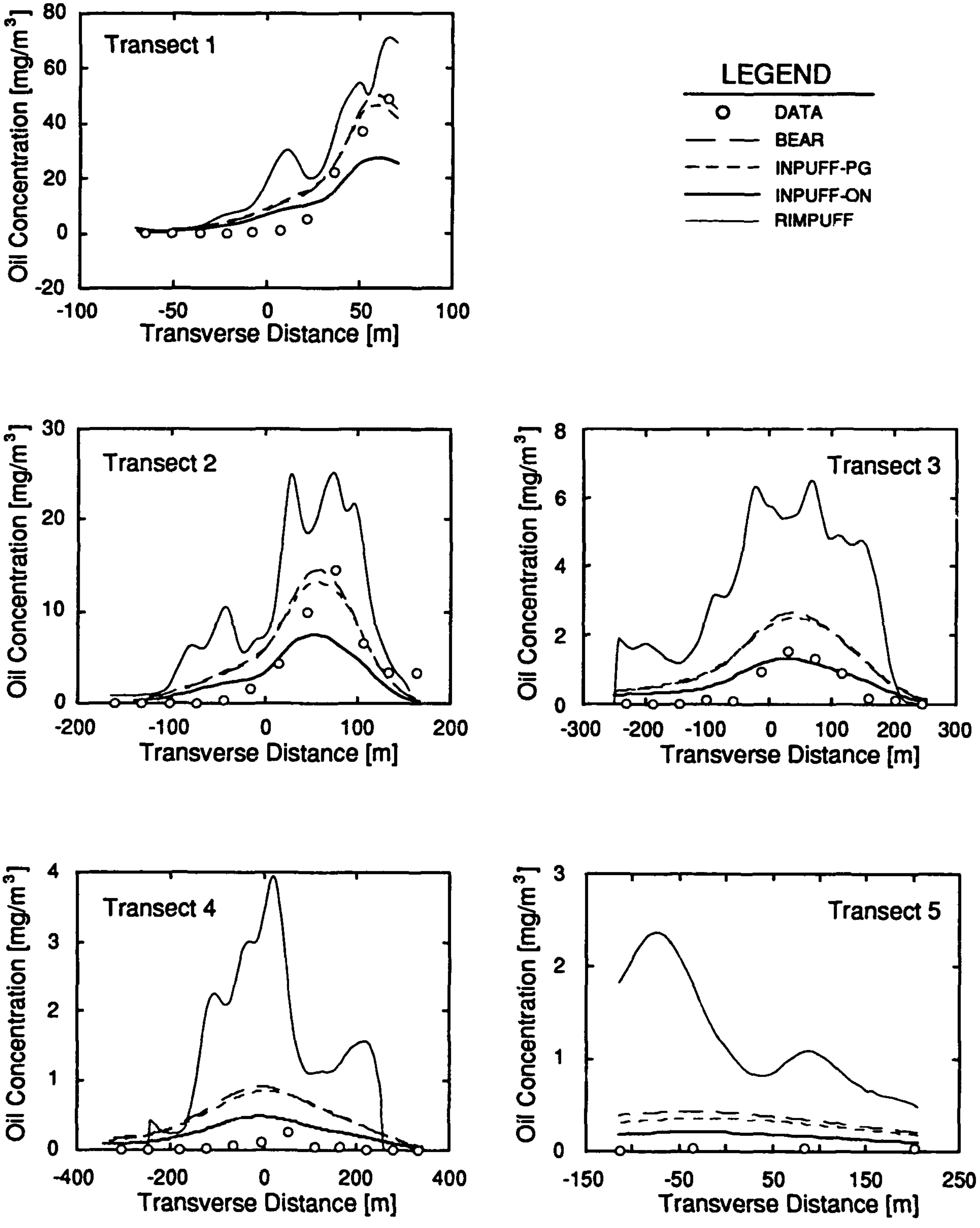

Figure 4.9 Comparison of predictions of RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1106871.

and 4.5 present the results for the two HC Group II Trials, and Figs. 4.6 – 4.9 present the results for the four Fog-oil Trials.

The second type of comparison is also graphical in nature and shows the variation of maximum concentration with downwind distance. From these results, we can determine if the models correctly predict the decay of concentration with distance from the source independent of magnitude. This comparison is important because none of the models includes the effect of the rising mean plume centerline which is characteristic of dispersion under the influence convective turbulence. This point was addressed in depth in the companion report by Liljegren et al. (1989). Figures 4.10 – 4.18 compare the predicted and measured concentration decay for the nine Atterbury-87 trials. Again, the first three of these figures concern the HC Group I Trials, the next two concern the HC Group II Trials and the last four concern the Fog-oil Trials.

The third type of comparison represents an attempt to better quantify the relative performance of the models. To this end, the number of predicted concentrations that are within a given factor (2, 3, 4, 5 or 10) of the data values are tabulated. These results are presented on a trial-by-trial basis in Table 4.1. These results are then grouped according to release type in Table 4.2 and according to stability class in Table 4.3. In tabulating the number of predicted concentrations that are within a given factor of the data, it is important to avoid including a large number of near-zero values which would severely skew the distribution. Furthermore, a second problem with this type of comparison is that the model predictions represent mean concentrations while the data values represent single realizations of a process which itself has a very large statistical variance. There are no standard methodologies for rejecting these zero and near-zero values nor is there a precise way to account for the basic difference between the predicted and measured values. Therefore, three different approaches were taken to determine the number of predicted concentrations that fall within a given factor of the data: (1) an approach that considers only model/data pairs where the measured concentration value is greater than 10 % of the observed maximum for the transect (Tables 4.1.a, 4.2.a and 4.3.a); (2) an approach that considers only model/data pairs where the measured concentration value is greater than twice the limit of detection (Tables 4.1.b, 4.2.b and 4.3.b); and (3) an approach that considers only model/data pairs where the measured concentration value is greater than the limit of detection and accounts for the statistical variance of the measured and predicted values (Tables 4.1.c, 4.2.c and 4.3.c).

In the first and second approach, the tabulation may be thought of as the percentage of predictions which fall within a given factor of the measured value for

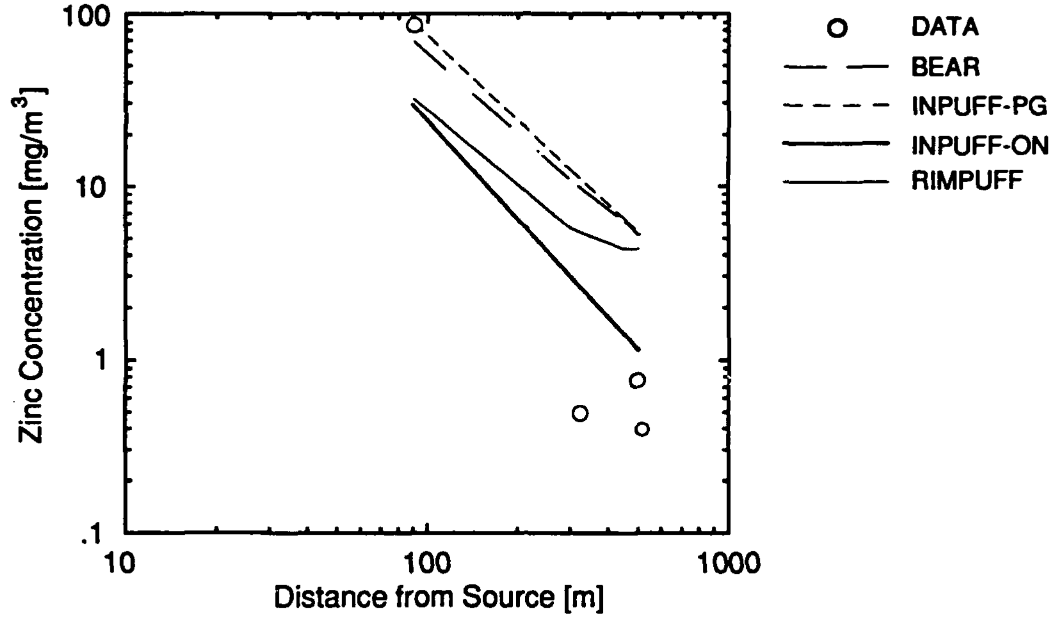

Figure 4.10 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1109871.

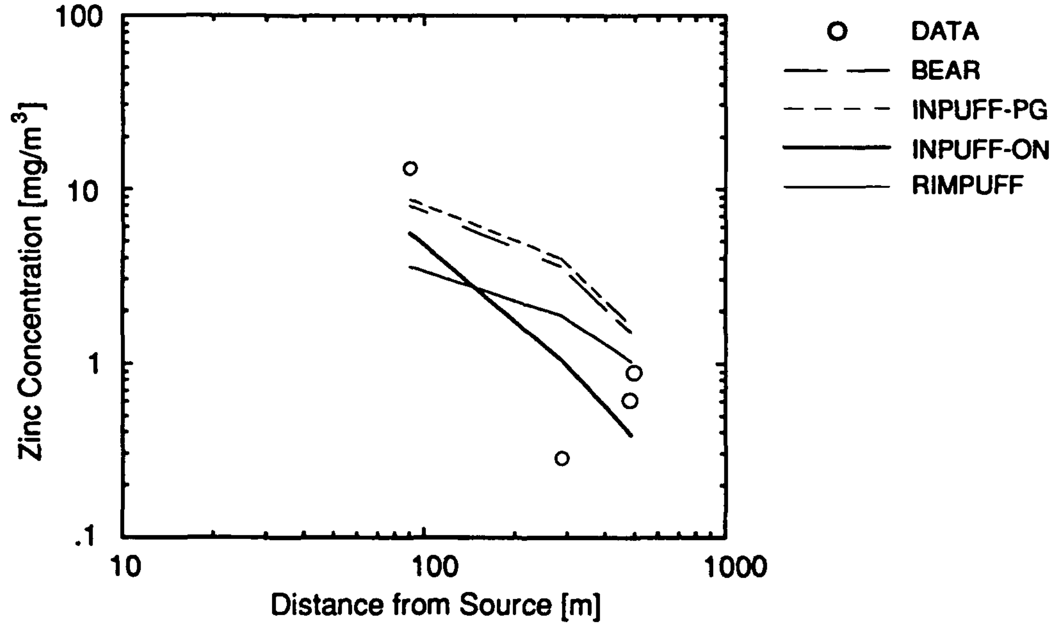

Figure 4.11 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1110871.

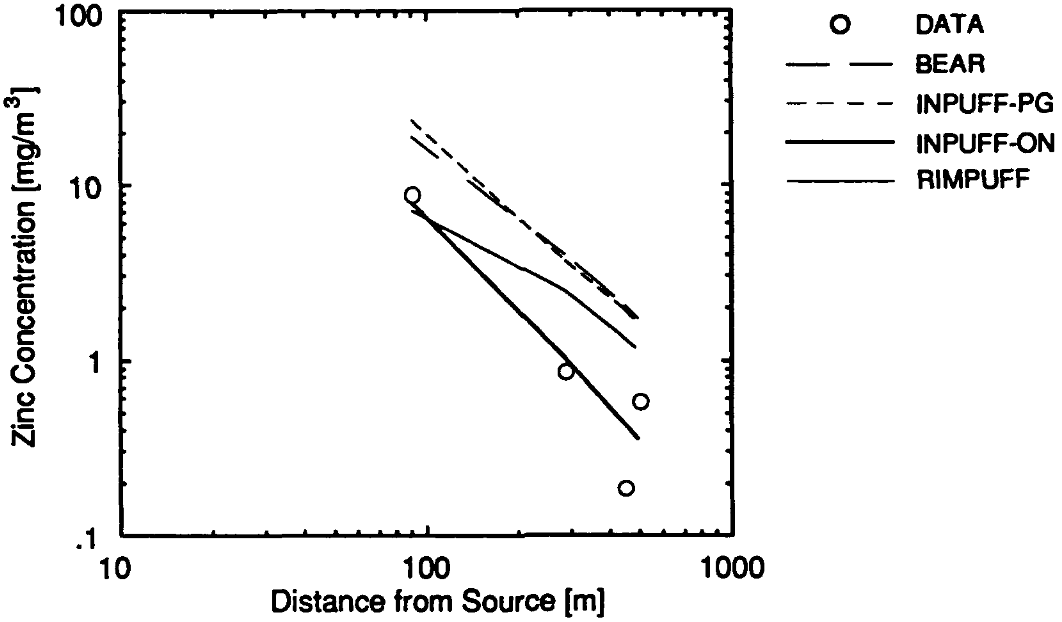

Figure 4.12 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1110872.

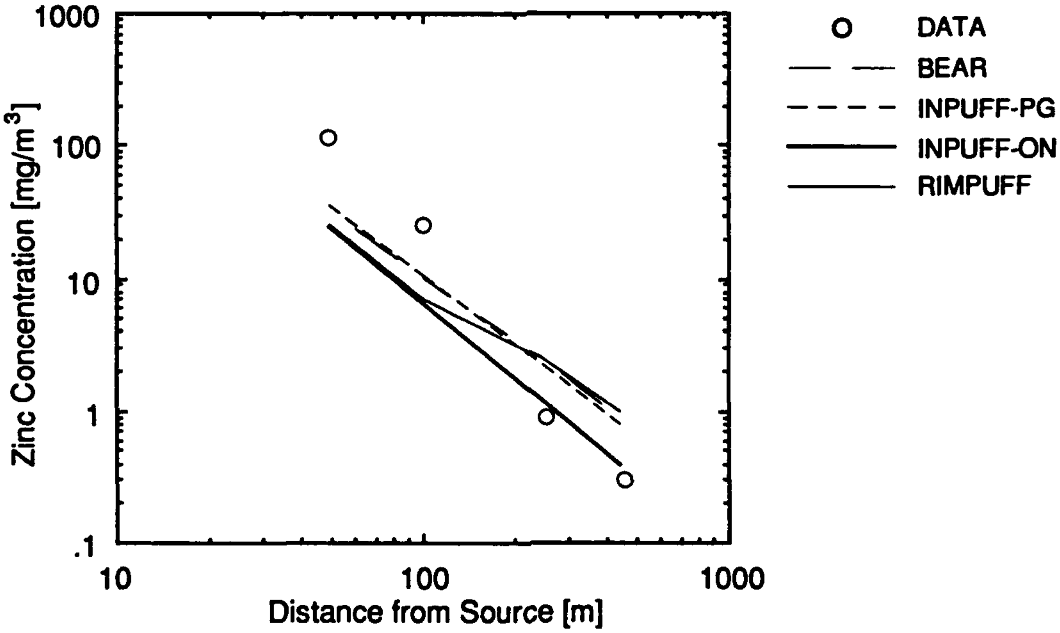

Figure 4.13 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1112871.

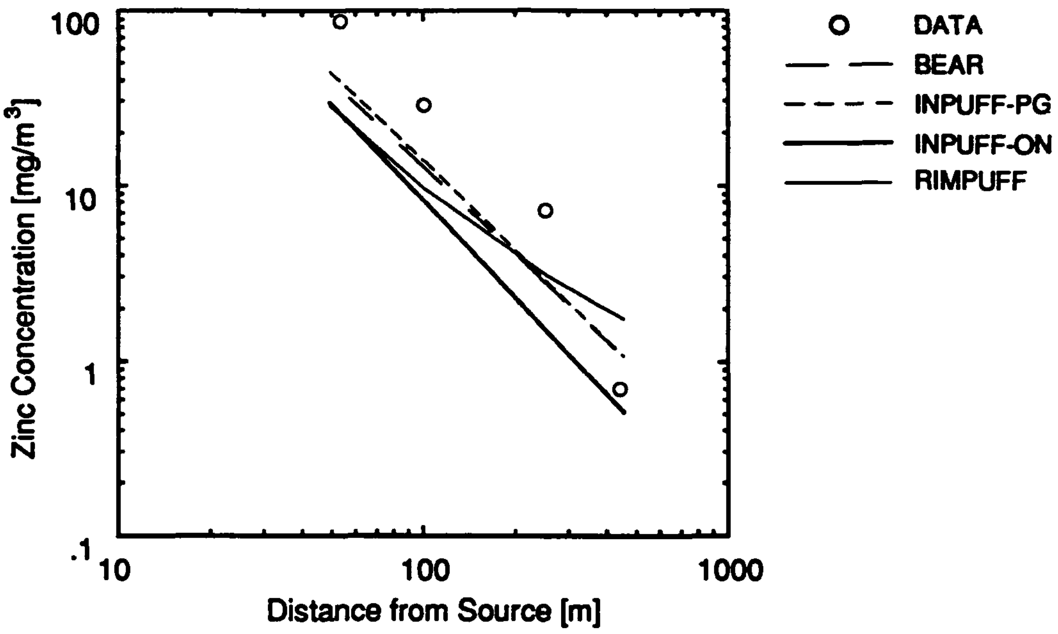

Figure 4.14 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average zinc concentration data from Atterbury-87 HC Trial 1113871.

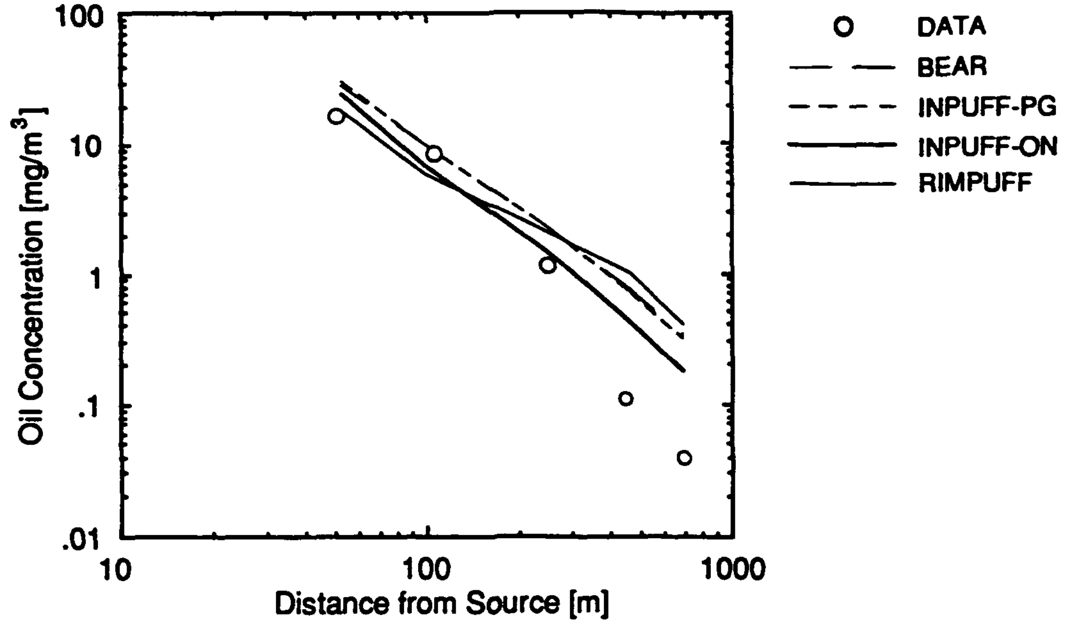

Figure 4.15 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1103871.

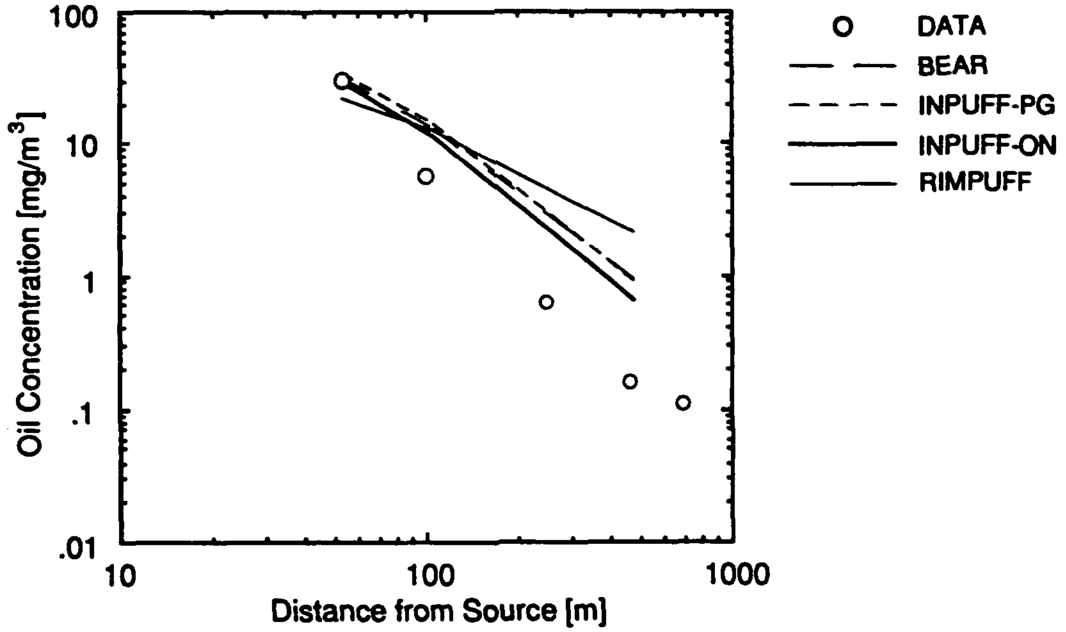

Figure 4.16 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1104871.

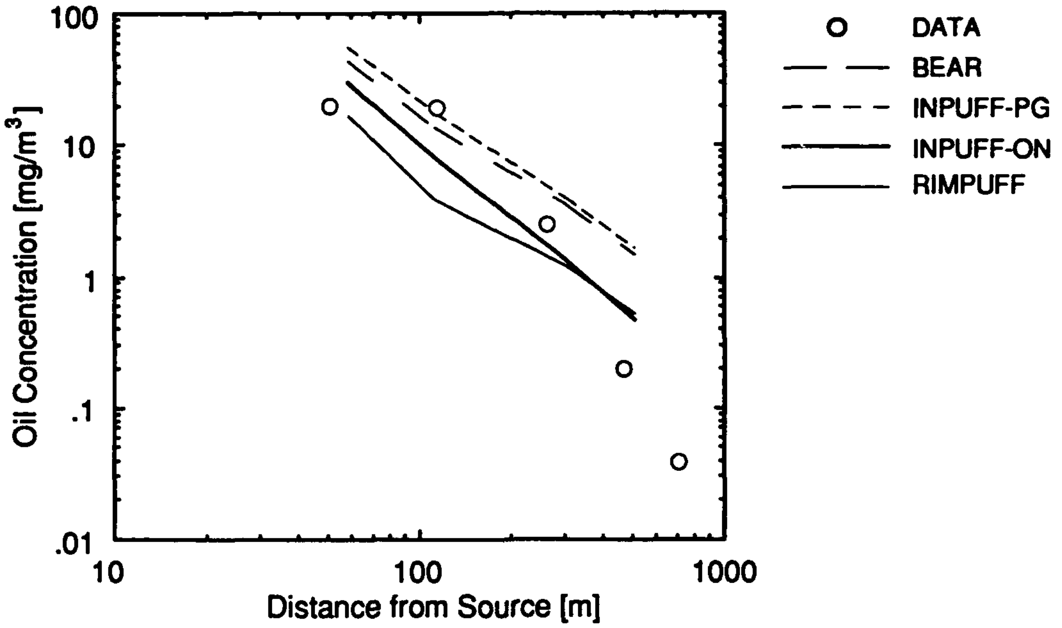

Figure 4.17 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1104872.

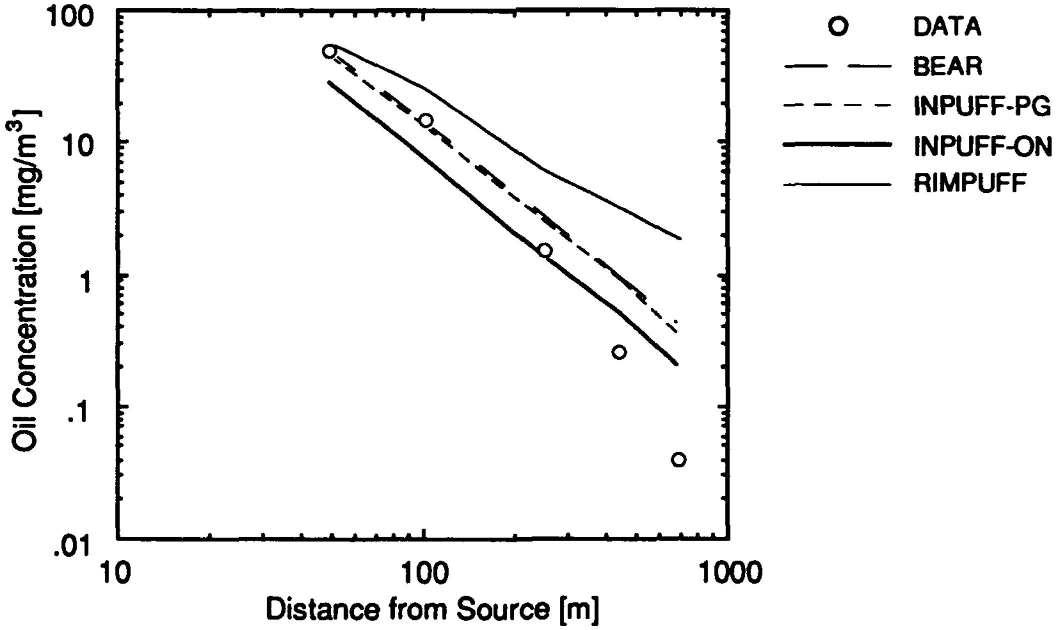

Figure 4.18 Comparison of predicted concentration decay with downwind distance using RIMPUFF, BEAR, INPUFF-ON and INPUFF-PG models with average oil concentration data from Atterbury-87 Fog-oil Trial 1106871.

Table 4.1.a Percentages of model predictions within a given factor of the data for the nine trials conducted during the Atterbury-87 Field Study (only observed values within 10% of the transect maximum are considered).

HC-I Trial 1110871 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	25	25	57	25
3	39	36	75	57
4	57	54	93	64
5	61	64	93	71
10	82	79	100	89

HC-I Trial 1110872 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	8	4	56	36
3	24	20	92	60
4	32	28	96	76
5	48	44	96	80
10	68	72	100	92

HC-I Trial 1109871 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	18	18	18	12
3	18	18	59	24
4	18	18	65	29
5	24	24	71	41
10	47	41	82	59

HC-II Trial 1112871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	29	24	29	18
3	41	41	53	41
4	59	59	65	47
5	65	71	71	53
10	76	76	76	71

HC-II Trial 1113871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	33	33	27	27
3	60	60	53	53
4	60	60	60	53
5	60	60	67	73
10	73	80	80	80

Table 4.1.a Percentages of model predictions within a given factor of the data for the nine trials conducted during the Atterbury-87 Field Study (only observed values within 10% of the transect maximum are considered).

Fog-oil Trial 1103871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	35	39	52	43
3	48	52	52	43
4	52	52	70	43
5	57	57	78	52
10	87	87	91	70

Fog-oil Trial 1104871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	18	24	24	18
3	41	41	24	24
4	41	41	41	24
5	47	53	47	29
10	59	59	59	35

Fog-oil Trial 1104872 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	36	44	48	28
3	48	48	64	52
4	52	56	80	60
5	60	60	80	76
10	76	72	88	80

Fog-oil Trial 1106871 (Stability Class B)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	42	42	54	21
3	50	50	67	25
4	63	63	67	38
5	63	67	71	46
10	79	79	96	63

Table 4.1.b Percentages of model predictions within a given factor of the data for the nine trials conducted during the Atterbury-87 Field Study (only observed values greater than twice the limit of detection are considered).

HC-I Trial 1110871 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	23	23	53	23
3	37	33	70	53
4	53	50	87	60
5	57	60	90	67
10	77	73	97	83

HC-I Trial 1110872 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	7	3	50	33
3	20	17	80	53
4	27	23	83	70
5	40	37	83	73
10	57	60	90	83

HC-I Trial 1109871 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	15	15	15	10
3	15	15	50	20
4	15	15	55	25
5	20	20	60	35
10	40	35	75	50

HC-II Trial 1112871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	20	20	32	16
3	32	32	52	32
4	48	48	64	36
5	52	56	68	44
10	64	64	76	60

HC-II Trial 1113871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	20	20	20	17
3	37	37	40	30
4	37	37	50	37
5	37	37	57	50
10	60	63	77	60

Table 4.1.b Percentages of model predictions within a given factor of the data for the nine trials conducted during the Atterbury-87 Field Study (only observed values greater than twice the limit of detection are considered).

Fog-oil Trial 1103871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	38	50	56	56
3	56	63	63	56
4	63	63	69	56
5	69	69	75	69
10	81	81	81	75

Fog-oil Trial 1104871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	23	23	31	23
3	46	46	31	31
4	46	46	46	31
5	54	69	54	38
10	69	69	69	46

Fog-oil Trial 1104872 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	43	48	48	29
3	52	52	62	52
4	57	62	76	62
5	71	71	76	76
10	81	76	90	81

Fog-oil Trial 1106871 (Stability Class B)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	45	45	59	23
3	55	55	77	27
4	73	68	77	45
5	73	77	82	55
10	86	86	95	73

Table 4.1.c Percentages of model predictions within a given factor of the data for the nine trials conducted during the Atterbury-87 Field Study - using a log-normal probability distribution (only observed values greater than the limit of detection are considered).

HC-I Trial 1110871 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	23	23	37	28
3	36	36	56	43
4	45	44	67	52
5	52	51	74	59
10	69	68	89	73

HC-I Trial 1110872 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	14	13	36	29
3	23	22	53	44
4	30	29	63	53
5	35	35	70	60
10	50	52	84	75

HC-I Trial 1109871 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	9	9	24	13
3	14	14	37	21
4	17	18	45	27
5	20	21	51	32
10	31	31	67	46

HC-II Trial 1112871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	19	20	27	18
3	30	32	41	28
4	38	40	50	35
5	44	46	56	40
10	59	61	72	55

HC-II Trial 1113871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	18	18	22	17
3	28	28	35	26
4	35	35	44	33
5	39	39	50	38
10	52	52	68	51

Table 4.1.c Percentages of model predictions within a given factor of the data for the nine trials conducted during the Atterbury-87 Field Study - using a log-normal probability distribution (only observed values greater than the limit of detection are considered).

Fog-oil Trial 1103871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	27	28	32	27
3	41	42	48	40
4	50	51	57	49
5	56	58	63	54
10	72	73	77	68

Fog-oil Trial 1104871 (Stability Class C)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	22	22	20	14
3	34	35	32	21
4	42	43	40	25
5	48	49	46	29
10	63	64	61	39

Fog-oil Trial 1104872 (Stability Class D)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	27	26	34	29
3	40	40	52	44
4	49	49	62	53
5	55	55	69	59
10	69	69	85	73

Fog-oil Trial 1106871 (Stability Class B)

Factor	BEAR	INPUFF-PG	INPUFF-ON	RIMPUFF
2	26	27	31	16
3	40	41	47	26
4	49	49	57	33
5	56	56	64	38
10	72	73	80	52

Table 4.2.a Summary of model/data comparisons for each of the three types of trials conducted during the Atterbury-87 Field Study (only observed values within 10% of the transect maximum are considered).

Factor	Model	All Tests	Fog-oil	HC-I	HC-II
2	BEAR	27	34	17	31
	INPUFF-PG	28	38	16	28
	INPUFF-ON	43	46	47	28
	RIMPUFF	26	28	26	22
3	BEAR	41	47	29	50
	INPUFF-PG	40	48	26	50
	INPUFF-ON	62	54	77	53
	RIMPUFF	43	37	50	47
4	BEAR	49	53	39	59
	INPUFF-PG	48	54	36	59
	INPUFF-ON	73	66	87	63
	RIMPUFF	50	43	60	50
5	BEAR	54	57	47	63
	INPUFF-PG	56	60	47	66
	INPUFF-ON	77	71	89	69
	RIMPUFF	60	53	67	63
10	BEAR	73	76	69	75
	INPUFF-PG	73	75	67	78
	INPUFF-ON	88	85	96	78
	RIMPUFF	73	64	83	75

Table 4.2.b Summary of model/data comparisons for each of the three types of trials conducted during the Atterbury-87 Field Study (only observed values greater than twice the limit of detection are considered).

Factor	Model	All Tests	Fog-oil	HC-I	HC-II
2	BEAR	25	39	15	20
	INPUFF-PG	26	43	14	20
	INPUFF-ON	41	50	43	25
	RIMPUFF	25	32	24	16
3	BEAR	37	53	25	35
	INPUFF-PG	37	54	23	35
	INPUFF-ON	60	61	69	45
	RIMPUFF	40	42	45	31
4	BEAR	45	61	34	42
	INPUFF-PG	44	61	31	42
	INPUFF-ON	69	69	78	56
	RIMPUFF	48	50	55	36
5	BEAR	51	68	41	44
	INPUFF-PG	53	72	41	45
	INPUFF-ON	73	74	80	62
	RIMPUFF	57	61	61	47
10	BEAR	68	81	60	62
	INPUFF-PG	67	79	59	64
	INPUFF-ON	85	86	89	76
	RIMPUFF	70	71	75	60

Table 4.2.c Summary of model/data comparisons for each of the three types of trials conducted during the Atterbury-87 Field Study - using a log-normal probability distribution (only observed values greater than the limit of detection are considered).

Factor	Model	All Tests	Fog-oil	HC-I	HC-II
2	BEAR	20	26	16	19
	INPUFF-PG	20	26	15	19
	INPUFF-ON	30	30	33	25
	RIMPUFF	21	22	24	17
3	BEAR	32	39	25	29
	INPUFF-PG	32	40	25	30
	INPUFF-ON	45	46	50	38
	RIMPUFF	33	34	37	27
4	BEAR	39	48	32	36
	INPUFF-PG	39	49	31	37
	INPUFF-ON	55	56	59	47
	RIMPUFF	41	41	46	34
5	BEAR	45	54	37	41
	INPUFF-PG	45	55	36	42
	INPUFF-ON	61	62	66	53
	RIMPUFF	46	46	51	39
10	BEAR	59	70	51	55
	INPUFF-PG	60	70	51	56
	INPUFF-ON	77	77	81	69
	RIMPUFF	60	60	66	53

Table 4.3.a Summary of model/data comparisons for each of the three stability classes present during the Atterbury-87 Field Study (only observed values within 10% of the transect maximum are considered).

Factor	Model	All Tests	B-Stability	C-Stability	D-Stability
2	BEAR	27	42	29	22
	INPUFF-PG	28	42	31	23
	INPUFF-ON	43	54	35	47
	RIMPUFF	26	21	28	26
3	BEAR	41	50	47	34
	INPUFF-PG	40	50	49	32
	INPUFF-ON	62	67	46	74
	RIMPUFF	43	25	40	51
4	BEAR	49	63	53	42
	INPUFF-PG	48	63	53	41
	INPUFF-ON	73	67	60	85
	RIMPUFF	50	38	42	60
5	BEAR	54	63	57	51
	INPUFF-PG	56	67	60	51
	INPUFF-ON	77	71	67	86
	RIMPUFF	60	46	51	69
10	BEAR	73	79	75	71
	INPUFF-PG	73	79	76	68
	INPUFF-ON	88	96	78	94
	RIMPUFF	73	63	64	82

Table 4.3.b Summary of model/data comparisons for each of the three stability classes present during the Atterbury-87 Field Study (only observed values greater than twice the limit of detection are considered).

Factor	Model	All Tests	B-Stability	C-Stability	D-Stability
2	BEAR	25	45	24	21
	INPUFF-PG	26	45	26	21
	INPUFF-ON	41	59	32	44
	RIMPUFF	25	23	25	25
3	BEAR	37	55	40	31
	INPUFF-PG	37	55	42	29
	INPUFF-ON	60	77	46	67
	RIMPUFF	40	27	36	47
4	BEAR	45	73	46	39
	INPUFF-PG	44	68	46	38
	INPUFF-ON	69	77	57	77
	RIMPUFF	48	45	39	56
5	BEAR	51	73	50	48
	INPUFF-PG	53	77	54	48
	INPUFF-ON	73	82	63	79
	RIMPUFF	57	55	50	64
10	BEAR	68	86	67	64
	INPUFF-PG	67	86	68	62
	INPUFF-ON	85	95	76	89
	RIMPUFF	70	73	61	76

Table 4.3.c Summary of model/data comparisons for each of the three stability classes present during the Atterbury-87 Field Study - using a log-normal probability distribution (only observed values greater than the limit of detection are considered).

Factor	Model	All Tests	B-Stability	C-Stability	D-Stability
2	BEAR	20	26	21	18
	INPUFF-PG	20	27	21	18
	INPUFF-ON	30	31	25	33
	RIMPUFF	21	16	19	25
3	BEAR	32	40	33	29
	INPUFF-PG	32	41	33	28
	INPUFF-ON	45	47	39	50
	RIMPUFF	33	26	29	39
4	BEAR	39	49	40	36
	INPUFF-PG	39	49	41	36
	INPUFF-ON	55	57	48	60
	RIMPUFF	41	33	36	47
5	BEAR	45	56	46	41
	INPUFF-PG	45	56	47	41
	INPUFF-ON	61	64	54	67
	RIMPUFF	46	38	41	53
10	BEAR	59	72	60	56
	INPUFF-PG	60	73	61	56
	INPUFF-ON	77	80	70	82
	RIMPUFF	60	52	54	68

those cases where smoke is present in measurable amounts. In the third approach, the probability of a prediction being within a given factor of the data is considered for measured values greater than the limit of detection. The probability is determined by assuming a log-normal distribution of the observed concentrations and assuming that the geometric mean is equal to 1. Both assumptions have been shown to be valid for our data (DeVaull et al., 1989). Table 4.4 shows the number of model/data pairs that are considered for each trial for each of the three approaches.

In these comparisons, we have chosen to use factors of 2, 3, 4, 5 and 10 for the tabulations. Since the data are believed to be accurate to within a factor of 2, a model which is similarly accurate can be expected to predict within a factor of about 2.8 if the differences are independent (correlation coefficient of zero) or a factor of about 4 if the differences are correlated with a correlation coefficient of -1. Thus, we expect a "good" model to be accurate within a factor of 4 perhaps 95 % of the time. On the other hand, we consider predictions which are in error by a factor of 10 or more to be clearly unsatisfactory. The factors of 2, 3, 4, 5 and 10 were chosen to span the range from excellent to unacceptable using five different levels of performance.

In general, we see that the three approaches taken to determine the number of predicted concentrations that fall within a given factor of the data demonstrate similar trends. The approach that considers the probability of the model prediction being within a given factor of the data leads to the lowest overall percentages. The approach that considers only data values that are greater than 10% of the observed maximum for the transect results in the highest overall percentages. For the purpose of this discussion, the results of all three approaches are averaged.

The temptation to focus too much attention on these quantitative performance measures must be avoided, however. In addition to the issues discussed above, it must be emphasized that the comparisons are made only at those points where sampling masts are located. This leads to inherently selective sampling of the concentration field. A model may do very poorly in the performance measures if it fails to correctly predict the centerline trajectory of the plume. Consider the extreme case in which the predicted plume completely misses the sampling transects, then the predictions are all zero and thus differ from the measured values by a factor of more than 10. The graphical comparisons of predicted and measured concentration decay are more telling in this respect since they are less sensitive to exact plume trajectory predictions. Other problems of this type are inherent in the performance measures; hence, all three types of comparisons must be carefully studied before conclusions are drawn.

Table 4.4 Summary of the number of model/data pairs used in the various approaches to determining the percentage of values within a given factor.

TRIAL	Approach No. 1	Approach No. 2	Approach No. 3
1103871	23	16	21
1104871	17	13	16
1104872	25	21	27
1106871	24	22	28
1109871	17	20	24
1110871	28	30	30
1110872	25	30	31
1112871	17	25	26
1113871	15	30	34

Approach No. 1 = data values greater than 10% of observed maximum along a transect.

Approach No. 2 = data values greater than twice the limit of detection.

Approach No. 3 = data values greater than the limit of detection - probability approach.

4.2.3 Discussion of Individual Trials

Consider first the trials in HC Group I which are summarized in Figs. 4.1 – 4.3, Figs. 4.10 – 4.12 and Table 4.1. We see that the INPUFF model using the on-site method clearly outperforms the other three modeling alternatives, including its own prediction when the Pasquill-Gifford-Turner (PGT) stability class method is used. In fact, there is typically very little difference between the predictions of the INPUFF Model using the PGT scheme and those of the BEAR Model. This is to be expected because the BEAR and INPUFF-PG methods are virtually identical. On average, these two models overpredict concentrations rather significantly. The RIMPUFF predictions usually fall between the fairly good predictions of the INPUFF-ON method and the over predictions typical of the BEAR and INPUFF-PG methods.

It is also obvious from Fig. 4.1 and Table 4.1 that none of the models predict the results of Trial 1109871 well. In fact, all of the model significantly overpredict this case with no model predicting within a factor of 2, more than 24 % of the time. No solid explanation for this apparent discrepancy exists at the present time, although we continue to investigate possible causes.

Figures 4.10 – 4.12 show the decay of concentration with distance for the three HC Group I trials. The data are not always monotonically decreasing which raises some question concerning their validity. We attribute the observed behavior to three important factors: (a) the problem of selective sampling noted earlier wherein data values are at discrete mast locations not at the mean plume centerline, (b) the inherent uncertainty in the data (estimated to be roughly a factor of 2) due to the difficulties of field work and (c) the large statistical variance in the dispersion process itself which implies that individual realizations will be poorly behaved compared with ensemble averages taken over many such realizations. The selective sampling problem is made particularly severe here by the fact that the expanding grid spacing runs counter to the spreading plume behavior. Despite the problems with the data, there is clearly a suggestion at least that the models tend to underpredict within roughly 250 m of the source and then overpredict at greater distances. We attribute this difference between the predicted and observed decay rates to the rising centerline effect clearly present under convective conditions. The effect is not very severe here as might be expected, since these data are for D stability.

Figures 4.4 and 4.5 show the two trials in HC Group II. Here, the stability class is C and the release point is upwind of the first transect. Here, the predictions are better, although the models clearly seem to underpredict close to the source then overpredict at greater distances. This behavior is clearly consistent with the rising centerline effect which is more severe here than in the three previous cases where the stability was near-neutral. The INPUFF-ON methodology seems to do quite well at Transects 3 and 4, although its statistical performance is significantly hurt by the severe underprediction at Transects 1 and 2.

Figures 4.6 – 4.9 show the model/data comparisons for the four fog-oil cases. The trends are essentially the same as for the five HC comparisons just discussed: (a) the model predictions appear reasonably good in qualitative terms but are somewhat disappointing in terms of quantitative performance, (b) the INPUFF-ON method generally outperforms the other three, and (c) the models tend to underpredict close to the source then overpredict farther from the source as is expected based once again on the rising centerline effect. In some cases, the models perform well close to the source in which case the overprediction farther from the source is generally worse.

4.2.4 Discussion of Systematic Trends

The question naturally arises: "Is model performance significantly different among the different types of releases or the different stability classes present?" Tables 4.2 and 4.3 address this question in terms of the quantitative performance statistics. Unfortunately, the two parts of the question are difficult to decouple, because (a) release type and stability class are not independently varied and (b) nine trials are insufficient to justify conclusions in a rigorously statistical sense given the large variance of the population from which the cases are drawn. Nevertheless, three conclusions seem evident:

1. The INPUFF-ON predictions are consistently better than the other three methods regardless of release type and stability class. Notably, the INPUFF-PG and BEAR predictions are virtually identical for all cases underscoring the similarity in theoretical formulations of both models. The RIMPUFF method differs in predictions and has fewer systematic behaviors than the other models, but overall appears to perform about as well as the INPUFF-PG and BEAR models.

2. The predictions are consistent for the fog-oil and HC trials for the best performing model, INPUFF-ON. However, for the other models, the predictions for the fog-oil trials are somewhat better than for the HC trials.

3. Model performance does seem to depend weakly on stability class with the INPUFF-PG and BEAR predictions generally being the best for the B stability trial. INPUFF-PG and BEAR predictions are consistently better for C stability than D stability trials.

5. SUMMARY AND CONCLUSIONS

Three Gaussian-puff dispersion models (the BEAR, INPUFF and RIMPUFF Models) were tested with field data from the Atterbury-87 smoke dispersion field study. The Atterbury-87 study consists of a total of nine smoke-dispersion experiments conducted in slightly to moderately unstable conditions (stability classes B through D). Five of these trials were carried out using hexachloroethane (HC) smoke pots as the source; the other four were conducted using a fog-oil smoke generator. Although the terrain of the dispersion site is relatively flat, the meteorology is complex owing to the effects of the surrounding hills and vegetation. The field data include average concentration measurements on four or five transects (depending on the trial) out to distances of 575 m. In addition, the data base includes time-dependent source measurements as well as meteorological data from a 10-m instrument tower and a 2-m mast.

The BEAR, INPUFF, and RIMPUFF models are similar in their basic treatment of transport and dispersion, but differ in implementation. These three were chosen because they represent the state of the art of models available for general use. The models treat the release as a series of Gaussian puffs each of which is transported and dispersed downwind with a time-dependent wind speed. An important difference between the models revolves around the way dispersion is handled. The BEAR model uses dispersion coefficients based on stability class which is, in turn, inferred from synoptic meteorological data. The INPUFF model offers two methods for treating dispersion. One method "INPUFF-ON" uses on-site measurements of the standard deviation in the horizontal and vertical wind directions. The second method, "INPUFF-PG" uses dispersion coefficients based on the Pasquill-Gifford-Turner stability class determined from synoptic data in the manner as does the BEAR model. Although the RIMPUFF model offers the option of using stability class, its predictions were always made with its preferred method which uses on-site measurements of the standard deviation in the horizontal wind direction.

The INPUFF-ON predictions are consistently better than the predictions of the other three models (BEAR, INPUFF-PG and RIMPUFF) and are within a factor of two of the data values 38 % of the time and within a factor of ten 83 % of the time. By contrast, the other three models predict within a factor of two 24 % of the time and within a factor of ten 67 % of the time. The predictions are consistent for the fog-oil and HC trials for the best performing model, INPUFF-ON. However, for the other models, the predictions for the fog-oil trials are somewhat better than for the HC trials. The comparisons also reveal that the models incorrectly predict the decay of concentration with distance from the source, a result which we attribute to the effect of the rising centerline under convective conditions. A second key conclusion involves the sensitivity of predictions to stability class for those models which use that approach. A change of just one class has a pronounced effect on predictions and, in fact, may change the comparison from one of relatively good performance to one of decidedly poor performance or vice versa. Moreover, we have observed that the D stability class is problematic in that it groups together conditions which are moderately stable with those that are moderately unstable, even though these two conditions have fundamentally different dispersion physics. Lastly, in evaluating model performance, it must be remembered that the meteorological and source data which serve as inputs to the models and the concentration data to which the model predictions are compared both contain considerable experimental uncertainty. Not only is there the uncertainty associated with the experimental procedures which are particularly difficult to carry out under field test conditions, but there is the added fact that each trial represents a single realization of a process which itself has a very large statistical variance. All things considered, a variation of a factor of two even between similar data sets is not surprising. Thus, although the models can be significantly improved in many respects, their current performance must be viewed in the proper light.

APPENDIX A: COORDINATE INFORMATION

Table A.1 gives the coordinates of the meteorological tower and the two release points. Table A.2 gives the coordinates of the sampling masts. All values are given in meters relative to a local origin within the grid.

Table A.1 Coordinates of the Meteorological Instrument Tower and the Two Release Points.

Location	East [m]	North [m]
Meteorological Instrument Tower	316.39	298.43
Release Point Used for Tests 1109871, 1110871 and 1110872	270.3	470.8
Release Point Used for Tests 1112871 and 1113871	-21.1	21.1

Table A.2 Coordinates of the Sampling Masts.

Transect 1		
Mast Number	East [m]	North [m]
1	-11.7	80.9
2	-1.7	70.6
3	8.6	60.2
4	18.8	50.1
5	28.8	39.8
6	39.4	29.1
7	49.4	19.3
8	59.3	9.2
9	69.7	-1.4
10	79.9	-11.5

Transect 2		
Mast Number	East [m]	North [m]
1	-41.5	188.7
2	-21.3	166.7
3	-2.3	146.1
4	18.0	124.3
5	38.7	102.1
6	59.1	80.0
7	79.0	58.3
8	98.8	36.8
9	118.2	15.6
10	138.0	-5.8
11	157.9	-27.2
12	178.0	-49.0

Table A.2 (continued) Coordinates of the Sampling Masts.

Transect 3		
Mast Number	East [m]	North [m]
1	0.3	348.2
2	31.3	317.3
3	61.5	287.0
4	91.8	256.7
5	122.6	225.9
6	153.6	194.9
7	184.0	164.5
8	215.1	133.4
9	246.4	102.1
10	276.7	71.8
11	306.7	41.9
12	337.1	11.4

Transect 4		
Mast Number	East [m]	North [m]
1	74.7	543.6
2	113.9	507.9
3	154.5	466.4
4	194.3	427.3
5	235.1	388.3
6	275.5	349.3
7	316.5	308.7
8	357.7	267.3
9	398.8	225.9
10	440.0	184.1
11	485.5	137.4
12	526.3	95.2

REFERENCES

Cramer, H. E., 1976: "Improved Techniques for Modeling the Dispersion of Tall Stack Plumes", Proceedings of the Seventh International Technical Meeting on Air Pollution Modeling and its Application No. 51, NATO/CCMS, 631-780 (NTIS PB 270 799).

DeVaull, G. E., W. E. Dunn and J. C. Liljegren, 1989: "Analysis Methods and Results of Hexachloroethane Smoke Dispersion Experiments Conducted as Part of Atterbury-87 Field Studies", work completed under Contract No. 84PP4822, AD-216048, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Draxler, R. R., 1976: "Determination of Atmospheric Diffusion Parameters," *Atmospheric Environment*, **10**, 99-105.

Golder, D., 1972: "Relations Among Stability Parameters in the Surface Layer", *Boundary Layer Meteorology*, **3**, 47-58.

Irwin, J. S., 1983: "Estimating Plume Dispersion - A Comparison of Several Sigma Schemes," *Journal of Climate and Applied Meteorology*, **22**, 92-114.

Irwin, J. S. and F. S. Binkowski, 1980: "Estimation of the Monin-Obukhov Scaling Length Using On-Site Instrumentation," *Atmospheric Environment*, **15**, 1091-1094.

Katz, S., A. Snelson, R. Farlow, R. Welker and S. Mainer, 1980: "Physical and Chemical Characterization of Military Smokes – Part I: Final Report on Hexachloroethane Smoke", work completed under Contract No. DAMD17-78-C-8085, IIT Research Institute, Chicago, Illinois.

Liljegren, J. C., W. E. Dunn, G. E. DeVaull and A. J. Policastro, 1989: "The Atterbury-87 Field Study of Smoke Dispersion and a New Stochastic Dispersion Model", work completed under Contract No. 84PP4822, AD212983, University of Illinois at Urbana-Champaign, Urbana, Illinois.

Ludwig, F. L., 1977: "A Theoretical Dispersal Model for Aerosols," prepared for US Army Missile Command, Redstone Arsenal, Alabama, by Stanford Research Institute, Menlo Park, California.

Mikkelsen, T., S. Larsen and S. Thykier-Nielsen, 1984: "Description of the Risø Puff Diffusion Model," *Nuclear Safety*, **67**, 55-65.

Nieuwstadt, F. T. M., 1980: "Application of Mixed-Layer Similarity to the Observed Dispersion from a Ground-Level Source", *Journal of Applied Meteorology*, **19**, 157-162.

Nieuwstadt, F. T. M., 1977: "The Computation of the Friction Velocity and Temperature Scale from Wind Profiles by Least-Squares Methods," *Boundary Layer Meteorology*, **14**, 235-246.

Petersen, W., J. Catalano, T. Chico and T. Yuen, 1984: "INPUFF – A Single Source Gaussian Puff Dispersion Algorithm – User's Guide", Report No. EPA-600/8-84-027, US Environmental Protection Agency, Research Triangle Park, NC.

Policastro, A. J., D. M. Maloney, W. E. Dunn, J. C. Liljegren and G. E. DeVaull, 1989: "Evaluation of Atmospheric Dispersion Models for Fog-Oil Smoke Dispersion," work completed under Contract No. 84PP4822, AD216055, Argonne National Laboratory, Argonne, IL.

Policastro, A. J., M. Wastag, L. Coke and W. E. Dunn, 1985: "Comparison of Smoke Dispersion Model Predictions with Smoke Week Data", Proceedings of Smoke/ Obscurants Symposium IX, Office of the Project Manager Smoke/Obscurants, Technical Report AMCPM-SMK-T-003-85, 299-316.

Smith, F. B. and J. S. Hay, 1961: "The Expansion of Clusters of Particles in the Atmosphere", *Quarterly Journal of the Royal Meteorological Society*, **87**, 82.

Turner, D. B., 1970: "Workbook of Atmospheric Dispersion Estimates," Office of Air Programs Publication No. AP-26 (NTIS PB 191 482), U.S. Environmental Protection Agency, Research Triangle Park, NC.

U.S. Environmental Protection Agency, 1987: "On-Site Meteorological Program Guidance for Regulatory Modeling Applications," Report No. EPA-450/4-87-013, U.S. Environmental Protection Agency, Research Triangle Park, NC.

DOCUMENT DISTRIBUTION LIST

No. of Copies

15 Commander
U.S. Army Biomedical Research and Development Laboratory
ATTN: SGRD-UBZ-RA
Fort Detrick
Frederick, MD 21702-5010

3 Commander
U.S. Army Medical Research and Development Command
ATTN: SGRD-RMI-S (Ms. Mary Frances Bostian)
Fort Detrick
Frederick, MD 21702-5012

1 Commander
U.S. Army Laboratory Command
Army Research Office
ATTN: SLCRO-GS (Dr. Walter Bach, Jr.)
P.O. Box 12211
Research Triangle Park, NC 27709-2211

1 Battelle-Pacific Northwest Laboratory
ATTN: Dr. Peter Van Voris
P.O. Box 999
Richland, WA 99352

1 Commander
U.S. Army Environmental Hygiene Agency
ATTN: HSHB-ME-AA (Mr. Jeff Kirkpatrick)
Aberdeen Proving Ground, MD 21010-5423

1 Commander
Chemical Research, Development and Engineering Center
ATTN: SMCCR-ST (Mr. Ron O. Pennsyle)
Aberdeen Proving Ground, MD 21010-5423

1 Commander
U.S. Army Atmospheric Science Laboratory
ATTN: SLCAS-BA-M (Dr. Ron Cionco)
White Sands Missile Range, NM 88002-5501

1 Commander
Dugway Proving Grounds
ATTN: STEDP-MT-M (James F. Bowers)
Dugway, UT 84022-5000

1 Commander
U.S. Army Materiel Command
ATTN: AMSCG-5
5001 Eisenhower Avenue
Alexandria, VA 22333-2300

1 Commander
U.S. Army Materiel Command
ATTN: AMCEN-A
5001 Eisenhower Avenue
Alexandria, VA 22333-2300

1 HQDA
ATTN: DASG-PSP-E
5111 Leesburg Pike
Falls Church, VA 22041-3258

1 HQDA
ATTN: DAEN-RDM
20 Massachusetts Ave, NW
Washington, DC 20314-5000

1 Commander
U.S. Army Forces Command
ATTN: AFEN-FDE
Fort McPherson, GA 30330

1 Commander
U.S. Army Construction Engineering Research Laboratory
ATTN: CERN-EN
Champaign, IL 61820-1305

1 Commander
U.S. Army Training and Doctrine Command
ATTN: ATEN-FN
Fort Monroe, VA 23651