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

ANNUAL REPORT

prepared by

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Health Effects Research Division
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This report summarizes the results achieved to date on field measurements and modeling carried out by Argonne National Laboratory and the University of Illinois relating to military smokes. Field measurements on the chemical characterization of smokes and their dispersion characteristics were studied at three sites: (a) Dugway Proving Ground, Utah (flat terrain), (b) Camp Atterbury near Columbus, Indiana (flat terrain),and (c) the Meadowbrook site (complex terrain) in Red Bluff, California. Smoke measurements typically included particle size distributions, average concentrations (or dosages), concentration fluctuations, vapor/particulate phase partitioning, and deposition. Airborne concentrations were measured from 25 - 2500m downwind. Sample experimental results for fog oil include the following: (a) droplet sizes have a mass median diameter of about 1 micron, and (b) the vapor phase is essentially nonexistent with a mass contribution of less than 1% as compared with 99% contribution of the particulate phase. (continued on reverse)

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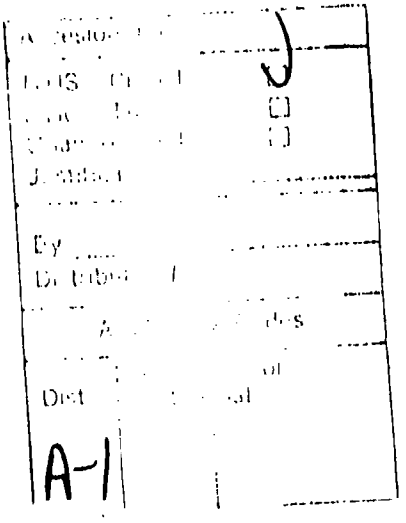
For the purposes of model vertification for fog-oil smoke, there are three data sets from the Dugway tests, four data sets from Camp Atterbury and eight data sets from the Meadowbrook site. All fog oil data were taken under convective conditions except for seven data sets at Meadowbrook which were acquired under stable conditions. For HC, there were five field surveys carried out at Camp Atterbury, all under convective conditions. The model verification results show that the four Gaussian puff models tested can predict within a factor of 2-3 under convective conditions to about 250m in flat terrain.



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EXECUTIVE SUMMARY

This report summarizes the results achieved to date on our project to carry out field measurements and modeling of smoke dispersion with fog oil and hexachloroethane (HC) smoke. Field measurements on the chemical characterization of smoke and their dispersion characteristics were studied at three sites: (a) Dugway Proving Ground, Utah, (b) Camp Atterbury near Columbus, Indiana, and (c) the Meadowbrook site in Red Bluff, California. The first two sites represent flat terrain and the third one represents complex terrain. Fog oil emission was from a single smoke generator (all three sites) and the HC smoke pot releases were carried out only at Camp Atterbury. Smoke measurements typically included particle size distributions, average concentrations (or dosages), concentration fluctuations, vapor/particulate phase partitioning, and deposition. Airborne concentrations were typically measured at downwind distances 25 m - 200 m at Dugway, 50 m - 675 m at Camp Atterbury and 50 m - 2500 m at the Meadowbrook site. In addition to the in-plume measurements, there were supporting data taken on source conditions and ambient meteorology (mean as well as turbulence quantities). The Meadowbrook tests were accomplished in conjunction with Project AMADEUS/WIND with the ambient meteorology along with aerial photographs of the plume taken by other research groups.

For the purposes of model verification for fog-oil smoke, there are 3 data sets from the Dugway tests, 4 data sets from Camp Atterbury and 8 data sets from the Meadowbrook site. All fog oil data were taken under convective conditions except for 7 data sets at Meadowbrook which were acquired under stable conditions. For HC, there were five field surveys carried out at Camp Atterbury, all under convective conditions. Model/data comparisons are complete for the fog-oil tests at Dugway and Camp Atterbury. The results show that the four Gaussian puff models tested can predict within a factor of 2-3 under convective conditions to distances of about 250 m. Beyond that distance, the plume tends to rise leading the models to significantly overpredict average concentrations at ground level. The centerline decay in average concentrations is poorly predicted by the models due, in part, to the fact of the rising centerline in the observed data. Lateral distributions of average concentration are approximately Gaussian in shape whereas the vertical distribution of average concentration is not Gaussian. Use of a more advanced stochastic model has shown that the rise in the plume and the centerline decay can indeed be predicted once the convective turbulence is accounted for in a smoke model.

The chemical characterization of the fog oil smoke in the field revealed that (a) droplet sizes are consistent with laboratory measurements of a mass median diameter of about 1 micron, (b) the vapor phase is essentially nonexistent with a mass contribution of less than 1% as compared to a 99% contribution of the particulate phase, (c) the particulate phase of the smoke acts like a tracer in its dispersion characteristics at least to the downwind distances measured, (d) no deposition was measured beyond about 50 m from the smoke generator, and (e) the standard deviation in concentration can vary from 2 times the local mean value at the plume centerline to 15 times the local mean at the plume edge.

The chemical characterization of the HC smoke in the field revealed that (a) particle sizes have mass median aerodynamic diameters of between 0.5 and 1.0 microns, (b) all field samples were found to contain very small quantities of vapor and scatter among the samples was high, (c) up to 35 different compounds were seen in the organic vapor phase, (d) the inorganic particulate phase was made principally of zinc and aluminum compounds -- 34 of 47 elements and cations tested for in the particulate samples were actually identified, most in trace amounts.

Future work would involve (a) the Meadowbrook site data reduction -- plume and meteorology, (b) model verification using the Meadowbrook data sets for fog oil and the HC data sets at Camp Atterbury, and (c) model improvement using all the smoke data from Dugway, Camp Atterbury, and Meadowbrook leading to a model that can be run on a fieldable personal computer.

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LIST OF ABBREVIATIONS

ABBREVIATION	MEANING
Al	Aluminum
AMADEUS	A Meteorological And Dispersion Experiment over Undulating Surfaces
ANL	Argonne National Laboratory
ASL	Atmospheric Sciences Laboratory
Cd	Cadmium
CONDORS	Convective Diffusion Observed by Remote Sensors
Hg	Mercury
HC	Hexachloroethane smoke
ICAP-AES technique	Inductively coupled argon plasma atomic spectrometer technique
ICP	Inductively coupled plasma
IITRI	Illinois Institute of Technology Research Institute
m	Meter
M3A3E3, M3A4	Types of fog-oil smoke generators
Pb	Lead
PNL	Pacific Northwest Laboratory
WIND	Winds In Non-uniform Domain
USABRDL	U.S. Army Biomedical Research and Development Laboratory

1.0 INTRODUCTION

The current research project addresses the need of the US Army Medical Research and Development Command to predict concentrations, particle sizes, and deposition rates to civilians, indigenous plants and wildlife resulting from the use of military smokes in field training exercises. To meet this need, two project objectives are set forth: (1) carry out a comprehensive field measurement program to obtain high quality data on the dosages and deposition rates resulting from smoke emitted by specific military smoke generating devices, and (2) use these field data, combined with results which can be synthesized from other studies of smokes, to evaluate the performance of predictive models.

It is the purpose of this document to summarize the results and present the current status of field measurements and mathematical modeling of fog-oil and HC smoke carried out under research project 84PP4822. Since the start of the project, field measurements on smoke characterization and dispersion were carried out at

(a) Dugway Proving Ground (April 1984) in Utah,

(b) Camp Atterbury in Indiana (August 1986 and November 1987), and

(c) The Meadowbrook site in Red Bluff, California as part of Project WIND/AMADEUS (September/October 1987).

Data acquired downwind of the smoke source include average concentration (dosage), concentration fluctuations, particle-size distributions, deposition, plume visibility, and vapor phase / particulate phase partitioning. Ambient profiles of meteorological data (wind speed, wind direction, humidity, and turbulence) and data on source characteristics were acquired to assist in interpreting the data and to provide the needed inputs for model verification work.

A major part of the effort in the above field characterization of the smokes was the development of field sampling techniques for these smokes (both vapor and particulate) and associated chemical analysis methods. A separate effort was carried out in the development of source instrumentation and the measurement of ambient meteorological data for the model verification work.

Results of the field studies are summarized below. Section 2 describes the field testing done with fog oil under flat terrain dispersion conditions. These field surveys were done at Dugway Proving Ground and at Camp Atterbury. Section 3 describes the fog-oil field tests done as part of Project AMADEUS under complex terrain dispersion conditions. Section 4 describes the field tests carried out for HC smoke under the flat terrain Camp Atterbury conditions.

2.0 FIELD CHARACTERIZATION OF FOG-OIL SMOKE IN FLAT TERRAIN.

Field studies were carried out at Dugway Proving Ground and Camp Atterbury to study fog-oil smoke behavior in flat terrain. Table 2.1 presents a list of the field tests carried out that are useful for model validation purposes. Results of the field characterization are as follows:

2.1. Source Characteristics of the Fog-Oil Smoke Generator

Source characteristics (mass release rate, exit temperature, and exit velocity) are well-documented under field test conditions. Fog-oil smoke exit temperatures vary from about 400 deg C to 500 deg C. The exit velocity of the smoke from the three ports of the generator is about 78 m/sec. The release rate rarely approached the nominal value of 45 g/s (48 gallons/hour) stated in the operator's manual and was in the range of 18 g/s to 43 g/s with an average of 30 g/s. Operating characteristics and problems appear consistent with current generation of military fog-oil smoke generators. Work with the M3A4 generators at

Table 2.1. Selected meteorological data, test information, and scaling parameters averaged over test durations for flat terrain field tests for fog-oil smoke.

Dugway Proving Ground Tests

Test Designation	T0009	T0010	T0011a	T0011b
Source Information				
Test Date	9-Apr-85	10-Apr-85	11-Apr-85	11-Apr-85
Begin Release (MDT)	13:38	14:20	9:38	10:30
End Release (MDT)	14:53	15:38	9:45	11:55
Release time (s)	4140	3720	420	5100
Release Rate (g/s)	43.2	41.7	38.1	37.6
Met Tower Information				
10 m Wind Speed (m/s)	5.2	2.6	7.2	6.3
10 m Wind Direction (deg)	11 E of N	201 E of N	338 E of N	5 E of N
10 m Sigma-theta (deg)	18.7	43.9	11.0	14.7
10 m Sigma-phi (deg)	8.8	15.7	4.8	7.1
10 m Ambient Temp (C)	18.5	22.7	16.0	18.2
Rel. Humidity (%)	23	21	36	31
Boundary Layer Scaling Parameters				
Estimated Obukhov Length, L (m)	-19	-2.2	-107	-22
Estimated Wind Power Exponent	0.114	0.093	0.150	0.0120
Estimated Friction Velocity (m/s)	0.34	0.22	0.42	0.41
Estimated Roughness Height (cm)	2	2	2	2

Camp Atterbury Field Tests

Test Designation	1103871	1104872	1106871
Source Information			
Test Date	11/3/87	11/4/87	11/6/87
Begin Test (CDT)	10:31:06	15:25:50	10:51:50
End Test (CDT)	11:27:00	16:14:00	12:08:00
Release Time (min)	55.9	48.2	76.2
2 m Wind Velocity (m/s)	2.6	1.7	0.8
2 m Wind Direction (°E of N)	241.4	247.1	223.6
2 m Sigma-theta (°)	28.6	26.0	33.8
2 m Ambient Temp (°C)	23.4	25.3	8.0
Met Tower Information			
10 m Wind Velocity (m/s)	5.5	4.7	1.6
10 m Wind Direction (° E of N)	239	261	240
10 m Sigma-theta (°)	16.2	18.6	35.4
10 m Sigma-phi (°)	8.8	8.2	14.9
Boundary Layer Scaling Parmeters			
Estimated Obukhov Length, L (m)	-5	-3	-5
Estimated Friction Velocity, u_* (m/s)	0.909	0.871	0.271
Estimated Roughness Height, z_0 (m)	0.20	0.20	0.20
Estimated Inversion Height, z_i (m)	700	700	700
Estimated Convection Velocity, w_* (m/s)	2.63	2.07	1.29

Camp Atterbury and Meadowbrook was less troublesome than the M3A3E3 generators used in the Dugway field tests. Figure 2.1 presents a sketch of a fog-oil generator and the instrumentation used to acquire source measurements.

2.2. Sampling Methodology for Fog Oil

A new sampling methodology and analysis procedure was developed for fog-oil and these procedures were extensively tested under both laboratory and field conditions. For the particulate phase, aspirated filter cassettes are used with an aspiration flow rate of about 24 liters/minute. The filters themselves were made of glass fiber. For the vapor phase, a Tenax-filled stainless steel tube is placed in series with (and behind) the filter cassette to collect the remaining fog oil vapor that would not be collected on the filter. The sampling filter cassette and the Tenax-filled tube are illustrated in Figures 2.2 and 2.3, respectively.

The advanced sampling method (used at Camp Atterbury) involved the use of fifty 8-m tall aluminum masts in which samplers were placed 2-m and 8-m elevations. A gasoline generator provides the power to operate up to five pumps at the base of each mast through heavy duty power cables (as shown in Figure 2.4). That pump provides the aspiration power for each filter cassette sampler. Additional Gillian pump samplers were used to measure the vapor/aerosol partition using a Tenax-filled sampling tube fronted by a filter cassette sampler.

2.3. Chemical Analysis Method for Fog Oil

The analysis of collected fog-oil samples (both particulate and vapor) is accomplished using a high temperature thermal desorption procedure followed by gas chromatography for chemical characterization and quantification of the collected oil. A flame ionization detector, which has a selective response to organic compounds, measures the mass concentration of the eluting sample. The total collected mass of oil in each sample can be found from the gas chromatography method. Complete resolution of the constituents in the oil is almost impossible because of the extremely large number of components in the fog oil. Fractions of oil components within a given molecular weight range have been determined for samples of the fog oil.

2.4. Chemical Characteristics of Fog-Oil Smoke

The chemical composition of the fog-oil smoke is consistent with previous laboratory studies. No chemical transformations during aerosolization or atmospheric transport (out to about 700 m downwind) were detected under the field conditions observed in these tests. Transformations, if any, are best identified through diagnostic laboratory work rather than field studies in which complicating factors may obscure subtle changes.

2.5. Vapor/Liquid Partitioning of the Fog-Oil Smoke

The vapor phase was found to be negligible (less than 1%) under the field conditions observed during the Dugway and Camp Atterbury experiments. Therefore, nearly all the fog oil vaporized in the smoke generator enters the aerosol phase. Further work in this area is best carried out in the laboratory where conditions can be carefully controlled and widely varied.

2.6. Particle Size Distribution of the Fog-Oil Smoke

Particle size in both the Dugway and Camp Atterbury tests was found to be very nearly log-normal with a mass median aerodynamic particle size of 0.8 to 1.0 microns. This range covers most of the field tests at the two sites. The geometric standard deviation was in the range 1.5 to 1.7. Figure 2.5 presents an example of the measurements obtained, representing a test on November 3, 1987 at Camp Atterbury. No variation in particle size distribution was found present either with meteorological conditions or distance from the source (out to about 300 m) at either site. These data are complete within the current state of particle size measurement techniques.

GENERATION AND SOURCE MONITORING

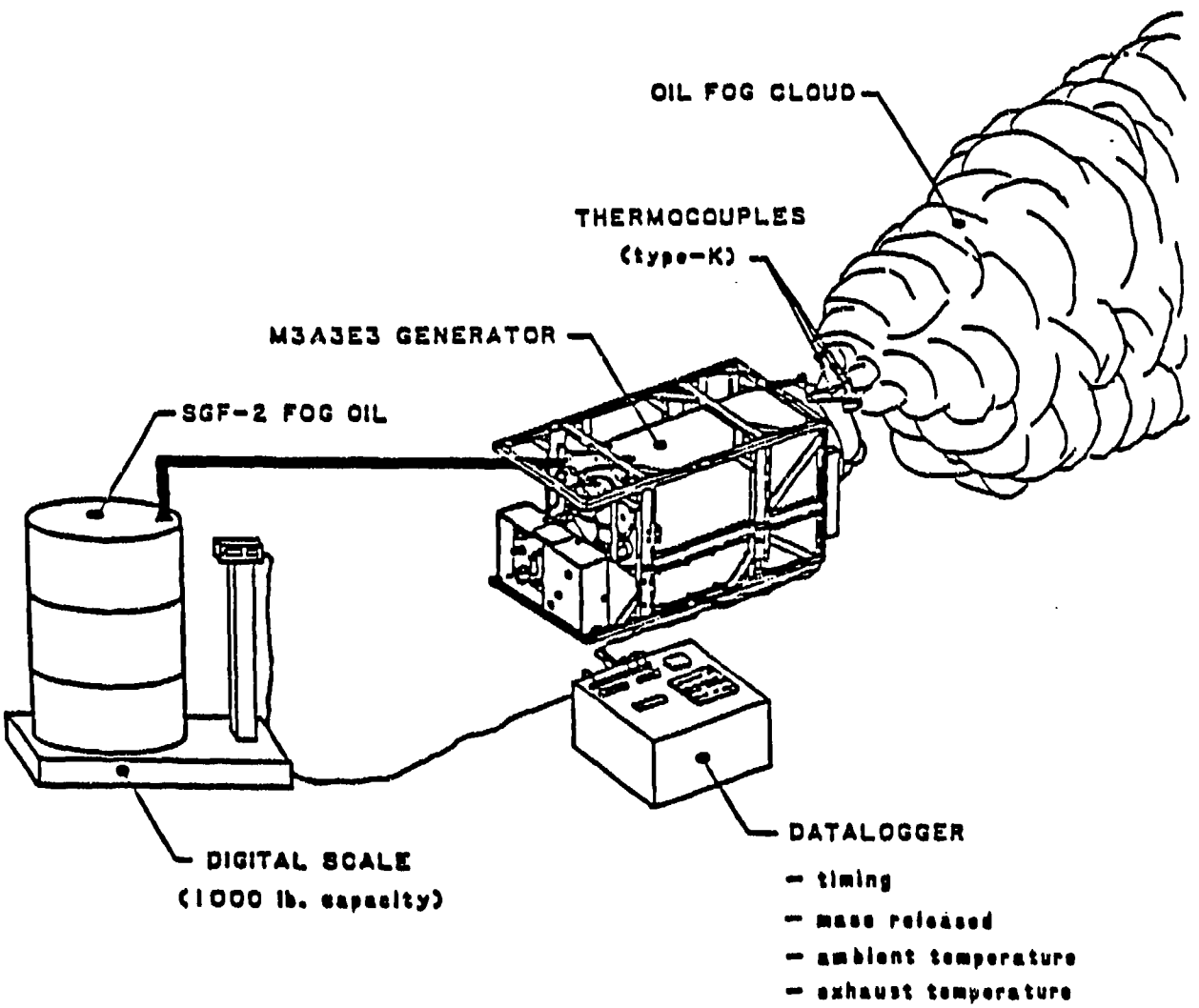

Figure 2.1. Sketch of fog-oil smoke generator and source monitoring instrumentation.

Filter Cassette Assembly

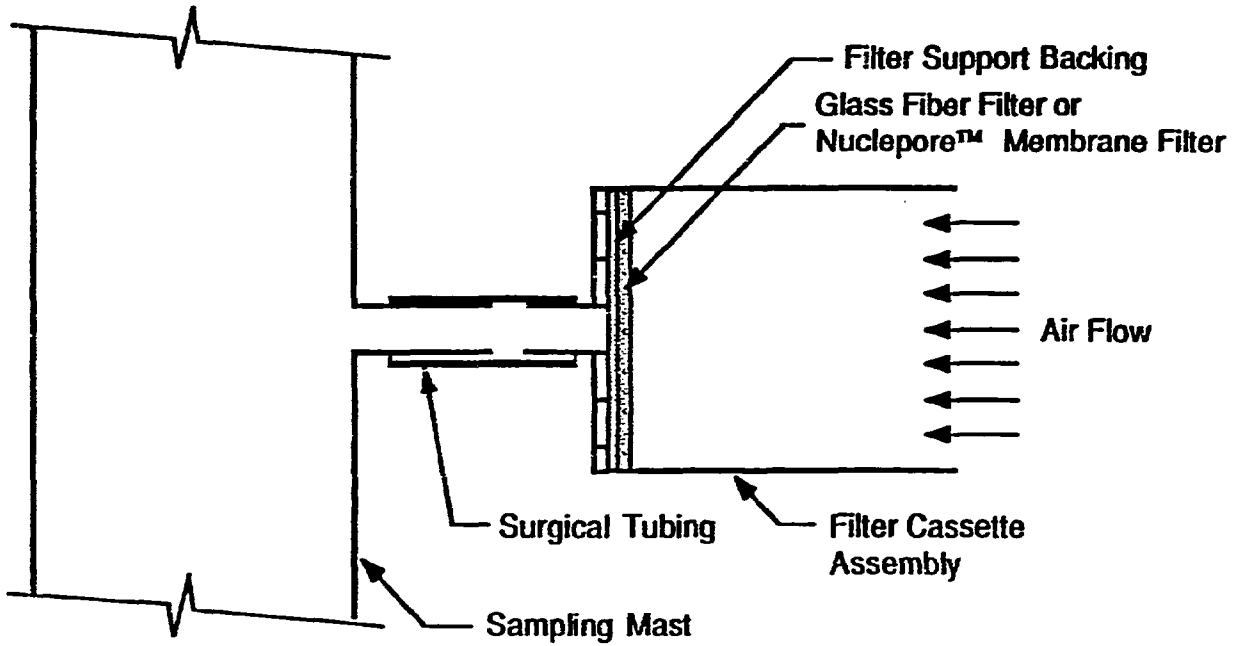

Figure 2.2. Sketch of filter cassette assembly used to measure the particulate phase for fog oil (and HC) smoke.

Adsorbent-filled Tube Sampler

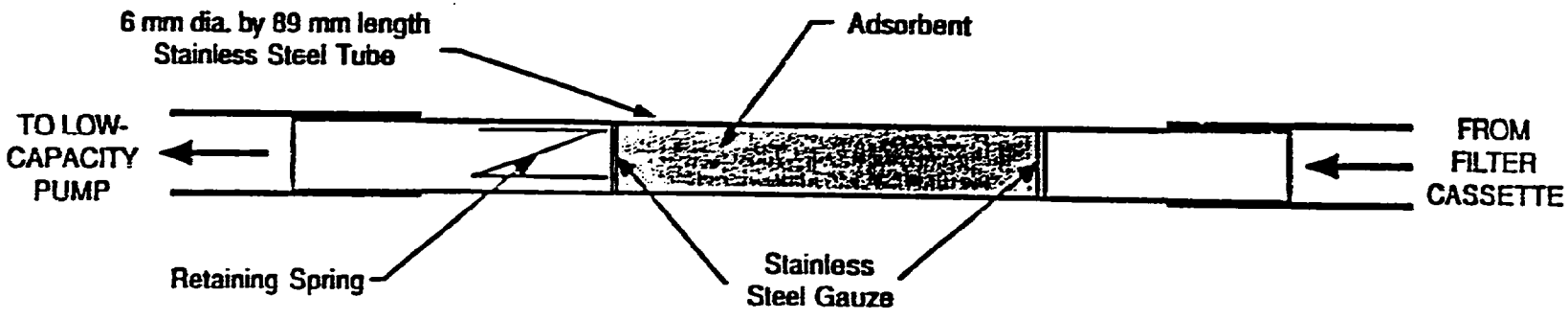

Figure 2.3. Illustration showing internal structure of adsorbent-filled tube sampler.

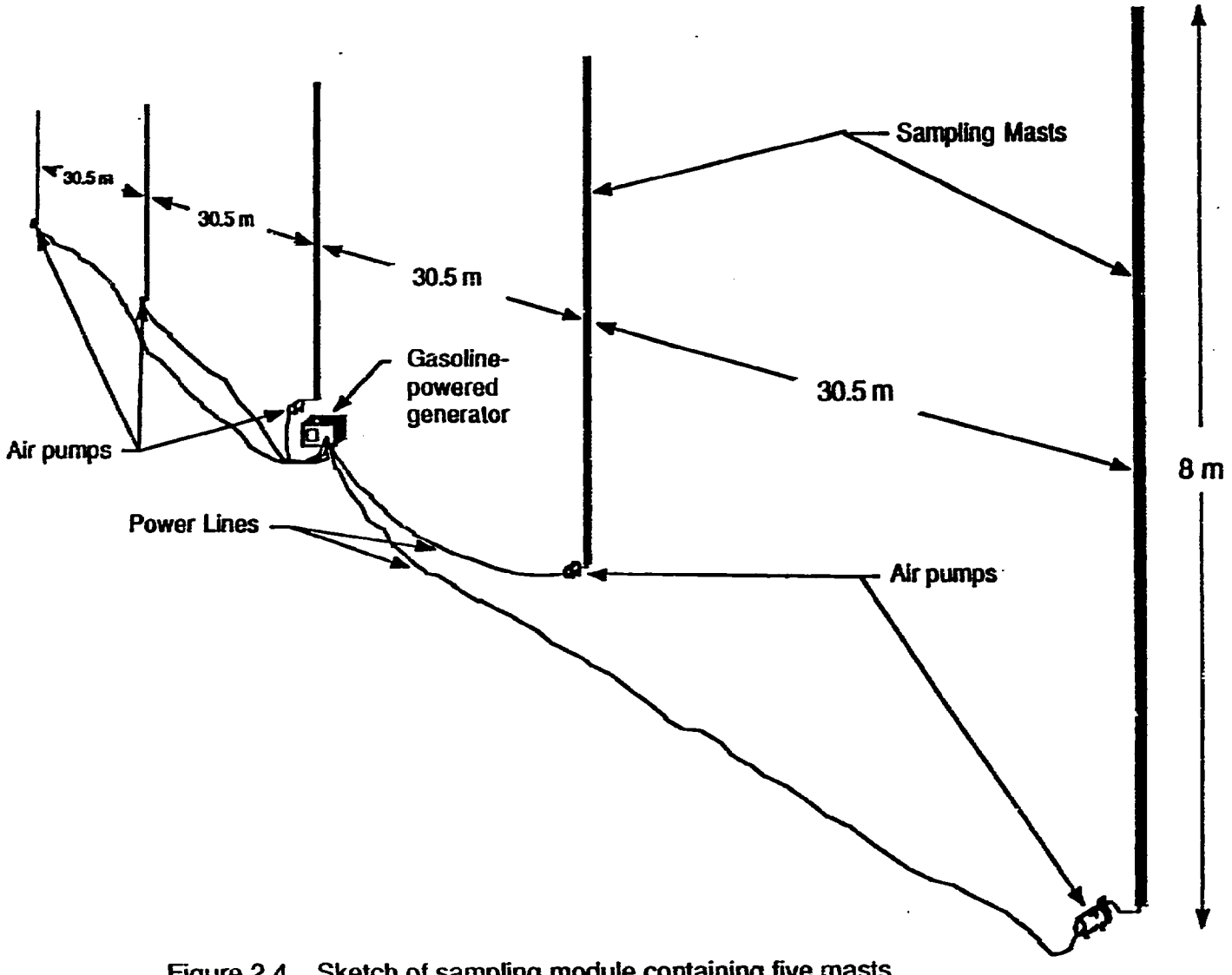

Figure 2.4. Sketch of sampling module containing five masts.

2.7. Average Concentrations (Dosages) and Plume Behavior of the Fog-Oil Smoke

Measurements made at distances from about 25 m to about 700 m confirm that the particulate phase acts like a tracer in its dispersion properties. Lateral distributions of average concentration (averaged over the time of smoke release) are approximately Gaussian in shape as illustrated in Figure 2.6 for several distances downwind at Camp Atterbury. The plume centerline was observed to rise with downwind distance under convective meteorological conditions. The rising centerline phenomenon under unstable conditions has been confirmed in the CONDORS field studies and in laboratory experiments of Willis and Deardorff. The decay of the concentration data with downwind distance was found to not be the result of Gaussian theory. The centerline decay may be seen to be the result of the observed rising centerline and a non-Gaussian vertical distribution of concentration. Only measurements under unstable and neutral conditions were made at Dugway and Camp Atterbury.

2.8. Concentration Fluctuations within the Fog-Oil Plume

Up to thirty-five aerosol photometers were used to measure particulate phase concentration fluctuations for the plumes at Camp Atterbury. The photometers work on the light-scattering principle and have a time resolution of under 1 second. The aerosol photometers were placed at the expected plume centerline location of each transect. The experimental data for point measurements of concentration fluctuations show that the standard deviation of concentration is between 2 to 15 times as large as the mean concentration for distances of 50 to 450 meters downwind of the smoke source under convective atmospheric conditions with the smallest ratio at the plume centerline and that ratio increasing at the plume edges. Figure 2.7 shows the concentration fluctuation results for a Camp Atterbury test at 450 m downwind of the source. The data compare well with some simple models for both the mean and variance in concentration. The results underscore the significant inhomogeneity in the plume as it spreads by means of puffs with clear air sometimes observed between spreading puffs.

2.9. Fog-Oil Plume Deposition

No deposition was detected beyond 20 m from the smoke generator. These results are consistent with the characteristics of the aerosol (mass median diameter of 1 micron) and the chemical nature of the fog oil.

2.10. Visibility of the Fog-Oil Plume

Visibility was not easily characterized given the three-dimensional nature and significant inhomogeneity of the cloud. The threshold for visibility is inherently subjective. Color video pictures of the plume were taken at Dugway and Camp Atterbury but that information was not sufficiently detailed to develop data on the threshold of visibility of the plume. However, aerosol photometer measurements and aerial photographs taken as part of the AMADEUS field study may provide much more detailed information on plume visibility.

2.11. Mathematical Modeling of Fog-Oil Smoke Plumes in Flat Terrain

Four time-dependent Gaussian puff models were tested with the field data acquired during the Dugway and Camp Atterbury field tests. The models predicted average concentration within factors of 2-3 for distances from the source of 25-250 m. Average concentrations began deviating much more rapidly from model predictions (with much lower measurements than predictions) at distances beyond about 250 m due to the convective plume rise phenomenon. The rising of the plume centerline at those distances (most noticeable beyond about 250 m) is due to the smoke being raised up with convection cells created at the ground. An illustration of the performance of the Gaussian puff models with Camp Atterbury data is given in Figure 2.8. Note the characteristic overprediction or underprediction of the models close to the source at 50 m, the general agreement of the models at the 100 and 250 m transects and the significant overprediction of the models at the 450 m transect. Clearly, the measured concentration decay with distance is not well represented by the Gaussian models. However, application of a stochastic model (employing the convective velocity scale and the mixing height as input parameters) led to the successful prediction of the rising of the plume centerline and good predictions of plume concentrations at ground

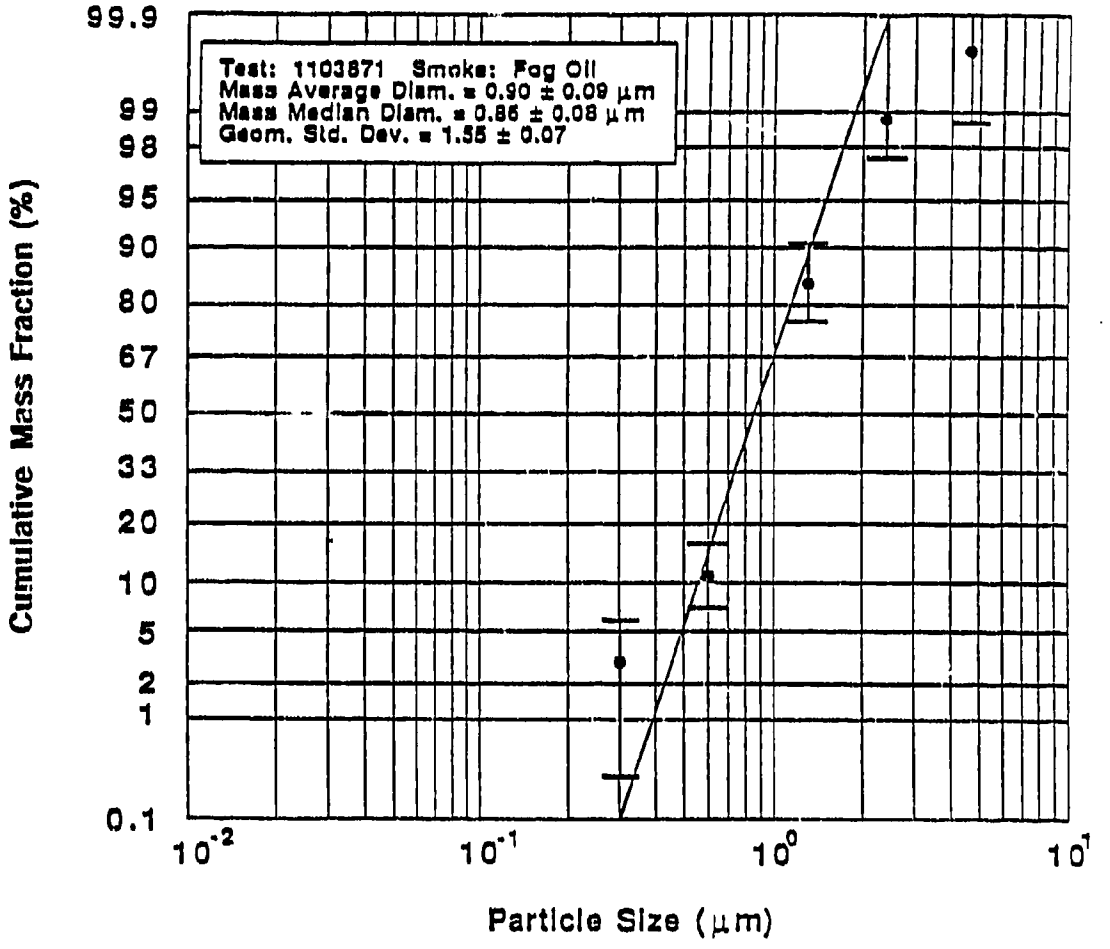

Figure 2.5. Cumulative mass fraction as a function of particle size for fog oil smoke...test 1103871 (November 3, 1987) at Camp Atterbury.

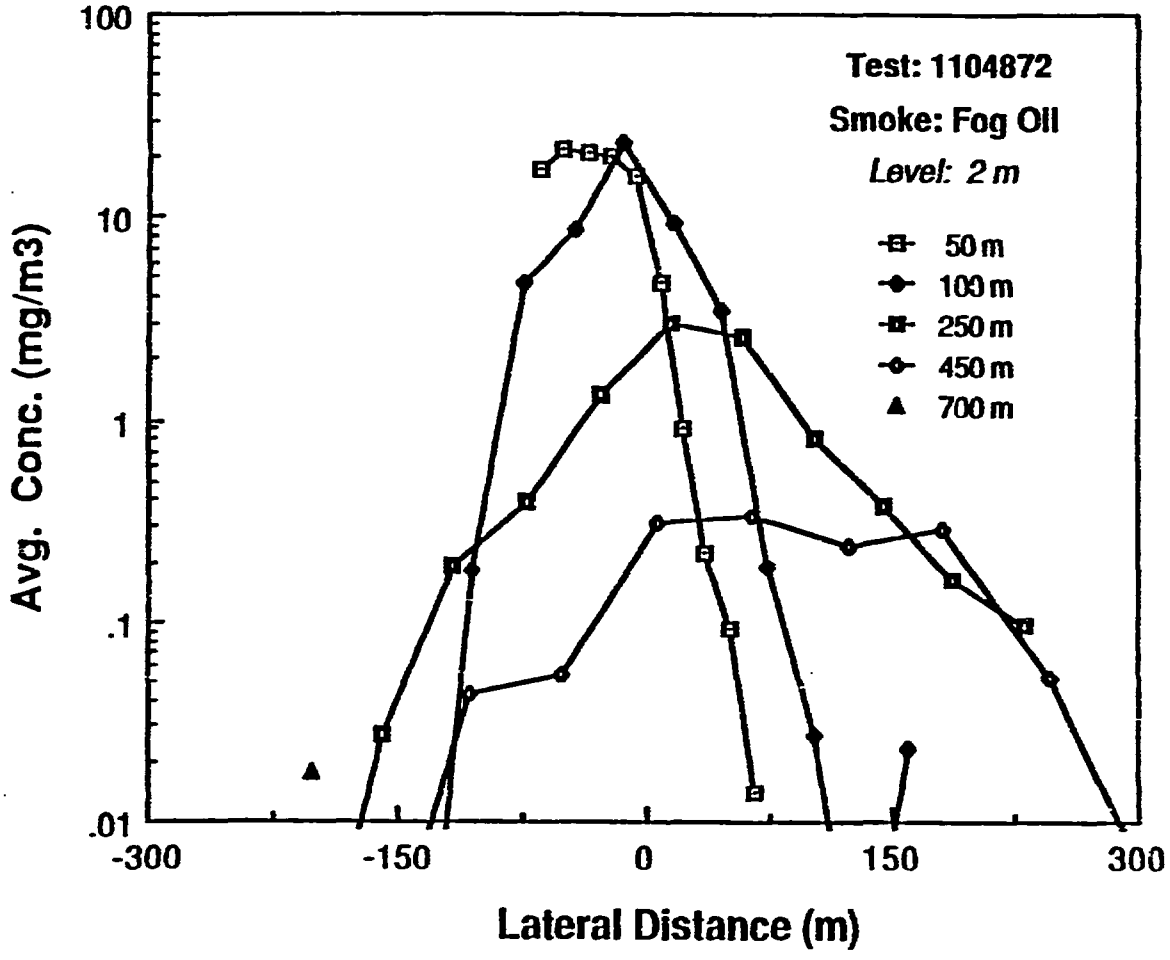

Figure 2.6. Variation of average fog oil smoke concentration with lateral distance -- as a function of downwind distance.

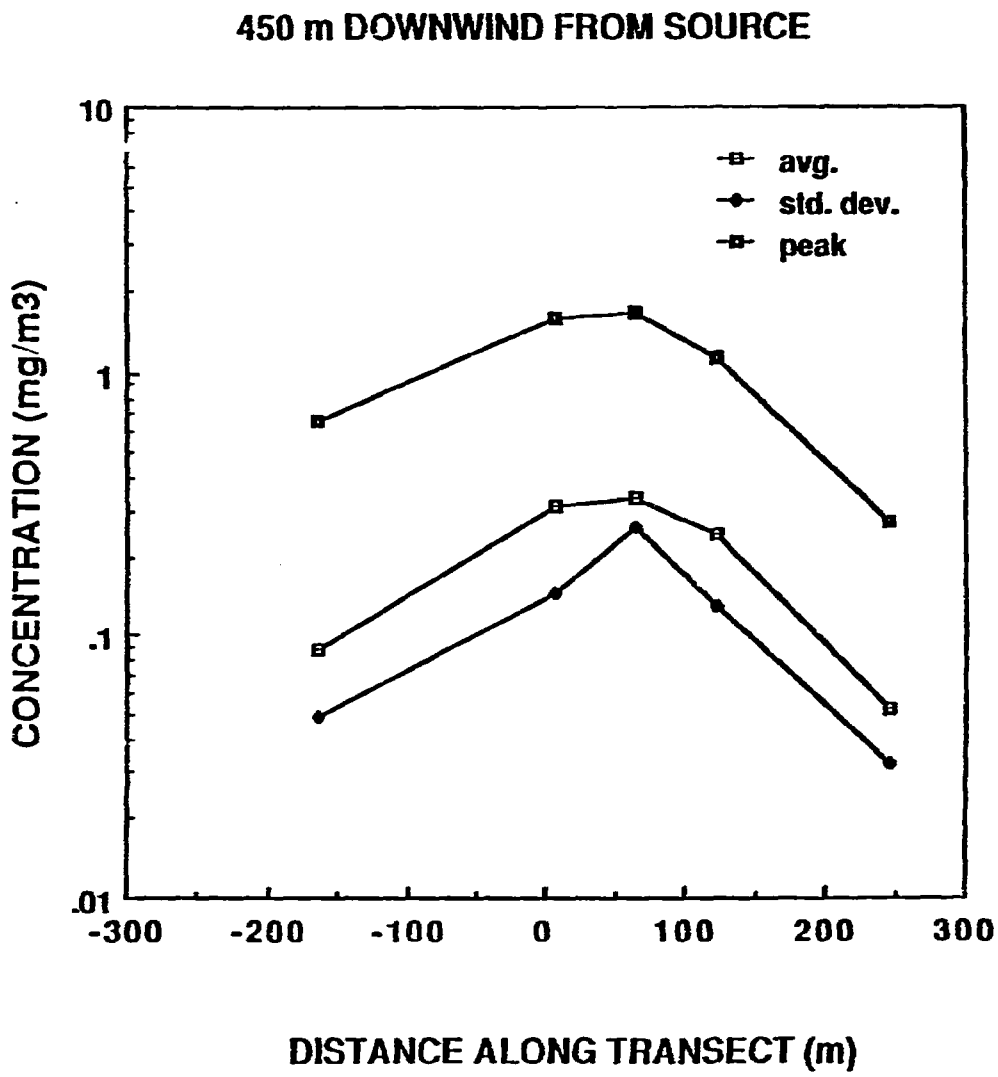

Figure 2.7. Variation of concentration fluctuations (average, standard deviation, and peak) with distance along a transect

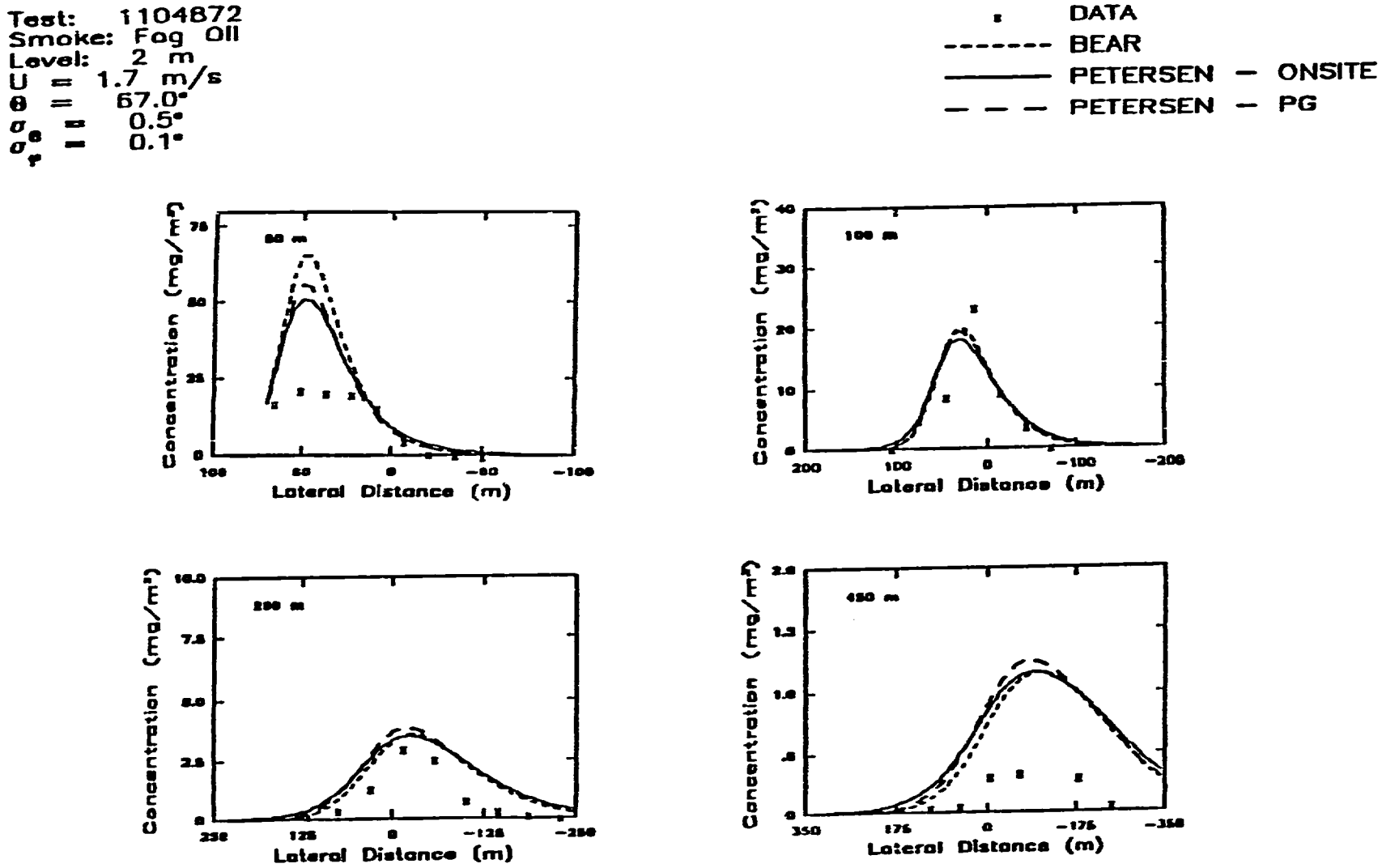

Figure 2.8. Comparison of Gaussian puff dispersion models with Camp Atterbury field data -- November 4, 1987 -- distances 50 m, 100 m, 250 m, and 450 m from the source.

level for all distance ranges from the smoke generator. The Gaussian puff models suffered from the assumption that the puff centerlines always stay at the height of release and do not rise. There appears to be no judicious choice of the sigma-z parameter of the Gaussian model to "correct" for the error of not allowing for a rising centerline.

3.0 FIELD CHARACTERIZATION OF FOG-OIL SMOKE IN COMPLEX TERRAIN

A field campaign was carried out in October 1987 at the Meadowbrook site in Red Bluff, California, as part of Project WIND/AMADEUS, in order to understand the behavior of fog-oil smoke plumes in a complex terrain environment. The earlier flat-terrain studies at Dugway Proving Ground and Camp Atterbury emphasized the chemical characterization of the smoke (vapor/particulate phase partitioning, particle sizes, etc.). Of lesser interest were the transport and diffusion of the smoke over the flat terrain. Now with the chemical characterization well understood from the flat terrain studies, the emphasis turned to studying the behavior of the fog-oil plumes in a complex terrain environment.

The Meadowbrook site was an excellent choice for a complex terrain study area because it allowed testing to be done both under daytime upslope winds (unstable meteorological conditions) and under nocturnal drainage flows (stable meteorological conditions). Table 3.1 identifies the 12 fog-oil tests carried out with a M3A4 smoke generator. Five are under unstable and seven are under stable atmospheric conditions.

The same field methodology and sampling apparatus was used at Meadowbrook as in the Camp Atterbury trials. Samples were taken of the smoke plume at 1-m, 2-m, 4-m and 8-m levels on 8-m tall masts. A total of 20 to 38 masts, depending on stability conditions, were used to collect samples for a given test. Measurements were carried out to 2500 m from the source. The meteorological data supporting the tests were taken by contractors sponsored by the Atmospheric Sciences Laboratory (ASL) of White Sands Missile Range. The cooperative relationship between USABRDL and ASL permitted this otherwise costly set of field tests to be accomplished with each member group sharing in the data and the results of the research.

At this writing, only a partial analysis of the data collected has been completed due to complexity and enormity of the data base. Much but not all of the ASL-sponsored data has been received but certain items (as explained below) still have not been obtained. As a result, no model/data comparisons have been made at this time with smoke data. A summary of the findings to date as well as a status of the data base will now be presented.

No significant differences were found in the fog oil tests relating to source characteristics, chemical characteristics of the smoke, vapor/liquid partitioning, and particle-size distribution between the Meadowbrook and Camp Atterbury tests. All such data collection and analysis were the responsibility of the University of Illinois and ANL and those data have been completely reduced. The smoke concentration and aerosol photometer data were also completely reduced with the following interesting results obtained:

(a) fog-oil smoke plume dispersion under stable conditions at Meadowbrook leads to relatively slow mixing between about 200 m downwind and 1.0 kilometers downwind (only 50% reduction in average concentrations over these distances). The presence of narrow walls to the valley leads to limited lateral mixing. The very stable atmospheric conditions leads to very little vertical mixing. The combination of the two results in very small mixing until the plume can resume its lateral mixing as the valley opens up into the larger prairie at about 1.0 km from the source.

(b) fog-oil smoke plume dispersion under unstable conditions at the Meadowbrook site is very rapid, leading to a rise in the plume centerline from immediately at the smoke generator to about 250 m from the smoke generator. The thermal dominated structure of the convective boundary layer is the cause of this smoke rise. Heat flux from the warm ground is mostly in the form of hot thermals which rise at relatively high velocities. Gaussian puff models generally assume that puff centerlines remain at the elevation of their release. Such models cannot predict the rapid decrease in centerline concentrations that occur at ground level after the rise of the centerline has occurred. A stochastic model which accounts for this

Stable Tests Designation:	0924871	0927871	0927872	0930871	1001871	1002871	1003871
Source Information							
Test Date	24-Sep-87	27-Sep-87	27-Sep-87	30-Sep-87	1-Oct-87	2-Oct-87	3-Oct-87
Begin Test (CDT)	00:18:00	03:17:40	06:44:00	06:47:30	06:52:00	07:17:00	06:56:00
End Test (CDT)	01:03:30	03:41:00	06:55:40	07:28:00	07:32:05	07:47:00	07:27:00
Transects in Operation	S1|2|3|4|5	S1|2|3|4|5	S1|2|3|4|5	S1|2|3|4|5|U3	S1|2|3|4|5|U3	S1|2|3|4|5	S1|2|3|4|5|U3
Mass Released (kg)	109.0	53.4	18.9	96.0	70.7	73.7	52.0
Release Time (min)	45.5	23.33	11.66	40.5	40.08	40	30
Rate of Release (g/s)	39.9	38.1	27.0	39.5	29.4	30.7	28.9
2 m Wind Velocity (m/s)	1.3	1.5	1.6	1.9	2.0	1.5	1.9
2 m Wind Direction (°E of N)	104	109	108	117	118	112	137
2 m Sigma-theta (°)	14.3	10.4	5.8	12.8	19.5	10.7	15.7
2 m Ambient Temp (°C)	13.9	9.3	7.5	14.0	15.8	15.0	16.4
2 m Relative Humidity (%)	63	32	39	21	22	35	41

Unstable Tests Designation	0921871	0923871	0926871	0928871	1002872
Source Information					
Test Date	21-Sep-87	23-Sep-87	26-Sep-87	28-Sep-87	2-Oct-87
Begin Test (CDT)	14:30:00	14:05:00	12:00:00	10:29:00	12:16:00
End Test (CDT)	15:00:00	14:50:00	13:06:40	10:53:00	12:36:00
Transects in Operation	U1|2|3	U1|2|3	U1|2|3	U1|2|3	U1|2|3
Mass Released (kg)	–	63.4	181.2	49.1	34.1
Release Time (min)	30	44.83	66.3	24	20
Rate of Release (g/s)	–	23.6	45.6	34.1	28.4
2 m Wind Velocity (m/s)	–	0.7	4.8	1.9	1.9
2 m Wind Direction (°E of N)		304	304	278	208
2 m Sigma-theta (°)	–	55.5	16.3	15.6	25.3
2 m Ambient Temp (°C)	–	–	26.7	27.7	31.6
2 m Relative Humidity (%)	–	–	22	12	14

Notes

1. All values are averaged over the period BEGIN-10 to END+10 minutes.
2. Source data for test 0921871 was lost due to computer failure.
3. Only last 9 minutes of source data record is available for test 0928871.

Table 3.1. Selected meteorological data and test information averaged over test durations for complex terrain field tests for fog oil at Red Bluff, California.

convective turbulence has been shown to predict this rising plume centerline phenomenon for the Camp Atterbury trials. Such a model when applied to the Meadowbrook site (and suitably modified for complex terrain applications) should predict the convective plume rise there as well.

At this writing, the surface station meteorological data (at the 10-m level) has been received from ASL and has been partially reduced and is undergoing validation. A total of twelve 10-m surface stations were deployed at the Meadowbrook site by three organizations. These data have been received and are currently being analyzed for stability as a function of terrain position. The meteorological data from the 32-m tower has also been received, but has not been analyzed. We are awaiting the transfer of the turbulence measurements made by Riso National Laboratory and their 350 aerial photographs of the plumes. These sequenced aerial photographs were taken for all daytime releases and provide the basis for obtaining quantitative information on plume visibility. These photographs have three potential uses:

(a) They can be used in a qualitative manner to better understand the mechanisms of plume dispersion which cannot be readily discerned from our pointwise measurements

(b) They can be used to obtain visible plume outlines from which plume trajectory and spreading can be determined, and

(c) They can be scanned to obtain vertically integrated visibility contours. These contours can potentially be used with our real-time data taken at a fixed height above the ground to infer information on plume structure.

Upper air data taken during the study have been received but not analyzed. Several times during the study, pibal (pilot balloon) releases were made to determine the structure of the upper atmosphere at the site. These data have been received but they have not been analyzed at this time. These data will be used to establish the vertical structure, and indirectly the stability, of the atmosphere. Mixing height data for the test periods is still to be obtained.

Once all data have been obtained and analyzed, model/data comparisons will be made to determine if existing complex terrain plume models (predicting the wind field as well as the concentration field) can predict the plumes observed at the Meadowbrook site.

4.0 FIELD CHARACTERIZATION OF HC SMOKE IN FLAT TERRAIN

Five field experiments were carried out at Camp Atterbury during November 1987 to study the chemical properties and the dispersion characteristics of HC (hexachloroethane) smoke in flat terrain. Key information about the tests are summarized in Table 4.1. At this writing, all data samples have been reduced and archived and the corresponding source and meteorological data have been reduced. No model/validation work has been carried out at this time. A summary of the findings from these five HC tests are as follows:

4.1. Source Characteristics of the HC Smoke Pot Emissions

In the five dispersion tests, approximately 20 pots were burned per test. Smoke temperatures at exit from the pots varied considerably with time from about 100 deg C to as high as 650 deg C. The smoke exit temperatures also depended upon the number of pots burning; as an additional pot would be ignated from the one above, the smoke temperature would increase. The precise mechanism causing this increasing smoke temperature is not clear at this time. Average release rates of zinc and aluminum were estimated from measurements of the zinc and aluminum content of the pots before and after the tests.

4.2. Sampling Methodology for the HC Smoke Plume

A very similar methodology was used for HC data collection as was used for the particulate and vapor phase of fog oil. The particulate phase was collected using aspirated filter cassettes using 37 mm cellulose ester filters. The vapor phase was collected (12 samples) using aspirated Tenax-filled stainless steel tubes. The Tenax polymer adsorbent tubes were fronted by a cellulose filter to remove particulates

Table 4.1. Selected meteorological data, test information, and scaling parameters averaged over test durations for flat terrain field tests for HC smoke.

Test Designation	1109871	1110871	1110872	1112871	1113871
Date	11/9/87	11/10/87	11/10/87	11/12/87	11/13/87
Begin Test (CDT)	15:45:00	11:27:30	16:37:41	13:31:20	10:21:00
End Test (CDT)	16:10:00	12:04:00	17:25:00	14:17:00	11:04:00
Duration (minutes)	00:25	00:36	00:47	00:45	00:43
Source Meteorological Measurements					
Location (see map, figure 2):					
x (m)	270.3	270.3	270.3	-21.1	-21.1
y (m)	470.8	470.8	470.8	21.1	21.1
2 m Wind Velocity (m/s)	2.3	3.6	2.5	1.9	1.9
2 m Wind Direction (°E of N)	12	26	13	220	221
2 m σ_θ (°)	18.7	19.7	19.9	28.6	31.2
2 m Ambient Temp (°C)	5.9	3.2	3.0	13.8	12.9
2 m Relative Humidity (%)	69	61	49	35	45
Met Tower Measurements					
10 m Wind Velocity (m/s)	4.4	7.1	5.2	4.9	4.3
10 m Wind Direction (° E of N)	25	34	24	226	241
10 m σ_θ (°)	11.0	13.2	14.4	15.3	15.5
10 m σ_ϕ (°)	8.0	9.3	8.3	9.8	9.9
10 m σ_u (m/s)	1.03	1.74	1.28	1.32	1.08
10 m σ_v (m/s)	0.80	1.63	1.22	1.34	1.15
10 m σ_w (m/s)	0.75	1.41	0.93	0.94	0.83
10 m - 2 m ΔT (°C)	-0.68	-0.95	-0.70	-0.76	-0.74
Cloud Cover	heavy overcast	medium overcast	mostly cloudy	clear	clear
Reduced Met Data and Estimated Scaling Parameters					
Wind Power Law Exponent	0.130	0.132	0.132	0.121	0.137
Obukhov Length, L (m)	-5	-5	-5	-5	-5
Friction Velocity, u_* (m/s)	0.728	1.207	0.874	0.819	0.713
Roughness Height, z_0 (m)	0.20	0.20	0.20	0.20	0.20
Inversion Height, z_i (m)	700	700	700	700	700
Convection Velocity, w_* (m/s)	1.87	3.54	2.32	2.59	2.29

and aspirated at 100 ml/min over the test duration. Meteorological data involved profiles of temperature, wind speed, wind direction, and turbulence (sigma-theta and sigma-phi) at four levels of a 10-m met tower. Source data included smoke temperature as a function of time and mass release rates of the various elements in the pots. The same sampling apparatus was used for the HC tests as the fog oil tests: 8-m masts with samplers located at the 1-m, 2-m, 4-m, and 8-m levels.

4.3. Chemical Analysis Method Used to Analyze the HC Vapor and HC Particulate Phases of the Smoke

The vapor phase was analyzed using gas chromatography methods which employ a separating column. The vapor analysis was focused on four compounds identified by USABRDL as alleged carcinogens: tetrachloromethane, tetrachloroethylene, hexachlororethane, and hexachlorobenzene. For the particulate phase, several different methods were used. All 912 filter samples were analyzed for Al and Zn using the inductively coupled argon plasma atomic spectrometer technique (ICAP-AES) with normal aqueous aerosol sample introduction. However, 22 filters were analyzed for six elements and six anions using four different techniques:

(a) Al, Cd, Pb, and Zn using the ICAP-AES technique with normal aqueous aerosol introduction,

(b) Hg using cold vapor atomic absorption technique,

(c) Arsenic using the ICP-hydride technique, and

(d) the anions using the ion chromatography technique.

Finally, 10 filters were analyzed for 40 elements and six anions using the four techniques described directly above :

(1) Hg using the cold vapor atomic absorption technique,

(2) Arsenic and Se using the ICP-hydride technique,

(3) the six anions using the ion chromatography technique, and

(4) the remaining 37 elements using the ICAP-AES technique with normal aqueous aerosol sample introduction.

4.4. Chemical Characteristics of the HC Vapor and HC Particulate Phases of the Smoke

The chemical composition of the vapor and aerosol phases are consistent with previous laboratory studies. The organic vapor phase contains possible carcinogens. The inorganic particulate phase is principally made of zinc and aluminum compounds. There is some uncertainty as to whether the metal particle is surrounded by water.

4.5. Vapor/Liquid Partitioning of the HC Smoke

All of the field samples were found to contain with very small quantities of vapor, and the scatter among the samples is high. The most heavily dosed sample had the following ratios of vapor mass to zinc: tetrachloromethane (0.10), tetrachloroethylene (0.05), hexachloroethane (0.05), and hexachlorobenzene (0.26). Up to 35 peaks (different compounds) were seen in that chromatogram. A more detailed analysis of these peaks was not requested in our study. For the other 11 chromatograms in the data set, the shape and ratio of the set of resolved peaks varied considerably between the different samples.

4.6. Particle Size Distribution of the HC Smoke

The particle-size distribution is roughly log-normal with mass median aerodynamic particle size of 0.8 +/- 0.1 microns with a geometric standard deviation of 2.2 +/- 0.3 microns. The IITRI lab study indicated 0.2 to 0.4 microns. PNL measured particle sizes in the 1.5 - 2.0 micron range. The differences in results between the two laboratory studies and between the lab and field tests is presently unexplained but not unexpected. Characteristics of smoke may very well depend on burn configuration and ambient conditions. Diagnostic laboratory studies may be able to isolate these effects, although the considerable difficulty in reproducing actual smoke pot behavior in the laboratory must first be overcome.

4.7. Average Concentration (Dosages) and Plume Behavior for HC Smoke

For the five HC dispersion tests, plots of mean zinc concentration, in mg/m^3 along each sampling transect have been prepared. Those concentrations are averages over the period of the test. A study of these data indicates that crosswind integrated concentration of zinc agrees with simple plume model predictions within a factor of 2 for distances of about 350-400 m downwind. The purpose of the predictions described above was to provide a simple check on the internal consistency of the HC particulate data.

4.8. Concentration Fluctuations, Deposition, and Plume Visibility for the HC Smoke Plume

Data were obtained on concentration fluctuations as they vary with time at different distances from the source. Such data have been reduced, validated, and archived but not analyzed in depth at this time. No measurements of deposition or plume visibility were made during these five HC tests. However, no deposition was seen by eye after the tests were completed.

4.9. Mathematical Modeling of HC Smoke Plumes

No models have been tested with these data as of this writing. It is intended that time-dependent Gaussian puff models (with plume rise) would be compared with these five data sets in the future.

5.0 REVIEW OF RESULTS OF FIELD TESTS AND MATHEMATICAL MODELING

Field tests were carried out at Dugway Proving Ground (flat terrain, fog oil, 3 tests), Camp Atterbury (flat terrain, fog oil, 4 tests; HC smoke, 5 tests) and at Meadowbrook (complex terrain, fog oil, 12 tests). The chemical characterization of the fog oil and HC smokes as well as their dispersion characteristics have been studied.

For some smoke variables, field characterizations agreed with laboratory results and for other parameters, there were differences. The chemical characterization of the fog oil smoke in the field revealed that

(a) droplet sizes are consistent with laboratory measurements of a mass median diameter of about 1 micron,

(b) the vapor phase is essentially nonexistent with a mass contribution of less than 1% as compared to a 99% contribution of the particulate phase for the test conditions observed,

(c) the particulate phase of the smoke acts like a tracer in its dispersion characteristics at least to the downwind distances measured,

(d) no deposition was measured beyond about 50 m from the smoke generator, and

(e) standard deviation in concentration can vary from 2 times the local mean value at the plume centerline to 15 times the local mean at the plume edge.

The chemical characterization of the HC smoke in the field revealed that

(1) particle sizes have mass median aerodynamic particle sizes between 0.5 and 1.0 microns,

(2) all field samples were found to contain very small quantities of vapor, and scatter among the samples was high,

(3) up to 35 different compounds were seen in the organic vapor phase,

(4) the inorganic particulate phase was made principally of zinc and aluminum compounds -- 34 of 47 elements and cations tested in the particulate samples were actually identified, most in trace amounts.

Although the Gaussian models tested with the fog-oil data indicated general agreement with the data within a factor of 2-3 for the average concentrations measured, there were problems with the models (under these largely unstable atmospheric conditions) in that

(i) such agreement was only within the first 250 m from the smoke generator with more significant discrepancies at further distances,

(ii) there is a tendency to significantly overpredict at distances greater than about 250 m. The discrepancies found at longer distances (greater than about 250 m) is due to a rise in the plume centerline, and

(iii) the decay of concentration with distance as predicted by the models does not agree with the data and may be assumed to be the result, in part, of the rising centerline seen in the observed plume. The rising centerline phenomenon has been observed in other field and laboratory studies and cannot be replicated by these Gaussian models. A new stochastic model tested with the data seems to represent the systematic behavior in the data (including the rising centerline) quite well.

Future work is planned involving two main areas,

(a) Meadowbrook site data reduction -- plume and meteorology

This work involves an in-depth evaluation of the AMADEUS field data, both the smoke data and the supporting meteorological data. The aerial photographs and the tracer data provide a useful complement to the smoke concentration data and will also be studied.

(b) model verification and improvement using the Meadowbrook, Camp Atterbury, and Dugway data sets

Promising models for dispersion over complex terrain will be tested with the Meadowbroook fog-oil data In addition, the HC data sets at Camp Atterbury will be tested with model predictions for HC smoke dispersion in flat terrain. Systematic deficiencies in comparisons with the complex terrain and flat data will be corrected through development of an improved model. The ultimate goal will be the development of a PC Model for flat and complex terrain applications. The PC Model would be a state-of-the-art atmospheric dispersion model which executes rapidly on a fieldable personal computer, and provides a variety of alternative output operations emphasizing graphical displays of various kinds. A major emphasis is placed on incorporating the latest advances in modeling technology (with empirical simplifications where necessary) into the model.

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