

EFFECT OF HOMOGENEOUS AND HETEROGENEOUS SURFACE ROUGHNESS ON HEAVIER-THAN-AIR GAS DISPERSION

Volume I

API PUBLICATION NO. 4491
HEALTH AND ENVIRONMENTAL SCIENCES DEPARTMENT
MARCH 1989

American Petroleum Institute
1220 L Street, Northwest
Washington, DC 20005



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Effect of Homogeneous and Heterogeneous Surface Roughness on HTAG Dispersion

Volume I

Prepared for the American Petroleum Institute
1220 L Street, NW
Washington, DC 20005

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March 1989

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EXECUTIVE SUMMARY

Numerical and advanced similarity models that are used to estimate the concentrations for heavier-than-air gas (HTAG) releases have only been tested against field data sets collected in flat homogeneous terrain. The models appear to predict reasonably well for that situation. Most HTAG releases for the petroleum industry will, however, be in industrial-type settings where the roughness elements are large and generally heterogeneous within the plant and then homogeneous or heterogeneous beyond the plant boundary. Because the models have not been evaluated for "real-world" applications of interest, the American Petroleum Institute's Air Modeling Task Force initiated this study to evaluate the effects of homogeneous and heterogeneous surface roughness on HTAG dispersion and to provide a data base for testing and refining numerical and advanced similarity models.

An initial set of tests was conducted to document the validity of the wind tunnel simulation method. One set of these tests demonstrated that the results in the wind tunnel were repeatable and that the concentrations measured in the wind tunnel were steady state averages with a corresponding full scale averaging time from 2 to 20 minutes. Another set of tests demonstrated that the dispersion of wind-tunnel-simulated neutrally buoyant plumes under stable and neutral stratification compared favorably with the dispersion observed to occur in the atmosphere for similar surface roughness conditions. Tests were also conducted to simulate two of the Thorney Island continuous release trials. The two trials simulated did not have any obstructions present, the wind speeds were low and the atmospheric stratification was neutral for one case and stable for the other. The wind tunnel measurements with a neutral and stable atmospheric boundary-layer simulation compared well with respective field observations.

To meet the primary study objectives, ground-level, point and area source releases of heavy and neutrally buoyant gases with relative densities (cloud to ambient) ranging from 1 to 4.2 were simulated in the wind tunnel. The point source was horizontally directed with the wind direction and the area source was vertically directed. Full scale mass release rates ranged from 0.2 kg/s to 250 kg/s, release Richardson numbers ranged from 0 to 1000, and homogeneous roughness configurations ranged from grassland (z_o of 3 cm) to a city (z_o of 50

cm). Heterogeneous roughness configurations were also simulated in the form of a generic tank farm and refinery or chemical process unit. Neutral stratification was simulated for the majority of the tests with the balance of the configurations set up to simulate stable stratification.

The concentration measurements obtained downwind of the point and area source releases demonstrated that increasing homogeneous or heterogeneous surface roughness decreases the concentrations for a fixed 10 m wind speed and atmospheric stability. The concentrations downwind of a process unit located in an urban area were found to be from 8 to 25 times less than those if the release were over a grassy plain between 300 and 800 m. The concentrations downwind of a tank farm located in a urban area were found to be from 3 to 8 times less than those over a grassy plain for the same distance range. Smaller reduction factors resulted when the process unit and tank farm were located in a grassy plain. For D stability, the largest reduction factors were observed for the dense clouds, and for F stability, the largest reduction factors were observed for neutrally buoyant clouds. For a homogeneous roughness typical of an urban area, concentration reductions ranged from 2.5 to 6 for the downwind distance range 300-800 m. For all roughness types, the concentration reduction factors tended toward lower values within 300 m of the release.

Simple equations were developed for predicting the nearfield concentration, plume height and plume width downwind of a point source and area source release in a homogeneous roughness, an area source release upwind of a tank farm, and an area source release near a process unit. The concentrations predicted with the equations agreed well with observations.

The analysis also showed that the vertical entrainment estimated from the wind tunnel measurements compared well with the entrainment values predicted using the equations in the SLAB and DEGADIS models (advanced similarity models frequently used for predicting the concentrations of HTAG clouds) for homogeneous roughness configurations to include the tank farm. The observed vertical entrainment values did not compare well with SLAB/DEGADIS predictions for HTAG releases near the process unit.

The SLAB and DEGADIS models were run using the inputs necessary to simulate various wind tunnel data subsets. A comparison of model centerline predictions with observations showed that the models agreed within a factor of two for point and small area source releases

in a homogeneous surface roughness with a tendency for the models to underpredict for the cases with the largest initial cloud density or initial Richardson number. This trend was particularly evident for the DEGADIS model and the large area source (the source with the largest initial Richardson numbers). Both models gave reasonable estimates (although not as good as the homogeneous roughness cases) out to the farthest distance measured (800 m) for a release upwind of a tank farm and near a process unit for stable and neutral stratification. The results of the model comparisons with the observations for the heterogeneous roughness cases (tank farm and unit) were sensitive to the assumed value of surface roughness height that was input. Surface roughness lengths of 0.45 and 0.7 m for the tank farm and process unit gave agreement that was generally within a factor of two out to 800 m.

PROJECT CHRONOLOGY

Contract initiation -- the official start date for Phase 1 of the contract was December, 1986. After reviewing the results of Phase 1, Phases 2 and 3 were initiated with an official start date of September 21, 1987.

Test plan development -- early in the project, a test matrix was proposed to the air modeling task force. Initially, the prime focus of the measurement program was on entrainment rates and near field dispersion (within 200 m) for homogeneous and heterogeneous roughness. For the final phase of testing, the focus of interest changed to far field dispersion and heterogeneous roughness.

Refinery visit -- before constructing typical refinery structures (heterogeneous roughness) the Texaco Refinery in Port Arthur, Texas was visited (October, 1987) by Dr. R. L. Petersen. Lee Gilmer of Texaco conducted the tour during which time photographs of typical chemical and refinery structures were obtained.

Model construction -- after the site visit, a 1:100 model of a typical tank farm and typical refinery or chemical unit was constructed. Also homogeneous roughness element configurations were constructed to simulate full-scale z_0 values of 3, 20 and 50 cm.

Wind-tunnel testing -- A total of 161 wind tunnel tests were conducted with the following breakdown: neutral homogeneous roughness tests -- 67; stable homogeneous roughness tests -- 16; neutral heterogeneous roughness tests -- 45; stable heterogeneous roughness tests -- 23; field/wind-tunnel comparison tests -- 3; continuous measurement tests -- 7. Mass release rates varied from 0.25 to 240 kg/s and initial relative cloud densities varied from 1 to 4.2. Atmospheric stratification varied from neutral to stable and wind speeds of 3 and 5 m/s were simulated. The surface roughness varied from grassland ($z_0 = 3$ cm) to a large process unit ($z_0 = 70$ cm).

Independent review of preliminary results -- at the completion of Phase 2 of testing (approximately halfway through the wind-tunnel tests), Drs. T. O. Spicer (University of Arkansas), D. E. Ermak (Lawrence Livermore Laboratory) and W. F. Snyder (Environmental Protection Agency) reviewed the results to date and the analysis plan. A meeting was held in March, 1988 with Drs. Spicer, Ermak and Petersen and Dan Van Der Zanden (Chevron and air modeling task force representative) at CPP's office in Fort Collins to discuss the results of the review. Dr. Snyder's comments were obtained by telephone. After addressing and discussing all comments with the air modeling task force, Phase 3 of wind tunnel testing was initiated.

Preparation of discussion draft -- approximately halfway through the wind tunnel testing program, a discussion draft report was prepared to obtain task force members' comments and to aid in the independent review.

Analyses -- during the course of the study, data were processed and analyzed as the test data were collected. The basic analyses that were performed included the following: comparison of average and continuous concentration measurements; demonstration of dispersion comparability for the wind tunnel; velocity/temperature profile characterization; field/wind tunnel comparisons; entrainment calculations and comparisons with SLAB and DEGADIS entrainment formulations; plots generated of C , σ_y , σ_z versus x to demonstrate the effects of roughness; SLAB/DEGADIS/wind-tunnel comparisons; development of empirical equations for predicting concentrations and dispersion rates of heavy gases released in a uniform and heterogeneous type roughness.

Meetings and reporting -- Dr. Petersen met with the air modeling task force on a regular basis during the course of the project. At the meetings, the results to date were presented and plans were developed for future activities. A draft was prepared and submitted to the task force at the conclusion of testing (August 1988) for review and comment prior to the submission of this final report.

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LIST OF SYMBOLS

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
A	Calibration Constant	(-)
B	Plume Width	(m)
B_{eff}	DEGADIS Plume Width	(m)
B_o	Buoyancy Ratio	(-)
β	Molecular Diffusivity	(m ² /s)
C	Concentration	(ppm or $\mu\text{g}/\text{m}^3$)
C_o	Tracer Gas Source Strength	(ppm or $\mu\text{g}/\text{m}^3$)
C_s	Concentration of Calibration Gas	(ppm or $\mu\text{g}/\text{m}^3$)
D	Stack Diameter	(m)
δ	Boundary-Layer Height	(m)
Δ	Difference Operator	(-)
$\Delta\theta$	Potential Temperature Difference	(K)
E	Voltage Output	(v)
Fr	Froude Number	(-)
γ	Density Ratio	(-)
g	Acceleration Due to Gravity	(m/s ²)
g'	Acceleration Due to Gravity Times Density Ratio	(m/s ²)
h	Plume Height As Defined in SLAB	(m)
H_b	Building or Roughness Height	(m)
H_{eff}	Effective Plume Height As Defined in DEGADIS	(m)
I	Gas Chromatograph Response to Tracer Gas	(v)
I_{bg}	Gas Chromatograph Response to Background	(v)

LIST OF SYMBOLS (continued)

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
I_s	Gas Chromatograph Response to Calibration Gas	(v)
i_x, i_y, i_z	Turbulence Intensity in the x, y, or z direction	(-)
λ	Relative Density	(-)
M_o	Momentum Ratio	(-)
μ	Viscosity	(m ² /s)
n	Calibration Constant, Power Law Exponent	(-)
ϕ_m	Similarity Function for Momentum	(-)
ϕ_h	Similarity Function for Heat Transfer	(-)
Q	Initial Mass Flow Rate	(kg/s)
Q_i	Mass Flow Rate at Location i	(kg/s)
ρ_a	Density of Ambient Air	(kg/m ³)
ρ_s	Density of Release Gas	(kg/m ³)
R	Velocity Ratio	(-)
Re_b	Building Reynolds Number	(-)
Re_s	Effluent Reynolds Number	(-)
Re_k	Roughness Reynolds Number	(-)
Re_z	Surface Reynolds Number	(-)
Ri	SLAB Richardson Number	(-)
Ri^*	DEGADIS Richardson Number	(-)
Ri_a	Ambient Richardson Number	(-)
Ri_o^*	Release or Initial Richardson Number	(-)
σ_y, σ_z	Horizontal and Vertical Dispersion Coefficients	(m)
t	Time	(s)
T	Mean Temperature	(K)

LIST OF SYMBOLS (continued)

<u>Symbol</u>	<u>Definition</u>	<u>Units</u>
T_a	Ambient Temperature	(K)
T_s	Exhaust Temperature	(K)
U	Mean Velocity	(m/s)
U_{10}	Wind Speed at 10 m height	(m/s)
U_*	Friction Velocity	(m/s)
U'	Longitudinal Root-Mean-Square Velocity	(m/s)
U_∞	Free Stream Wind Velocity	(m/s)
U_{eff}	Cloud Speed As Defined in DEGADIS	(m/s)
U_h	Velocity at Cloud Height	(m/s)
U_m	Matching Velocity	(m/s)
U_{max}	Maximum wind speed	(m/s)
U_r	Wind Speed at Reference Height and Location	(m/s)
U_s	Exit Velocity	(m/s)
v	Arbitrary Variable	(-)
V	Volume Flow Rate or Lateral Velocity	(m ³ /s)
W'	Vertical Root-Mean-Square Velocity	(m/s)
x,y,z	Cartesian Coordinates	(m)
x_v	Virtual Source Distance	(m)
y	Plume Center of Mass in y Direction	(m)
y_o	Offset in the y Direction	(m)
z	Height Above Local Ground Level	(m)
z_o	Surface Roughness Factor	(m)
z_∞	Free Stream Height - 600 m above ground level	(m)

LIST OF SYMBOLS (continued)**Subscripts**

m	pertaining to model
f	pertaining to full scale

Abbreviations

R3	Target 3 cm z_o and uniform roughness
R20	Target 20 cm z_o and uniform roughness
R50	Target 50 cm z_o and uniform roughness
Tf3	Tank farm with 3 cm z_o and uniform roughness up- and downwind
Tf50	Tank farm with 50 cm z_o and uniform roughness up- and downwind
Rf3	Process unit with 3 cm z_o and uniform roughness up- and downwind
Rf50	Process unit with 50 cm z_o and uniform roughness up- and downwind
WD1,WD2,WD3,WD4 suffix denotes wind direction and release location as defined in Figure 2-5	
PG	Pasquill-Gifford Stability Category
SA	Small Area Source
LA	Large Area Source

ACKNOWLEDGEMENTS

The study was accomplished through the coordinated efforts of the following CERMAK PETERKA PETERSEN, INC. staff members:

Dr. Ronald L. Petersen	Principal Investigator
Dr. Michael A. Ratcliff	Project Engineer/Scientist
Mr. Steve Mike	Model Construction/ Data Acquisition
Mr. Lee Tierney	Data Processing
Mr. John Greg	Data Collection
Mr. Dan Rayburn	Drafting
Ms. Janna Arras	Drafting
Ms. Delores Roccaforte	Technical Typing

1.0 INTRODUCTION

Current numerical models that are used for estimating the concentrations of heavier than air gas (HTAG) releases have only been tested against field and wind tunnel data bases with small surface roughness. A review of the literature conducted by Petersen (1987) revealed that data bases with large surface roughness are not generally available or the roughness configuration is not appropriate for petroleum industry applications. Since the petroleum industry is interested in accurate predictions of HTAG concentrations in the vicinity of facilities with a wide variety of structure heights and shapes, the American Petroleum Institute's Air Modeling Task Force initiated this study to develop a data base that includes the effect of large surface roughness elements on HTAG dispersion.

The purpose of this study was to obtain a set of data that can be used to expand the understanding concerning the effect of surface roughness on HTAG dispersion and that can be used for testing, refining and validating numerical or advanced similarity models. A secondary purpose was to compare the concentrations predicted using the SLAB and DEGADIS models with the concentrations measured in the wind tunnel under a wide range of release and surface roughness conditions.

The complete study consisted of three phases. Phase I was reported on by Petersen (1987) and consisted of a review of past work on surface roughness and an assessment of the assumed entrainment algorithms in the SLAB and DEGADIS models. This report discusses the results of the remaining two phases. During Phase 2, preliminary tests were conducted under neutral atmospheric stratification to help refine the sampling methodology and to document wind-tunnel dispersion comparability with the atmosphere. Thereafter, testing was conducted to measure the effect of homogeneous (uniform) and heterogeneous (non-uniform) surface roughness on HTAG dispersion under neutral stratification due to point source, small area source and large area source releases with initial relative densities (cloud to ambient) of 1, 1.4 and 4 and initial cloud Richardson numbers ranging from 0 to 1000. The uniform surface roughness simulated full scale z_0 values nominally ranging from 3 to 50 cm (grassy plain to an urban area with 3 to 4 story structures). The heterogeneous roughness cases

simulated a typical refinery tank farm and a generic refinery or chemical process unit (hereafter referred to as the process unit). Phase 3 consisted of additional testing of the point and small area sources to assess the effect of flow rate, exit velocity, wind speed, wind direction and ambient stability.

For all tests, concentrations due to the various simulated releases were measured in ground level and vertical arrays and subsequently converted to full-scale concentrations. The data were then analyzed to determine the effect of surface roughness on HTAG dispersion, to test the entrainment relations in SLAB and DEGADIS and to test the performance of SLAB and DEGADIS.

Section 2 discusses the wind tunnel modeling approach. Section 3 follows with a discussion on the effects of roughness on HTAG dispersion. The results of concentration measurements are shown in Section 4. Model versus wind tunnel observations are discussed in Section 5, followed by overall conclusions in Section 6. Appendices A through F are included in this volume of the report and deal with the following: experimental methods, comparison of laboratory and field experiments, atmospheric dispersion comparability, documentation tests, method for calculating Monin Obukhov length from temperature and wind data and listing of calculated entrainment and dispersion values. Volume II of the report contains Appendices G through L which deal with the following: concentration time series, concentration data tabulations, vertical and lateral concentration profiles, velocity and temperature profiles, temperature measurements for stratified flows and calibration information.

2.0 WIND TUNNEL MODELING APPROACH

2.1 Similarity Requirements and Conditions Simulated

To assess the effects of surface roughness on HTAG dispersion in the wind-tunnel, certain similarity criteria must be met. Appendix A provides a detailed discussion on the derivation of the relevant similarity criteria and the reasons certain criteria can be neglected. Based on the discussions in the Appendix, past CPP fluid modeling experience (Petersen, 1985; 1986), and Meroney (1986), the following summarizes the criteria that were used to conduct this study:

- match (equal in model and full scale) velocity ratio, R

$$R = U_s/U_{10};$$

- match density ratio, γ

$$\gamma = (\rho_s - \rho_a)/\rho_a;$$

- match densimetric Froude number, Fr

$$Fr = U_s/(g\gamma D)^{1/2}, \quad (2-1)$$

- insure fully turbulent boundary layer -- Roughness Reynolds number ($Re_{H_b} = H_b U_* / \nu$) greater than 70 or dispersion comparability and field/wind tunnel comparison tests to evaluate adequacy of simulation methods;
- maintain a Peclet/Richardson ($Pe^*/Re^* = U_*^3/[g\gamma\beta]$) number ratio greater than 0.5 or dispersion comparability and field/wind tunnel comparison tests;
- similar geometric dimensions;
- equivalent Richardson-number or atmospheric stability;
- equality of dimensionless boundary and approach flow conditions;

where

U_s	=	exhaust gas velocity (m/s),
U_{10}	=	ambient wind speed at 10 m (m/s),
U_*	=	friction velocity (m/s),
D	=	exhaust diameter (m),
H_b	=	roughness height (m),
ρ_s	=	exhaust gas density (kg/m ³),
ρ_a	=	ambient density (kg/m ³),
β	=	molecular diffusivity (m ² /s), and
ν	=	viscosity (m ² /s).

It should be noted that heat transfer effects were not simulated and an isothermal plume was utilized for the HTAG experiments.

The range of full scale conditions that were simulated is summarized below:

Release Types	- Point source at ground level directed with the wind - Small (5 m diameter) area source with low momentum directed vertically - Large (22 by 22 m) area source with low momentum directed vertically
Homogeneous Surface Roughness Lengths (z_0 - cm)	- 3, 20 and 50
Heterogeneous Roughness Types	- process unit and tank farm
Atmospheric Stability	- D and F
Wind Speeds (U_{10} - m/s)	- 3 and 5.6
Mass Release Rates (Q - kg/s) • Point Source • Area Sources	- 0.25 to 28 kg/s - 11 to 250 kg/s
Relative Cloud Densities (λ)	- 1, 1.4 and 4
Release Richardson Numbers (Ri^*_0) • Point Source • Area Sources	- 0 to 1000 - 0 to 900

The conditions selected represent the range of typical source and meteorological conditions that would be expected for petroleum industry applications.

Using the above scaling requirements, model conditions were computed for each condition simulated. The model and full scale parameters for point and area source simulations with homogeneous roughness, a 5.6 m/s wind speed, relative density of 4 and neutral stratification are given in Tables 1a through 1g. Tables 2a through 2g show similar tables for the stable stratification simulations. The tables would be similar for other relative densities except for all terms that use source density. The tables also provide the model to full scale conversion factors for each physical parameter. The conversions for speeds, lengths, volume flows and densities are summarized below:

$$\begin{aligned}
 U_m &= U_f/10, \\
 L_m &= L_f/100, \\
 V_m &= V_f/10^5, \text{ and} \\
 \rho_m &= \rho_f.
 \end{aligned}$$

2.2 Wind Tunnel Test Plan

Tables 3a-b and 4a-b summarize the wind tunnel tests that were conducted as part of Phases 2 and 3 of the study. Tables 3a and 4a give the full scale parameters for each test and Tables 3b and 4b give the model parameters for each test. The tables identify the release type (point or area source), target z_o and/or roughness configuration, normalized friction velocity (U^*/U_{10}), volume flow rate, Pasquill-Gifford stability category, effective initial release height $(H_{eff})_i$, release diameter, relative density, release Richardson number and the downwind measurement locations. For all cases, including the heterogeneous roughness tests, the reported friction velocity is that measured in the surrounding homogeneous roughness.

The release Richardson number for the continuous releases was computed as follows (Meroney, 1986; Havens and Spicer, 1985):

$$Ri^*_o = g' (H_{eff})_i / U^{*2} \quad (2-2)$$

where

$$g' = g(\rho_s - \rho_a) / \rho_a \quad \text{and}$$

$$(H_{eff})_i = V / U_{10} / D. \quad (2-3)$$

According to Britter (1980) a plume would be passive if Ri^*_o was less than 1 and significant lateral and upwind spreading would occur for Ri^*_o greater than 10 and 40 respectively. These limits are for low momentum vertically directed releases and may not be appropriate for the horizontally directed point source releases evaluated in this study.

Phase 2 of the study was subdivided into the following study elements: 1) preliminary tests of point source releases in homogeneous roughness; 2) repeatability tests on item 1; 3) surface roughness tests examining homogeneous and heterogeneous roughness for point and area source releases; 4) field/wind-tunnel comparison tests for the Thorney Island experiments (McQuaid and Roebuck, 1984); and 5) continuous measurement tests to examine peak to mean ratios. The preliminary tests were conducted to verify that the concentration sampling technique and grid layout was adequate to define plume concentrations downwind of the release. The repeatability tests were conducted to obtain information on the expected reproducibility of the results. Thereafter a series of tests were conducted with various release and roughness configurations. Two of the Thorney Island experiments were then simulated (Trials 45 and 46). The results of the testing and comparison with the field are

given in Appendix B. Tests 55 through 61 were the only concentration measurements obtained with a continuous analyzer. These tests were conducted to give an indication of the time required for the mean concentration to be independent of averaging time and to give an indication of the peak to mean concentration ratio. The results of the analysis of this data set are provided in Appendix D.

The test scenario for Phase 3 is given in Table 4. This phase of the study was also divided into several study elements as follows: 1) uniform roughness stable tests for small area sources; 2) repeatability tests for small area sources under stable stratification; 3) point source volume flow/exit velocity tests; 4) wind speed tests for point sources; 5) small area source volume flow tests; and 6) final tests which tested wind direction sensitivity. The main goal of all tests except the final tests was to document dispersion rates of clouds in the region dominated by the cloud density (generally within 200 m of the release). For the final tests, measurements were taken to document the dispersion out to a downwind distance of 800 m.

The initial testing for both Phases 2 and 3 included a data set with uniform roughness ($z_o = 3$ cm) and a neutrally buoyant cloud for evaluating the comparability of the wind tunnel dispersion with that observed in the atmosphere. The results of this analysis, as reported in Appendix C, demonstrate that the horizontal and vertical dispersion coefficients observed in the atmosphere compare well with those modeled in the wind tunnel for Pasquill-Gifford D and F stability.

Appendix D summarizes the results of the repeatability tests, continuous concentration measurements and averaging time tests. The results of the analysis of all other tests is discussed in ensuing report sections.

2.3 Scale Models, Test Setup and Wind Tunnel

Homogeneous Roughness Model

A 1:100 scale model of three homogeneous surface roughnesses was constructed. The roughnesses were designed to obtain full scale z_o values of approximately 3, 20 and 50 cm (referred to as roughness configurations R3, R20 and R50). The 3, 20 and 50 cm z_o values are target values and the measured z_o values for each setup deviated from the target values.

Figures 2-1a through 2-1c show plan views of the roughness patterns used for the R3, R20 and R50 uniform roughness configurations and the relative location of the HTAG release. Figure 2d shows a second view of the R50 configuration that defines the different release locations used for testing (location LO was used for all tests except tests 81 through 85). For

testing under neutral stratification, the roughness elements were constructed of wood cubes (1.3, 1.9 and 5.1 cm) installed on 1.2 by 2.4 m (4 x 8 ft) plywood sheets at the relative locations shown in Figure 2-1. Figure 2-2a shows the R50 configuration installed in the wind tunnel.

For stable testing, 1.3 cm chain was used for the low surface roughness tests (R3 configuration) and two dimensional square roughness elements of thin aluminum sheets for the large roughness tests (R20 and R50 configurations). These roughness elements were installed on the aluminum tunnel floor so that the surface could be cooled to create a stable atmospheric boundary-layer. Plan views of the stable uniform roughness configurations are shown in Figures 2-1e through 2-1g. Tests were conducted with the aluminum roughness sections uncooled¹ to establish the surface roughness length. The resulting z_0 values were 0.2 cm, 17.6 cm, and 59.9 cm (also referred to as R3, R20, R50 roughness configurations). When interpreting the stable R3 test results, it should be noted that the actual surface roughness was significantly less than 3 cm (i.e., 0.2 cm).

Heterogeneous Roughness Models

The heterogeneous roughness models consisted of a tank farm and refinery or chemical process unit (referred to as the process unit). Figures 2-2b and 2-2c show photographs of each model, and Figures 2-3 and 2-4 show plan and elevation views of the models. The tank farm model consisted of 18 cylindrical tanks with a height of 9.1 m and diameter of 35.1 m spaced at 61 m center to center. Around each tank was a berm of 2 m height. For the process unit, the main pipe rack structure was 21 m high, 168 m long and 31 m wide. Several other structures surrounded this structure as shown in Figure 2-2c. Figures 2-5a through 2-5f show the different wind directions and source locations studied for the tank farm and process unit along with the concentration measurement locations.

Two wind directions were studied for the tank farm and 4 release locations/wind directions were studied for the process unit. Upwind of the tank farm and process unit, uniform roughness with target z_0 values of 3 and 50 cm was positioned. Downwind of the tank farm and unit, roughness was installed starting at the locations indicated in Figures 2-5a through 2-5f. The tank farm releases are referred to as Tf with a suffix indicating the type of upwind and downwind roughness (i.e., R3, R20 or R50) and the wind direction (WD1 or WD2). The process unit is designated by Rf with two suffixes. The first suffix refers to

¹ the surface roughness length does not vary with stability but is considered to be a property of the surface. Hence, use of the uncooled (neutral) wind tunnel setup is a valid approach for determining the z_0 for the stable boundary layer simulations.

release location/wind direction (WD1, WD2, WD3 or WD4) as shown in Figures 2-5c through 2-5f and the second refers to the type of upwind roughness.

Gas Release Model

Three different release types were simulated: a point source, small area source and large area source. The point source was a horizontal release at ground level from a 0.24 m diameter (0.24 cm in model) pipe. The small area release was also at ground level but was released in the vertical direction. The diameter of the release was 5 m (5 cm in model) and a series of fine screens were used inside the release to insure a uniform flow upon exit. The large area source consisted of a series of 9 small area releases arranged in a square array. The effective width of the array was 22 m.

Gas mixtures were released from the point and area sources at the locations indicated in Figures 2-1a through 2-2g for the homogeneous roughness tests and Figures 2-5a through 2-5f for the heterogeneous roughness tests. The relative location of the release point in the tunnel is indicated in Figure 2-6.

The gas mixtures, which are specified at the end of Tables 3 and 4, had relative densities of 1, 1.4 and nominally 4 (actual relative densities were 3.9, 4.0 and 4.2). The mixtures consisted of a tracer gas (ethane or propane) and other constituents (nitrogen, freon, argon or SF₆) mixed in appropriate proportions to give the desired initial gas density. A precision gas flow meter, calibrated with a soap bubble technique for each mixture, was used to monitor and regulate the rate of gas flow for each simulation.

Concentration Measurement Sampling Grid

Ground level sampling taps (brass tubes projected through the tunnel floor) were installed in horizontal rows 0.5 m (0.5 cm model) above the surface of the wind tunnel for neutral stratification. For stable stratification, the tubing could not be projected through the cold aluminum tunnel floor; hence, brass tubing (0.32 cm ID) was hung from an elevated platform so that the intake was approximately 0.5 m (0.5 cm in model) above the tunnel surface. The ground-level sampling arrays are shown in Figures 2-1 and 2-5 for the homogeneous roughness and heterogeneous roughness tests, respectively. Vertical sampling rakes with sampling taps at six or seven elevations were installed in the center of each horizontal sampling array. Not all downwind measurement locations were sampled for all tests. The coordinates of each measurement point are given with the measured concentrations in Appendix H. The coordinate system is defined with positive x in the direction of the wind, positive y to the left of positive x and positive z in the vertical direction.

Wind Tunnel Setup

Figure 2-7 shows the wind tunnel that was used for all testing, and Figure 2-6 is a schematic of the wind-tunnel test setup. For stable testing, the cold chamber beneath the wind-tunnel floor was filled with dry ice. A fan system then circulated the cold air to cool the aluminum surface and thereby generate a stable atmospheric boundary layer. Surface temperatures were measured at six locations along the surface of the aluminum and at 2, 10 and 30 m full scale near the release point. The temperature measurements for each stable run are given in Appendix K. In general, the surface temperatures were approximately -15°C and the ambient temperature about 15°C .

2.4 Data Acquisition, Data Analysis and Quality Assurance

The variable of prime interest in this study is the concentration of the cloud at any point in space as function of the wind speed (U), volume release rate (V), source concentration (C_0), source density (ρ), surface friction velocity (U_*), and location (x,y,z). Measurements of all these quantities were obtained using the techniques described in Appendix A. The data processing and analysis methods are also described in the appendix.

To ensure that accurate and reliable data were collected, certain quality control steps were taken. These included:

- use of certified mixtures for source gas,
- multipoint calibration of hydrocarbon analyzer with certified standard gas,
- calibration of flow measuring device with soap bubble meter,
- calibration of velocity measuring device with mass flow meter,
- wind tunnel testing to determine optimum sampling methodology,
- monitoring of 10 m wind speed during all tests,
- repetition of several runs to provide an indication of expected errors and repeatability,
- comparison of wind tunnel diffusion and velocity characteristics with those observed in the atmosphere.
- independent review of the results for Phase II of the study by Drs. Donald L. Ermak (Lawrence Livermore National Laboratory), Thomas O. Spicer (University of Arkansas) and William F. Snyder (USEPA).

Source gas certifications and volume flow, velocity, and gas analyzer calibrations are given in Appendix L.

3.0 ROUGHNESS EFFECTS ON HTAG ENTRAINMENT RATES

3.1 Calculation of Vertical and Horizontal Entrainment from Wind Tunnel Experiments

General

Entrainment is the mechanism whereby ambient air mixes with a heavier-than-air, buoyant or neutrally buoyant gas (HTAG) cloud. The entrainment mechanism is usually divided into a vertical and horizontal component for continuous releases. Estimates of vertical entrainment as a function of downwind distance were obtained from the wind tunnel observations for comparison with the entrainment predicted in the SLAB and DEGADIS models. Horizontal entrainment estimates obtained from the wind tunnel observations were compared with a suggested equation by Petersen (1987). This approach was taken because the versions of SLAB and DEGADIS utilized in this study did not have analytical expressions for horizontal entrainment and the equation suggested by Petersen (1987) may be useful for future consideration.

Basic Equations

Entrainment is defined based on the continuity equation which is given below in cartesian coordinates for steady state conditions:

$$\partial(\rho U)/\partial x + \partial(\rho V)/\partial y + \partial(\rho W)/\partial z = 0 \quad (3-1)$$

If Equation 3-1 is integrated over a plume cross section (y-z plane) in Figure 3-1, the following equation results (Ermak and Chan, 1985):

$$[\rho U h B]' = \rho_a (V_e h + W_e B) \quad (3-2)$$

where the ' indicates a derivative with respect to x, h is the plume height, B the plume width, U the plume velocity in the x direction, ρ the plume density, ρ_a the ambient air density, and V_e and W_e are entrainment velocities in the y and z direction. The entrainment

velocities, V_e and W_e , are not directly measurable quantities but bulk parameters that indicate the amount of air mixing with the HTAG cloud.

For three dimensional flows, the following additional equations taken from the SLAB model (Ermak and Chan, 1985) are necessary to completely describe the entrainment:

$$UB' = V_e + V_g \quad (3-3)$$

$$(\rho UBhV_g)' = g(\rho - \rho_a)h^2 \quad (3-4)$$

The first equation describes the horizontal spreading of the plume and the second equation is derived from conservation of momentum in the y direction.

For adiabatic mixing of an ideal gas, Equation 3-2 can be rewritten as follows:

$$(Uh)' = W_e - V_g h/B. \quad (3-5)$$

Past experiments (McQuaid, 1976; Kantha et al., 1977) have been conducted to determine W_e that were two dimensional (diffusion in the x-z plane only) and hence V_e and V_g were equal to zero. The present experiments were all three dimensional, and both horizontal and vertical entrainment as well as gravity spread are present. Since V_g could not be directly measured and its significance will decrease with downwind distance, it was assumed that the gravity spread term is negligible ($V_g=0$). With this assumption the following two equations result for predicting vertical and horizontal entrainment in terms of the SLAB model:

$$(Uh)' = W_e \quad (3-6)$$

$$UB' = V_e \quad (3-7)$$

For the DEGADIS model, the following relation applies for predicting vertical entrainment when gravity spread is insignificant:

$$(U_{eff} H_{eff})' = w_e^1 \quad (3-8)$$

and when gravity spread is significant, the following equation is appropriate:

$$(U_{eff} H_{eff} B_{eff})' = w_e B_{eff} \quad (3-9)$$

where

$$H_{eff} = \frac{1}{C_c} \int_0^\infty C dz \quad (3-10)$$

$$U_{eff} = \frac{\int_0^\infty C U dz}{\int_0^\infty C dz} \quad (3-11)$$

$$B_{eff} = b + \frac{\sqrt{\pi}}{2} S_y \quad \text{when gravity spread is significant} \quad (3-12)$$

$$B_{eff} = \frac{\sqrt{\pi}}{2} S_y \quad \text{when gravity spread is not significant} \quad (3-13)$$

S_y is the DEGADIS crosswind similarity parameter which equals $\sqrt{2} \sigma_y$ when $b = 0$. The "b" in Equation 3-12 represents the width of the flat portion of the concentration distribution assumed in the DEGADIS model. When $b=0$, gravity spread effects are insignificant while the dispersion can still be dominated by the density of the cloud. Since B_{eff} is not simply related to σ_y when gravity spread is significant and b was observed to be approximately 0

¹In DEGADIS, w_e is referred to as w_e' . In this report, the " ' " indicates a derivative and to avoid confusion, the " ' " has been dropped from w_e' .

for most wind tunnel concentration profiles, Equation 3-13 has been utilized in the present analysis (i.e., gravity spread effects have been neglected).

SLAB Vertical Entrainment

In the SLAB model, W_e is computed using the following equation:

$$W_e = 2.7 k U_* / \phi(Ri) \quad (3-14)$$

where k is von Karman's constant (0.4), U_* is the friction velocity and $\phi(Ri)$ is taken to be

$$\phi(Ri) = 1 + 5 Ri \quad (3-15)$$

where the Richardson number is given by

$$Ri = [Ri_a + \alpha g(\rho - \rho_a)h / (\rho U_*^2)]. \quad (3-16)$$

Ri_a is taken to be h/L where L is the Monin Obukhov length and $\alpha=0.05$. For this study, h/L is not allowed to exceed 0.2 which is a theoretical limit discussed in Appendix E. The cloud density, ρ , has been assumed equal to the cloud centerline density ρ_c for the purposes of computing Ri from the wind tunnel experimental data.

DEGADIS Vertical Entrainment

The relation for w_e in DEGADIS is as follows:

$$w_e = (U_* k)(1+n) / \phi(Ri^*) \quad (3-17)$$

where

$$\begin{aligned} \phi(Ri^*) &= (0.88 + 0.099 Ri^{*1.04} + 1.4 \times 10^{-25} Ri^{*5.7}) \\ Ri^* &= g' H_{eff} / U_*^2 \\ g' &= g(\rho_c - \rho_a) / \rho_a \end{aligned} \quad (3-18)$$

and ρ_c is the density at the plume centerline.

Horizontal Entrainment

Petersen (1987) suggested the following equation, derived from similarity theory for neutrally buoyant plumes, for estimating horizontal entrainment:

$$V_e = 1.73 U_* \phi_3 [f(x) + x f'(x)] \quad (3-19)$$

where $\phi_3 = 1.9$ for stable and neutrally stratified flows and $f(x)$ is the function suggested by Pasquill and Smith (1983) for accounting for plume meander. The function can be approximately estimated using the following equation:

$$f(x) = 1.37x^{-0.122} \quad (3-20)$$

which results in the following equation that was tested against the wind tunnel data:

$$V_e/U_* = 3.3 [f(x) + x f'(x)] G(Ri) \quad (3-21)$$

where $G(Ri)$ is, at present, some unknown function of Ri . Equation 3-21 (with $G=1$) was used to compare against the computed horizontal entrainment from the wind tunnel observations.

Summary

In the wind tunnel, the quantities ρ_c and h or H_{eff} were estimated from the concentration measurements which leaves W_e (DEGADIS) or w_e (SLAB) and V_e as the only unknowns which can be calculated directly from the experimental data. To be consistent with the definitions in SLAB, the parameters U , h , and B were determined from the measured concentration and velocity data as follows for SLAB: $h^2 = 3 \sigma_z^2$, $B^2 = 3 \sigma_y^2$, $U = U_a(h/10)^n$. The wind power law exponent n was determined from velocity measurements obtained during each experiment. The appropriate value was used in the calculation. The horizontal and vertical dispersion coefficients (σ_y and σ_z) were computed by integrating the measured concentration distribution in the horizontal and vertical direction (see Equations A-14 and A-15). For the DEGADIS model, the parameters U_{eff} and H_{eff} were computed from the

concentration data using Equations 3-10 and 3-11. In the analysis it should be noted that the cloud velocity has been assumed equal to the local wind velocity.

In summary, the vertical entrainment was computed from the wind tunnel concentration measurements using the following equations developed assuming negligible gravity spread effects for SLAB model comparisons:

$$W_e = (Uh)' \quad (3-22)$$

and the following equation for DEGADIS model comparisons:

$$w_e = (U_{eff} H_{eff})' \quad (3-23)$$

For horizontal entrainment, the following equation was utilized:

$$V_e = UB' \quad (3-24)$$

The quantities U or U_{eff} and h or H_{eff} were measured at several downwind distances, and the derivatives were computed using a series of best fits through at least three data points. At the source location, the plume height was defined to be the pipe diameter for the point source and $V/U_{10}D$ for the area sources.

3.2 Comparison of SLAB, DEGADIS and Wind Tunnel Vertical Entrainment

The vertical entrainment as a function of downwind distance was computed for each wind tunnel experiment using the equations discussed above for comparison with SLAB and DEGADIS vertical entrainment rates. As discussed previously, the use of these equations assumes that gravity spread is insignificant. The entrainment values are tabulated in Appendix F for each distance where sufficient data were collected such that a computation could be made. The wind tunnel computed entrainment values were normalized by the friction velocity (W_e/U_*) for SLAB comparison and $U_* (1+n)$ for DEGADIS comparisons

$[w_e/U_*(1+n)]$. The SLAB curve was computed assuming $k = 0.4$ and the DEGADIS curve with $k = 0.35$ to be consistent with each respective model formulation.

The normalized vertical entrainment values for different subsets of the wind tunnel data base were plotted versus the local cloud Richardson number defined in Equation 3-16 for SLAB and Equation 3-18 for DEGADIS. The computed vertical entrainment for SLAB and DEGADIS was also superimposed on each plot (Equation 3-14 for SLAB and Equation 3-17 for DEGADIS). Figures 3-2a through 3-2h show the observed and SLAB computed entrainment values for subsets of the data base analyzed. Similar data subsets comparing observed entrainment with DEGADIS predictions are presented in Figures 3-3a through 3-3h.

Figures 3-2a, 3-2b, 3-3a, and 3-3b show the SLAB and DEGADIS predicted and observed entrainment versus Ri or Ri^* for the point source (PS), small area (SA), and large area (LA) releases with homogeneous surface roughness. As indicated by these figures, the observations compare reasonably well with the theory used in both models. In these figures, heavy gas effects are important in the region where the curve starts to bend to lower entrainment values. The importance of heavy gas effects diminishes when the entrainment rate becomes constant with cloud Richardson number. Also included in the figures is the initial Richardson number (Ri^*_o) defined in Equation 2-2. The Ri^*_o values can be used to indicate whether heavy gas effects are likely to be important using the criteria of Britter (1980) (discussed in Section 2) who suggested that a plume downwind of a release would be passive (region of entrainment that does not vary with cloud Richardson number) from a source for Ri^*_o less than about 1.

The vertical entrainment for the point source releases (Figures 3-2a for SLAB and 3-3a for DEGADIS) are all in the entrainment region where heavy gas effects are not important (Ri^*_o values range from 1 to 40). The results in these figures suggest that heavy gas effects quickly become insignificant (within 20 m - the closest measurement point) for a point source with Ri^*_o values below 40.

For the small/large area source tests with uniform roughness (Figure 3-2b or 3-3b), the initial Richardson numbers Ri^*_o are larger than those for the point source and range from 2 to 112. Vertical entrainment values with low Ri or Ri^* values approach the horizontal line in the figure while values with larger Ri or Ri^* values tend to follow the curve in the heavy gas region of dispersion. There is a slight tendency for the observed entrainment values to be larger than those predicted using the equations in SLAB and no tendency for DEGADIS. If gravity effects were important, the wind tunnel computed entrainment values would be even larger than reported and the agreement with the SLAB/DEGADIS relations would not be as good as shown.

Figures 3-2c and 3-3c show the normalized entrainment for SLAB and DEGADIS for the point and uniform roughness with exit velocity ratios ($R = U_s/U_{10}$) ranging from 3 to 26 and initial Richardson numbers ranging from 3 to 1044. The results in Figures 3-2a or 3-3a were for a velocity ratio of 1. For the low velocity ratio cases ($R=3$) in Figure 3-2c, the entrainment values tend to follow the theoretical equation for SLAB. For velocity ratios of 9 and above, significant scatter is noted about the theoretical line. These results suggest that the assumed entrainment relations in SLAB are not appropriate for a horizontal point source release with a high exit velocity (velocity ratio of 6 or greater). For DEGADIS (Figure 3-3c), there is less scatter for all velocity ratios and there does not appear to be any trend (more or less scatter) with increasing velocity ratio. There is more scatter, however, than the $R=1$ test results (Figure 3-3a), indicating that the relation in DEGADIS is not as accurate for large velocity ratios. Considering both the SLAB and DEGADIS entrainment relations, the entrainment values do not fall in the region dominated by heavy gas effects as one would expect for the large initial Richardson number cases. This indicates that the initial Richardson number criteria (Britter, 1980) defining passive and dense clouds is not appropriate for horizontal point source releases with a large exit velocity.

Figures 3-2d and 3-3d show the SLAB and DEGADIS predicted entrainment for a small area source release and two higher volume flow rates (or larger Ri^*_o). These results are similar to those in Figures 3-2b and 3-3b for the small area source only with larger volume flow rates and larger initial Richardson numbers. Except for a couple of outliers, the entrainment

values follow the theory, further justifying the use of the entrainment relations in SLAB and DEGADIS for area sources and uniform roughness.

Figures 3-2e and 3-3e show the entrainment results for the small area source, uniform roughness and stable stratification. Cases with $Ri^*_o = 0$ are also presented for this case since the Ri value will not be zero for the SLAB model formulation under stable stratification. For DEGADIS, Ri^* would equal zero when $Ri^*_o = 0$. However, the initial density was specified to be slightly greater than air so that results could be plotted on the logarithmic scale. The entrainment values for the stable case and SLAB formulation (Figure 3-2e) tend to be slightly less than theory for Ri values below about 0.5 and greater than theory for Ri values above 1. For DEGADIS, the observed values are less than theory for Ri^* less than 10 and greater than theory for Ri^* greater than 20. Also shown in the figure are the entrainment calculations for three repeats of the run with $Ri^*_o = 56$. The results for all three runs appear to be consistent demonstrating the repeatability of the results.

Figures 3-2f through 3-2h and 3-3f through 3-3h show the normalized entrainment versus Richardson number for point and small area source releases and non-uniform surface roughness (simulated tank farm and process unit). The SLAB formulation appears to agree reasonably well for the tank farm and point (Figure 3-2f) and small area source releases (Figure 3-2h). While there is more scatter than for the uniform roughness cases, the agreement is still qualitatively good. For the process unit and small area source, significant scatter is noted for both the SLAB and DEGADIS formulations (Figures 3-2g and 3-3g). Also for DEGADIS, significant scatter is noted for the tank farm and point or small area source releases.

The results for the heterogeneous roughness tests do suggest (with the exception of the tank farm) that SLAB or DEGADIS will not accurately predict the entrainment rates, and perhaps the concentrations, in areas around industrial sites. A large fraction of the disagreement noted in the figures may be due to errors in the specification of the friction velocity, U_* . In the wake of a structure, the friction velocity varies significantly with location. The U_* value used was based on measurements at one or two locations and wide scatter in the results is to be expected. It is possible that if the actual U_* values were used, better agreement

would be observed. Presently, SLAB or DEGADIS cannot account for spacial variations in U_* and if applied for the tank farm or process unit, the U_* values used for generating Figures 3-2f through 3-2h or 3-3f through 3-3h are typical of the values that would be input.

3.3 Observed and Predicted Horizontal Entrainment

The horizontal entrainment as a function of downwind distance was computed for each wind tunnel experiment using the equations discussed in section 3.1 for comparison with entrainment rates computed using Equation 3-21. As discussed previously, the equations used for calculating entrainment were developed based on the assumption that the gravity spread is insignificant. The horizontal entrainment values are tabulated in Appendix F for each distance where sufficient data were collected such that a computation could be made. The computed entrainment values were normalized by $U_*[f(x)+x f'(x)]$, for different subsets of the wind tunnel data base and then plotted versus the local cloud Richardson number defined in Equation 3-16 for SLAB. If the relation presented is valid, the computed entrainment values should fall about a line equal to 3.3 (see Equation 3-21) for small Ri values. If cloud density does not affect horizontal entrainment, all calculated values should be constant for any Ri .

Figures 3-4a and b show the observed horizontal entrainment versus Ri for the homogeneous roughness cases with point and small/large area sources. The normalized entrainment for the point source appears to scatter about a constant value of approximately 2 which is below the constant value of 3.3 as predicted by Equation 3-21. For the small/large area source, the data falls around the 3.3 line but with significantly more scatter. The scatter may be due to the assumption that gravity effects are insignificant. If gravity effects were accounted for, the entrainment values for the large density ratio and small surface roughness cases would be decreased and the scatter may be reduced.

Figure 3-4c shows the observed horizontal entrainment for the point source and velocity ratios ranging from 3 to 26. At small Ri , the results appear to approach a value of 1 and at larger Ri the values scatter about a value of 3. For a small area source and larger volume

flow rates (or large Ri^*_o values), the observed horizontal entrainment again scatters about a value of 1 or 2 (see Figure 3-4d). For stable stratification and a small area source (Figure 3-4e), the horizontal entrainment shows behavior similar to the other results. Considering Figures 3-4c through 3-4e, there appears to be a trend of increasing entrainment with increasing Ri . In other words, for denser plumes, the plume widths would be greater. This trend was also noticed when analyzing σ_y versus x for various subsets of the data base as discussed in Section 4.2.

Figures 3-4f through 3-4h show the observed horizontal entrainment for the point and small area source and heterogeneous roughness configurations (tank farm and process unit). Significant scatter is noted for all cases and no trend is evident except for the tank farm and small area source (Figure 3-4h). The results for this case fall about a value of 2. Not as many data points are presented for the heterogeneous roughness cases since many horizontal profiles did not contain sufficient data to accurately predict the horizontal dispersion coefficient.

The results of the horizontal entrainment analysis are inconclusive but suggest that the relation has merit with a derived constant of 1 or 2 instead of 3.3. The large scatter presented is partly due to that fact that the computed horizontal entrainment is more sensitive to the assumption that $V_g=0$. A better test of Equation 3-21 would be to insert the equation into the SLAB model and test concentration, plume height, and plume width predictions against the wind tunnel observations. Alternately, more detailed velocity and concentration measurements could be obtained such that both V_g and V_e could be determined experimentally. It is possible that a three component (x,y,z) velocity probe could be utilized to measure the induced lateral speed (V_g) due to gravity spread effects.

4.0 CONCENTRATION MEASUREMENT RESULTS

4.1 General

The concentration measurements for each test described in Tables 3 and 4 were analyzed to determine the maximum ground level concentration ($C_{\max}$), plume height (σ_z) and plume width (σ_y). This section of the report shows how these quantities vary with surface roughness (homogeneous and heterogeneous), initial cloud density, initial Richardson number, release type (point or area), wind direction, release location, and volume flow rate. Also included in this section is a discussion of generalized equations that were developed for predicting $C_{\max}$, σ_y and σ_z as a function of cloud density, wind speed, and surface roughness for uniform surface roughness configurations. An equation was also developed for predicting $C_{\max}$, σ_y , and σ_z downwind of a process unit. (Throughout the balance of the report, $C_{\max}$ will be referred to as C .) The final section includes information on the concentration reduction factors (maximum concentration for grassland divided by the maximum for the roughness of interest) that can be expected due to homogeneous and heterogeneous surface roughness.

4.2 Qualitative Evaluation of C , σ_y and σ_z

In this section, maximum concentrations, σ_y and σ_z are plotted versus downwind distance for various subsets of the data base to illustrate the effect of roughness, initial density, initial Richardson number, exit velocity or volume flow rate, wind speed, wind direction and atmospheric stability. When using the results to infer trends, one should be aware that the plotted data does have a degree of uncertainty. The maximum concentrations have the least uncertainty (on the order of 15%) and the horizontal and vertical dispersion coefficients have a higher degree of uncertainty (on the order of 20%). As discussed in Appendix A (Section A.4), some of the horizontal and vertical concentration profiles were not detailed enough to obtain sufficiently accurate σ_y and σ_z estimates. These points will be missing from the plots presented in this section.

Effect of Surface Roughness

Figures 4-1 and 4-2 show the maximum concentrations versus downwind distance due to a point and small area source for D stability, relative cloud densities of 1.0, 1.4, and 4 and varying surface roughnesses and initial Richardson numbers. Only nearfield measurements (within 300 m) were taken for the cases presented in these figures. Figures 4-3 and 4-4 show similar graphs for the small area source for test cases where measurements were taken out to 800 m under D and F stability. Each figure has three plots, designated a, b or c, one for each relative cloud density.

In Figures 4-1 and 4-2 concentrations appear to generally decrease with increasing roughness, but large scatter in the results is noted at all distances for the point source release (Figure 4-1) and within 50 m of the release for the small area source release (Figure 4-2). This large scatter may be explained by the fact that in the limit as one gets closer to the release, the concentrations will approach the same value regardless of surface roughness, and the roughness elements near the release will have perturbing effects of varying degree. Beyond 50 m, a more definite trend emerges for the small area source release (Figure 4-2). The process unit with surrounding R50 roughness has consistently lower values than the R3 and R50 roughnesses. The tank farm in R3 surrounding roughness tends to have similar concentrations as the R50 roughness alone, and the tank farm in R50 roughness tends to be similar to the process unit in R3 roughness. The initial Richardson number effect is not clearly demonstrated in these figures.

Figures 4-3 and 4-4 show the maximum concentrations versus downwind distance due to a small area source for D and F stability, various surface roughnesses and measurements collected beyond 300 m. For D stability (Figure 4-3), the maximum concentrations vary consistently with surface roughness configuration. The lowest concentrations are seen for the process unit in R50 roughness, followed by the tank farm in R50 roughness, and the tank farm in R50 and R3 roughness. For stable stratification (Figure 4-4) a slightly different pattern emerges. The process unit in R50 roughness and/or the tank farm in R50 roughness have the lowest concentrations for the cases with initial relative densities of 1 and 1.4 (Figures 4-4a and b). For the cases with initial relative density of 4, all cases presented (tank farm in R3 and process unit in R3 and R50 roughness) have similar concentrations (Figure 4-4c).