ANALYSIS OF VAPOR BARRIER EXPERIMENTS TO EVALUATE THEIR EFFECTIVENESS AS A MEANS TO MITIGATE HF CONCENTRATIONS

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FLUID MECHANICS AND WIND ENGINEERING PROGRAM

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FINAL REPORT

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on behalf of

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PREFACE

INDUSTRY COOPERATIVE HF MITIGATION/ASSESSMENT PLAN

ANALYSIS OF VAPOR BARRIER EXPERIMENTS TO EVALUATE THEIR EFFECTIVENESS AS A MEANS TO MITIGATE HF CLOUD CONCENTRATIONS

This report is one of several work products generated by the Industry Cooperative HF Mitigation/Assessment Program. This ad hoc industry program was begun in late 1987 to study and test techniques for mitigating accidental releases of hydrogen fluoride (HF) and alkylation unit acid and to better estimate ambient impacts from such releases.

The hazards of HF have long been recognized, and operating practices have been aimed at minimizing the possibility of a release and mitigating the effects of a release should it occur. These practices have been continually monitored and improved to maximize safety protection based on the available technical data. This recent program has been aimed at further improvements based on new technical data.

This program has been sponsored and funded by twenty companies from the chemical and petroleum industries. These include Allied-Signal, Amoco, Ashland, Chevron, Conoco/Dupont, Dow, Elf Aquitaine, Exxon, Kerr-McGee, Marathon, Mobil, Phillips, Saras, Shell Internationale, Sohio, Sun, Tenneco, Texaco, Unocal, and 3M.

This document was prepared by the Fluid Mechanics and Wind Engineering Program, Colorado State University, as a part of its work for the Vapor Barrier Technical Subcommittee. The authors wish to acknowledge the interaction and encouragement of Rudolf Diener, EXXON Research and Engineering Company and Chairman of the Vapor Barrier Subcommittee, and the support and constructive criticism provided by all of the subcommittee members.

The results from this program are being published with the intent of making them available to any party with an interest in the subject matter. All are free to used these results subject to the rights of others. It is intended that the information presented herein will contribute to the further maximization of safety protection. However, neither the sponsors of this work nor their contractors accept any legal liability or responsibility whatsoever for the consequences of its use or misuse by anyone.

ABSTRACT

ANALYSIS OF VAPOR BARRIER EXPERIMENTS TO EVALUATE THEIR EFFECTIVENESS AS A MEANS TO MITIGATE HF CLOUD CONCENTRATIONS

Accidental releases of Hydrogen Fluoride (HF) can result in initially dense, highly reactive and corrosive gas clouds. These clouds will typically contain a mixture of gases, aerosols and droplets which can be transported significant distances before lower hazard levels of HF concentration are reached. Containment fences or vapor barriers have been proposed as a means to hold-up or delay cloud expansion, elevate the plume downwind of the barriers, and enhance cloud dilution.

Previous related field and laboratory experiments have been analyzed to estimate the effectiveness of barrier devices. The experiments were examined to determine their relevance to Hydrogen Fluoride spill scenarios. Wind tunnel and field data were compared where possible to validate the laboratory experiments. Barrier influence on peak concentrations, cloud arrival time, peak concentration arrival time, and cloud departure time were determined. These data were used to develop entrainment models to incorporate into integral and depth averaged numerical models. The models were then run to examine barrier performance for a typical Hydrogen Fluoride spill for a wide range of vapor barrier heights, spill sizes, meteorological conditions and release configurations. Finally the results of the data analysis and numerical sensitivity study were interpreted and expressed in a form useful to evaluate the efficacy of vapor barrier mitigation devices.

EXECUTIVE SUMMARY

ANALYSIS OF VAPOR BARRIER EXPERIMENTS TO EVALUATE THEIR EFFECTIVENESS AS A MEANS TO MITIGATE HF CLOUD CONCENTRATIONS

Accidental releases of Hydrogen Fluoride (HF) can result in initially dense gas clouds that will typically contain a mixture of gases, aerosols and droplets which can be transported significant distances before lower hazard levels of HF concentration are reached. Containment fences, vapor barriers, and water-spray curtains have been proposed as a means to hold-up or delay cloud expansion, elevate the plume downwind of the barriers, enhance cloud dilution, and/or remove HF from the gas cloud by deposition.

Exxon Research and Engineering Company, in conjunction with and on behalf of an ad hoc Industry Cooperative Hydrogen Fluoride (HF) Mitigation and Assessment Group has funded this study to assess the effectiveness of vapor barriers in diluting and delaying heavier-than-air HF vapor clouds. This data will provide a foundation of information to use to develop mitigation strategies, initialize numerical plume models, and/or design follow-up field and laboratory experiments. A secondary purpose of this study is to review evidence related to the accuracy and credibility of laboratory simulation of dense gas dispersion in the presence of vapor barriers. This information will be used to assess the value of future physical modeling experiments directed toward the mitigation of HF vapor clouds.

Previous related field and laboratory experiments have been analyzed to estimate the effectiveness of barrier devices. The experiments were examined to determine their relevance to Hydrogen Fluoride spill scenarios. Wind tunnel and field data were compared where possible to validate the laboratory experiments. Barrier influence on peak concentrations, cloud arrival time, peak concentration arrival time, and cloud departure time were determined. These data were used to develop entrainment models to incorporate into integral and depth averaged numerical models. The models were then run to examine barrier performance for a typical Hydrogen Fluoride spill for a wide range of vapor barrier heights, spill sizes, meteorological conditions and release configurations. Finally the results of the data analysis and numerical sensitivity study were interpreted and expressed in a form useful to evaluate the efficacy of vapor barrier mitigation devices.

<u>Dilution Performance of Vapor Barriers in the Near-field Region</u>

Eleven data sets from field and laboratory experiments dealing with the influence of vapor barrier fences and water spray curtains on the dispersion of dense gas clouds were examined. Tests were paired into sets of data which reflected the dilution of the cloud with and without the barriers present. Peak concentration ratios, cloud arrival time ratios, peak arrival time ratios, and departure time ratios were calculated for each test pair. Consideration of the regions immediately downwind from the fences and sprays (distances less than 300 m downwind of the barriers) reveals that:

Vapor Barrier Fences:

@ Additional dilution occurs downwind of the fence as the turbulence produced by the shear at the top of the fence persists for about 30 fence heights. Near field reduction in concentrations ranges from 1.1 to 5.0.

@ Cloud arrival time, peak arrival time, and departure time ratios often increase directly downwind of a fence because lower winds in the wake advect the cloud more slowly. However, farther downwind the cloud arrives earlier because once the cloud leaves the wake region it is transported downwind with the greater depth averaged velocities associated with the increased cloud height. Near field increase in arrival, peak arrival, and departure times range from 1.1 to 5.0.

Water Spray Curtains: Removal Characteristics

@ Concentrations in a gas cloud will decrease abruptly as a result of chemical reaction and removal processes associated with HF and water spray interaction, even when accelerated entrainment associated with the water spray curtain is not considered. The removal efficiency will be a function of water/HF volume ratios, water droplet sizes and cloud concentrations.

Dilution Performance of Vapor Barriers in the Mid to Far-field Region

HF is hazardous at ppm levels. Thus, far-field concentrations are of interest in evaluating mitigation strategies. Most laboratory and field experiments were originally constructed to consider the behavior of flammable gases; hence, measurements were only taken at distances out to 1000 m downwind or less. Consideration of the regions modestly far downwind of barriers and spray curtains (300 m to 1000 m) reveals that:

Vapor Barrier Fences:

@ Entrainment levels return to pre-fence levels at distances greater than 30 to 50 fence heights downwind of the fence location. After that point the concentrations generally asymptote to levels found in the absence of the fence or barrier about 2000 m downwind of fences placed between 10 and 100 meters downwind of the spill site. A numerical model extrapolation suggests no discernible barrier effect will be present beyond 200 fence heights.

@ Peak concentrations measured during the experiments did not generally fall below 10,000 ppm of simulant or 150,000 ppm HF over the measurement domain.

Water Spray Curtains: Removal Characteristics

- @ The reduction in HF cloud concentrations induced by water spray/cloud deposition processes persists at all downwind distances.

Proposed Entrainment Models

Given a box or depth-integrated type numerical model simple expressions to account for the increased entrainment associated with water spray curtains or fence barriers may be used with confidence. These models do not account for chemical reactions, deposition, gravity current reflection, rapid flow speed up through a porous barrier, or the presence of a hydraulic jump downwind of a barrier. Both the initial dilution and post-barrier concentration decay are predicted well.

Laboratory Simulation of a Hydrogen Fluoride Spill

The capabilities and limitations of physical modeling techniques for HF gas clouds were reviewed. Performance envelopes were constructed to illustrate the constraints of facility size and gravity spreading. The following conclusions were made:

- @ Laboratory simulation of a pure HF release with an isothermal simulant is not recommended. Reliable simulations would be limited to prototype wind speeds greater than 5 m/sec at scales less than 1:100. Model concentrations must be adjusted upward by a factor of 15 in the far downwind regions.

- @ Laboratory simulation of a pre-diluted HF cloud can be accomplished. Reliable simulations should be possible at all distances for prototype wind speeds greater than 5 m/sec at scales less than 1:100.

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LIST OF SYMBOLS

Symbol	Definition	Units
A,a,b, c,d,e	Regression constants in ANOVA	--
A_i	Area of intersection between gas cloud and water spray	$[L^2]$
B	Characteristic cloud width calculated by cross-section averaged numerical programs	[L]
C_m	Model concentration	--
C_p	Prototype concentration	--
C_w, C_{wi}, C_{wf}	Concentrations measured with barrier present	--
C_{wo} C_{wof}	Concentrations measured without barrier present	--
C_D	Fence drag coefficient factor	--
C_p^*	Molar specific heat capacity at constant constant pressure	$[L^2/T^2]$
D	Molecular diffusivity	$[L^2/T]$
d_g	Diameter of water spray intercept area with gas clouds	[L]
f-N	Surface pattern comparison factor, % predicted within N	--
Fr	Froude number, $U^2/(g(SG - 1)L)$	--
<u>Fr</u>	Flux Froude number, $U^3L/(Qg(SG - 1))$	--
g	Gravitational acceleration	$[L/T^2]$
H_f	Fence height	[L]
$H_{V.G.}$	Vortex generator height	[L]
H	Characteristic cloud height calculated by cross-section averaged numerical programs	[L]
L_c	Characteristic length, typically 10 m	[L]

Symbol	Definition	Units
L_{ci}	Characteristic length for instantaneous spills used by Koenig and Schatzman (1986)	[L]
L_{cc}	Characteristic length for continuous spills spills used by Koenig and Schatzman (1986)	[L]
L_s	Lateral water-spray nozzle separation	[L]
M,MW	Molecular weight	--
MR	Multiplicative factor used in water-spray entrainment model	--
ν	Kinematic viscosity	$[L^2/T]$
N	Number of water-spray nozzles	--
P	Fence porosity	--
Pe	Peclet number, UL_c/D	--
π	3.1417	--
Q, Q_s	Source strength spill rate	$[L^3/T]$
Q_e	Air entrainment rate	$[L^3/T]$
Q_G	Spill rate gas	$[L^3/T]$
Q_L	Spill rate liquid	$[L^3/T]$
Ri	Richardson number, $g(1 - SG)L_c/U^2$	--
ρ	Density	$[M/L^3]$
RH	Relative humidity	--
S	Water-spray intersection interval	[L]
SG	Specific gravity	--
T_{amb}	Ambient air temperature	$[\Theta]$
T_{dap}	Dew point temperature	$[\Theta]$
T_s, T_f	Source gas temperature	$[\Theta]$
Ta_w, Ta_{wo}	Cloud arrival times with and without barrier	[T]

Symbol	Definition	Units
Tpa_w, Tpa_{wo}	Peak concentration arrival time with and without barrier	[T]
Tda_w, Tda_{wo}	Cloud departure times with and without barrier	[T]
U_{ci}	Characteristic wind speed for instantaneous spills used by Koenig and Schatzman (1986)	[L/T]
U_{cc}	Characteristic wind speed for continuous spills used by Koenig and Schatzman (1986)	[L/T]
U_{10}	Wind speed at 10 m reference height	[L/T]
U(H)	Wind speed at fence height	[L/T]
U_g	Frontal velocity of dense cloud	[L/T]
u_*	Friction velocity	[L/T]
V, Vol	Total gas volume released	[L^3]
$\underline{V}_c$	Dimensionless continuous volumetric spill rate, $Q/(UL^3)$	--
V_i	Dimensionless instantaneous volume spill, Vol/L^3	--
w_e	Air entrainment rate	[L/T]
w_*	Convection velocity	[L/T]
x, y, z	Coordinate system, origin at spill location	[L]
x_f	Downwind distance from spill location to fence	[L]
Y	Downwind distance used for Thorney Island Trials	[L]
Z_o	Surface roughness length	[L]

DEFINITION OF KEY TERMS AND ABBREVIATIONS

Arrival Time		The time after the release a minimal level of concentration arrives at a specified downwind location
Peak Arrival Time	-	The time after the release a peak concentration arrives at a specified downwind location
Departure Time	-	The time after the release the concentration falls below a minimal level at a specified downwind location
Arrival Time Ratio	-	The ratio of the cloud arrival time with a barrier to the cloud arrival time without a barrier at a specified downwind location
Peak Arrival Ratio	-	The ratio of the cloud peak arrival time with a barrier to the cloud peak arrival time without a barrier at a specified downwind location
Departure Time Ratio	-	The ratio of the cloud departure time with a barrier to the cloud departure time without a barrier at a specified downwind location
Concentration Ratio	-	The ratio of the peak concentration with a barrier to the peak concentration without a barrier at a specified downwind location

ANALYSIS OF VAPOR BARRIER EXPERIMENTS TO EVALUATE THEIR EFFECTIVENESS AS A MEANS TO MITIGATE HF CLOUD CONCENTRATIONS

1..0 INTRODUCTION

Over the past twenty years there has been a marked increase in concern about the consequences of large and small scale releases of flammable or toxic gases into the atmosphere. This new awareness reflects the increasing scale, in number and extent, of industrial and transport operations involving these hazardous materials. The occurrence of recent disastrous accidents has focused attention on the potential risks of these operations. Regulation of production, storage and transport of such products, the design of mitigation equipment, and the preparation of accident response strategies requires an accurate evaluation procedure to predict the consequences of hazardous gas release.

Exxon Research and Engineering Company, in conjunction with and on behalf of an ad hoc Industry Cooperative Hydrogen Fluoride (HF) Mitigation and Assessment Group has funded this study to assess the effectiveness of vapor barriers in diluting and delaying heavier-than-air HF vapor clouds. This data will provide a foundation of information to use to develop mitigation strategies, initialize numerical plume models, and/or design follow-up field and laboratory experiments. A secondary purpose of this study is to review evidence related to the accuracy and credibility of laboratory simulation of dense gas dispersion in the presence of vapor barriers. This information will be used to assess the value of future physical modeling experiments directed toward the mitigation of HF vapor clouds.

Examination of the Acute Hazardous Events Database prepared by EPA (and earlier statistics about vapor cloud accidents) reveals that three-quarters of all events occur in-plant (production, operations or storage) and one-quarter occur in-transit (truck, rail, pipeline, etc.). In-plant events are about equally divided between storage, valves and pipes, and processing. In-transit events are associated with truck and rail modes. Collisions and leaks cause most transportation deaths and injuries Storage and pipeline failures cause the majority of in-plant deaths and injuries (Crum, 1986; Wiekema, 1984; Davenport, 1977).

Thus, the majority of hazardous gas accidents result from failure of confinement whether from a stationary tank, pipeline or mobile storage container. Disregarding whether the loss of containment is due to a small leak, a complete rupture, or continuous high volume release from an aperture, the puff, plume or cloud will interact with the container, the nearby buildings, vapor barriers, water spray or the ground and the surface boundary layer to produce dilution behavior which can not be predicted by conventional isolated plume theories.

It is appropriate to review what is known about the physics of the initial formation phase of a cloud or plume, the interaction of dense gas clouds with barriers and the ability of fluid modeling to illuminate the entrainment mechanisms further.

1.1 The Formation Phase of a Hazardous Cloud

Hartwig and Flothman (1980) prepared diagrams outlining important processes occurring during a hazardous gas release scenario. They identified self-generated dilution as an important unresolved issue during consequence analysis. Brenchley (1981) and DeSteese (1982) reviewed the hazard characteristics of operation, storage and transportation for ammonia and liquid petroleum gas products. They tabulated the typical container sizes, accident statistics, and hazards. They recommended research on mixing models, source physics, and the instantaneous character of the cloud concentration distribution. McQuaid (1982) identified three phases in the estimation of the consequences of a hazardous cloud release:

a.) The initial formation of a cloud or plume near the source,
b.) The dispersion of the cloud or plume to where it ceases to be a hazard, and
c.) The consequences if the cloud or plume is ignited or passes over a population.

The formation phase of cloud generation is dependent on the quantity of gas released (or rate of evolution from a liquid), the nature of the release (leak or rupture), and the geometry of tank, pipe and/or local buildings. Griffiths and Kaiser (1979) examined in detail the implications of different types of spills of ammonia. They evaluated small and large releases from vapor spaces in pressurized containers, small and large releases from liquid spaces, onto land, onto and under water and the effect of buildings. For ammonia they determined small leaks from vapor spaces were not a major problem, but they concluded further research was necessary about:

a.) The effect of intermediate size holes from vapor spaces in storage containers,
b.) The interaction of plumes with nearby buildings which could destroy plume buoyancy or alternatively encourage dense plume persistence, and
c.) Plume release configurations which might suppress lift-off.

Other relevant studies have examined the character of sources resulting from the evaporation from liquid pools (Shaw and Briscoe, 1978), mixing down wind of relief valves (Jagger and Edmondson, 1981; Samimy and Addy, 1983), cloud formation during massive containment rupture or explosion (Kaiser and Walker, 1978; Jagger and Kaiser, 1980; Bodurtha, 1980), and plume formation during losses from large exhaust jets (Abramovich, 1963; Ricou and Spalding, 1961; Wilson, 1981). Most quantitative estimates are based on conjecture about the release process, most verification is based on examining plume behavior downwind from the source, and few measurements are available in the direct vicinity of the release.

Hardee and Lee (1975) developed a simple model to predict the growth of a hazardous cloud near a rupture-type containment accident. The model used two-phase flow expansion in an isentropic process. Total momentum is calculated and used to predict subsequent cloud growth, but no adjustments are made for the possible consequences of plume buoyancy or interaction with surrounding structures. Hirst (1986) has shown that liquid mass release through short circular orifices in pressurized propane tests are reliably predicted by the Bernoulli equation, but for gas or two-phase situations the mass flow is substantially less. At the other extreme of sophistication Wilson (1981) has developed a jet-plume model for estimating dispersion downwind of a buried pipeline. He incorporated transient mass release rates, expansion and acceleration of the compressible plume outside the rupture area, interaction of the supersonic jet with soil crater walls, and entrainment of ambient air into the head of the starting plume. This excellent model was calibrated and compared against full scale pipe-rupture experiments performed in Alberta during 1978. Validation of all possible source conditions against full-scale field tests is possible, but represents a very costly approach to model verification. Fluid modeling should provide equivalent data at great savings.

1.2 Fluid Modeling of Atmospheric Phenomena

Recently Briggs and Binkowski (1986) reviewed the state of numerical model prediction of plume behavior in the atmosphere. They concluded *"a major need is for diffusion experiments, both in the field and in laboratory settings. The laboratory studies are needed to test theoretical results in specific simplified situations that are free of confounding influences."* The acceptance of fluid modeling by the meteorological community as a viable prediction tool is reaffirmed through their assertion that *"confidence in these tools [fluid modeling] has increased to the point that they have been used extensively to investigate diffusion from releases on and near buildings and terrain features. ....In addition to being less expensive than field experiments, laboratory modeling offers control over the meteorological variables, so that both the flow and surface characteristics can be idealized....It is obvious that this tool has not been fully exploited...it makes sense to use laboratory facilities as much as possible."*

Complex Terrain and Building Aerodynamics:

Successful modeling of some of the more complex atmospheric surface layer and building aerodynamic phenomena in a wind tunnel have only been accomplished in the last fifteen years. Although guidelines for modeling flow over complex terrain are essentially similar to those for modeling hydraulic flows or flow around buildings, a few unique features are different. Irregular terrain may alter atmospheric airflow characteristics in a number of different ways. These effects can generally be grouped into those due to inertial-viscous interactions associated with a thick neutrally stratified shear layer and to thermally induced interactions associated with stratification or surface heating (Meroney, 1980).

Meroney (1980) compared three model/field investigations of flow over complex terrain, suggested performance envelopes for realizable modeling in complex terrain, and discussed recent laboratory studies which provide data for valley drainage flow situations. Not all of the model/field comparison experiments performed in the past were successful. Many early studies had model approach flow velocity exponents near zero, were modeled as neutral flows when the field observed strong stratification effects, or simulated unrealistic boundary layer depths, integral scales, or turbulence intensities which did not match their atmospheric counterpart. But few studies claimed unreasonable correlation, and some were strongly self-critical. Nonetheless most studies accomplished their prestated limited objectives. It would appear that the simulation wisdom developed in the last few years is appropriate for physical modeling of flow over complex terrain.

The interaction of an approach wind field with bluff bodies or structures constructed on the earth's surface is broadly termed "Building Aerodynamics." In a review article on this subject Meroney (1982) discusses the character of bluff body flow about rectangular buildings and cylindrical cooling towers. Defects in velocity profiles can easily persist to 10 to 15 building heights downwind. Turbulence excesses and deviations in temperature profiles may persist to 20 or 30 building heights downwind. Field and laboratory measurements of plume dispersion about the Rancho Seco Nuclear Power Station in Sacramento, California, confirm that cooling tower wake effects persist for significant downwind distances under a variety of stratification conditions (Allwine, Meroney and Peterka, 1979; Kothari, Meroney and Bouwmeester, 1979).

For accidental releases the quantity desired for safety measures is the "immission," which is either the concentration of the gas or the dosage. Such quantities depend upon the "emission," which is the released quantity of mass or volume, and the "transmission," which is the combined effect of the wind field at the moment of release and thereafter plus the mixing properties of the wind field determined by obstacles, surface roughness, and thermal heating. The transmission function can be divided into three regions--the region-of-release, the near-field, and the far-field. The region-of-release depends upon the source characteristics and its immediate surrounding. The near-field region is governed by the local characteristics of the industrial plant and its surroundings. In the far-field the ground is characterized by homogeneous surface roughness and heating characteristics. These regions will depend upon the nature of the mitigation device or barrier considered; for example a fence may be expected to perturb the velocity field for 10 heights downwind, the turbulence field for 20 to 30 heights downwind, and the entrainment rate over a similar distance. On the other hand, a water spray curtain produces most of its dilution or reduction very close to the water spray device. The far-field region will exist once dense-gas gravitational effects are minimal and the perturbations of barriers decay. The effect of water-spray removal of vapor or particles will, of course, persist at all downwind distances, to the extent that it does not modify (reduce) the dynamic mixing of the vapor cloud. The distance to such a region will depend upon both spill size and barrier height.

A number of studies have been performed in the CSU Fluid Dynamics and Diffusion Laboratory to establish the near-field effect of buildings on flow fields and dispersion. Hatcher et al. (1977) examined flow and dispersion in stratified flow downwind of the Experimental Organic Cooled Reactor, Idaho Falls; Allwine et al. (1979) studied the Rancho Seco Reactor, Sacramento; Kothari et al. (1979) studied the Duane Arnold Energy Center, Iowa. In each case field measurements were compared to laboratory measurements with good agreement.

Relatively few studies have examined the composite effect of combined building and industrial equipment upon plume dispersion. Recently Plate and Baechlin (1987) reported a wind tunnel study of dispersion over a model of one of the largest chemical plants in the world, the Badische Anilin und Soda Fabrik (BASF) in Ludwigshafen, FRG. Measurements of wind field and concentration over the 1:500 scale model are being used to develop a catalog of ground level concentration fields for typical plant situations. Point sources of neutral density source gases were studied to produce generic plume behavior for different wind directions.

<u>Hazardous Gas Dispersion:</u>

Meroney (1982) reviewed the use of fluid modeling to evaluate the dispersion of dense gases. He notes that wind tunnels have simulated a wide range of conditions associated with dense gas transport and dispersion (bunded tanks, spills on water, water spray mitigation equipment, vertical emission through stacks, etc.) Measurements of dense fluid behavior in both air and water facilities appear reproducible and consistent. Idealized release configurations appear optimal for testing numerical or analytical models. Wind tunnels are primarily limited by operational constraint associated with the necessary low wind speeds and low Reynolds numbers.

In a two volume Gas Research Institute report Meroney (1986) provides guidelines for using fluid modeling to generate Liquid Natural Gas (LNG) dispersion information. The second volume reviews the fluid modeling science and the extensive model/field validation efforts performed over the last ten years. The wind tunnel was found to reproduce field data over a wide variety of scales. The comparisons between field and model data from the Thorney Island Freon-air experiments, the Maplin Sands LPG and LNG experiments, and the China Lake LNG experiments were particularly satisfying.

More recently British Maritime Technology (Davies and Inman, 1986) has completed a report on their own fluid model experiments performed to reproduce the Thorney Island experiments, and, again, plume shape and concentration fields were reproduced in almost every respect including instantaneous structure of the cloud interior. They concluded that,

a.) There was no evidence that the neutrally stable wind tunnel boundary layer failed to represent the dispersion in the more stable full-scale atmospheric conditions,

b.) Reductions in the downwind dispersion distance to a given concentration level due to vapor fences were reproduced by the laboratory experiments, and

c.) For trials involving sharp-edged mixing elements, such as buildings or fences, there was no evidence for a lower validity level for the simulation Reynolds number. For continuous and instantaneous releases onto unconfined terrain the lower limits of the simulation Reynolds number ($U_{10m}*L_{Dm}/\nu$) for conservative simulations (ie. model/full scale > 1) were 100 and 30000 respectively. (U_{10m} is the scaled 10 m velocity in the wind tunnel, and L_{Dm} is the buoyancy length scale of the release).

Releases of pressurized, superheated Hydrogen Fluoride are known to produce a heavy (Specific Gravity = 10), cold, two phase vapor plume close to the source. (Vapor or boiling pool releases of HF will not produce such dense clouds.) The gas cloud subsequently condenses water vapor, changes molecular polymer state through dissociation and association and consequently absorbs and releases heat to the surroundings. Special problems associated with the simulation of Hydrogen Fluoride spills and the subsequent behavior of its vapor cloud are discussed further in Section 7.0 of this report.

Dense Vapor Interaction with Fences, Barriers and Obstacles

Dense gas plumes dispersing over the ground undergo mixing due to the turbulence produced by gravity driven vapor spreading and the turbulence associated with the atmospheric surface flow. However, these conditions may be considerably perturbed by the additional complications of surface obstructions. Such interference may cause additional plume dilution or temporary pooling of higher gas concentrations. Researchers at Colorado State University have examined a cross section of barrier, water spray and obstacle configurations. Tests include the influence of high and low barrier dikes (Meroney et al., 1976, 1977, 1980, and 1981); tanks, fences and vegetation barriers (Kothari and Meroney, 1981); and fences and vortex generators (Kothari and Meroney, 1982), and water spray curtains (Andriev et al, 1983, Heskestad et al, 1983, Meroney and Neff, 1983, and Meroney et al, 1983). Recently, Neff and Meroney (1986) completed a pre-field-test wind tunnel series of the Falcon LNG vapor barrier test series, and are now preparing a post-field test program on the Falcon tests.

British Maritime Technology (Davies and Inman, 1986), as mentioned above, completed a series of wind tunnel simulation tests of some of the

Thorney Island dense gas spill experiments which included barriers. These tests were found to replicate most features of the field experiments, and they did not seem to be sensitive to model perturbations associated with low Reynolds numbers or low Peclet to Richardson number ratios developed during the model tests.

Researchers at the University of Hamburg (Konig and Schatzmann, 1986) examined the behavior of instantaneous and continuous releases of dense gases in a wind tunnel when dispersing in the vicinity of model walls, between model buildings, over model street canyons, and when confined by fences. Their data is unique in that they studied situations which actually tend to "reduce" dilution rather than enhance it. Significantly, the release scenarios they considered are frequently encountered in industrial complexes and cities.

1.3 Report Organization

The previous remarks summarize the current status of understanding for dense gas dispersion, obstacle (buildings, tanks, dikes, fences and sprays) and terrain aerodynamics and physical simulation of these flows. Currently there are no analytic algorithms or numerical programs capable of producing the necessary flow defect/dispersion information. The following chapters discuss additional insight gathered during the detailed analysis of the dense gas dispersion literature. Chapter 2.0 considers specific characteristics of Hydrogen Fluoride gas and proposes simple algorithms to allow for additional entrainment of air or removal of HF developed by vapor barriers or water spray curtains. Chapter 3.0 summarizes the applicable data bases available during this review. Chapter 4.0 provides the results from further evaluation of the data bases identified in Chapter 4.0. In Chapter 5.0 the entrainment models proposed in Chapter 2.0 are compared to the data extracted from previous studies in Chapter 3.0. Subsequently, the calibrated numerical models are used to predict potential mitigation of HF spills by sprays and barriers in Chapter 6.0. Chapter 7.0 summarizes some thoughts about the effective simulation of HF cloud behavior through fluid modeling. Conclusions drawn from the review, analysis, and numerical interpretations are provided in Chapter 8.0.

2.0 DISPERSION OF HYDROGEN FLUORIDE GAS CLOUDS

Hydrogen fluoride is a colorless, corrosive toxic liquid or gas, depending on the temperature. Hydrogen fluoride is used to prepare fluorides, to manufacture fluorine, as a catalyst in isomerization, condensation, dehydration, polymerization, and hydrolysis reactions, and a fluorinating agent in organic and inorganic reactions. It is also used as an alkylation catalyst in the petroleum industry, for etching and polishing of glass, and in the manufacture of aluminum fluoride and synthetic cryolite.

Because hydrogen fluoride's boiling point of 292.67°K (19.5°C) is often exceeded by the temperature at which it is transported or used, it is typically shipped in cylinders under its own vapor pressure of 2.1 kPa (0.3 psig) at 20°C. The gas is both toxic and corrosive. The concentration that produces acute effects varies with the time of exposure. The American Industrial Hygiene Association recommends levels of EPRG1 = 5 ppm, EPRG2 = 20 ppm and EPRG3 = 50 ppm for the Emergency Response Planning Guidelines. These are exposure levels that the general populace can experience without receiving other than mild transient adverse health effects, irreversible or serious health effects, or developing life-threatening health effects, respectively. Less severe exposures cause irritation of the nose and eyes, smarting of the skin, some degree of conjunctival and respiratory irritation. The 1979 ACGIH has also established a Threshold Limit Value (TLV) of 3 ppm (2 mg/m^3) for exposures of people in occupational settings.

2.1 Source Characteristics

Diener (1988) suggested two typical scenarios for hypothetical HF releases. One covers HF Alkylation units and the other covers typical transport and production scenarios. For conservatism, the upper bounds on release rates were deliberately set on the high side. The envelopes indicated are however fairly typical and representative.

<u>HF Alkylation Unit Scenarios</u>

Pressure	:	100 - 200 psig
Temperature	:	100°F (57°C)
Flowrate	:	1 - 500 gpm HF or alkylation unit acid
Duration	:	1 - 10 minutes
Release Type	:	release in middle of typical refinery setting from line rupture (1" - 3" range), flange leak, pump mechanical seal leak, etc; majority of releases at or near grade but possibility of elevated releases
Aerosols		total aerosolization expected (i.e. no liquid pool)

Transportation/Production Scenarios

Pressure	:	10 - 80 psig
Temperature	:	40 - 100°F (4 - 57°C)
Flowrate	:	1 - 100 gpm pure anhydrous HF
Duration	:	1 - 10 minutes
Release Type	:	release in middle of typical chemical plant/tank farm setting or from tank truck/rail car during transit resulting from line rupture (1" - 3" range), flange leak, pump mechanical seal leak, etc.; majority of releases at or near grade but possibility of elevated releases as well as all-vapor releases
Aerosols	:	liquid pool formation possible, especially at low pressure/temperature range

2.2. State Equations for Hydrogen Fluoride

HF can exist as unassociated HF or as an HF polymer, with association (an exothermic process) favored by low temperatures. When pressurized superheated HF is released into the atmosphere, a series of competing phenomena occur. As the turbulent jet expands and entrains air, any liquid droplets entrained by the flashed HF vapor will vaporize thereby drastically reducing the cloud temperature. Air dilution will reduce the HF partial pressure thus favoring dissociation but the temperature reduction resulting from liquid HF vaporization will favor HF association.

Simultaneously, the rapid temperature drop due to entrained liquid HF vaporization will condense out moisture from the ambient air as frost or droplets. This condensed water will react with the HF forming a stable, maximum boiling water/HF azeotrope. The result is a persistent HF/water fog. The process of condensing water from the ambient is exothermic, as is the process of mixing HF and water in the liquid phase. The net result is a cloud whose properties are changing significantly as it entrains air and is advected downwind.

Schotte published a paper in 1987 that discussed measurements of vapor HF/air mixtures with relative humidities from 0% to 100%. He developed equations for liquid HF releases to predict temperature changes, onset or disappearance of fog, amount of fog, fog density, and concentration of HF in the fog. EXXON Research and Engineering incorporated Schotte's model along with a flash algorithm into a FORTRAN program (Diener, 1988b). Allied Corporation produced graphs of the HF-H_2O-Air system from the Schotte equations coded by EXXON (Hague, 1988). Calculations for HF release conditions (pressurized superheated HF) suggest that the initial source cloud consists of 80% - 90% liquid aerosol and initial cloud temperatures of 0 to 14°C. The subsequent rise and fall or liquid aerosol fraction and cloud temperature are quite complex, but the effective cloud density decreases monotonically with increase in entrained air (See Figures 2.1-1 and 2.1-2). It is this cloud density state relation which determines cloud spreading behavior and effects the turbulent mixing rates.

Any gas or hypothetical gas which reproduces this density state behavior with dilution can be used in laboratory or numerical models to predict cloud transport and dilution. An ideal gas can be conceived with molecular weight of 20 (same as HF), a very cold source temperature, and a specified molar specific heat capacity that will have the same number of molecules per volume as an HF aerosol cloud. Careful selection of the ideal gas molar specific heat capacity permits the ideal gas to reproduce the density behaviors noted in Figures 2.2-1 and 2.2-2. Figures 2.2-3 through 2.2-7 examine the combinations of temperature and molar specific heat capacity required to reproduce the Schotte density curves. Figures 2.2-3, 2.2-4, and 2.2-5 examine density versus lbs. Air/lbs. HF released ratio. Figure 2.2-6 indicates the variation of cloud density with mole fraction of HF, and Figure 2.1-7 displays the consequent diluted cloud temperatures. Note that ridiculously low ideal gas temperatures (circa 5 - 20°K) are required to represent in a gas the number of gas molecules stored by the real cloud in a liquid aerosol.

Also noted on Figures 2.2-3 to 2.2-5 are the molecular weight values (205 - 1037) required for an isothermal gaseous simulant to reproduce the extremely large initial cloud specific gravity (S.G. = 12 to 20) and subsequent density history. Note that an isothermal simulant will not permit a buoyant cloud to exist at low concentrations. Since the densest isothermal cloud simulant commonly used in laboratory measurements is SF_6 (S.G. = 5.05), it is not likely that laboratory simulations will correctly consider the inertial characteristics of a dispersing HF cloud modeled as a pure HF release. This will be discussed further in Chapter 7.0, where laboratory modeling of pre-diluted HF plumes is found acceptable.

2.3. Hydrogen Fluoride Spill Experience

Although accidental releases of Hydrogen Fluoride have occurred , little information can be gleaned from post spill analysis about the cloud mixing process. Hence, in 1986 Amoco Oil Company and the Lawrence Livermore National Laboratory (LLNL) conducted a series of six experiments involving atmospheric releases of anhydrous hydrofluoric acid at the Department of Energy Liquefied Gaseous Fuels Test Facility. The purpose of these tests was to examine source characteristics, dispersal properties and water spray mitigation techniques. A description of the experimental design and limited results were presented in papers by Blewitt et al. (1987a, 1987b).

These tests were designated the "Goldfish" test series by LLNL. Test conditions extracted from the Blewitt et al. (1988a) paper are shown in Table 2.3-1. Note that the first three tests were unmitigated releases (i.e. no water sprays); whereas the next three tests considered the mitigating influence of water sprays. The first three tests (Goldfish Trials 1, 2, and 3) have been used in Chapter 5.1 of this report to validate the numerical models used herein for entrainment model evaluation. Goldfish Trial 1 was also chosen to be the reference case against which sensitivity calculations discussed in Chapter 6.0 were performed for the mitigating effects of water sprays and vapor fences operating at various locations, wind speeds, spray strengths and barrier heights.

During small scale tests Allied Corporation observed that up to 78.8% of the HF could be removed from a gas cloud by water sprays when water/HF volume ratios were 64/1. Blewitt et al. (1988b) reported reductions of approximately 36% to 49% in downwind concentrations during Goldfish Trials 5 and 6. This report did not examine any other data which included extraction of gases from the cloud by mitigating devices, but both the reduction and diluting aspects of water sprays have been considered.

The kinematics and dynamics of the initial motion of a HF cloud will be determined by the ratio of gravity forces acting on the cloud and the inertia of the ambient atmosphere together with the ratio of the source strength of the HF cloud and the diluting capacity of the atmosphere. The appropriate governing parameters for an instantaneous HF cloud release will be the Froude number, $Fr = U^2/(g(SG-1)L)$, and the Volume Ratio, $V_i = V/L^3$, where U is a characteristic wind speed, L is a characteristic length scale, and SG is the cloud specific gravity at release conditions. For a continuous HF plume the relevant parameters are the Flux Froude number, $\underline{Fr} = U^3L/(Qg(SG-1))$ and the Volume Flux Ratio, $\underline{V}_e = Q/(UL^2)$, where Q is the source volume flow rate at release conditions. Based on the scenarios described by Diener (1988) in section 2.1 above the parameter ranges relevant for typical HF spills of pure HF are:

Instantaneous Spills

$Fr = 0.0011$ to 0.11,

$V_i = 0.15$ to 1.5,

Continuous Spills

$\underline{Fr} = 0.045$ to $22{,}600$, and

$\underline{V}_e = 0.000005$ to 0.025.

An alternative range of spill conditions can be identified if one focuses attention on the behavior of the HF plume only after all unflashed HF evaporate (i.e. at minimum cloud temperature). This condition typically occurs once the mass ratio lbm air/lbm HF is greater than 5. At this state point the cloud volume is larger, but the cloud specific gravity is significantly less. For many situations only jet mixing occurs below a mass fraction ratio of 5; hence, gravity mixing dynamics are not dominant in this region. Based on the scenarios described by Diener (1988) in section 2.1 above the parameter ranges relevant for typical HF spills of pre-diluted HF are:

Instantaneous Spills

$Fr = 0.035$ to 3.5,

$V_i = 1.2$ to 12,

Continuous Spills

$\underline{Fr} = 0.171$ to 85,500, and

$\underline{V}_c = 0.00004$ to 0.2.

These parameter ranges are outlined on Figures 2.3-1 and 2.3-2. The figures also contain points reflecting the conditions for which various dense gas experiments relevant to HF dispersion were obtained. Notice there are wide parameter ranges where no data has been taken; thus, conclusions drawn from tests performed over the limited space of the spill envelope must be extended with great caution to other spill conditions.

2.4 Entrainment Models for Vapor Barriers and Water Spray Curtains

Models for dense-cloud dispersion are desired which produce the detailed nuances of behavior perceived during laboratory and field experiments. When a flow field is only weakly three dimensional so that some dimensions can be decoupled from the others, a set of simple relations can be obtained by integrating the conservation equations over that dimension. When the flow situation is steady and diffusion in one direction is weak with respect to advection, it is possible to integrate over a plume cross-section and calculate plume width, average height, and cross-section averaged velocities, concentrations, temperatures, and humidity. Such a "box" type model is numerically very fast since the conservation equations reduce to a set of coupled ordinary differential equations. Alternatively when vapor generation is transient, and there are opportunities for upwind flow, a set of coupled partial differential equations of only two dimensions and time can be created by integrating the conservation equations over just the depth. Such a "shallow layer" or "slab" type model provides information about time- and space-dependent cloud widths, heights, and depth-averaged velocities, concentrations, temperatures, and humidities.

Such models can be modified to handle the increased dilution which occurs in the presence of water spray curtains or vapor barrier fences. A box model (Meroney and Lohmeyer, 1984; Meroney, 1983; and Andreiev et al., 1983) and a slab model (Meroney and Lohmeyer, 1984, and Meroney, 1984a and 1984b) have been adapted to consider HF dilution by water sprays and vapor barrier fences.

Both numerical models normally use the concept of an entrainment velocity, we, across the upper cloud surface to mix the cloud with ambient air. The entrainment velocity is a semi-empirical function of boundary-layer and cloud variables such that,

$$w_e = f(U_g, u_*, w_*, Ri_*),$$

where U_g = plume frontal velocity,
u_* = friction velocity,
w_* = convective velocity, and
Ri_* = local plume Richardson number.

Various expressions which describe the entrainment of air into dense gas clouds have been proposed for isolated clouds dispersing in homogeneous surroundings (Blackmore et al., 1982; Ermak et al., 1982; Havens and Spicer, 1985; Meroney, 1984a).

Removal of HF from Gas Cloud by Water Sprays

Reductions in HF cloud concentrations can occur through chemical reaction between the cloud and water spray. HF reacts with the liquid water and leaves the cloud as the water deposits on the ground. Laboratory and field tests described by Blewitt et al. (1987c) measured HF removal ranging from 9 to 80%.

The chemical mechanisms, their rate constants, and the manner in which the cloud reacts with different size droplets has not been documented. A simple removal rate model can be presumed, however, that can be used to project cloud behavior after a portion of the HF mass is removed. Care must be taken to assure corrections are applied to the cloud fluxes of momentum, mass, and energy after removal.

Entrainment due to a Vapor Barrier

A vapor barrier or fence placed downwind of a dense vapor cloud can induce a variety of fluid mechanic responses by the cloud. Britter (1982) reviewed a number of special hydraulic effects expected from stratified fluids in the presence of surface obstacles or sloping terrain. Later Rottman et al. (1985) considered the Thorney Island Phase II trials with respect to the observed gravity current behavior. Essentially the cloud may behave like a moving layer of liquid traveling either as a rapid (super critical) or tranquil (subcrictical) flow, where $Fr > 1$ or $Fr < 1$, respectively passing over a surface obstruction. When the flow is rapid the obstacle may block and reflect the cloud upwind; increase upwind depth and accelerate the cloud over the obstacle; or increase upwind depth, accelerate the cloud over the obstacle, and then mix aggressively in a hydraulic jump. Calculations suggested that with low ambient winds the gas cloud would not pass over a fence if the height of the fence is more than 2.5 times the height of the approaching gravity current. When the approach flow is tranquil and the cloud height is greater than the fence height, then the cloud upper surface may dip down briefly as it passes over the obstacle.

Rottman et al. also concluded that when a rapid flow passes through a porous fence the cloud may accelerate and the cloud height will decrease. This could lead to earlier arrival times downwind of the fence.

If a barrier interacts with a cloud after the gravity driven phase of its motion is reduced, then the primary action of the fence will be to modify local wind profiles and increase turbulence due to strong wind shears located at the top of the fence. This increased turbulence will increase air entrainment into the cloud. Since the turbulence will decay more or less linearly out to about thirty fence heights downwind, the dense cloud will perceive an initial step increase in mixing rate which then decays slowly back to ambient levels. The entrainment rate due to a barrier may be expected to be proportional to the approach wind speed at fence height, U(H), a fence drag coefficient, C_D, and fence porosity, P. The following simple model is proposed to described the increased entrainment resulting from a vapor barrier fence:

$$(w_e)_{fence} = C_D U(H)(1 - P)(1 - (x - x_f)/(30H)),$$

where x is distance downwind of the source, x_f is fence location, and the relation is not used downwind of x_f. This model will be used in the numerical models to compare with selected field and model data. Subsequently, it will be used to prepare sensitivity calculations of reference case Goldfish Trial No. 1 in the presence of vapor barriers.

Table 2.3-1 Spill and Meteorological Conditions During Goldfish Trials

Goldfish Spill Conditions:
1986 Amoco, LLNL Tests
RNM - 22 June 1988

Property	Number 1	Number 2	Number 3	Number 4	Number 5	Number 6
Spill Conditions						
Spill Rate (gpm)	469.2	175.1	171.6	67.5	32.5	33.0
HF Temp (oC)	40.0	38.0	39.0	36.0	40.0	38.0
Duration (sec)	125.0	360.0	360.0	840.0	960.0	960.0
Wind Speed (m/s)	5.6	4.2	5.4	6.8	3.8	5.4
Air Temp (oC)	37.0	36.0	26.5	21.3	21.3	21.5
Dew Point (oC)	-8.5	1.1	6.6	-2.0	5.6	4.6
RH %	5.0	12.0	28.0	20.0	35.0	32.0
Spray Conditions						
X-spray (m)				14.3	30.5	31.7
Spray width (m)				8.5	22.9	22.9
Number Nozzles				4.0	25.0	25.0
Height nozzles (m)				3.7	0.3	3.7
Q water (gpm)				67.5	700.0	700.0
time on (min)				0-7	0-9	9-?
time off (min)				7-14	9-17	0-9
Numerical Model Set						
Density (kg/m3)	12.2	12.2	24.4	11.9	14.0	12.8
Q gas (m3/sec)	2.325	0.884	0.433	0.343	0.140	0.156
Ts (oK)	313.2	311.2	312.2	19.5	23.0	21.0
Molecular weight	20.0	20.0	20.0	20.0	20.0	20.0
Cp ratio	0.83	0.83	0.90	1.00	1.00	1.00
Tair (oK)	310.2	309.2	299.7	294.5	294.5	294.7
u* (m/sec)	0.374	0.280	0.360	0.454	0.253	0.360
Zo (m)$^{+}$	0.005	0.005	0.005	0.005	0.005	0.005
Results						
% reduction seen				10-25%	44%	47%
C300 off	28000.0	20000.0	20000.0	3200.0	2028.0	1440.0^
C300 on				2700.0	574.0*	916.0
C1000 off	3050.0	2000.0	2100.0	400.0		
C1000 on				187.0		
C3000 off	410.0		200.0			
C3000 on						

Notes:
- * Centerline of cloud did not cross array
- ^ Estimate from Test 5 using SLAB calculations
- \+ Assumed roughness

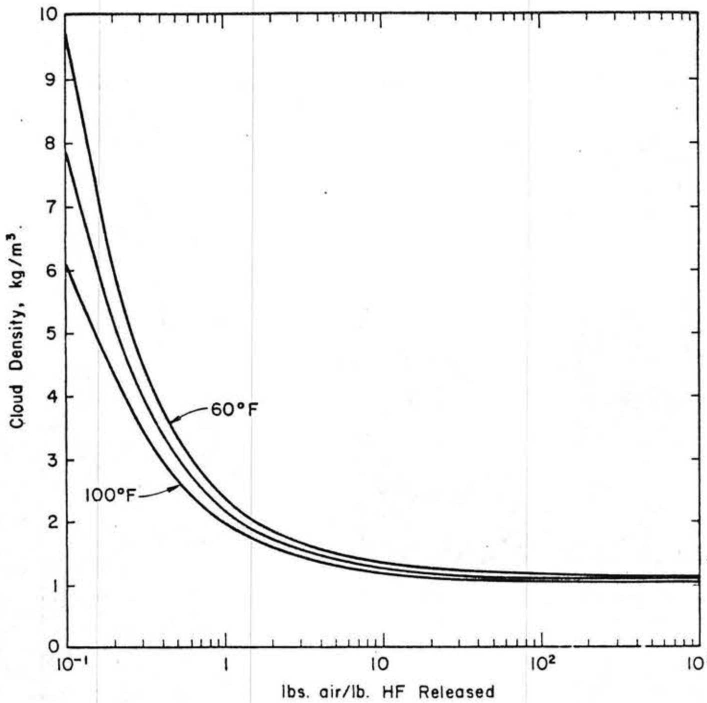


Fig. 2.2-1 Cloud Density vs Air Dilution for VariousInitial Temperatures with 60% Relative Humidity (W. J. Hague, 1988)

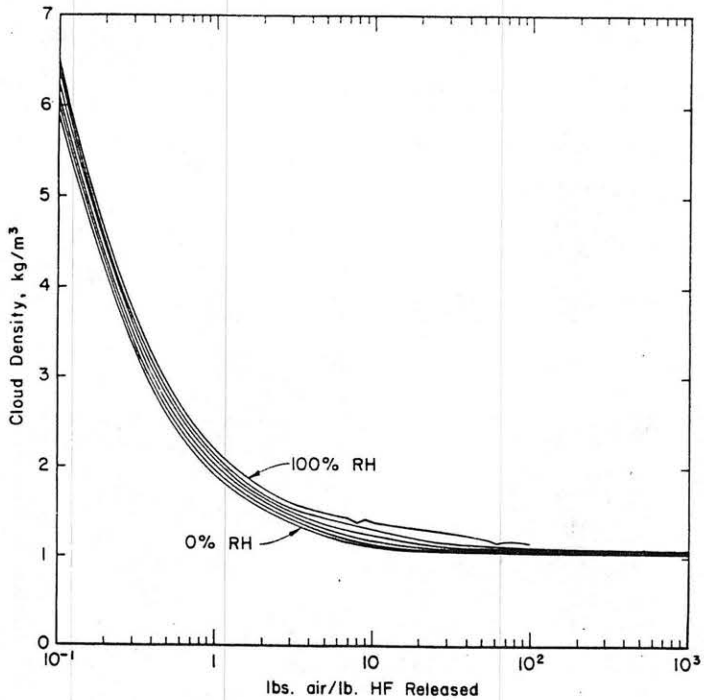


Fig. 2.2-2 Cloud Density vs Air Dilution for VariousHumidity Conditions with Temperatures of 100°F (W. J. Hague, 1988)

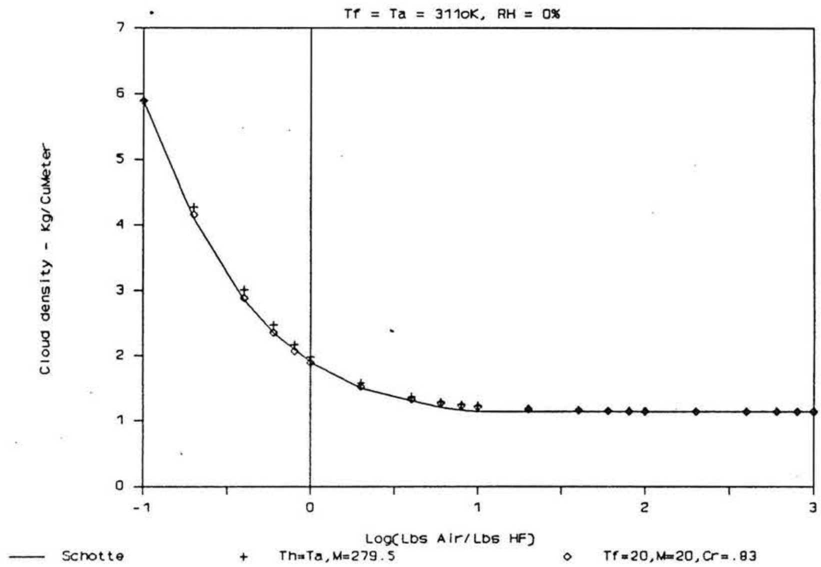


Fig. 2.2-3 Cloud Density vs Air Dilution, Isothermal and Ideal Gas Conditions to Simulate Goldfish Trials 1 and 2

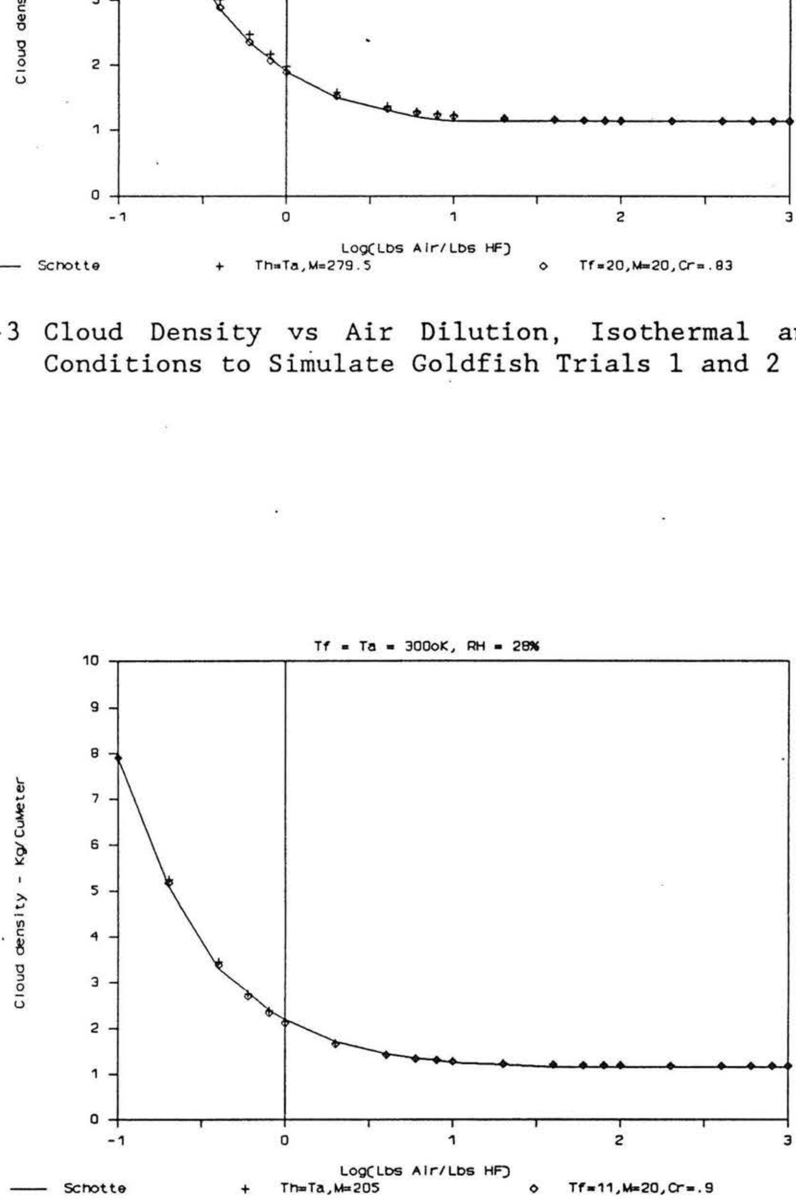


Fig. 2.2-4 Cloud Density vs Air Dilution, Isothermal and Ideal Gas Conditions to Simulate Goldfish Trial 3

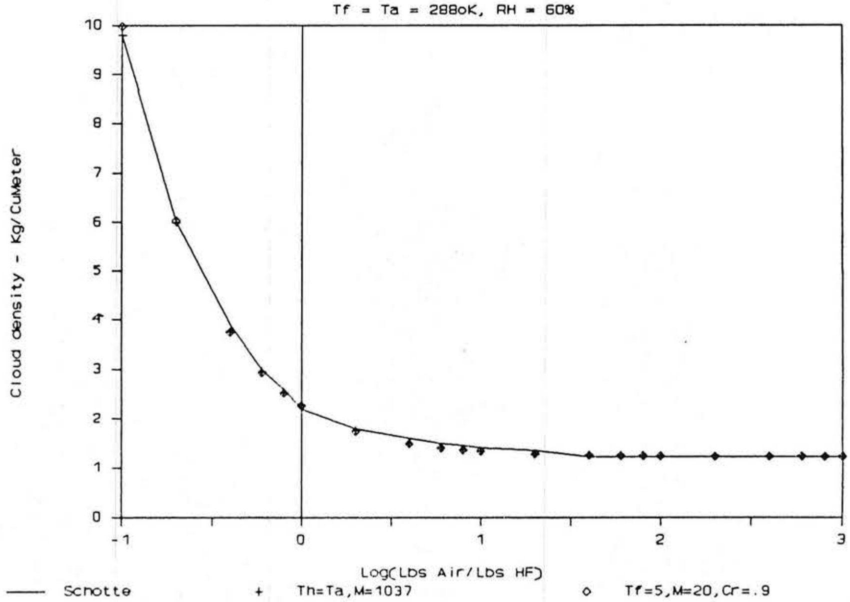


Fig. 2.2-5 Cloud Density vs Air Dilution, Isothermal and Ideal Gas Conditions to Simulate 60% Relative Humidity and Air Temperatures of 15° C

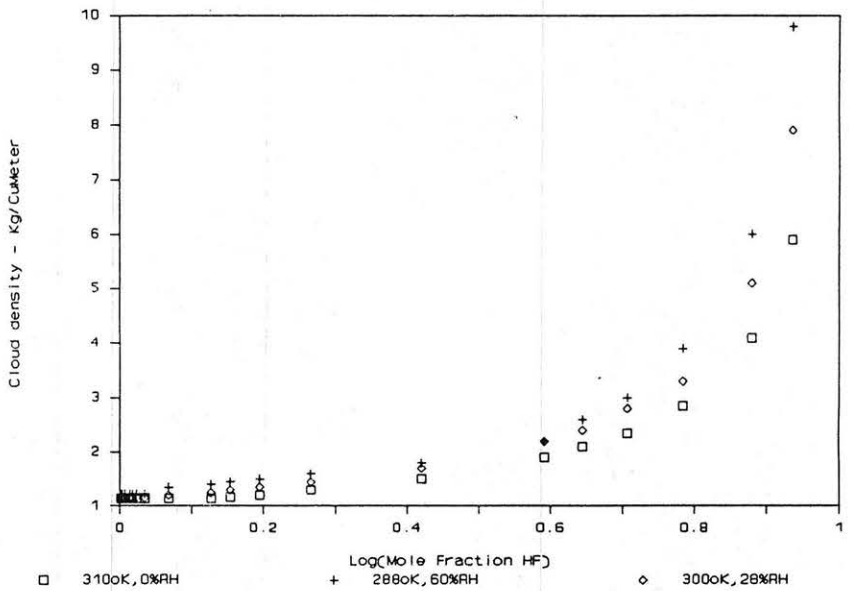


Fig. 2.2-6 Cloud Density vs Mole Fraction, Ideal Gas Simulants

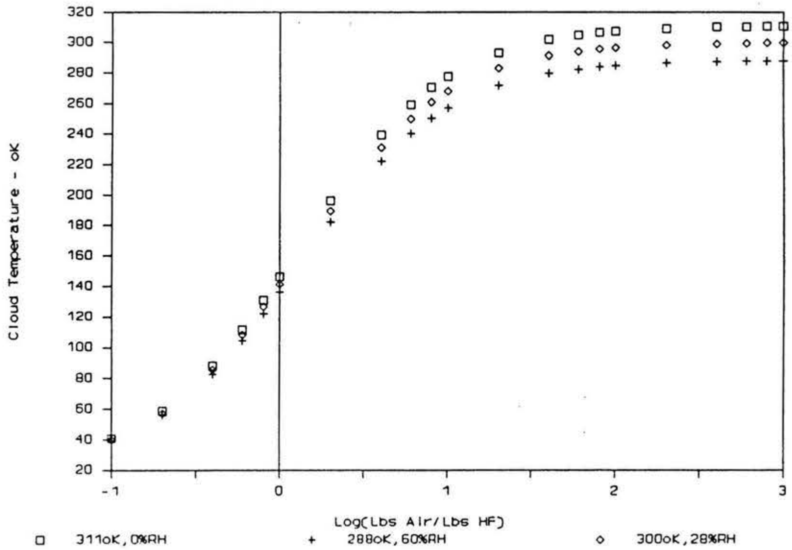


Fig. 2.2-7 Cloud Temperature vs Air Dilution, Ideal Gas Simulants

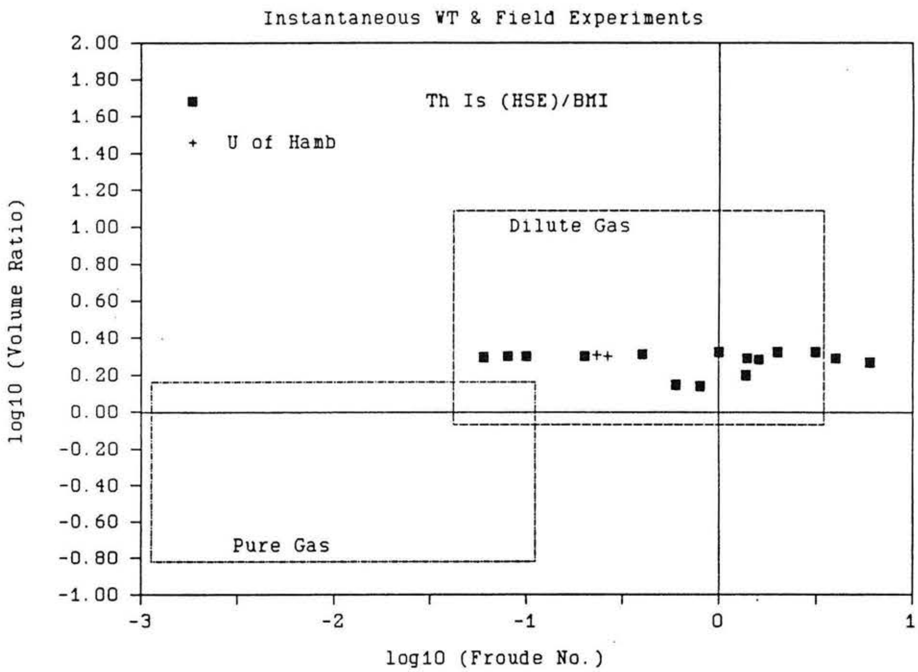


Fig. 2.3-1 Hydrogen Fluoride Accident Envelope, Volume Flux Ratio vs Flux Froude Number, Continuous Spills

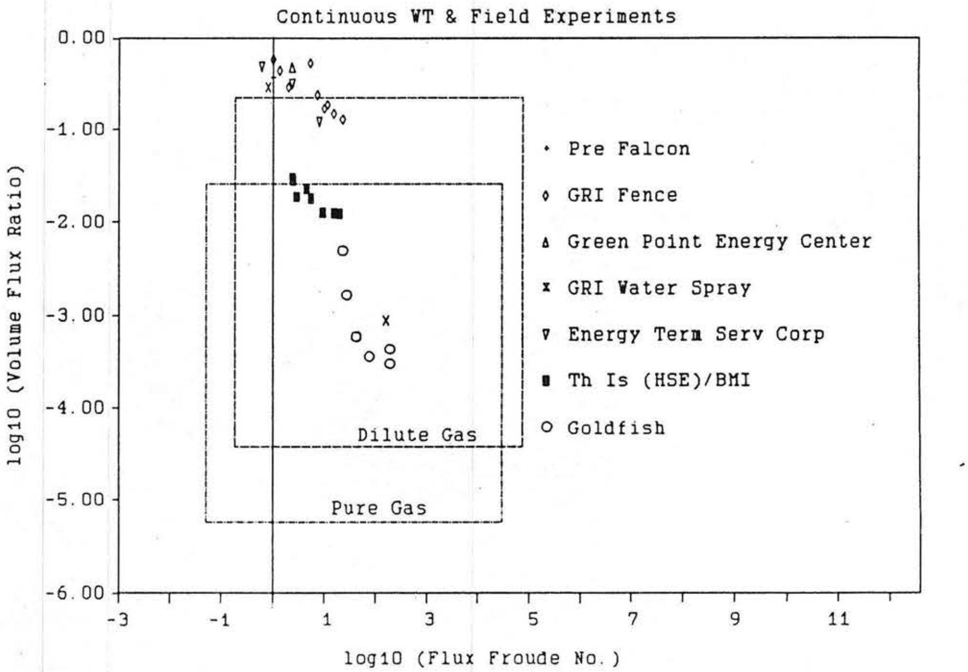


Fig. 2.3-2 Hydrogen Fluoride Accident Envelope, Volume Ratio vs Froude Number, Instantaneous Spills

3.0 APPLICABLE DATA BASES

Puttock, Blackmore and Colenbrander (1982) identified over 22 field experiment programs on dense gas emissions. Subsequently, further field measurements have been performed on the release of Freon-air mixtures at Thorney Island, the release of hydrocarbon fuels at Maplin Sands, and the release of hydrocarbon fuels, ammonia, rocket fuels, and even HF at the DOE Liquefied Gaseous Fuels Test Facility at Frenchman's Flats, Nevada. A number of these experiments have also been simulated in fluid modeling facilities (Meroney, 1986a). This section will identify those experiments relevant to the HF mitigation program for review in Chapter 4.0.

3.1 Field Experiments

The only field experiments performed on the release of HF to the atmosphere seem to be the Goldfish Trials performed by Amoco and LLNL at the DOE test facility (Blewitt et al, 1987a). The parameter values found for the six experiments are noted on Table 2.3-1. The first three trials have been used to validate the numerical models discussed in Chapter 5.1. The second three trials included water spray barrier effects, but, since strong removal of HF by chemical reaction and subsequent deposition occurred, the trials are not considered further in this report.

Phase II and III of the Thorney Island test series included solid fences, porous fences, cubical buildings, and a vapor barrier enclosure (McQuaid and Roebuck, 1984). Some of these tests involved instantaneous release of a cylindrical volume of heavy gas, others permitted continuous release of gas from a point source located a short distance from the cylindrical tent. Thorney Island test cases considered in this report are noted on Table 3.1-1b, Table 4.6-1 and 4.6-2.

During the summer of 1987 LLNL performed a series of five spills of LNG onto a water pond contained within a surrounding vapor barrier fence. During three of these trials substantial disruption of the cloud occurred due to RPT (Rapid Phase Transition) explosions and fire. During one test most of the concentration instrumentation was not operative. During Trial No. 4 a good set of measurements was obtained. Due to the program disruption by the fire a no-barrier case was never completed. Unfortunately, the field data were not available for evaluation during the time of the work effort for this report.

Remember that a single field event has a large number of uncontrolled or poorly specified variables that effect the resultant concentration field. The wind field is normally non-stationary, source flow rates and conditions are typically only approximate, and often the upwind and downwind fetch are non-homogeneous. Evaluation of such data is only possible within the natural limits to predictability permitted by the turbulent nature of the flow fields. Even if it were possible to introduce two separate field plumes into the same resolved wind field, there would be some variance in the dynamics of the two plumes due to the unresolved turbulence. This means that an effort to discriminate between models based on one data set is likely to be unjustified. The best safeguard against making large modeling errors will be an evaluation methodology which searches for trends across a large set of field experiments.

A summary of some of the wind, site, and source characteristics for each test series is summarized in Table 3.1.

3.2 Laboratory Experiments

Twelve laboratory studies have been identified which included the effects of obstacles, vapor barriers, or fences on the dispersion of dense gas clouds. A summary of some of the wind, site, and source characteristics for each test series is summarized in Table 3.1. The early dense gas tests by Meroney et al. (1976, 1977) were found to be dominated by the large tanks considered, and the gas concentration instrumentation was not as reliable as that used in subsequent experiments. Hence, these experiments were eliminated from further consideration.

Large tanks and dikes were present during the studies by Kothari and Meroney (1980, 1981). Since these tests included complicated surrounding building complexes typical of industrialized areas, the data were examined for gross tank effects on the dense cloud.

Systematic studies of various vapor barriers, vortex generators, and tank arrangements were considered by Kothari et al. (1981) and Kothari and Meroney (1982). Only continuous releases were tested; hence, any effect on plume arrival, peak arrival or departure time could not be evaluated.

Water spray barriers were tested by Meroney et al. (1983, 1984) and Heskestad et al. (1985). One set of model tests replicated the water spray conditions tested during the Health and Safety Executive (HSE) field tests on carbon dioxide dilution (Moodie, Taylor, and Beckett, 1981). (Unfortunately, anemometry was subsequently found to be sheltered by gas tanks during the HSE field experiment, making much of the field data suspect.)

The British Maritime Institute (BMI) modeled the Thorney Island Trials at a variety of model scales and various model parameter assumptions (Davies and Inman, 1986). They replicated each experiment several times, so their data tends to bound the range of behaviors possible in the field. The time series for each measurement location are archived on tape, but have not yet been distributed outside the BMI. Since both field and laboratory data now exist for the Thorney Island Trials, these data were evaluated by the Surface Pattern Comparison technique described by Meroney (1986). Results are considered in Chapter 4.0.

Finally Koenig and Schatzman (1986) performed a variety of model experiments on instantaneous and continuous spills to evaluate the influence of street canyons between tall buildings, street intersections, cross-wind depressions or roadways, and longitudinal walls and fences.

Their data are significant in that they display the potential of obstructions to reduce spread and inhibit mixing.

Table 3.1-1a Data Sets Relevant to HF Mitigation Review

Authors (Date)	Title	Mitigation Devices Studied	Model Scales	Spec. Grav. Low	Spec. Grav. High	Source Type	Source (m3/m) Low	Source (m3/m) High	Boiloff Rate	Zo (m)	Power Law	Wind Speed Low	Wind Speed High	Structure Hts. Low	Structure Hts. High	Structure Wdth Low	Structure Wdth High	Stab.	Total Tests
Meroney et al (1976)	Wind Tunnel Study of the Negatively Buoyant Plume Due to an LNG Spill	High dikes	1:130,200,666		1.4	Area	1583	64279	V		0.23	3	7	24.4	39.3	73.2	79.2	N, S	45
		Low dikes	1:200,666		1.4	Area	3766	60315	V̇		0.23	3	7	6.4	36.9	93	100.6	N, S	52
Meroney et al (1977)	Dispersion of Vapor from Lng Spills - Simulation in a Meteorological Wind Tunnel	High dikes	1:200,400		1.4	Area	1528	42475	C, V			3.1	7.2		24.4		79.2	N, S	19
		Low dikes	1:400		1.4	Area	3681	39644	C, V			3.1	7.2		6.4	93	100	N, S	9
		AGA Capistrano	1:106		1.4	Area	453	4531	C, V			5.4	5.4		0.6		24.4	N	4
Kothari & Meroney (1980)	Dispersion of Vapor from LNG Spills at Green Point Energy Center: Simulation in a Wind Tunnel	Low dikes	1:400		1.38 4.18	Area	800	64000	Step		0.16	2.23	8.93			100	100	N	141
Kothari & Meroney (1981)	Dispersion of Vapor from LNG Spills at Energy Terminal Service Corporation: Simulation in a Wind Tunnel	Dikes Vapor barrier fences	1:250		1.38	Area	50.8	101.7	C, Step		0.27 0.22	2.9	6.69	2.44	4.88	50	410	N	40
Kothari et al (1981)	LNG Plume Interaction with Surface Obstacles	Tanks	1:250	1	1.38	Area		7593	C	0.04	0.22	4	7		50		50	N	44
		Buildings	1:250	1	1.38	Area		7593	C	0.04	0.22	4	7		18.75		18.75	N	20
		Tree fences	1:250	1	1.38	Area		7593	C	0.04	0.22	4	7		7.5	30%poro	300	N	20
Kothari & Meroney (1982)	Accelerated Dilution of LNG Plumes with Fences and Vortex Generators	Fences	1:250	1	1.38	Area	5062	10124	C			4	12	5	10	75	150	N	84
		Vortex Generators	1:250	1	1.38	Area	5062	10124	C			4	12	5	10	75	150	N	72
Meroney et al (1983)	Model Study of LNG Vapor Cloud Dispersion with Water Spray Curtains	Water spray & Dike	1:5		1.5	Area		8286	C	0.00015			0.5		0.2		3	N	3
		Water spray & Dike	1:100		1.5	Area	3000	21444	C	0.003		2.2	8	0	4		60	N	141
		Water spray & Bldg	1:100		1.5	Area		6000	C	0.003			3	fence 16	4tank 28	23fence	6tank 22- 36	N	9
Meroney et al (1984)	Wind Tunnel Simulation of Field Dispersion Tests (by UK Health and Safety Executive) of Water-spray Curtains	Water sprays CO2 point source	1:28.9		1.5	Point	22.6	67.9	C	0.0043		1.7	3.2					N	13

Table 3.1-1b Data Sets Relevant to HF Mitigation Review

Authors (Date)	Title	Mitigation Devices Studied	Model Scales	Spec. Grav. Low	Spec. Grav. High	Source Type	Source (m3/m) Low	Source (m3/m) High	Boiloff Rate	Zo (m)	Power Law	Wind Speed Low	Wind Speed High	Structure Hts. Low	Structure Hts. High	Structure Wdth Low	Structure Wdth High	Stab.	Total Tests
Heskestad et al (1985)	Dispersal of LNG Vapor Clouds with Water Spray Curtains: Phase 2B: Extended Wind Tunnel Experiments	Water sprays with surfacants	1:100		1.5	Area		6000	C	0.003			3		4		60	N	51
McQuaid & Roebuck (1984)	Large Scale Field Trials on Dense Vapour Dispersion	Unobstructed		0.99	4.2	Volume	1320	2100	Inst			1.7	7.5					C D E F	16
		Buildings		2	4.2	Volume	1850	1950	Inst			1.9	9		9		9	B D E	4
		Fences solid		1.92	4.2	Volume	1400	2000	Inst			1.4	5.9		5		100	C D E F	4
		Fences permeable		1.92	2.03	Volume	1850	1925	Inst			5.8	6.8		10	porous	100	D E	2
		Unobstructed		1.6	2	Point	250	260	C			1.5	3.3					D E F	4
		Tank & Fence		1.4	1.8	Point	185	340	C			1.4	5.8		2.4	25	50	D E F G	13
Davies & Inman (1986)	Wind Tunnel Modelling of the Thorney Island Heavy Gas Dispersion Trials	Unobstructed	1:40,100,150	0.99	4.2	Volume	1320	2100	Inst			1.7	7.5					N	22
		Buildings	1:40,100,150	2	4.2	Volume	1850	1950	Inst			1.9	9		9		9	N	7
		Fences solid	1:40,100,150	1.92	4.2	Volume	1400	2000	Inst			1.4	5.9		5		100	N	6
		Unobstructed	1:40,100,150,	1.6	2	Point	250	260	C			1.5	3.3					N	11
		Tank & Fence	1:40,100,150,	1.4	1.8	Point	185	340	C			1.4	5.8		2.4	25	50	N	37
Neff & Meroney (1986)	LNG Vapor Barrier and Obstacle Evaluation: Wind-tunnel Pre-field Test Results	Fence	1:100		1.38	Area	2208	8826	C			2	5	9.4	14.1	44	88	N	7
		Fence & Vortex generator	1:100		1.38	Area	2208	8826	C			2	5	9.4	14.1	44	88	N	10
Konig & Schatzmann (1986)	Wind Tunnel Modeling of Density Current Interaction with Surface Obstacles	Thrny Is	1:165	1.41	4.18	Volume		2000	Inst		0.16	0	5.7					N	24
		Thrny Is & Fence	1:165	1.41	4.18	Vol or Area		2000	Inst or C		0.16	0	Ucc		5		100	N	15
		Street Canyons	1:165	1.41	4.18	Vol or Area		2000	Inst or C		0.16	0	Ucc						
		Inf long wall																N	12
		Finite long wall																N	12
		Low parallel fences																N	12
		Steet canyon																N	17
		Street crossing																N	2
		Sunken freeway																N	20
		Street canyon 45o																N	8

4.0 RESULTS FROM DATA BASE EVALUATION

The primary purpose of this data review and analysis is to develop general relations that can be used to predict downwind concentrations for different barrier configurations. Concentrations due to a heavy gas release are expected to be a function of some combination of the following dimensionless variables:

<u>Atmospheric Conditions:</u>

Surface roughness coefficient,	Z_o/L_c,
Surface friction coefficient,	u_*/U_{Lc},
Convective velocity coefficient,	w_*/U_{Lc},

<u>Site Configuration:</u>

Barrier dimensions,	H/L_c, W/L_c, and L/L_c,
Water spray gas removal efficiency	Reduction
Water spray rate,	$(w_e)_{spray}/U_{Lc}$,

<u>Spill Characteristics: (Instantaneous):</u>

Froude Number,	$U_{Lc}^2/(g(SG - 1)L_c)$,
Volume Ratio,	$Q/(U_{Lc}L_c^2)$, and
Specific Gravity ratio,	ρ_s/ρ_{air}, or

<u>Spill Characteristics: (Continuous):</u>

Flux Froude Number,	$U_{Lc}^3L_c/(Qg(SG - 1))$,
Volume Flux Ratio,	$Q/(U_{Lc}L_c^3)$, and
Specific Gravity ratio,	ρ_s/ρ_{air},

where the reference wind speed, U, is evaluated at some reference height, L_c. L_c was chosen to be 10 meters at prototype scale for all situations. In some cases the initial momentum of a jet release is also important, but none of the trials examined involved a high velocity source jet.

For each experiment studied the data with a barrier obstacle or water spray has been paired by source Froude numbers and volume release rate with a release without such a barrier (or if a reference case is missing against a reference barrier situation). Thus, concentration data were examined for variation of the concentration ratio,

$$C_{\text{with barrier}}/C_{\text{no barrier}} = C_w/C_{wo},$$

with other parameters such as downwind distance, X/L_c, etc. Similar consideration was given to cloud arrival time ratio, Ta_w/Ta_{wo}, peak concentration arrival time ratio, Tpa_w/Tpa_{wo}, and departure time ratio, Tda_w/Tda_{wo}. Cloud arrival and departure times were generally chosen to be defined as the time when the concentration first reaches 1% or drops below 1%, respectively (In some cases arrival and departure times were related to the appearance of concentration levels equal to 10% of peak values measured at the sampling point). Drift in base line zero concentration was considered in the selection of peak concentrations and times.

Vertical concentration profiles of peak concentrations for comparable pairs have been plotted where available.

Two sets of data were selected for additional evaluations. Surface pattern comparisons were made between the Thorney Island Trials field data (McQuaid and Roebuck, 1984) and the BMI laboratory tests (Davies and Inman, 1986). A multiple regression ANOVA was applied to selected data from the pre-Falcon test series (Neff and Meroney, 1986).

4.1 Dispersion of Vapor from LNG Spills at Green Point Energy Center: Simulation in a Wind Tunnel," Kothari and Meroney, 1980

Experiment Configuration:

A 1:400 scale model of the Greenpoint Energy Center (GEC) tank farm located in Brooklyn, NY, was placed in the Environmental Wind Tunnel (EWT) at Colorado State University (CSU) to determine the dispersion of LNG spills from an accidental release under neutral atmospheric conditions. LNG dispersion about GEC tank number two was examined for three wind speeds (5, 12.3 and 20 mph), for spills simulating boiloff from partial and full tank spills onto soil and insulated dike surfaces.

Six pairs of measurements were selected for barrier effects evaluation. Reference Tests 145, 146, 147, 148, 149, and 150 were compared with Tests 4, 5, 6, 7, 8, and 9, which included a tank and surrounding dike. Lateral traverses of ground level concentrations at two downwind locations, 122 m and 269 m were reported (Figure 4.1-1).

Results of Comparison:

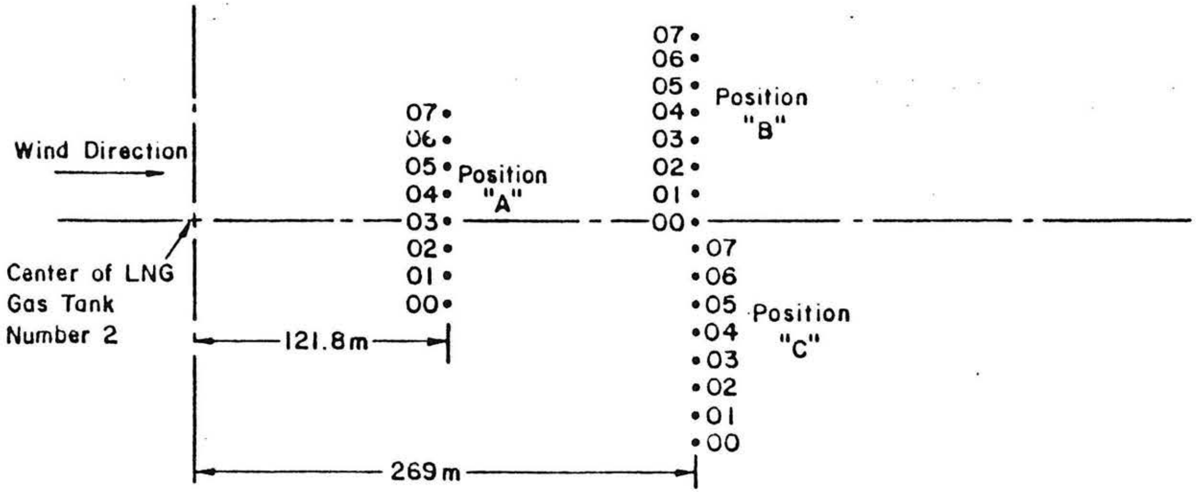
Lateral concentration ratio profiles at 121.8 m (Figures 4.1-2, 3, & 4) for continuous spills and instantaneous spills onto soil and insulation display an average reduction in centerline concentrations of about 50%, whereas profiles at 269 m (Figures 4.1-5, 6, & 7) suggested average reductions of at most 20%. At the lateral edges of the cloud the barriers cause wider plumes; hence concentration ratios generally exceed 1.0. LNG boiling at slower rates off the insulated dike showed smaller reductions in concentration ratio. For many locations the concentration ratios are highly irregular, sometimes exceeding 2 or 3 along the center of the plume. Cross-wind asymmetries in cloud concentrations are caused by the non-homogeneous velocity field produced by wind flow over the tank-farm complex. Such variations may be considered typical of such non-idealized source conditions.

Time ratios did not exhibit any systematic variation from 1.0 for arrival time, peak time or departure time.

Conclusions:

Peak concentration ratios decrease along plume centerline directly downwind of a dike, but ratios increase at plume edges as the barrier forces spread laterally. No systematic effect of the dike on time ratios could be detected.

There were no systematic variations noted with wind speed or source strength; however, boiloff from the insulated dike showed the least systematic deviations.



Lateral Distance between Sampling Points = 20m

Source Gas = Argon

Not to Scale

Note: Longitudinal Distance for Rack Position "B" and "C" for Run Numbers 49, 50, 51, 52, 53, 54, 67, 68, 69, 70, 71, and 72 was 223m Instead of 269m.

Figure 4.1-1 Experimental Configuration and Measurement Grid, Green Point Energy Center

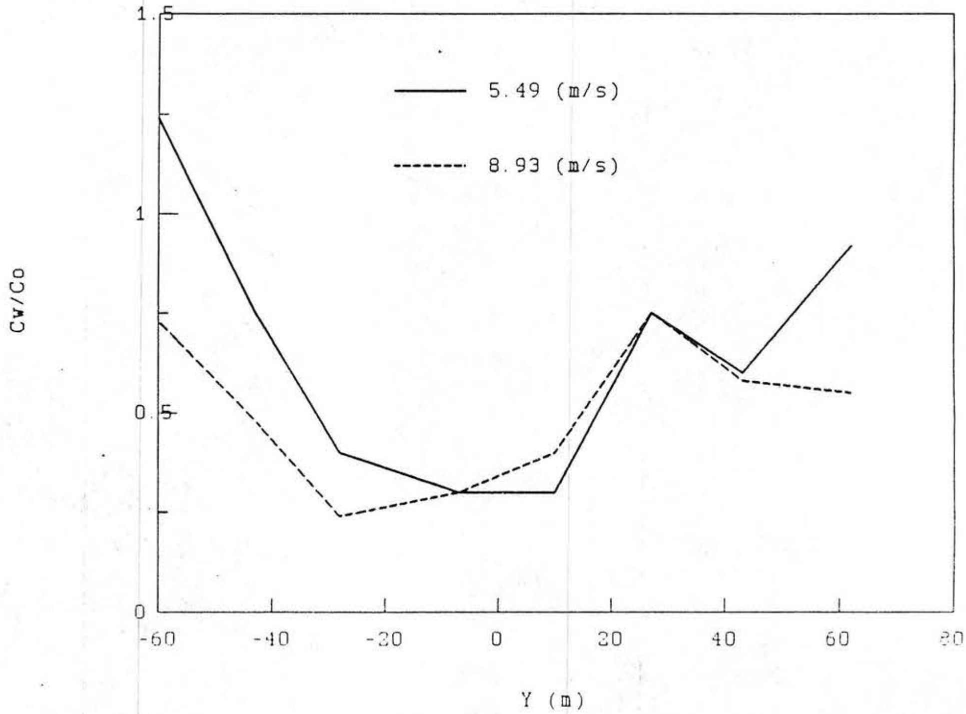


Fig. 4.1-2 Peak Concentration Ratio vs Crosswind Distance at X = 122 m, Continuous Spill at Green Point Energy Center

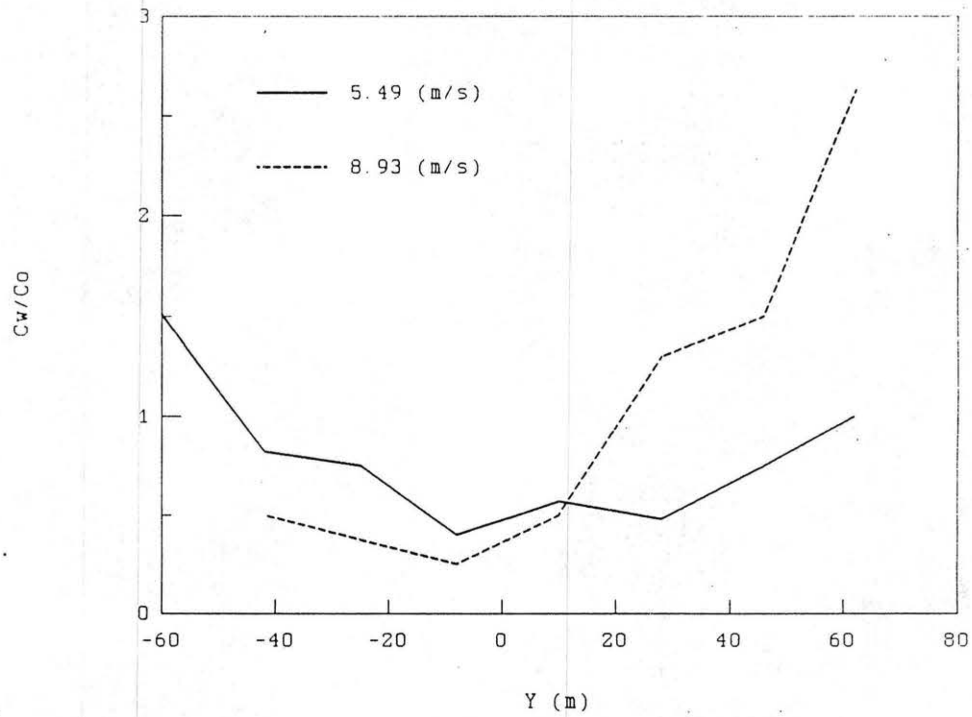


Fig. 4.1-3 Peak Concentration Ratio vs Crosswind Distance at X = 122 m, Instantaneous Spill onto Soil Dike Floor at Green Point Energy Center

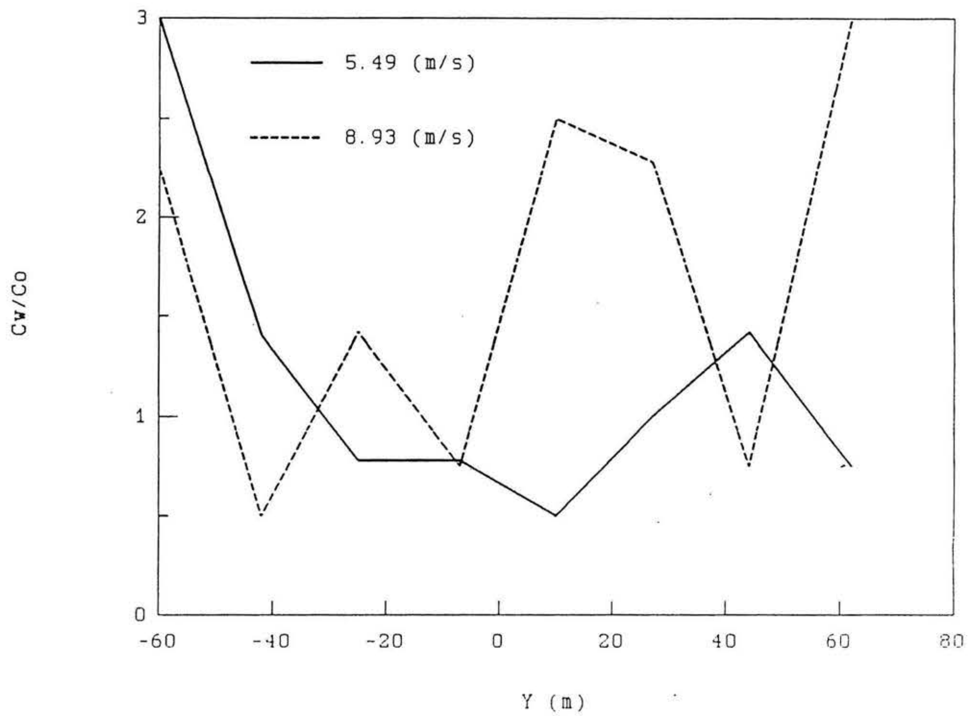


Fig. 4.1-4 Peak Concentration Ratio vs Crosswind Distance at X = 122 m, Instantaneous Spill onto Insulated Dike Floor at Green Point Energy Center

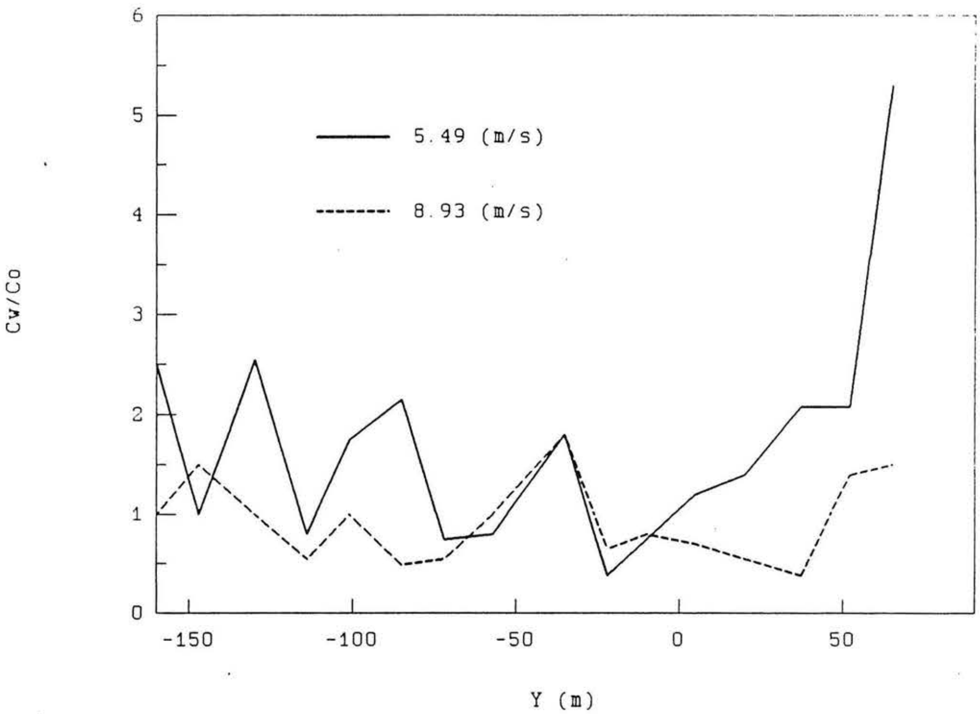


Fig. 4.1-5 Peak Concentration Ratio vs Crosswind Distance at X = 269 m, Continuous Spill onto Soil Dike Floor at Green Point Energy Center

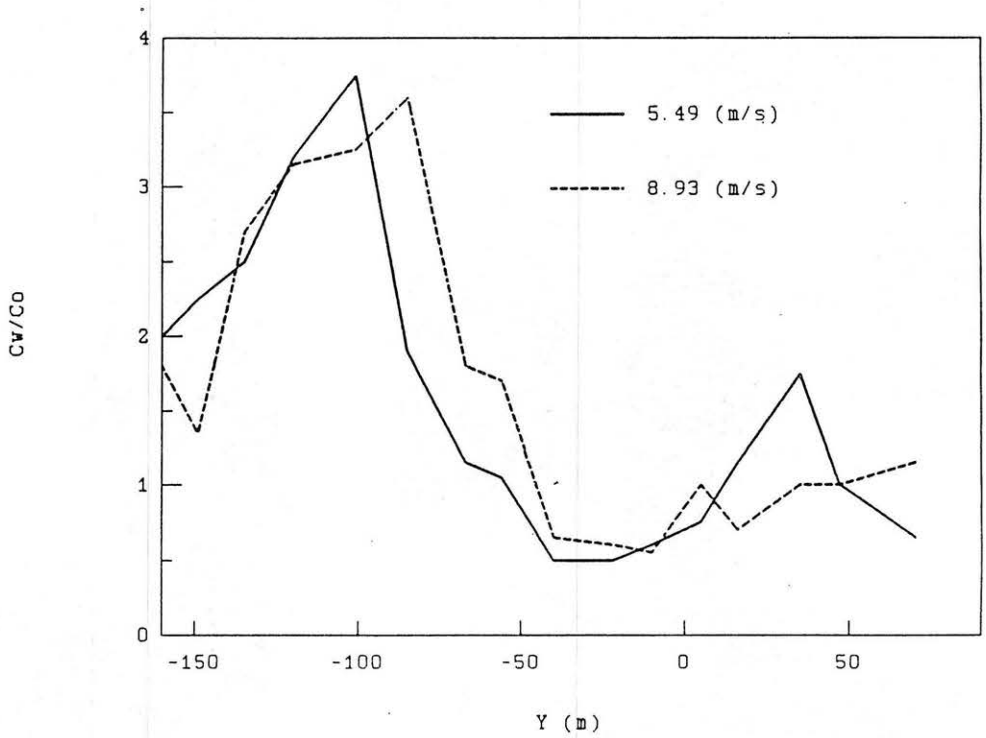


Fig. 4.1-6 Peak Concentration Ratio vs Crosswind Distance at X = 269 m, Instantaneous Spill onto Soil Dike Floor at Green Point Energy Center

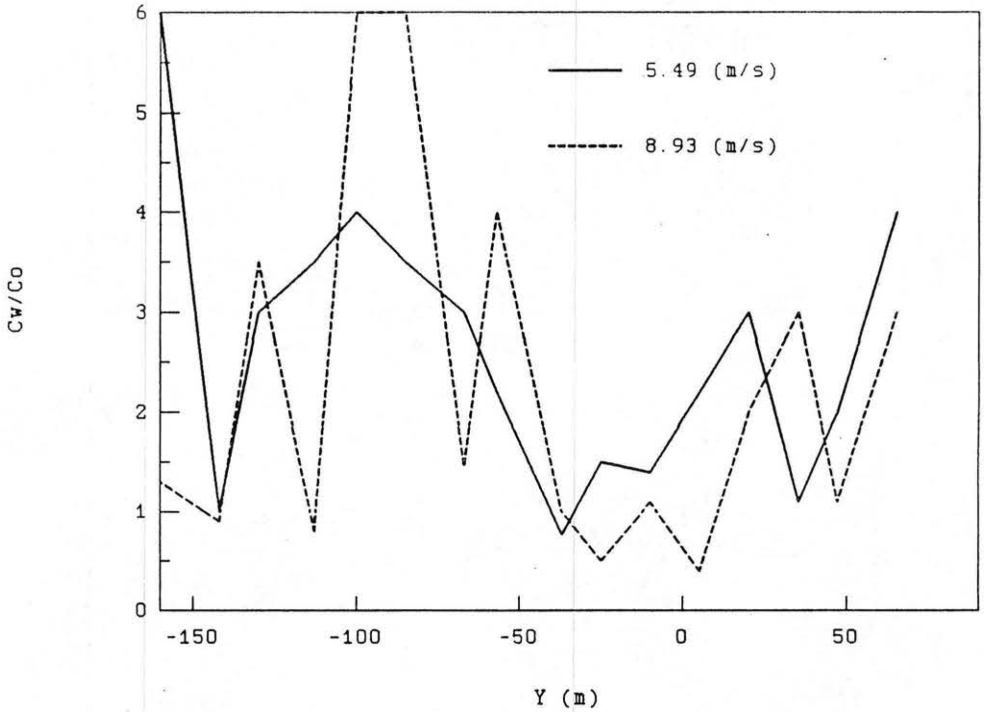


Fig. 4.1-7 Peak Concentration Ratio vs Crosswind Distance at X = 269 m, Instantaneous Spill onto Insulated Dike Floor at Green Point Energy Center

4.2 Dispersion of Vapor from LNG Spills at Energy Service Terminal Corporation: Simulation in a Wind Tunnel," Kothari and Meroney, 1981

Experiment Configuration:

A 1:250 scale model of the Energy Terminal Service Corporation (ETSC) facility at Staten Island was placed in the EWT at CSU to study the dense gas cloud behavior resulting from an accidental LNG release under neutral stability. A total of three wind speeds, five LNG release locations, three wind directions, two boiloff rates for unlimited spill duration, one boiloff rate for 10 minutes spill duration, and three vapor barrier fence heights were investigated. Since all tests were performed in the presence of large storage tanks and vapor barriers, shorter fences in Runs 1, 3, 5, 7, 9, 11, 31, and 33 were compared against taller fences but otherwise equivalent situations in Runs 2, 4, 6, 8, 10, 12, 32, and 34 (See Table 4.2-2).

Results of Comparison:

For a wind direction of 315° (wind directly over the large storage tanks; Figures 4.2-1 & 2) an increase of vapor barrier height from 2.44 to 4.88 m produced up to 70% reduction in concentrations near the fence (circa 10 to 25 m; Figures 4.2-3 & 4) and no significant decrease further from the fence (circa 30 to 50 m; Figure 4.2-5). No significant trend was noted for different wind speeds.

For a wind direction of 270° (wind at 45 degrees to the line connecting the two storage tanks; Figures 4.2-6) an increase of vapor barrier height from 2.44 to 4.88 m produced inconsistent results. In one set of measurements a wind speed of 4.46 m/sec produced concentration reductions of 40% and a wind speed of 6.69 m/sec produced no significant improvement; but in the other measurements just the opposite trend was observed (Figure 4.2-7 versus 4.2-8).

For a wind direction of 215° (wind passes over the process area parallel to the storage tanks; Figure 4.2-9) an increase of vapor barrier height from 2.44 to 4.88 m produced 40 to 50% reduction in concentration ratios at a location 25 m downwind of the fence (Figure 4.2-10), a reduction of 20 to 40% reduction at a location 50 m downwind of the fence (Figure 4.2-11), and no consistent results at a location 75 m downwind of the fence (Figure 4.2-12). No consistent dependence upon wind speed was noted.

For a wind direction of 215° for a release from area P* (the north end of area P has been removed) noted on Figure 4.2-13 an increase of vapor barrier height from 4.88 m to 7.32 m produced 20% to 40% reduction in concentration ratio at locations 50 m downwind of the fence (Figure 4.2-14), and a reduction of 20% to 50% at locations 75 m downwind of the fence (Figure 4.2-15). Again no consistent trends with wind speed are discernable.

Conclusions:

For a variety of wind speeds, obstacle orientations, and spill areas a doubling in height of the vapor fence resulted in 20 to 40% reduction in concentrations at distances of x/Href = 5 to 15, and minimal reductions at distances of x/Href > 20.

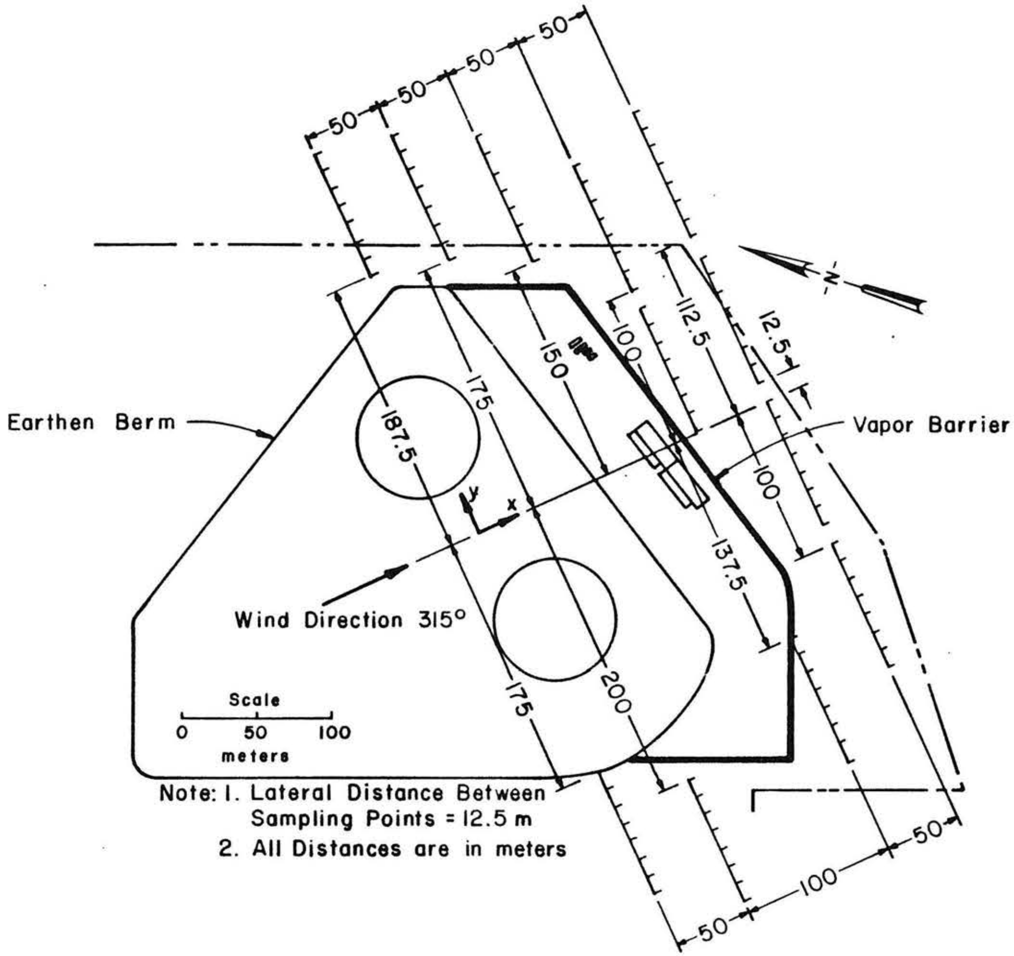


Fig. 4.2-1 Experimental Configuration and Measurement Grid, 315°, Energy Terminal Service Corporation

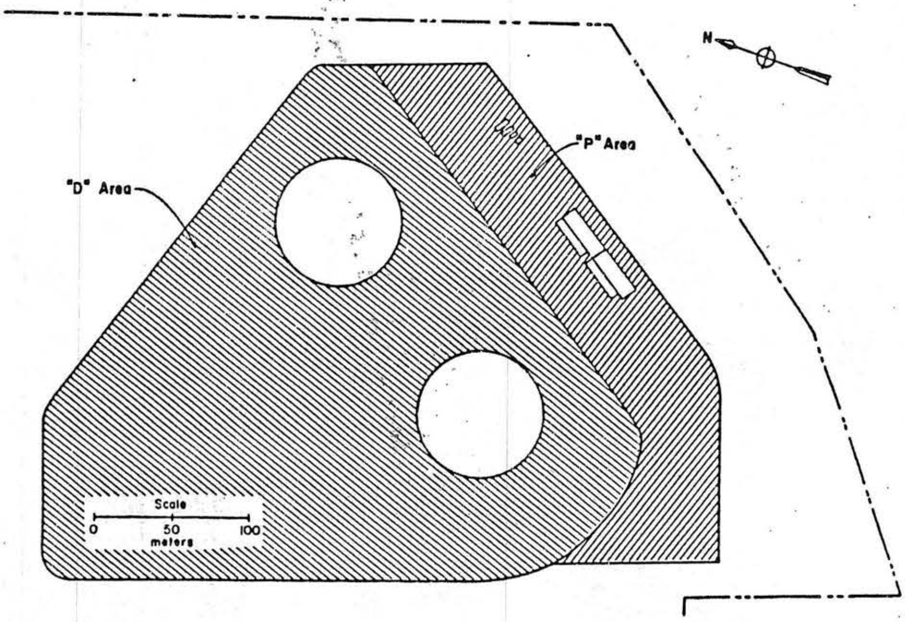


Fig. 4.2-2 LNG Release Areas "P" and "D", Energy Terminal Service Corporation

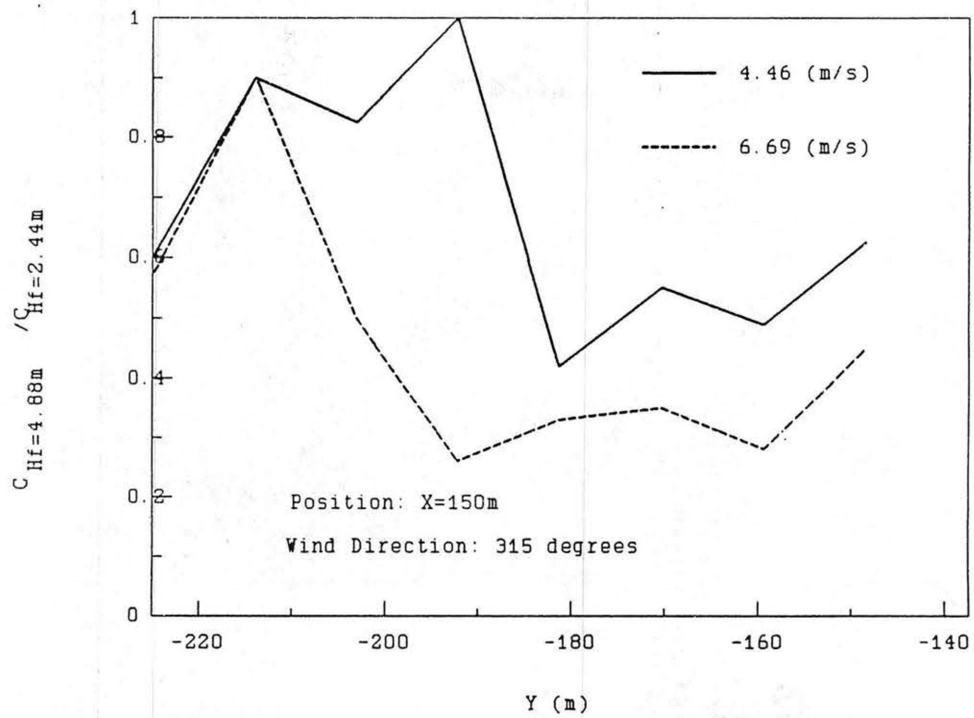


Fig. 4.2-3 Peak Concentration Ratio vs Crosswind Distance, Energy Terminal Service Corporation

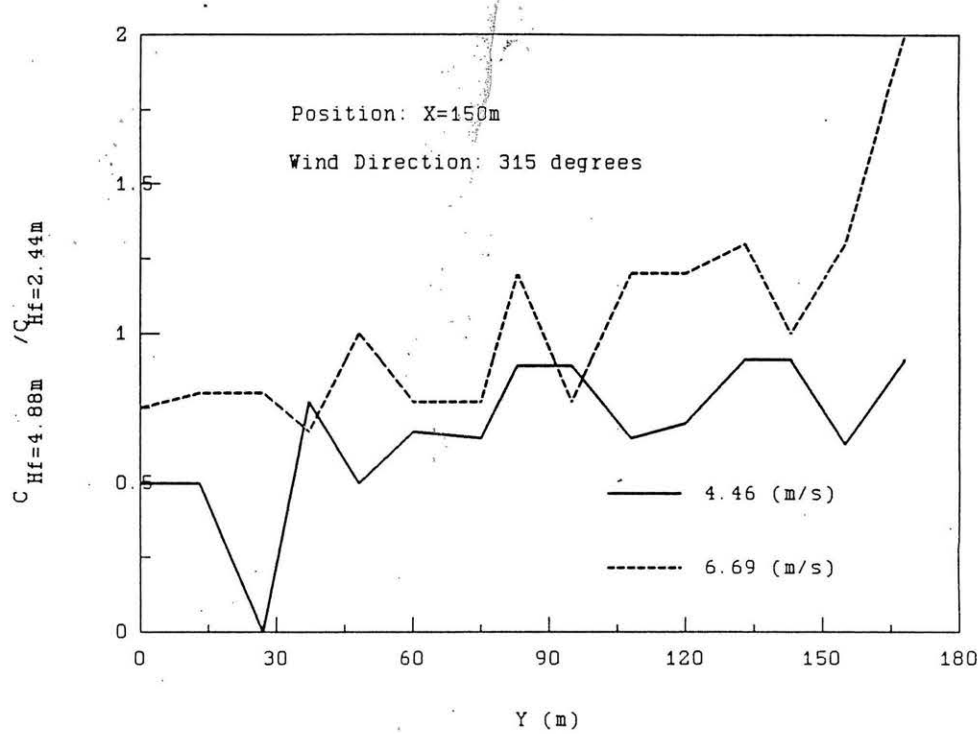


Fig. 4.2-4 Peak Concentration Ratio vs Crosswind Distance, Energy Terminal Service Corporation

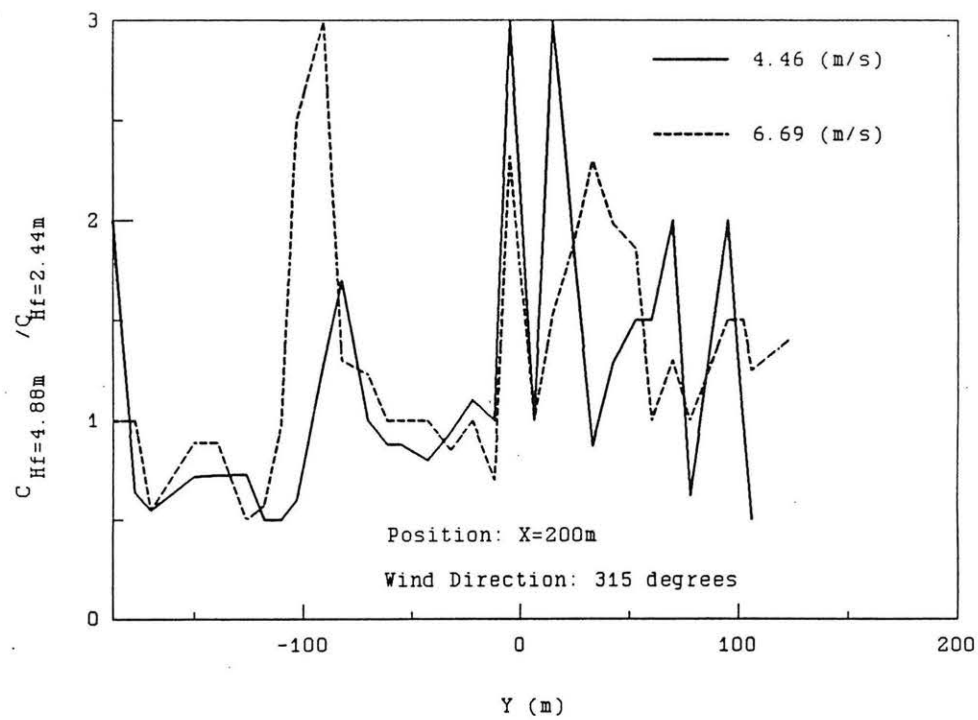


Fig. 4.2-5 Peak Concentration Ratio vs Crosswind Distance, Energy Terminal Service Corporation

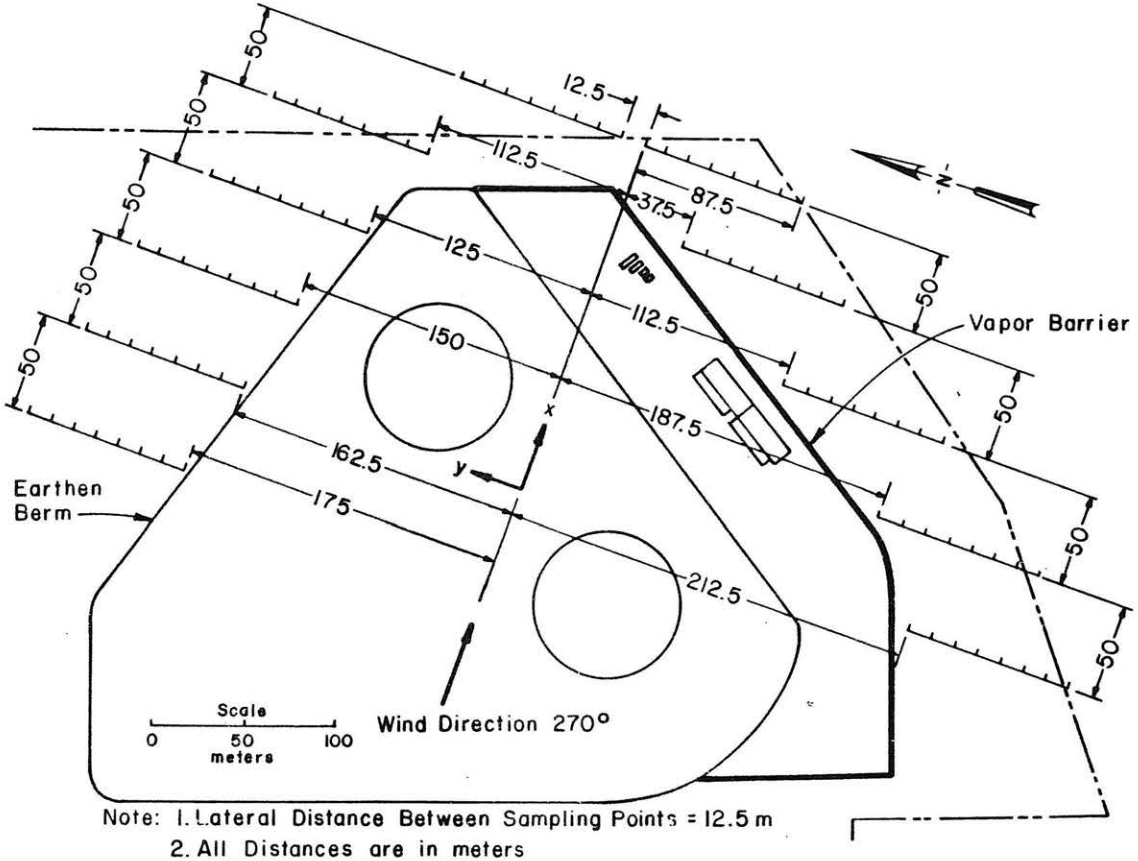


Fig. 4.2-6 Experimental Configuration and Measurement Grid, 270°, Energy Terminal Service Corporation

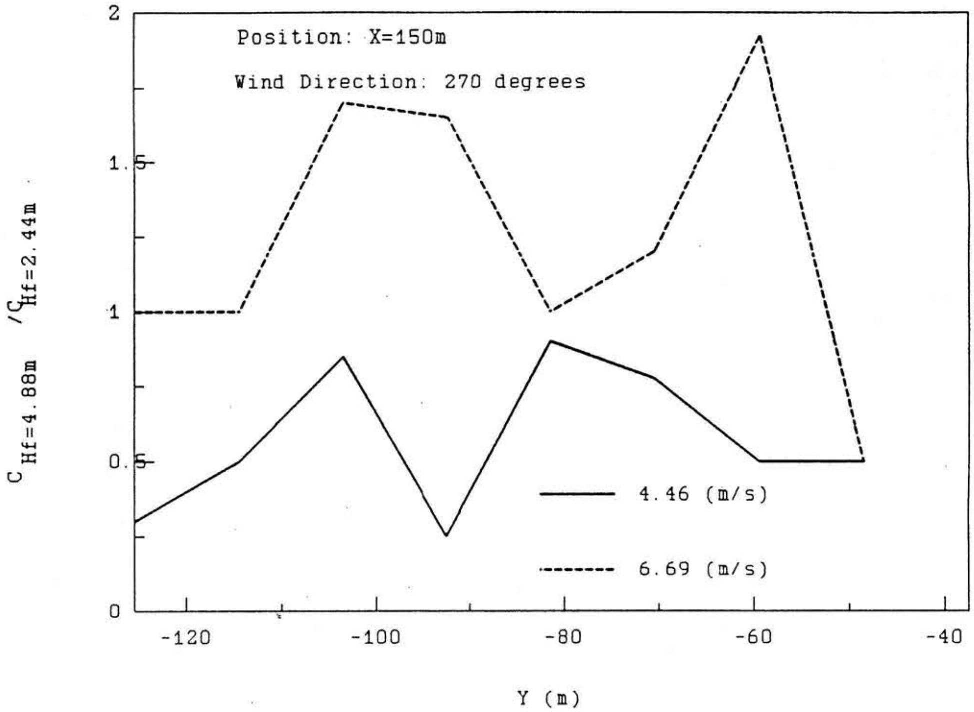


Fig. 4.2-7 Peak Concentration Ratio vs Crosswind Distance, Energy Terminal Service Corporation

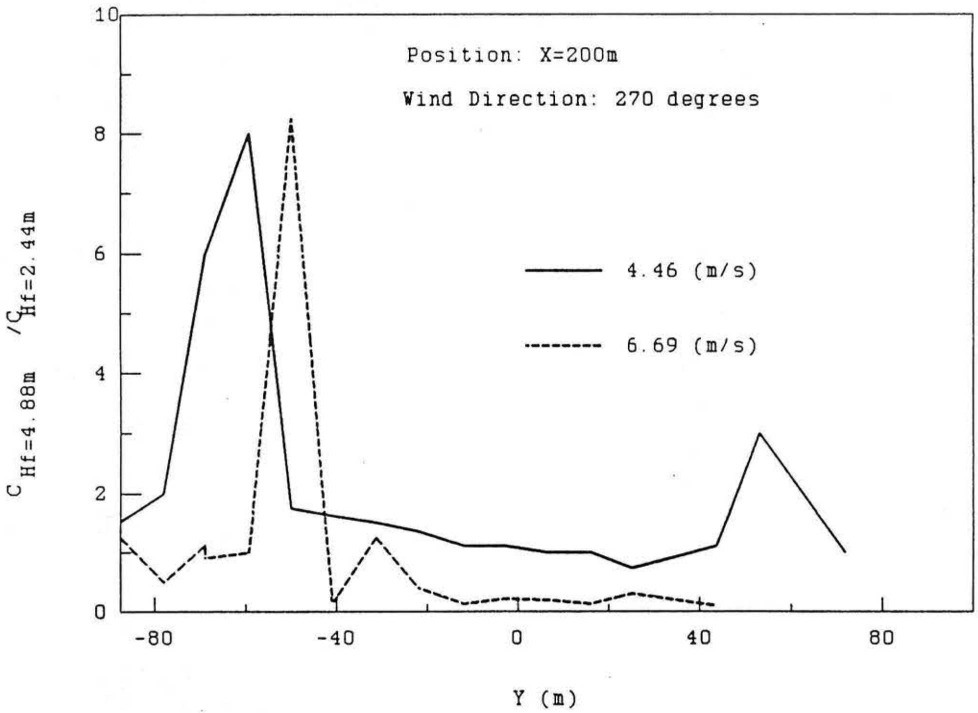


Fig. 4.2-8 Peak Concentration Ratio vs Crosswind Distance, Energy Terminal Service Corporation

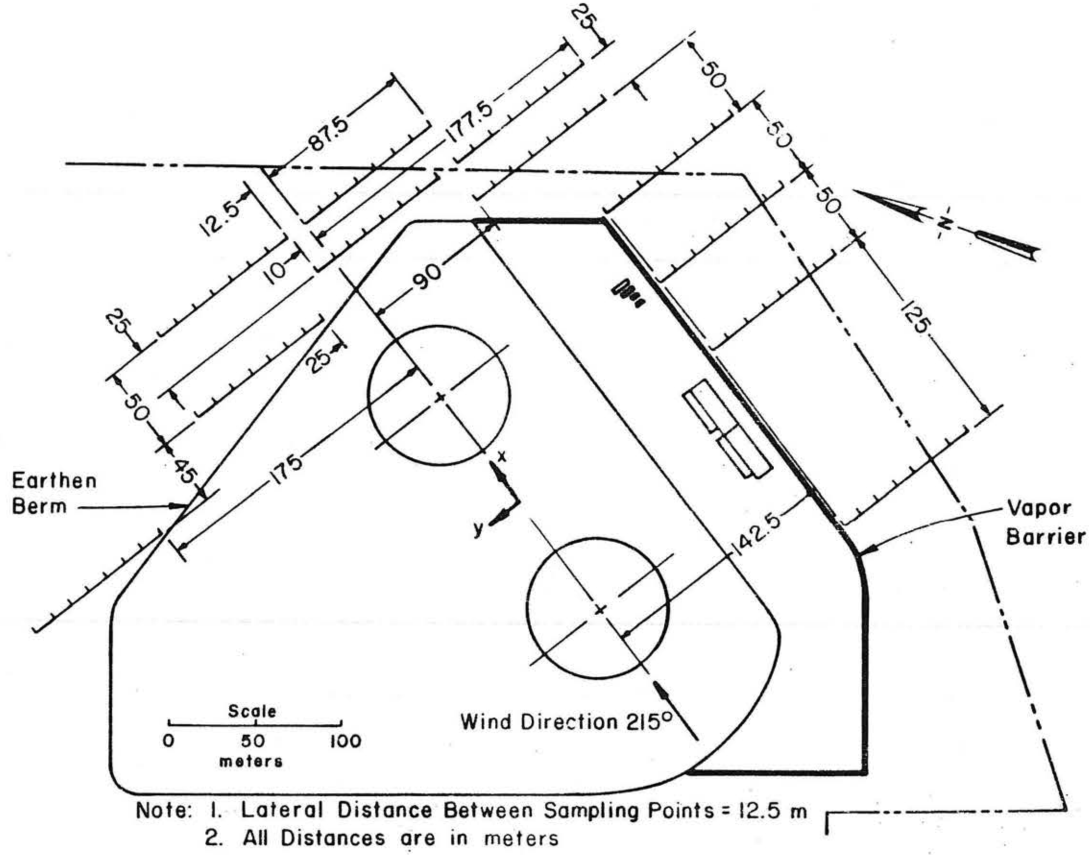


Fig. 4.2-9 Experimental Configuration and Measurement Grid, 215°, Energy Terminal Service Corporation

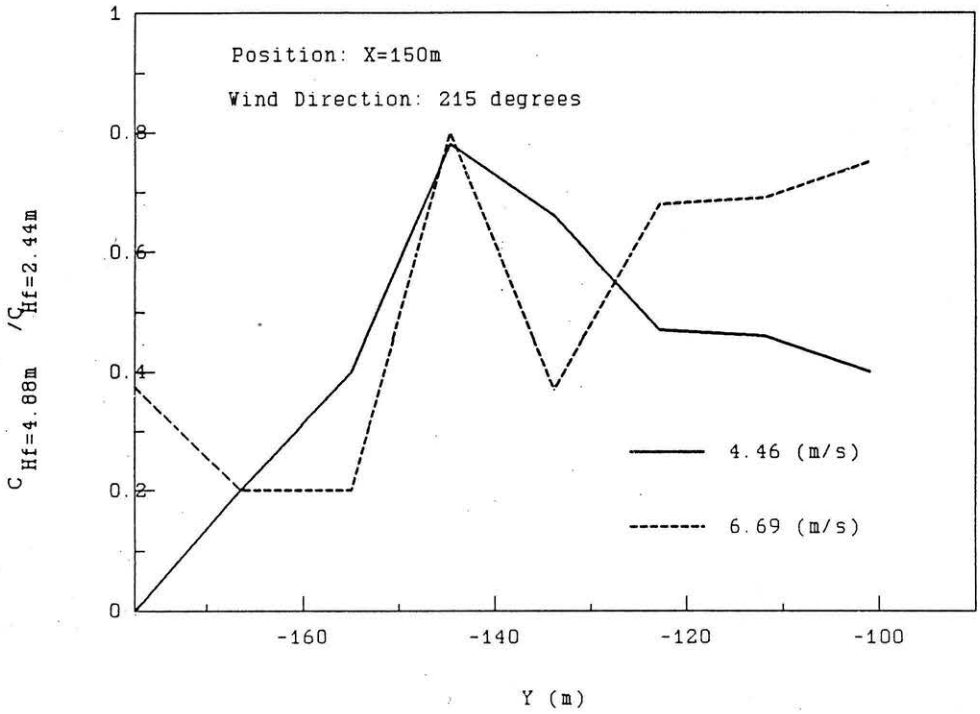


Fig. 4.2-10Peak Concentration Ratio vs Crosswind Distance, Energy Terminal Service Corporation

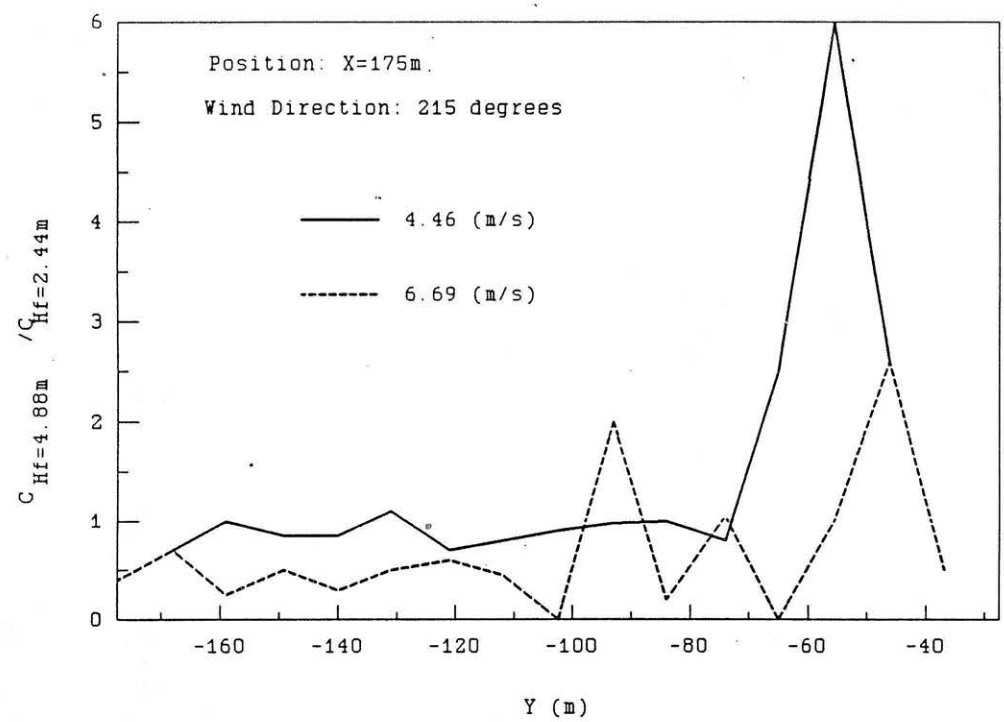


Fig. 4.2-11Peak Concentration Ratio vs Crosswind Distance, Energy Terminal Service Corporation

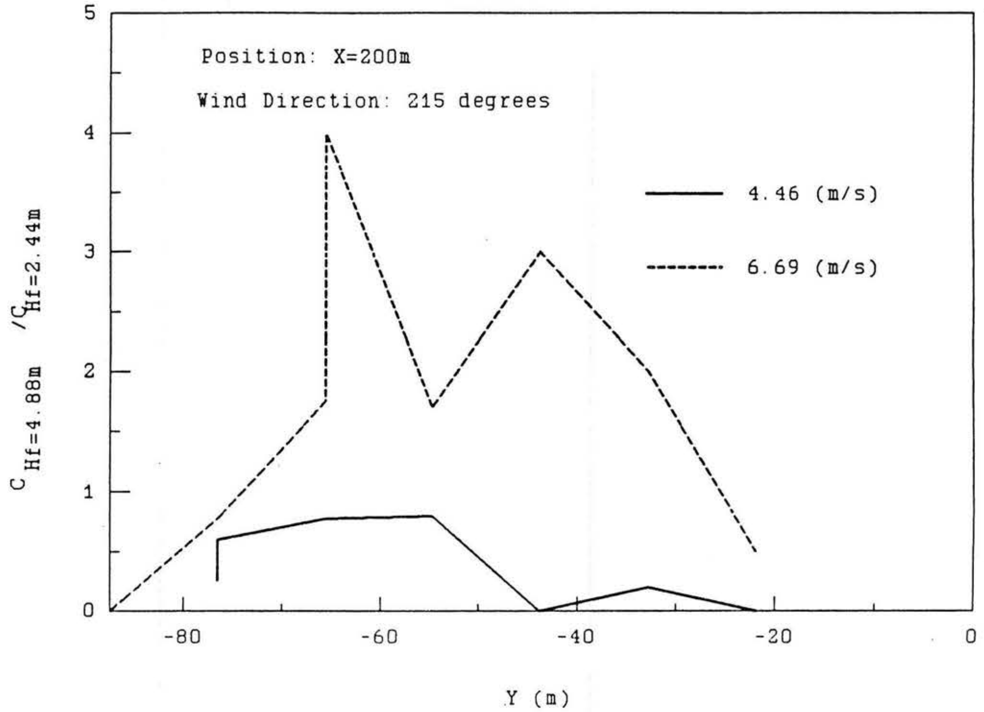


Fig. 4.2-12Peak Concentration Ratio vs Crosswind Distance, Energy Terminal Service Corporation

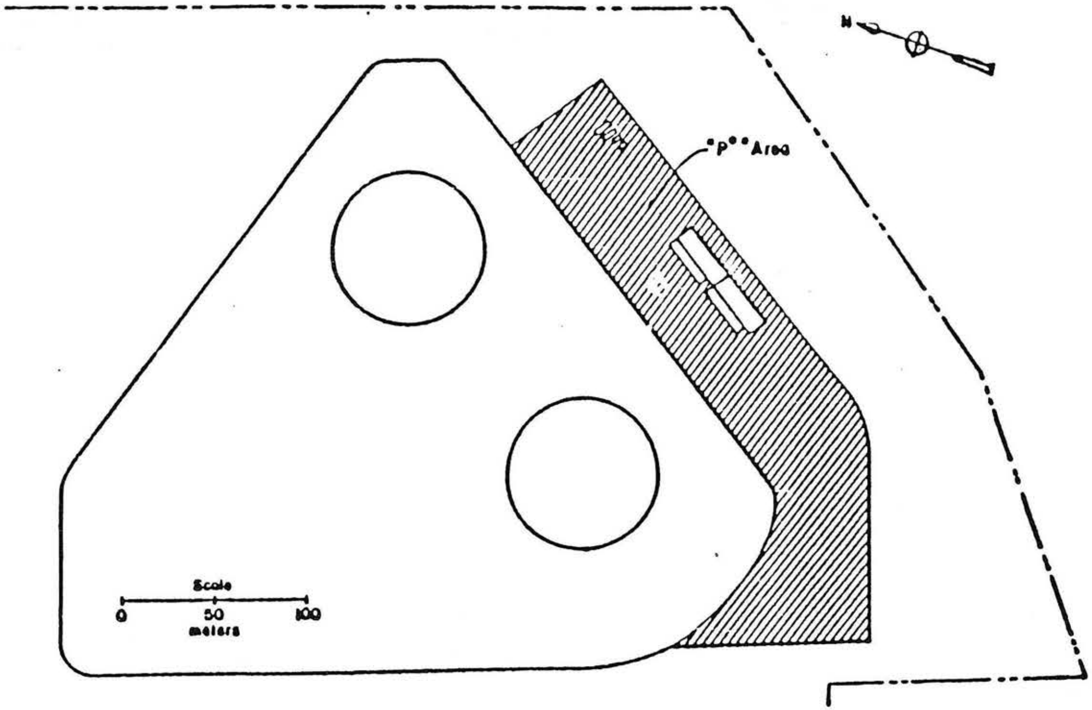


Fig. 4.2-13 Experimental Configuration and Measurement Grid, 215°, Source Area P*, Energy Terminal Service Corporation

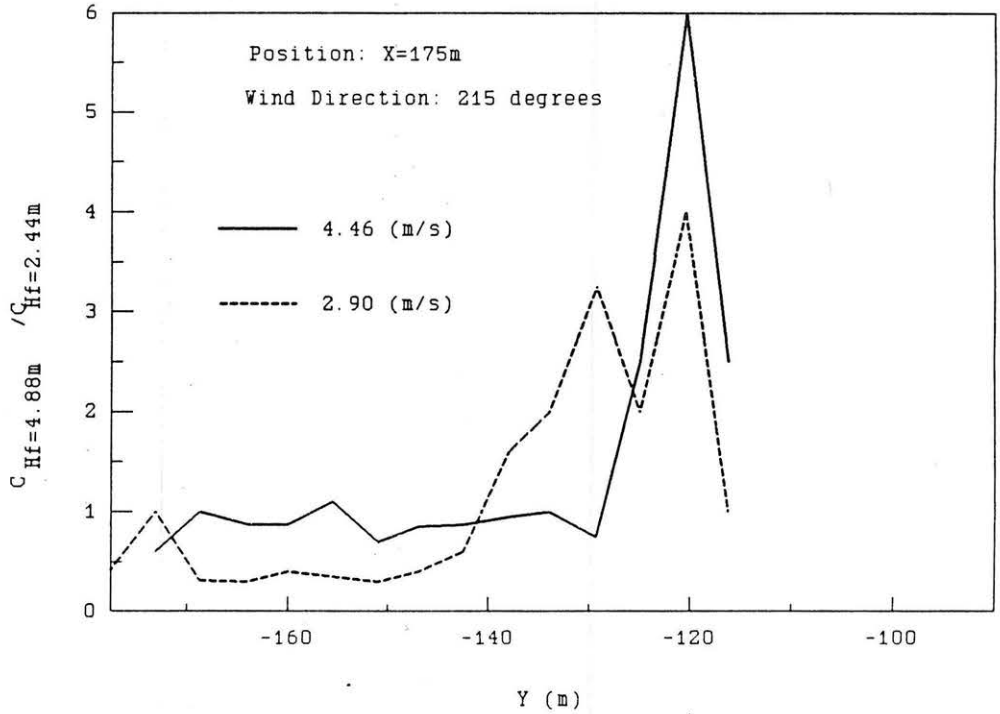


Fig. 4.2-14Peak Concentration Ratio vs Crosswind Distance, Energy Terminal Service Corporation

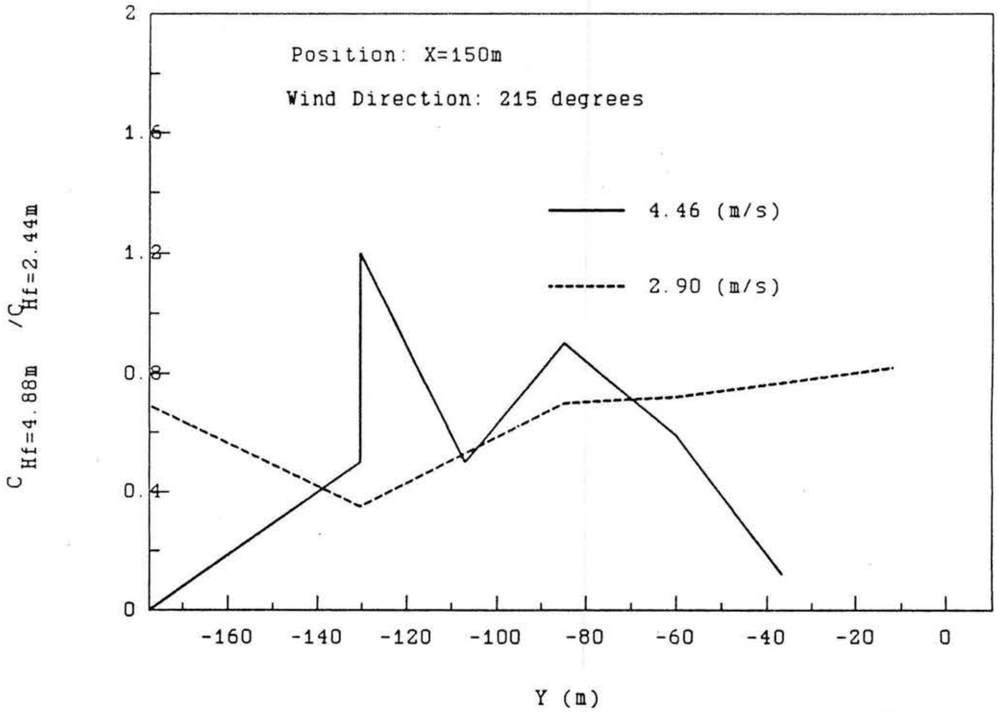


Fig. 4.2-15Peak Concentration Ratio vs Crosswind Distance, Energy Terminal Service Corporation

4.3 "LNG Plume Interaction with Surface Obstacles," Kothari, Meroney, and Neff, 1981

Experiment Configuration:

A wind-tunnel test program was conducted for dense gas dispersion over 1:250 scale models of tanks, buildings, and tree rows placed up and downwind from an LNG release point. One wind direction, two wind speeds (4 and 7 m/sec) and one spill rate (30 cubic meters/min LNG boiling continuously from a 75 m pool) were investigated for neutral and dense source gases. Twenty-two arrangements of tanks, buildings and tree fences were examined (Figures 4.3-1a to 4.3-1e). Tanks, buildings and tree lines had heights of 50, 18.75 and 7.5 meters respectively. Surface concentrations were measured over a grid ranging from 100 to 750 m downwind of the release point (Figure 4.3-1a). A total of 44 tests were performed using a flame-ionization detector (FID) or an aspirated hot-wire katherometer (AHWK). The AHWK was used to measure fluctuating concentration measurements; hence, the report includes tables of rms and peak concentration data.

Results of Comparison:

Ratios of centerline peak concentration with and without the configuration obstacles were plotted versus downwind distance for each test case. As noted on Figure 4.3-2 higher wind speeds generally resulted in greater mitigation rates. When the tank was placed directly over the source the peak concentration ratios fell to a minimum between 0.05 to 0.3 at 3 to 4 obstacle heights downwind of the source, then the ratio began to increase with downstream distance. Eventually the ratio is expected to approach 1.0 at distances exceeding several kilometers.

When the obstacle is placed farther upwind of the spill point mitigation is less; however, dilution increases with the size and number of surrounding obstacles (Figure 4.3-3). A minimum ratio usually occurred some 4 to 6 obstacle heights from the source, even when the obstacle was placed upwind. Obstacles placed downwind of the source reduced concentrations slightly upwind of the obstacle, but the major reduction occurred immediately downwind of the object (Figure 4.3-4). The most reduction in peak concentrations appeared to occur when the obstacles were located between 1 obstacle height upwind or downwind of the spill center. (Figure 4.3-5a and 4.3-5b).

The 7.5 m tree line of 30% porosity placed 75 m downwind of the source produced significant plume dilution. Concentration ratios consistently fell below 0.2 and often as low as 0.025 at 15 fence heights downwind of the tree line (Figure 4.3-6).

Conclusions:

For a variety of wind speeds, obstacle types, and obstacle orientations reductions in plume concentrations were measured in the wake of the objects. Maximum dilution occurred when the objects were placed close to the spill, but dilution continued to occur even when the object was downwind of the release location. Obstacles need not be large (tall) to produce concentration reductions, but they are more effective when distributed laterally across the plume path (i.e. buildings and tree line). Although most measurements were made in the near field to the source (i.e. less than 15 tank heights downwind), there was some evidence that the peak concentration ratio increases after reaching a minimum some 3 to 4 obstacle heights downwind of the release point.

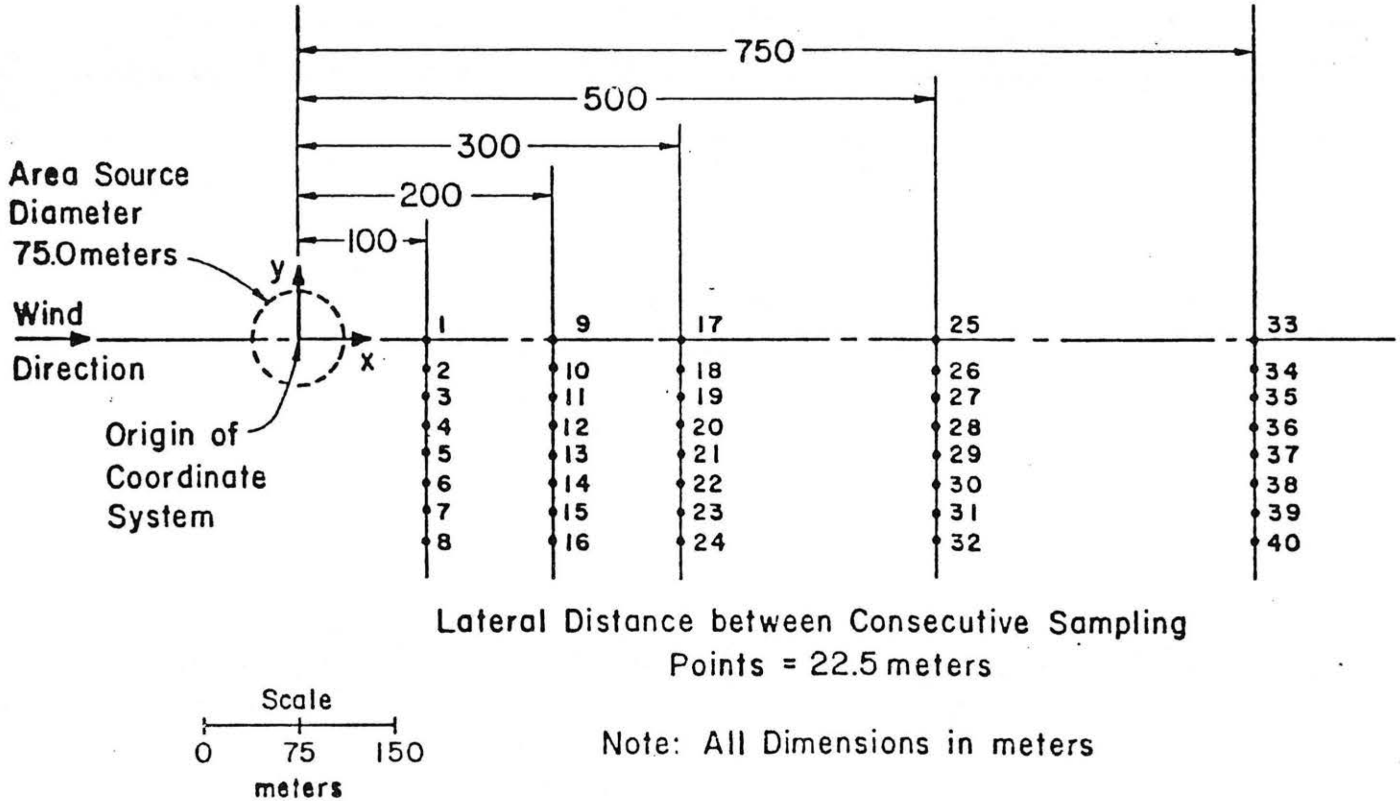
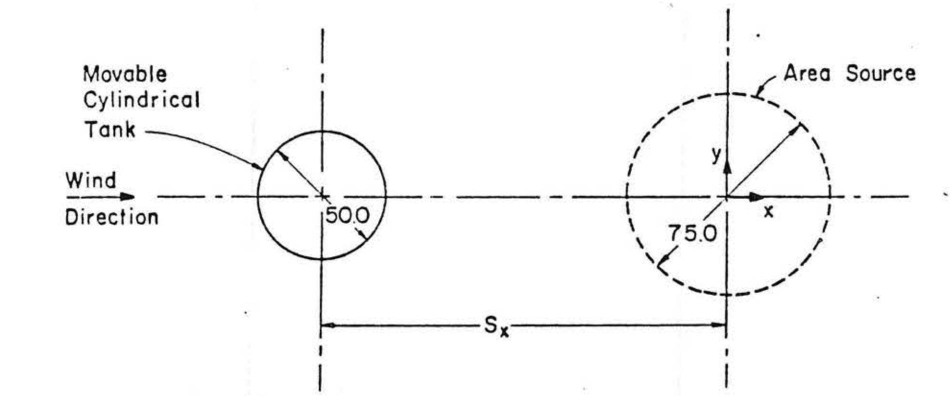


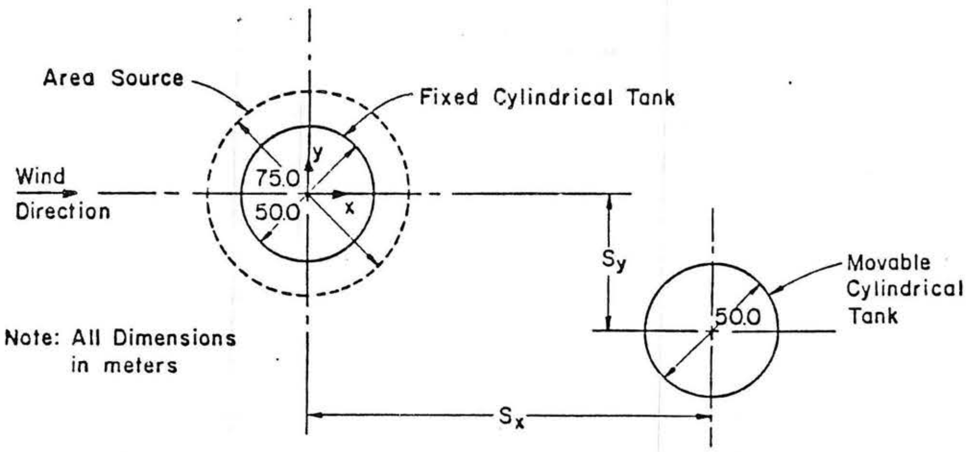
Fig. 4.3-1a Concentration Measurement Locations and Configuration 1 - 22 Spill Arrangement



Configuration	Displacement in x Direction S_x, meters
2	0.0
3	-250.0
4	-150.0
5	-50.0
6	50.0
7	150.0
8	250.0

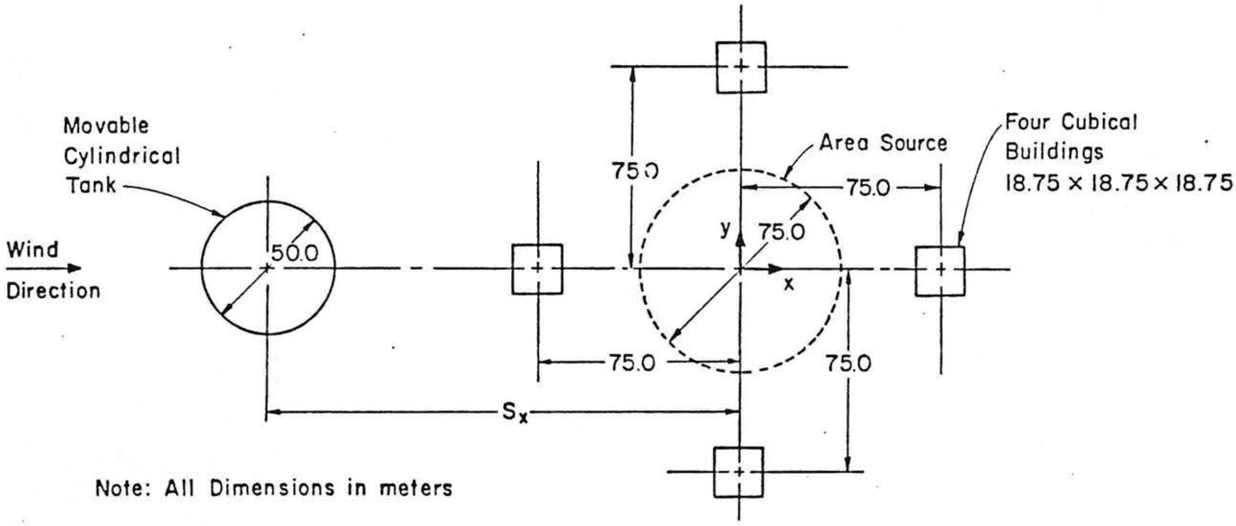
Note: All Dimensions in meters

Fig. 4.3-1b Concentration Measurement Locations and Configuration 1 - 22 Spill Arrangement



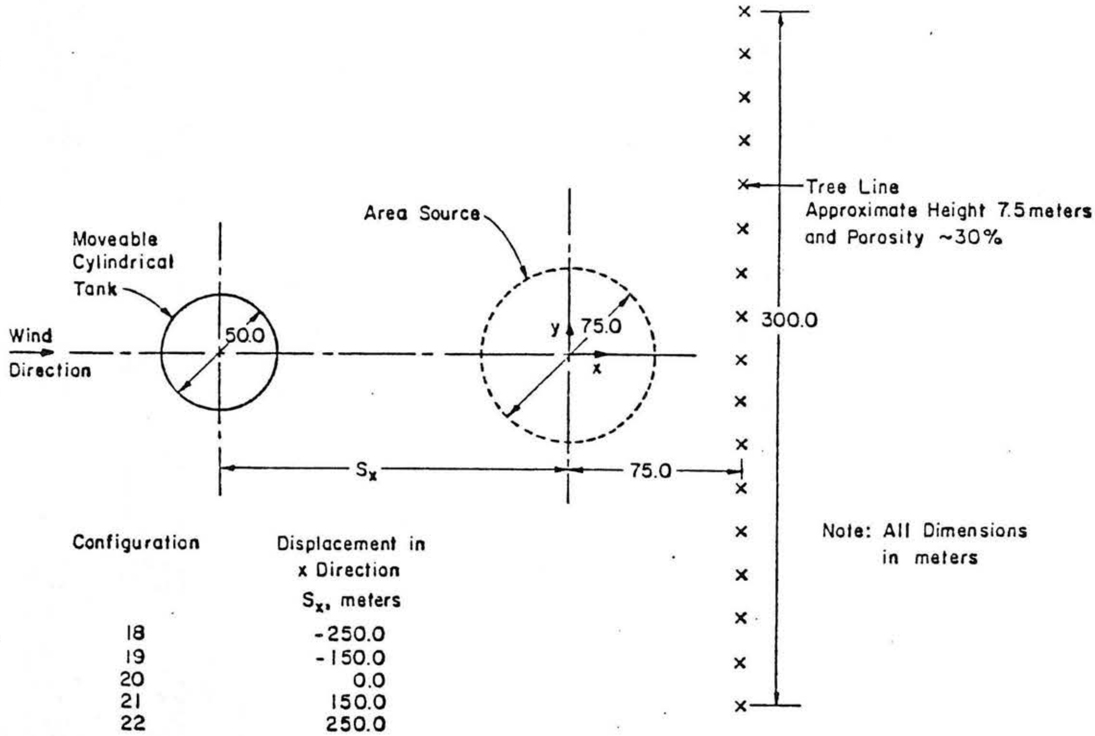
Configuration	Displacement in x Direction S_x, meters	Displacement in y Direction S_y, meters
10	150.0	0.0
11	150.0	-50.0
12	250.0	0.0

Fig. 4.3-1c Concentration Measurement Locations and Configuration 1 - 22 Spill Arrangement



Configuration	Displacement in x Direction S_x, meters
13	-250.0
14	-150.0
15	0.0
16	150.0
17	250.0

Fig. 4.3-1d Concentration Measurement Locations and Configuration 1 - 22 Spill Arrangement



Configuration	Displacement in x Direction S_x, meters
18	-250.0
19	-150.0
20	0.0
21	150.0
22	250.0

Fig. 4.3-1e Concentration Measurement Locations and Configuration 1 - 22 Spill Arrangement

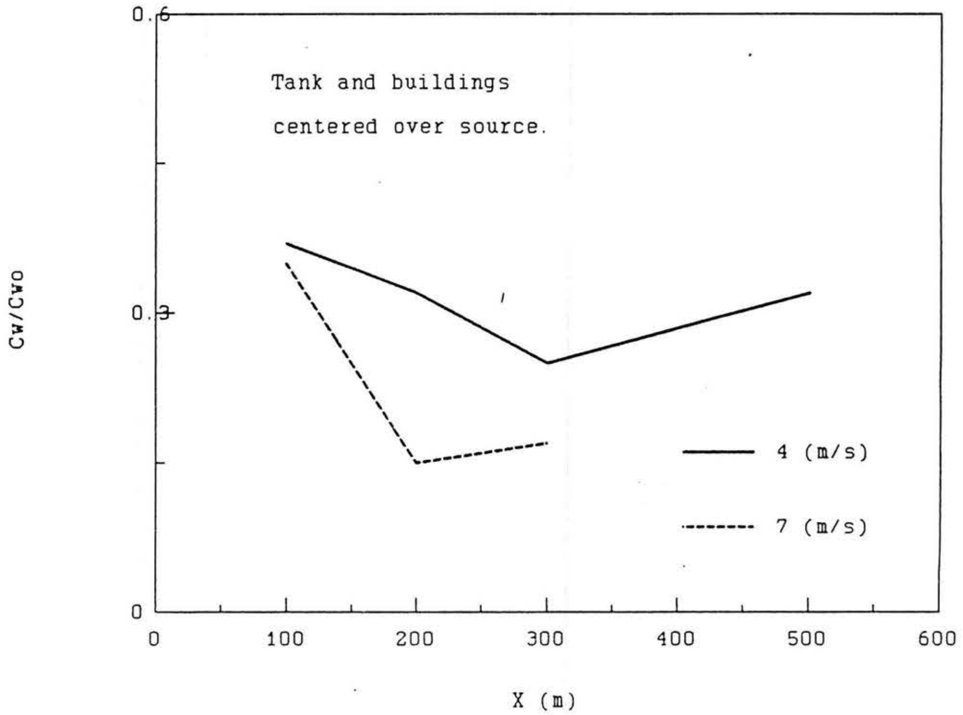


Fig. 4.3-2 Peak Concentration Ratio vs Downwind Distance, Configuration 15 , U = 4 and 7 m/sec

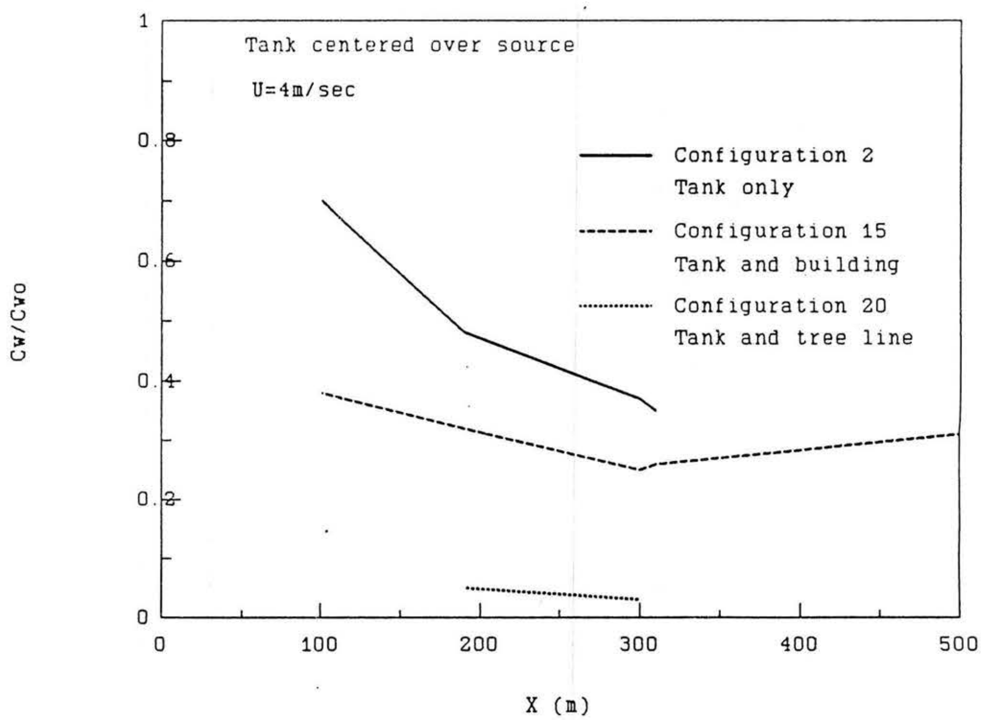


Fig. 4.3-3 Peak Concentration Ratio vs Downwind Distance, Configurations 2, 15 and 20

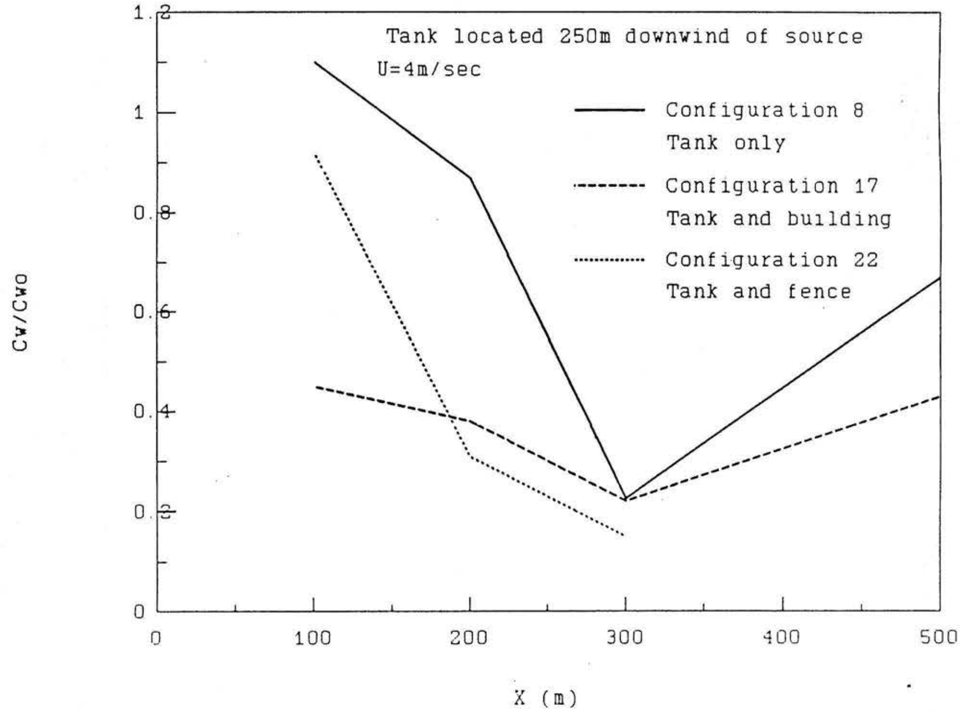


Fig. 4.3-4 Peak Concentration Ratio vs Downwind Distance, Configurations 8, 17 and 22

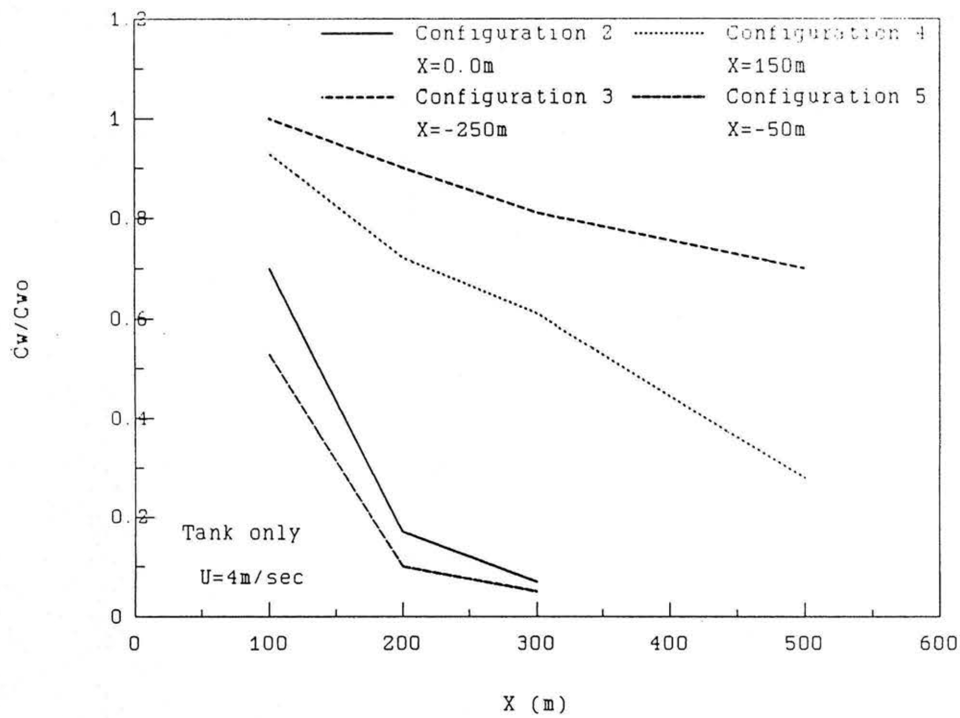


Fig. 4.3-5a Peak Concentration Ratio vs Downwind Distance, Configurations 2, 3, 4 and 5

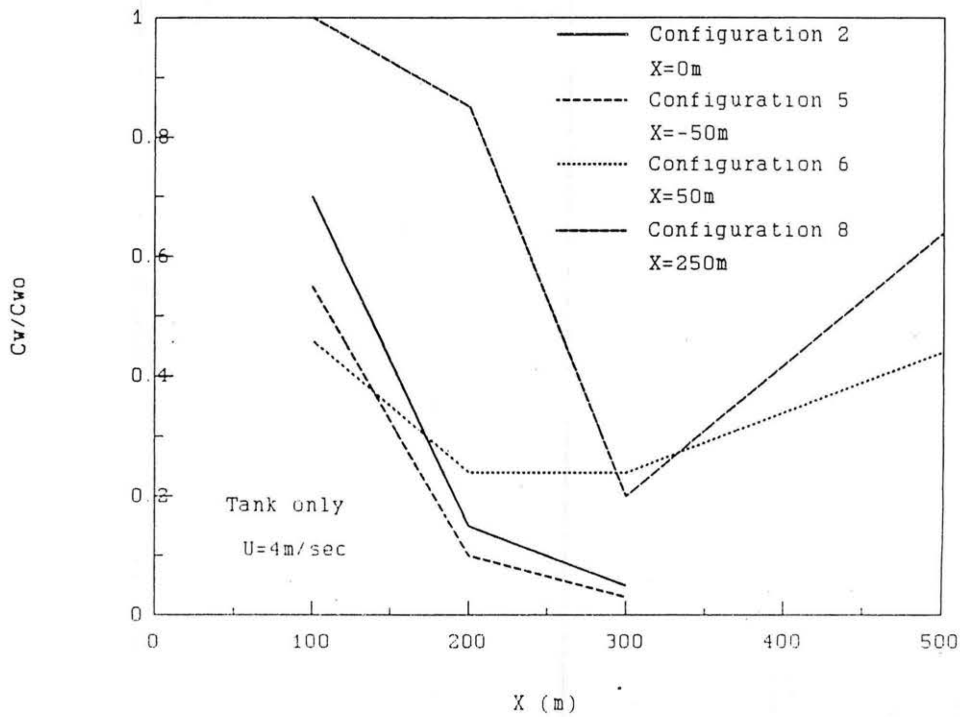


Fig. 4.3-5b Peak Concentration Ratio vs Downwind Distance, Configurations 2, 5, 6, and 8

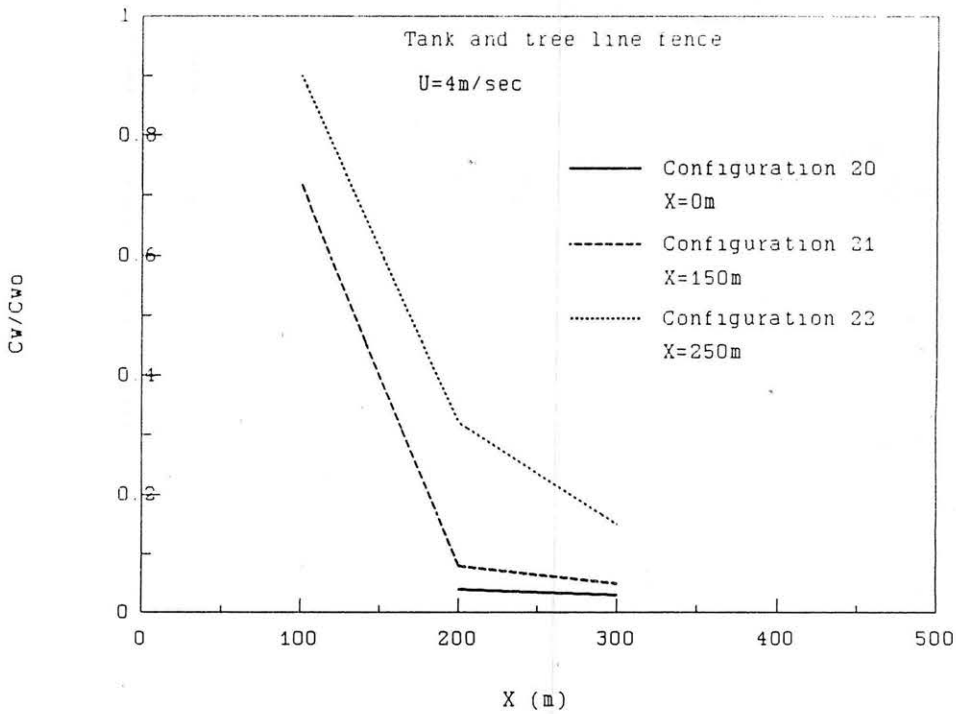


Fig. 4.3-6 Peak Concentration Ratio vs Downwind Distance, Configurations 20, 21, and 22

4.4 "Accelerated Dilution of Liquefied Natural Gas Plumes with Fences and Vortex Generators," Kothari, and Meroney, 1982

Experiment Configuration:

A wind-tunnel test program was conducted for dense gas dispersion over a 1:250 scale model with continuous releases from an LNG spill to determine the effects of fence and vortex generator vapor barriers. The experiments considered three simulated LNG spill rates (20, 30, and 40 cubic meters LNG/min), four wind speeds (4, 7, 9, and 12 m/sec), two barrier heights (5 and 10 m), three enclosure arrangements (Figure 4.4-2), and a solid fence or a vortex-spire barrier (Figures 4.4-3 and 4.4-4). A total of 204 tests were performed. Surface concentrations were measured over a grid ranging from 100 to 500 m downwind of the 75 m diameter spill pool (Figure 4.4-1).

Results of Comparison:

Ratios of centerline peak concentration with and without the barriers present were plotted versus downwind distance for each test case. Both fences and vortex generators produced smaller peak concentration ratios as wind speed increased (Figure 4.4-5); however, speeds above 7 m/sec produced similar levels of dilution (Frequently, the barriers were less efficient at 12 m/sec than at lower speeds, which may reflect a diminishing influence of gravity spreading on plume dynamics). Taller barriers (10 m) were also two times more effective than shorter barriers (5 m).

Solid fences diluted the gas cloud more effectively than the vortex spire arrangement; although in many cases the differences were minor (Figure 4.4-6). Fences placed directly around the spill area did not reduce peak concentrations as effectively as fences placed a bit farther away (Figure 4.4-7). Although the two-fence arrangement (Configuration 3) generally reduced peak concentrations the most, it often did not perform significantly different than the one-fence arrangement (Configuration 2).

Conclusions:

Solid fence and vortex-spire barriers reduced peak concentrations along the centerline of simulated LNG spills out to distances of 500 m (wake distances of 85 fence heights for the 5 m fence or 42.5 fence heights for the 10 m fence). Peak concentration ratios rose slowly from minimum values observed near 200 m. Apparently the peak concentration ratio must asymptote to one significantly beyond the end of the measurement domain used for these tests. (Note: Numerical calculations discussed in Section 5.2 suggest a possible return to no-fence concentrations at distances of about 200 fence heights downwind of the vapor barrier.) The fences were less effective at the lowest wind speed tested (4 m/sec); however, performance remained the same for winds speeds greater than 7 m/sec. Barrier performance varied directly with barrier height for all configurations. The fences were more effective when placed about 1 spill diameter away from the spill pool.

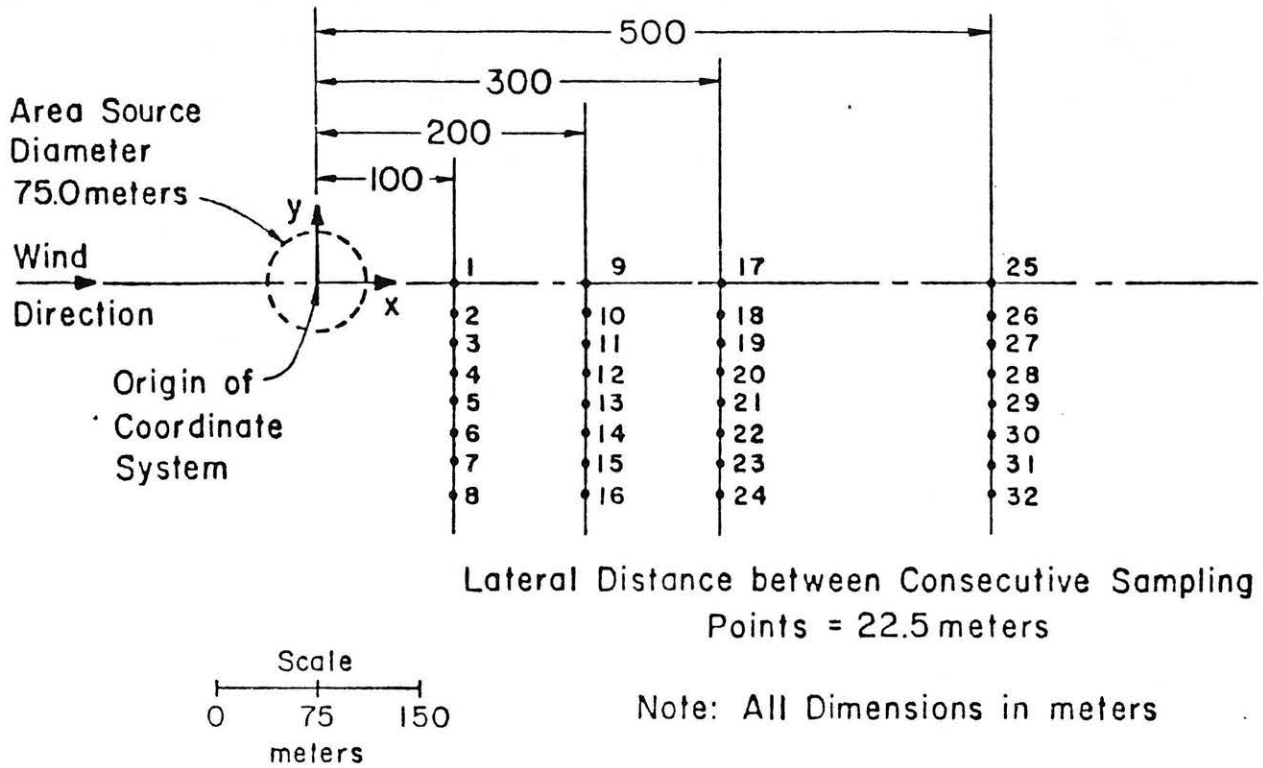


Fig. 4.4-1 Concentration Measurement Locations and Configuration 0 Spill Arrangement

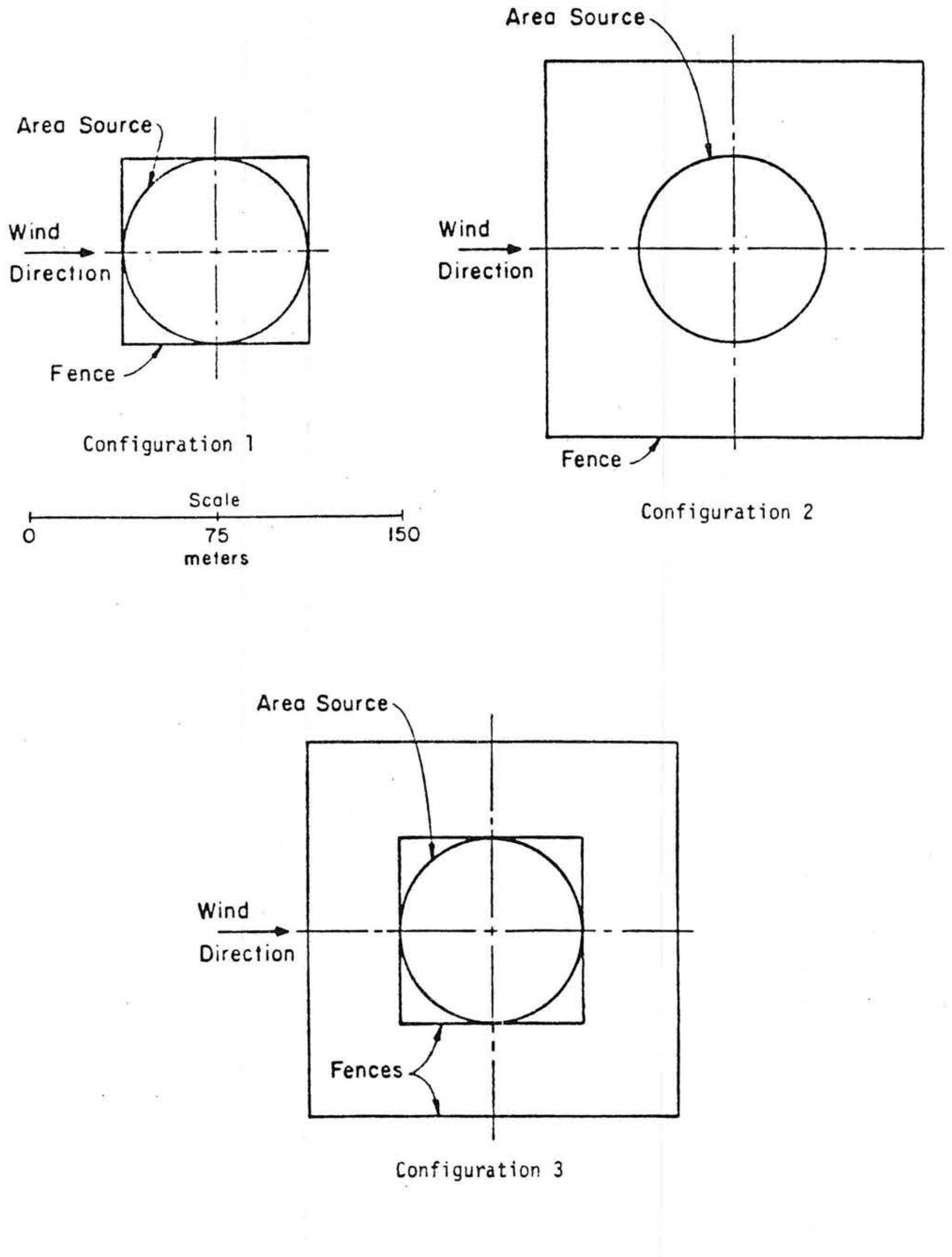
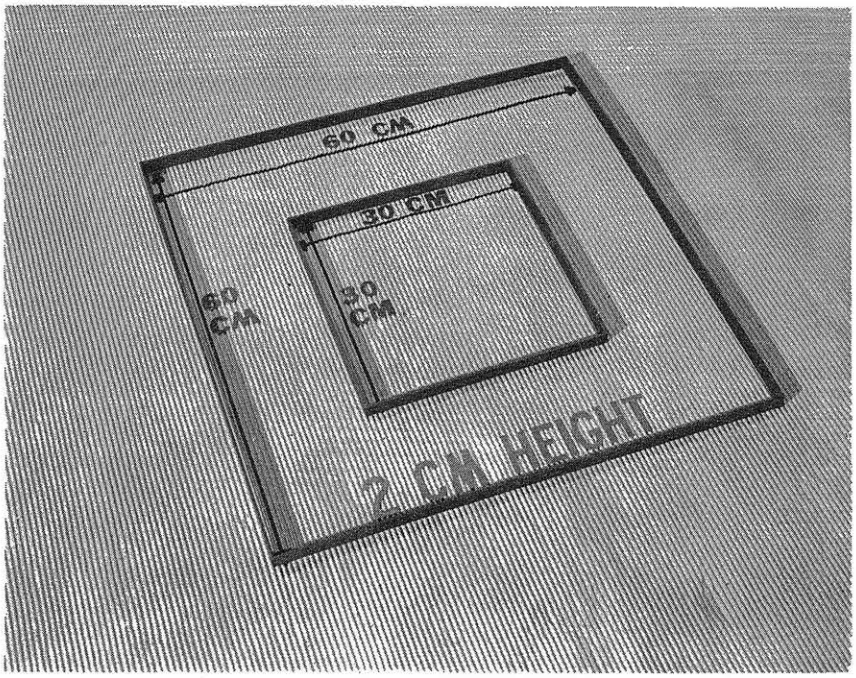


Fig. 4.4-2 Fence and Vortex Spire Configurations 1, 2, and 3



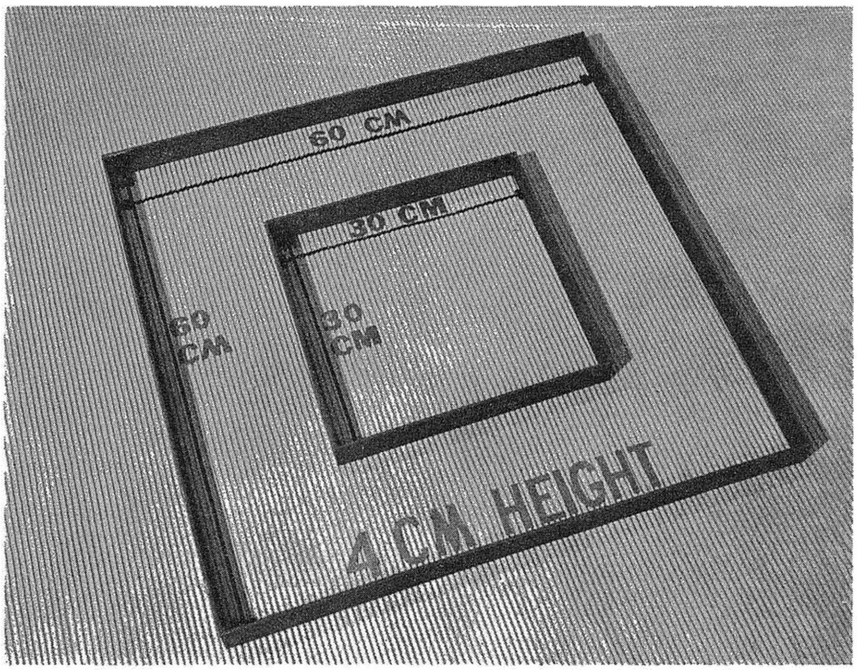
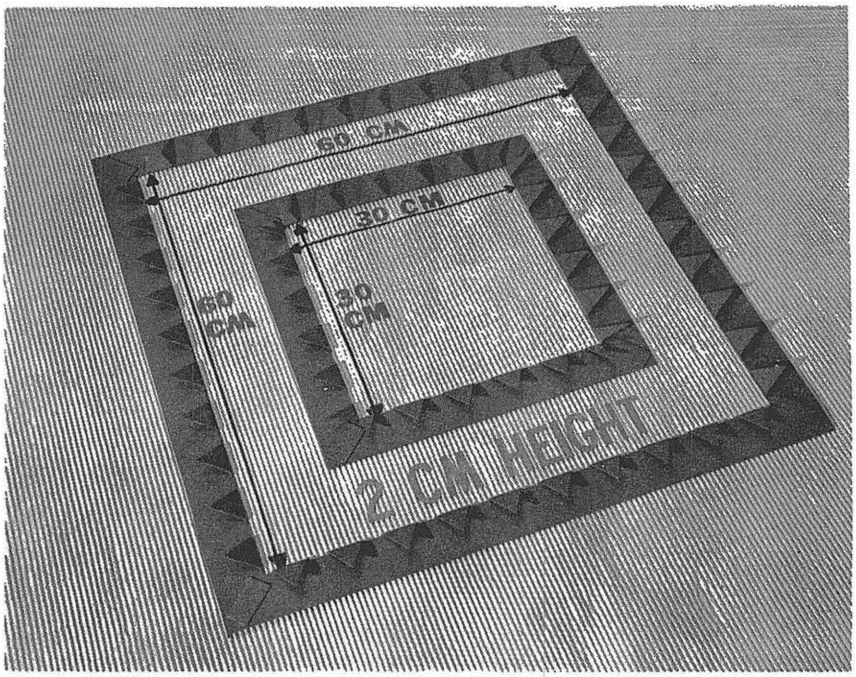


Fig. 4.3-3 Model Fence Enclosures



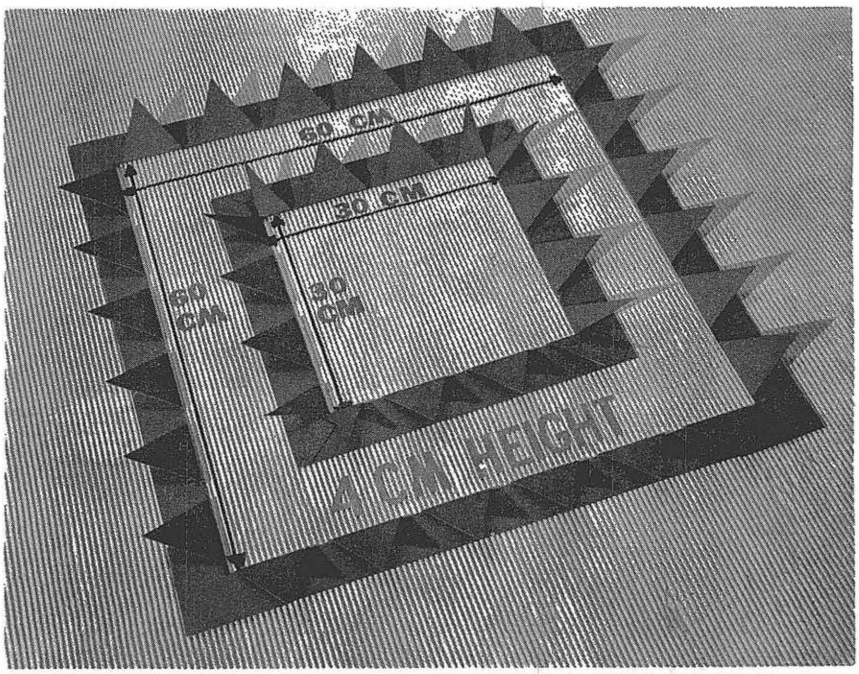


Fig. 4.3-4 Model Vortex Spire Enclosures

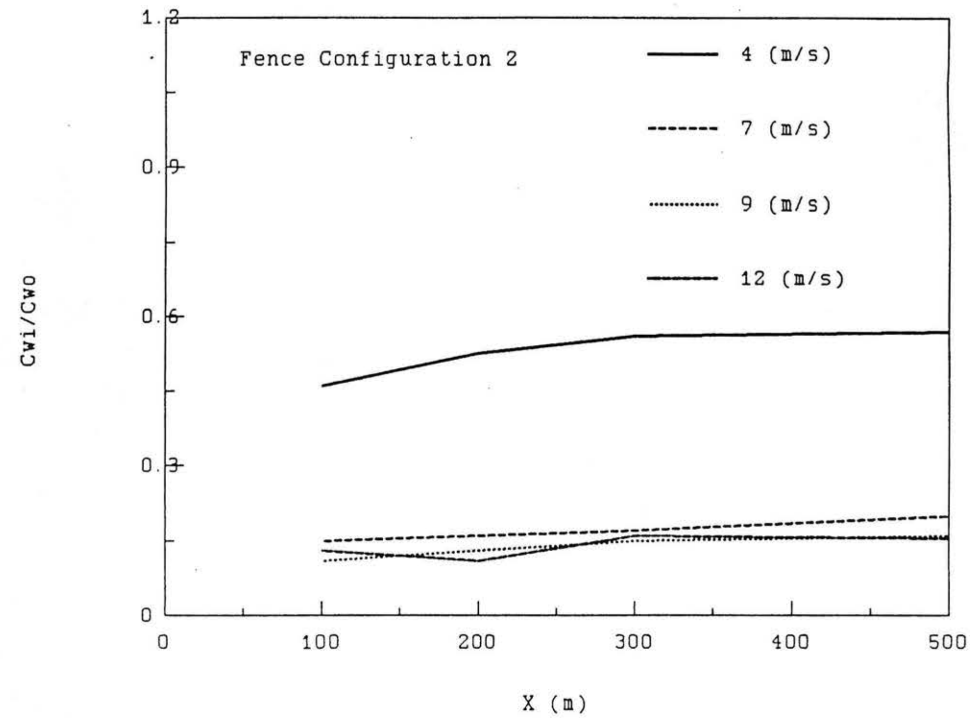


Fig. 4.4-5 Peak Concentration Ratio vs Downwind Distance, Q = 20 m^3/min LNG, Fence Height = 10 m, Wind Speed = 4, 7, 9, and 12 m/sec

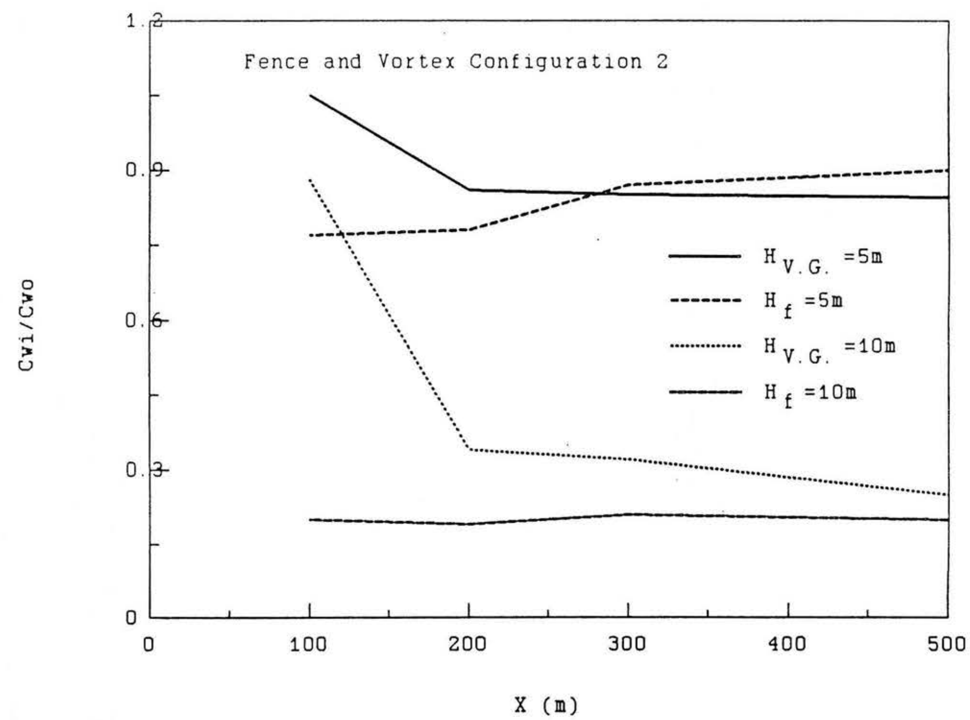


Fig. 4.4-6 Peak Concentration Ratio vs Downwind Distance, Q = 20 m^3/min LNG, Fence Heights = 5 and 10 m, Wind Speed = 4 m/sec, Fences and Vortex Spires

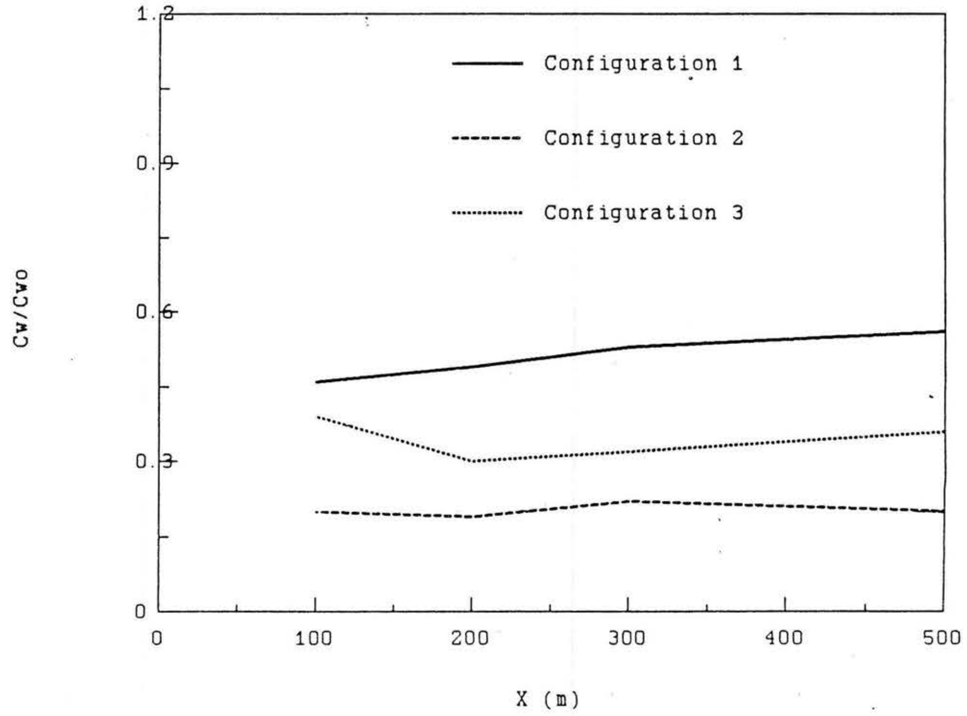


Fig. 4.4-7 Peak Concentration Ratio vs Downwind Distance, $Q = 20\ m^3/min$ LNG, Fence Height = 10 m, Wind Speed = 4 m/sec, Configurations 1, 2, and 3

4.5 "Model Studies of LNG Vapor Cloud Dispersion with Water Spray Curtains," Meroney et al., 1983, 1984, and Heskestad et al., 1985

Experiment Configuration:

A series of model tests were funded by Factory Mutual Research, Inc. and the Gas Research Institute to evaluate the ability of water spray curtains to reduce concentrations around an LNG spill below flammability limits. Water sprays are not expected to remove natural gas from LNG spill clouds. The objective of the water spray is to entrain air and dilute the cloud below the flammability limit. Thus, these experiments do not simulate the potential for HF reduction due to water-spray induced deposition. Since the desire was to determine concentration reductions immediately downwind of the spray curtain measurements were only made out to equivalent distances of 390 m from the release point. One series of measurements were also made to validate the simulation methodology using field data from the CO2/water spray tests performed by Moodie et al. (1981) at a scale ratio of 1:28.9. Carbon dioxide was released from a point source upwind of an array of water spray nozzles (Figure 4.5-1). Both ground level and vertical profiles of concentration were taken.

Most of the measurements were made over a 1:100 scale model of a 60 m x 60 m bunded spill area (Figure 4.5-2). Many different arrangements of water spray release points, nozzle orientations, nozzle sizes were considered (Figure 4.5-3). Vapor barrier fences varied in height from 4 to 16 m. A small (S), medium (M), and large (L) tank were situated within the bunded area during some tests (Figure 4.5-4). Tank diameters ranged from 22 to 36 m, and tank heights ranged from 23 to 28 m. LNG boiloff rate (3000 to 21,400 cubic meters/sec gas) and wind speed (1.7 to 8 m/sec) were also varied.

These data have been extensively examined previously to evaluate the optimum performance of a water spray curtain (Heskestad et al., 1983) or to calibrate a numerical dispersion model (Meroney and Neff, 1985.) This review will focus on the various vertical profiles measured, the effects of discharge on barrier influence on the dense gas cloud, and the relative reductions in peak concentration seen downwind of various size tanks.

Results of Comparison:

Consideration of data from Meroney, Neff and Heskestad (1984) showed that peak concentrations were reduced to values of 0.21 some 5 m downwind of the water curtains modeled, then the ratio began to rise at farther distances downwind (Figure 4.5-5). A vertical concentration profile measured along the centerline at a distance of 18.3 m reveals that the water spray re-distributed the mass of the plume upward and reduced peak concentrations by 75 % (Figure 4.5-6).

A water spray system was found to reduce peak centerline concentration ratios to 0.1; however, a tank placed within the spill area tended to lift the gas into the upper separation cavity downwind of the tank. Thus, aerodynamic turbulence pre-mixed the gas to significant heights, even before the cloud reached the water spray curtain. Figure 4.5-7 shows that concentration ratios with the tanks present increase from 0.2 to 0.8.

Figures 4.5-8 to 4.5-11 display centerline vertical concentration profiles with and without a water spray activated for the conditions of bund alone, small tank, medium tank, and large tank. Without water spray or tank the dense plume remains below a height of 10 m, but the tanks mix the gas up to a height of 20 or 30 m. The water spray curtain then distributes the cloud to heights above 30 m.

Increased water flow through the spray nozzles tends to increase the entrainment velocity, w_e. Figure 4.5-12 summarizes the net effect of increasing water discharge for all data disregarding nozzle or spray arrangement. Water flow rate appears to dominate dilution; whereas nozzle number, size and orientation produce only second order effects.

The increased entrainment associated with larger water discharge rates leads to deeper, well-mixed plumes downwind of the spray curtain (Figures 4.5-13 and 4.5-14).

Conclusions:

Water spray curtains were found to dilute dense gas clouds by factors ranging from 3 to 50. Large tanks and fences result in increased mechanical mixing which dilutes the dense gas before it reaches the water curtain; hence, effectiveness of the curtain decreases. Nonetheless, the combined effect of tank and water spray curtain on air entrainment was more than the enhanced mixing induced by either object alone. Water spray curtains mix dense gas clouds to considerable heights as a result of their entrainment of air into the gas cloud. Water spray curtain effectiveness increases directly with the rate water is discharged through the curtain.

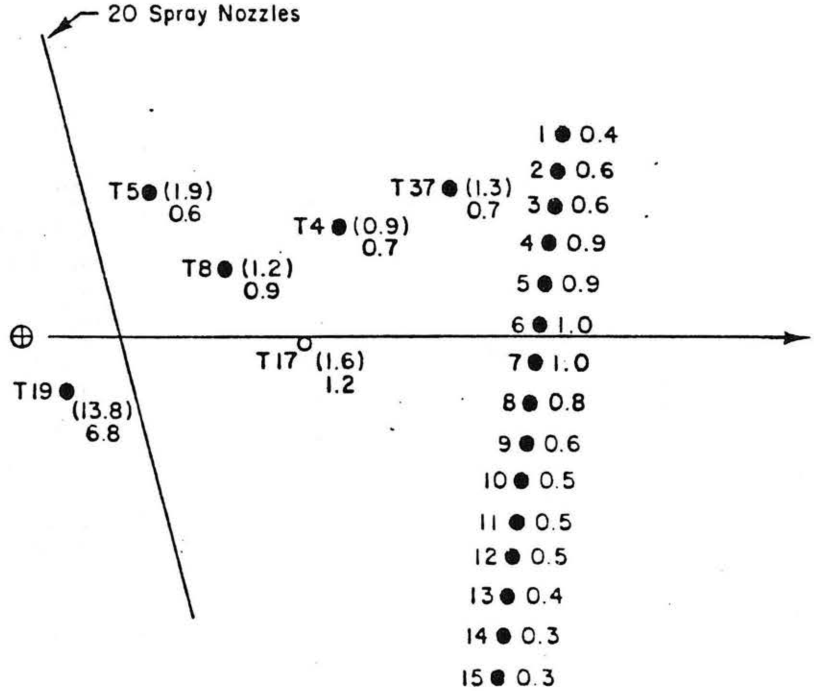


Fig. 4.5-1 Experimental Configuration and Measurement Grid, Health and Safety Executive CO2/Water Spray Trial No. 46

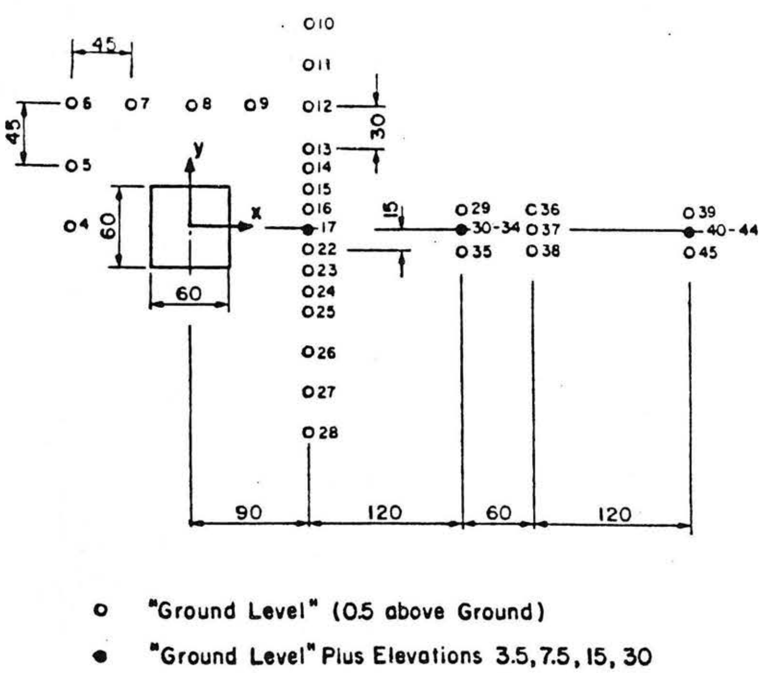


Fig. 4.5-2 Experimental Configuration and Measurement Grid, Generic Bunded Spill Area

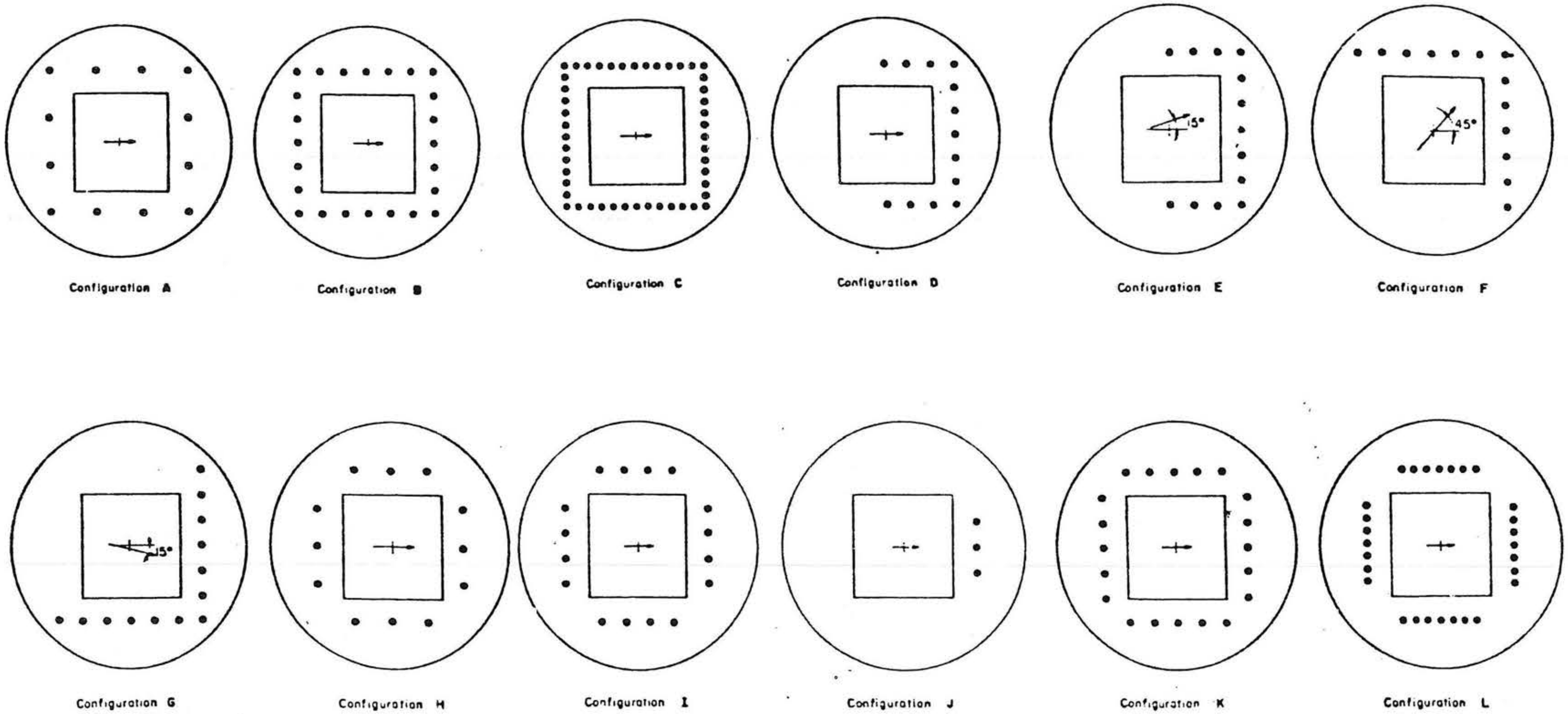


Fig. 4.5-3 Water Spray Configurations for Generic Bunded Spill Area

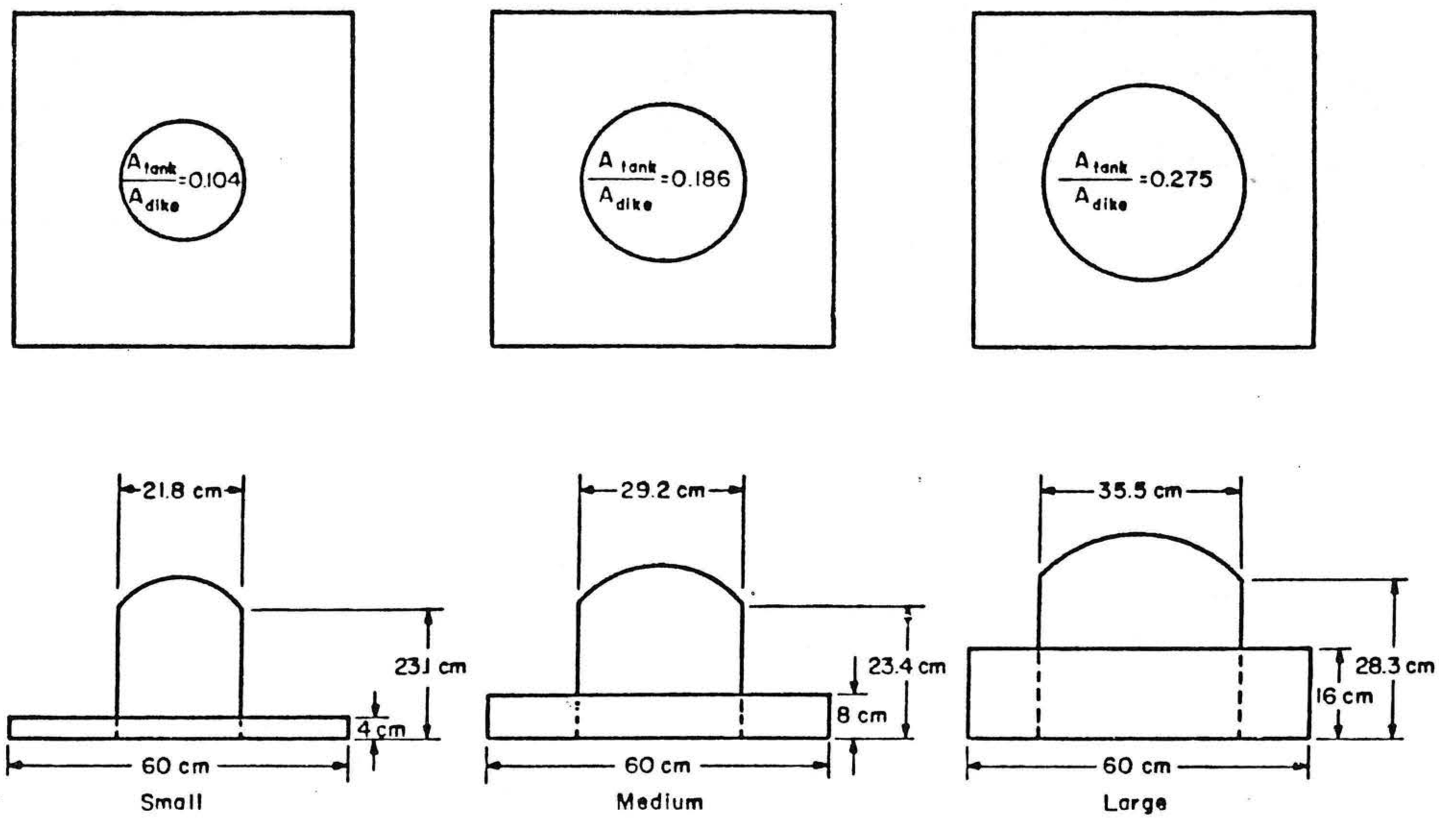


Fig. 4.5-4 Tank and Fence Configurations for Generic Bunded Spill Area

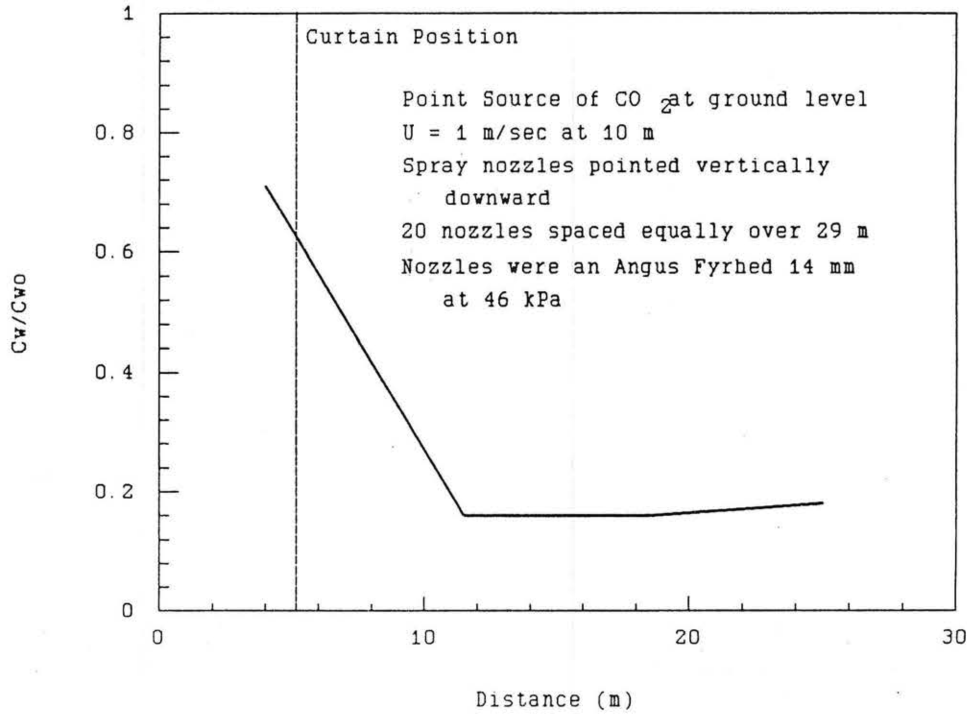


Fig. 4.5-5 Peak Concentration Ratio vs Downwind Distance, HSE Trial No. 46

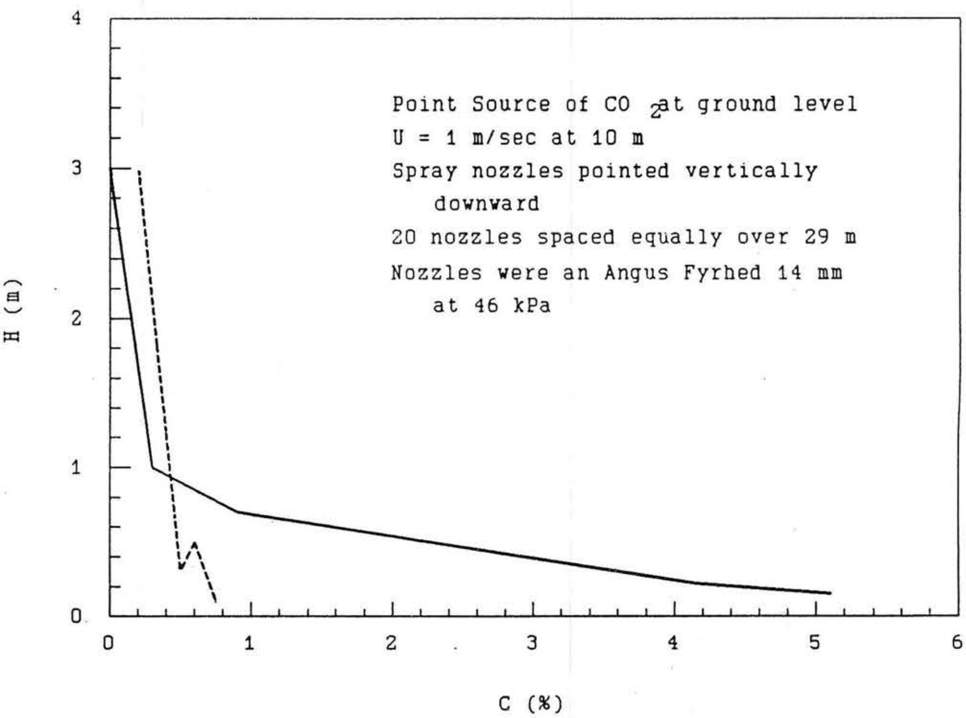


Fig. 4.5-6 Vertical Concentration Profiles at X = 18.3 m, HSE Trial No. 46

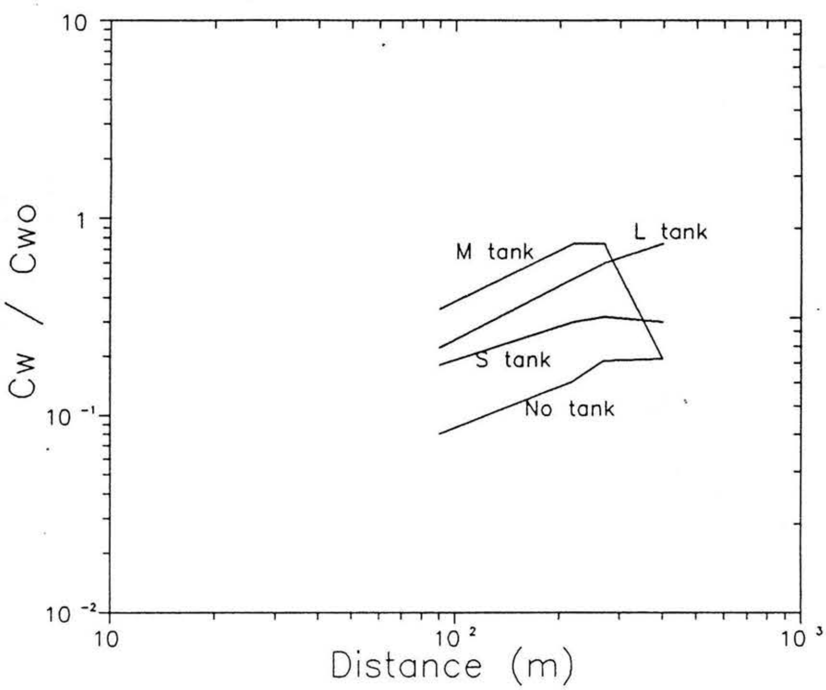


Fig. 4.5-7 Peak Concentration Ratio vs Downwind Distance, Water Spray together with Small, Medium and Large Tank Obstacles

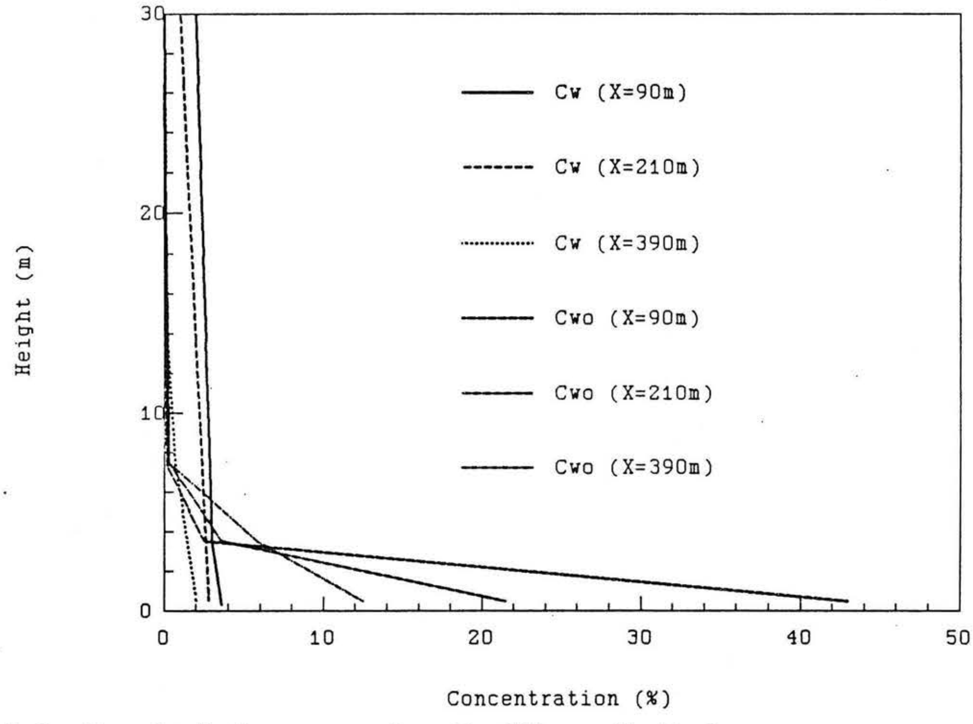


Fig. 4.5-8 Vertical Concentration Profiles, No Tank

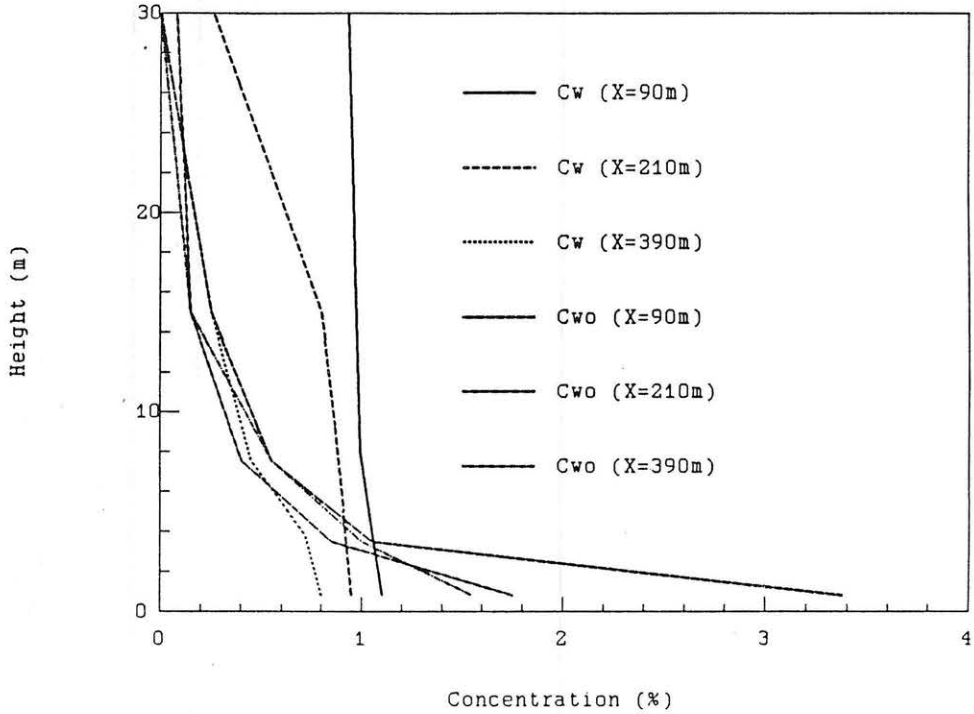


Fig. 4.5-9 Vertical Concentration Profiles, Small Tank

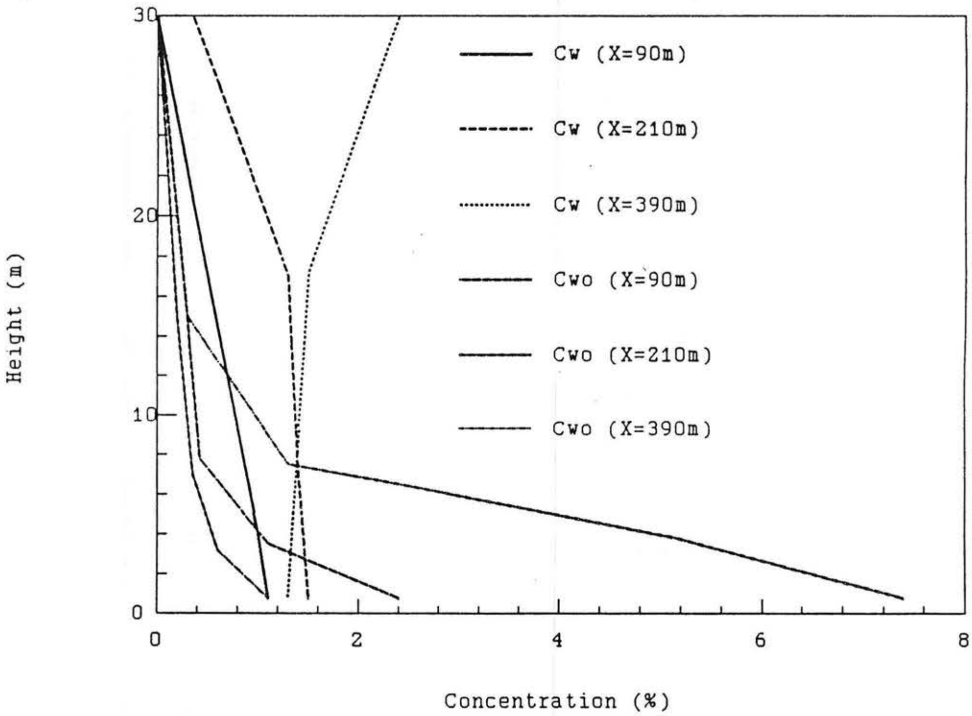


Fig. 4.5-10 Vertical Concentration Profiles, Medium Tank

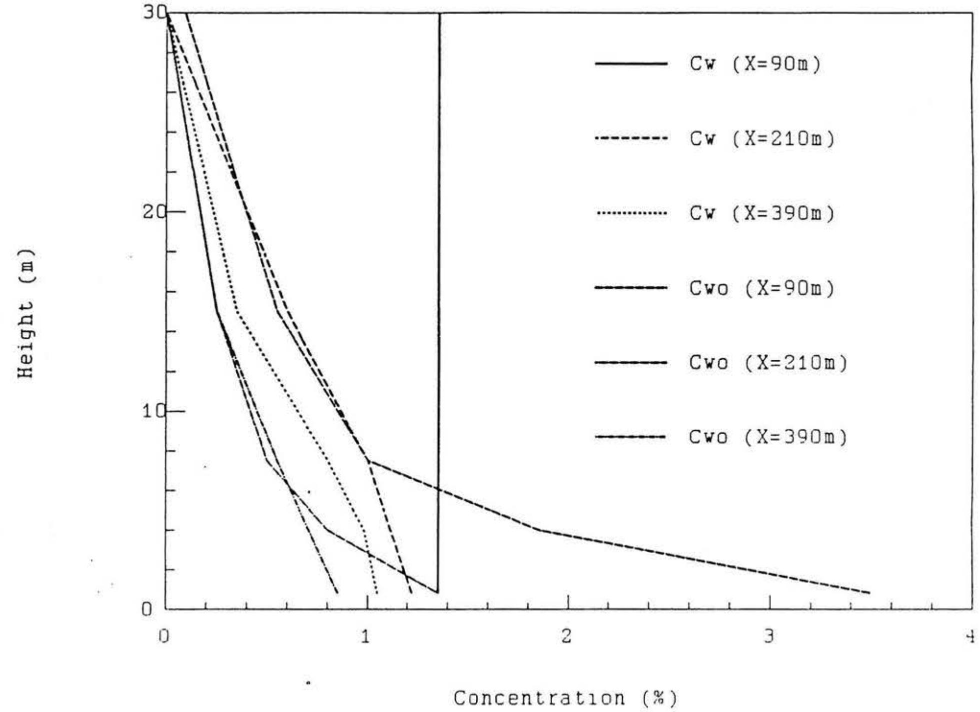


Fig. 4.5-11 Vertical Concentration Profiles, Large Tank

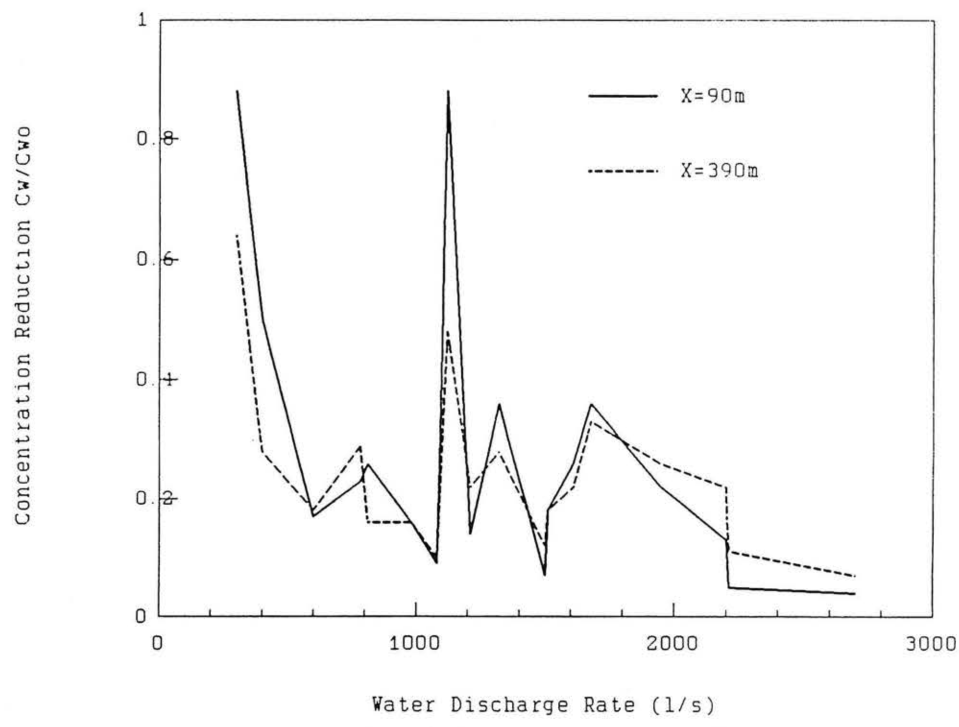


Fig. 4.5-12 Peak Concentration vs Total Water Spray Discharge Rate

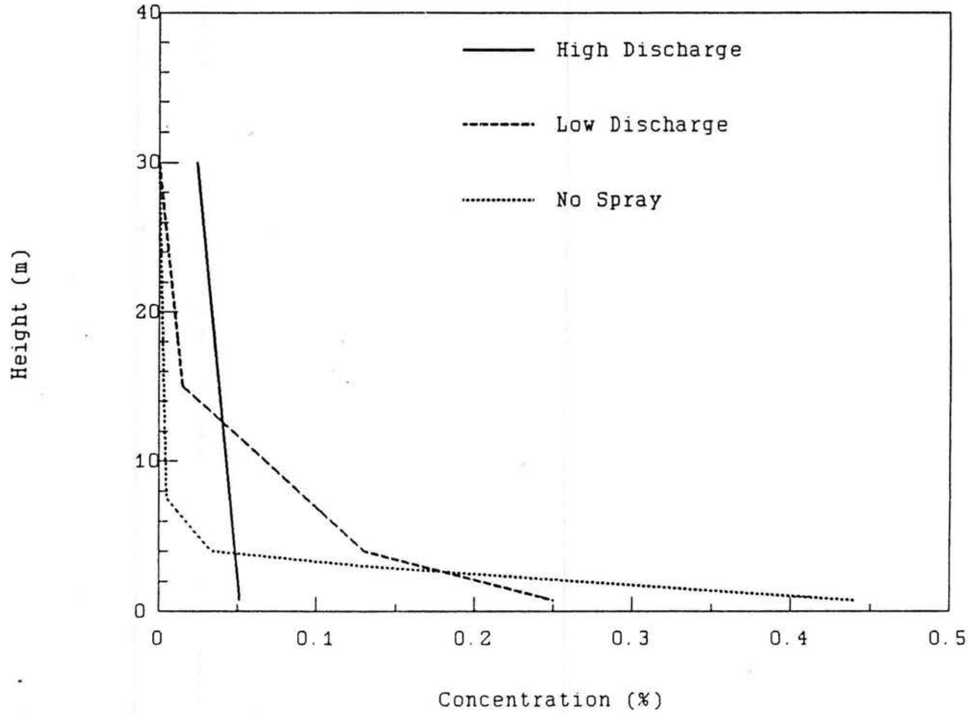


Fig. 4.5-13 Vertical Concentration Profiles at X = 90 m for Various Water Spray Discharge Rates

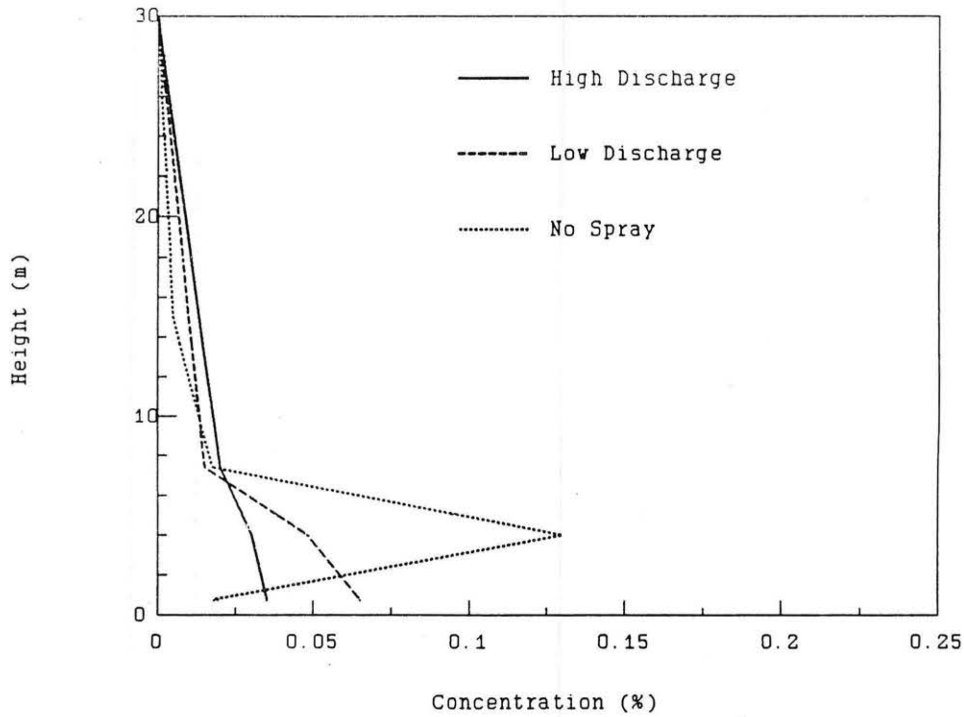


Fig. 4.5-14 Vertical Concentration Profiles at X = 390 m for Various Water Spray Discharge Rates

4.6 "Large Scale Field Trials on Dense Vapor Dispersion," McQuaid and Roebuck, 1984

Experiment Configuration:

In 1976 the Health and Safety Executive (HSE) initiated a program of research on the atmospheric dispersion of heavy gases. The principal theme of the experimental part of the program was the study of the dispersion of fixed-volume clouds. The clouds were initially placed at atmospheric pressure and temperature in a ground-level container which was then suddenly removed. The Thorney Island Heavy Gas Dispersion Trials (HGDT) project was the large-scale constituent of their program, and it was the subject of the report by McQuaid and Roebuck (1984).

The HGDT project as originally planned was limited to experiments on clouds dispersing over uniform, unobstructed ground. After these experiments had commenced, a second series of experiments were performed in which the effects of several types of obstruction were studied. The former experimental program was designated Phase I and the later instantaneous spills were designated Phase II and the later continuous spills designated Phase III.

Figure 4.6-1 indicates the measurement domain about the test location. Figures 4.6-2 display the alternative arrangements of solid fences (5 m), porous fences (10 m), buildings (9 m square), and vapor barrier enclosures (2.4 m x 26 m x 54 m studied.)

Since each field trial was performed at a unique combination of spill rate, meteorology, and obstruction conditions, no two tests were really carried out at identical conditions. Nonetheless, the data were stratified by Froude number and volume release conditions to identify pairs of data suitable for comparison. Seven sets of data pairs from Phase I and II were identified. Only three sets of data pairs (or triplets) were found in the Phase III series suitable for comparison. Table 4.6-1 summarizes the characteristics of the spill sets selected for comparison. The peak concentration, time of arrival, time of peak concentration arrival, and time of departure for each near cloud centerline measurement station were measured on figures provided by HSE. Base line drift of the measuring instrumentation was removed from the figures, and arrival and departure time was defined as the time at which concentrations reached 5% of their peak values.

Results of Comparison:

In the following figures Y represents downwind distance, the release location was always at Y = 200 m and the solid and porous fences were always located at Y = 250 m. During the continuous gas tests the wind approached either along or perpendicular to the longer fence dimension. Note that clouds are delayed by the barriers for time ratios greater than one and accelerated at ratios lower than one.

During the tests for instantaneous spills upwind of the 5 m solid fence it was found that the peak concentration ratios decreased from 0.4 to 0.1 downwind of the fence then slowly increased beyond 400 m (30 fence heights) (Figure 4.6-3). Cloud arrival, peak arrival and cloud departure times changed from +20 to -40%, +50 to +200%, and +50 to +400 % immediately downwind of the fence (0 to 40 fence heights downwind). But farther downwind the cloud arrival, peak arrival and cloud departure times were -40 to -60%, 0 to -40%, and 0 to -10% of their no fence values (Figures 4.6-4 to 4.6-6). Apparently the lower wind speeds directly in the wake of the fences initially slow cloud movement, but beyond the wake region the deeper cloud is advected with higher average wind speeds.

During the tests for instantaneous spills upwind of the 10 m porous fences it was found that the peak concentration ratios increased at the fence line (1.2 to 3.3), but then the ratio fell to levels near 0.2 at about 15 fence heights downwind (Figure 4.6-7). Rottman et al. (1985) suggested that a gravity current might actually decrease its height passing through a porous barrier, which would explain the increased cloud concentrations detected locally. Farther downwind the turbulence generated by the fence increases entrainment levels and results in reduced concentration ratios. Cloud arrival, peak arrival and cloud departure times appear delayed in the wake region of the porous fences, but further downwind the ratios approach a magnitude near one (Figures 4.6-8 to 4.6-10).

The presence of a 9 m square building downwind of a spill site appears to perturb the instantaneous gas cloud much like the presence of a fence barrier. Enhanced mixing of the plume resulting in a more dilute and larger cloud produces reduced peak concentration ratios (0.1 to 0.4), and reduced arrival, peak arrival and cloud departure time ratios. If the building is not directly downwind dilution can occur but time ratios quickly return to one. An upwind building situated to one side of the spill will also result in plume dilution and negligible changes in time ratios.

A vapor barrier enclosure that surrounds a continuous source of dense gas appeared to <u>increase</u> peak concentration ratios directly downwind of the enclosure (2.2 to 8.0). Farther downwind peak concentration ratios decreased (0.3 to 2.0) (Figure 4.6-11). One explanation for the increased peak concentration ratios is associated with the tendency for the enclosure to restrain the initial upwind and lateral spreading of a dense cloud. A narrower cloud will produce higher centerline concentrations. The enclosures also seem to loft a small amount of gas to heights at which increased wind speeds advect the gas faster downwind; thus, one notes reduced arrival times in two of the three sets of comparisons (i.e. 0.1 to 0.2), but the third case produced peculiarly large arrival time ratios (1 to 9?). Nonetheless, peak arrival and departure time ratios ranged between 0.5 to 1.5 for all three data sets (See typical Figures 4.6-12 to 4.6-14).

Conclusions:

The HGDT tests at Thorney Island provides tantalizing glimpses of the physics of plume dynamics downstream of a variety of obstacles. As expected normal meteorological variability produces perturbations in measurements which are often confusing as they are educational. Nonetheless, a few conclusions may be made from the comparison exercise.

@ Solid barrier fences reduce ground level concentrations measured downwind of instantaneous spills of dense gas. The additional mixing produced by the fence appears to have reduced effect beyond the wake region (30 fence heights).

@ Solid barrier fences initially delay the cloud movement through the wake region, but the cloud actually arrives earlier farther downstream.

@ Porous barriers may increase concentrations directly downstream of the fence; however, farther downstream peak concentrations are reduced.

@ Small buildings perturb a dense cloud much like a solid fence when placed directly downwind of the spill. Buildings placed off centerline from the cloud trajectory have minimal effects on time ratios.

@ Enclosures placed around continuous sources of dense gas may increase concentrations downwind of the enclosure. Farther downstream the peak concentration ratios remained near one.

Table 4.6-1 Spill and Meteorological Conditions During Thorney Island Trials

INSTANTANEOUS RELEASES

TRIAL NO.	S.G.	U10 M/S	VOL M^3	H M	(X)f M	U* M/S	Zo MM	Fr	U*/U10	Zo/VOL^(1/3) *10-4	H/VOL^(1/3)	(X)f/VOL^(1/3)	V/L^3
16	1.68	4.8	1580	-	-	.17	20	1.42	.04	17.17	-	-	1.58
20	1.92	5.7	1920	5	50	.46	20	1.65	.08	16.09	.40	4.02	1.92
7	1.78	3.2	2000	-	-	.07	2	.34	.02	1.59	-	-	2.00
21	2.02	3.9	2050	5	50	.41	20	.47	.11	15.74	.39	3.94	2.05
8	1.70	2.4	2000	-	-	0	2	.16	0	1.59	-	-	2.00
22	4.20	5.9	1400	5	50	.12	2	.59	.02	1.79	.45	4.47	1.40
19	2.12	6.4	2100	-	-	.48	20	1.87	.08	15.62	-	-	2.10
23	1.80	5.8	N/A	10	50	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
13	1.96	7.5	1950	-	-	.51	20	3.59	.07	16.01	-	-	1.95
24	2.03	7	N/A	10	50	.4	150	N/A	N/A	N/A	N/A	N/A	N/A
9	1.73	1.7	2000	-	-	.03	2	.05	.02	1.59	-	-	2.00
26	2.00	1.9	1970	9	50	.24	2	.06	.13	1.60	.72	3.99	1.97
15	1.41	5.4	2100	-	-	.37	2	3.06	.07	1.56	-	-	2.10
28	2.00	9	1850	9	50	.3	2	6.06	.03	1.63	.73	4.07	1.85
11	2.00	5.1	2100	-	-	N/A	N/A	1.06	N/A	N/A	-	-	2.10
29	2.00	5.6	1950	9	27	.25	2	1.43	.04	1.60	.72	2.16	1.95

CONTINUOUS RELEASES

TRIAL NO.	S.G.	U10 M/S	VOL M^3	RATE(Q) M^3/min	H M	W M	L M	U* M/S	Zo MM	Fr	U*/U10	Zo/VOL^(1/3) *10-4	Q/(U10*L^2) *10-2
46	2.00	3.4	1690	260	0	0	0	N/A	N/A	.12	N/A	N/A	1.27
33	1.83	2.5	1870	340	2.4	26	54	.15	10.00	.10	.06	8.12	2.27
49	1.60	2.4	1907	260	2.4	54	26	N/A	N/A	.10	N/A	N/A	1.81
45	2.00	2.3	1972	260	0	0	0	N/A	N/A	.05	N/A	N/A	1.88
43	1.33	1.5	1899	265	2.4	26	54	N/A	N/A	.07	N/A	N/A	2.94
50	1.38	1.6	1800	270	2.4	54	26	N/A	N/A	.07	N/A	N/A	2.81
38	1.60	3.8	1867	280	0	0	0	N/A	N/A	.25	N/A	N/A	1.23
37	1.60	3.4	1891	255	2.4	26	54	.39	10.00	.20	.11	8.09	1.25

TRIAL NO.	Fr	VOL/(H*W*L)	H/VOL^(1/3)	W/VOL^(1/3)	L/VOL^(1/3)
46	9.26	-	0	0	0
33	4.47	.55	.19	2.11	4.38
49	5.43	.57	.19	4.35	2.10
45	2.87	-	0	0	0
43	2.36	.56	.19	2.10	4.36
50	2.44	.53	.20	4.44	2.14
38	20.00	-	0	0	0
37	15.73	.56	.19	2.10	4.37

Table 4.6-1 Obstacle Configurations During Thorney Island Trials

INSTANTANEOUS RELEASES

TRIAL NO.	WIND DIR. (DEG)	Fr	CONFIGURATION
16	-14.3	.35	UNOBSTRUCTED
20	-6.5	.36	5M WALL AT 50M
7	45.3	.14	UNOBSTRUCTED
21	-6.1	.15	5M WALL AT 50M
8	-15.8	.09	UNOBSTRUCTED
22	-7.6	.11	5M WALL AT 50M
19	30.2	.37	UNOBSTRUCTED
23	28.6	.43	2x10M POROUS FENCE AT 50M
13	30.8	.57	UNOBSTRUCTED
24	28.8	.46	4x10M POROUS FENCE AT 50M
9	-26.9	.05	UNOBSTRUCTED
26	5	.04	9M SQUARE BLDG, 50M DOWN RANGE
15	.8	.72	UNOBSTRUCTED
28	41.9	.82	9M SQUARE BLDG, 50M AT 45 DOWN RANGE
11	69.6	.28	UNOBSTRUCTED
29	27	.32	9M SQUARE BLDG, 27M AT 30 UP RANGE

CONTINUOUS RELEASES

TRIAL NO.	WIND DIR. (DEG)	Fr	CONFIGURATION
46	76.6	.12	UNOBSTRUCTED
33	1.8	.13	2.4M FENCE LONGITUDINAL
49	1.2	.11	2.4M FENCE TRANSVERSE
45	-34.5	.05	UNOBSTRUCTED
43	10	.08	2.4M FENCE LONGITUDINAL
50	42.9	.08	2.4M FENCE TRANSVERSE
38	-25.1	.25	UNOBSTRUCTED
37	-26.5	.17	2.4M FENCE LONGITUDINAL

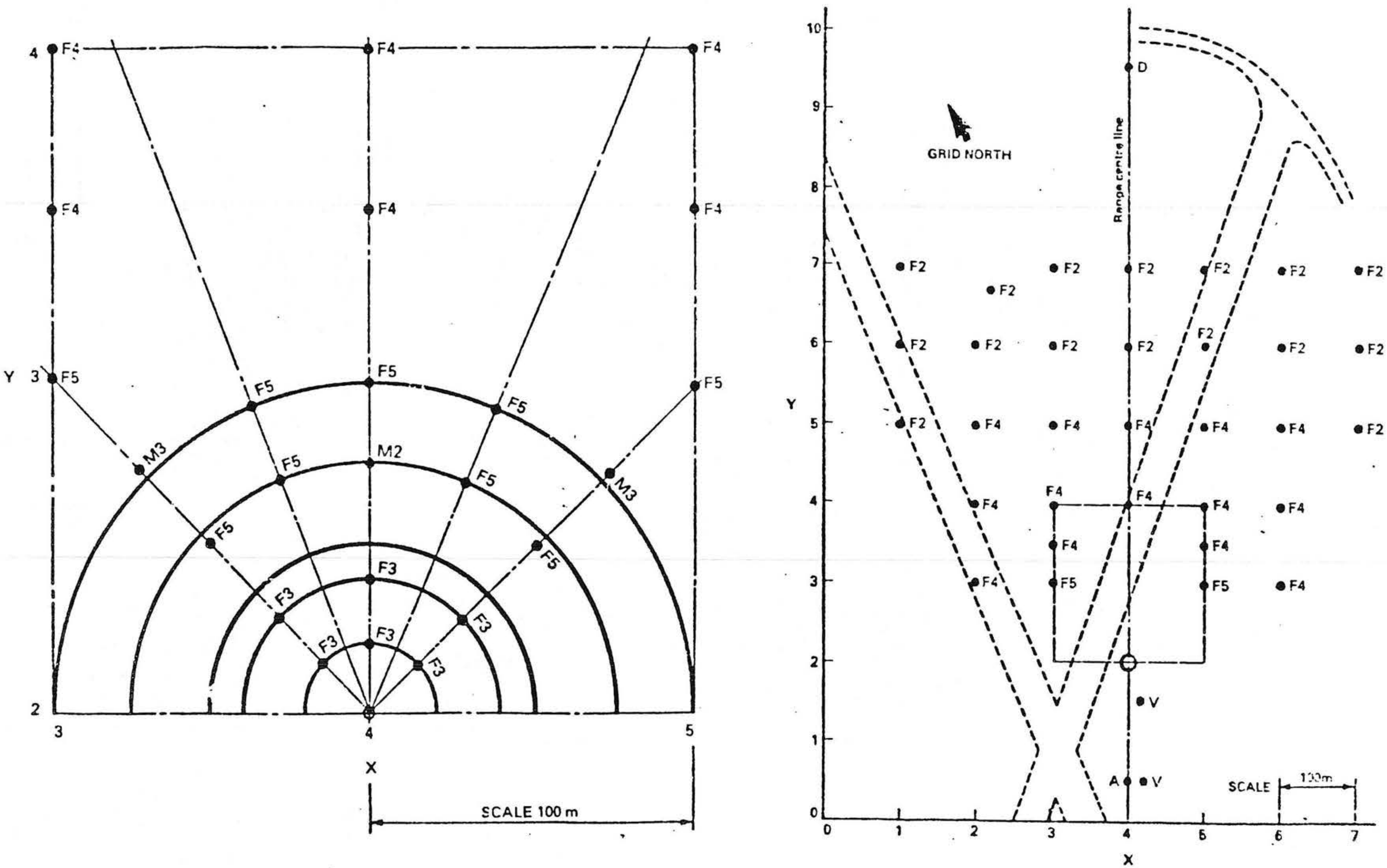


Fig. 4.6-1 Spill Configuration and Measurement Grid, Thorney Island Trials

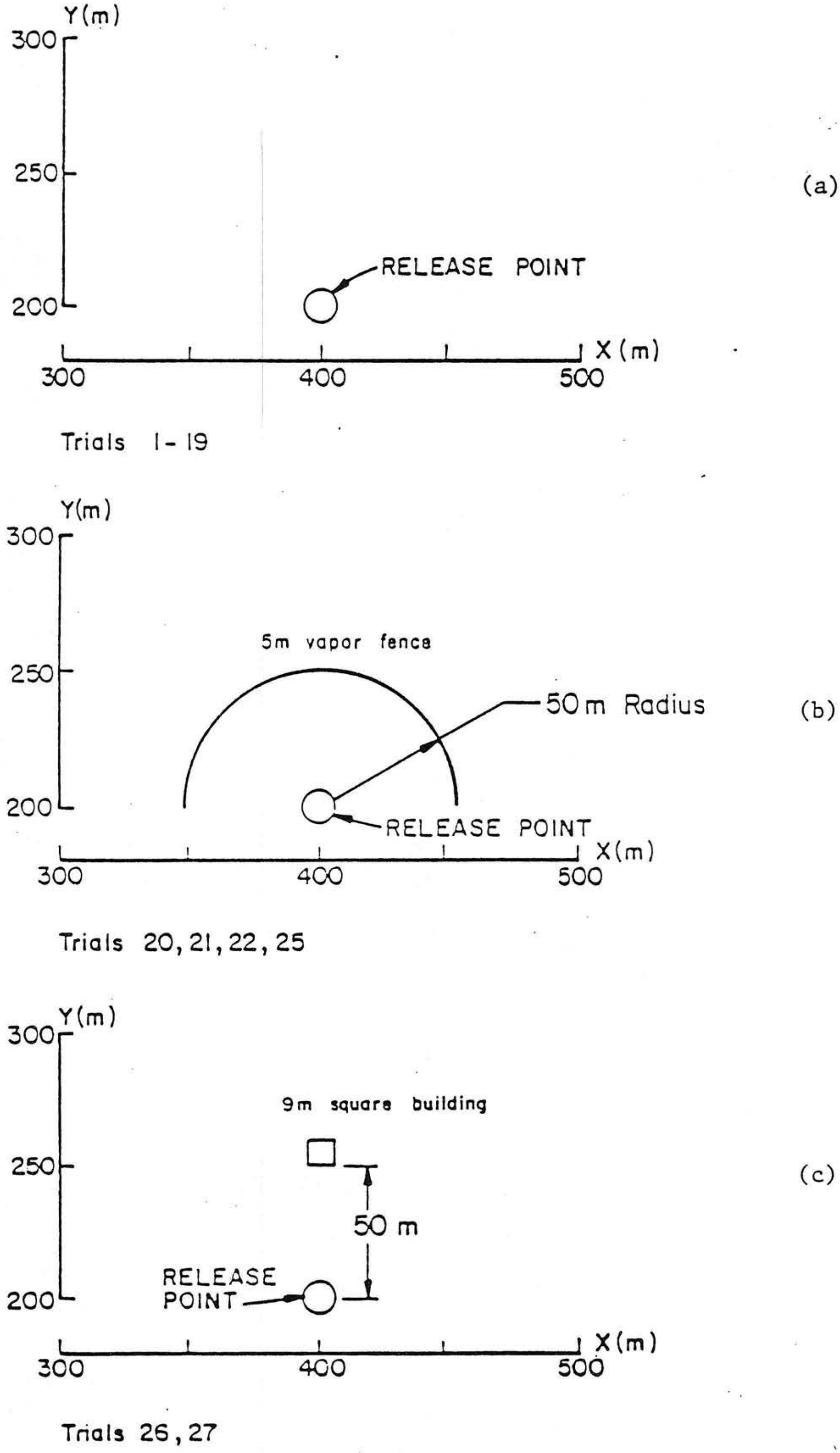


Fig. 4.6-2 Obstacle Configurations During Thorney Island Trials

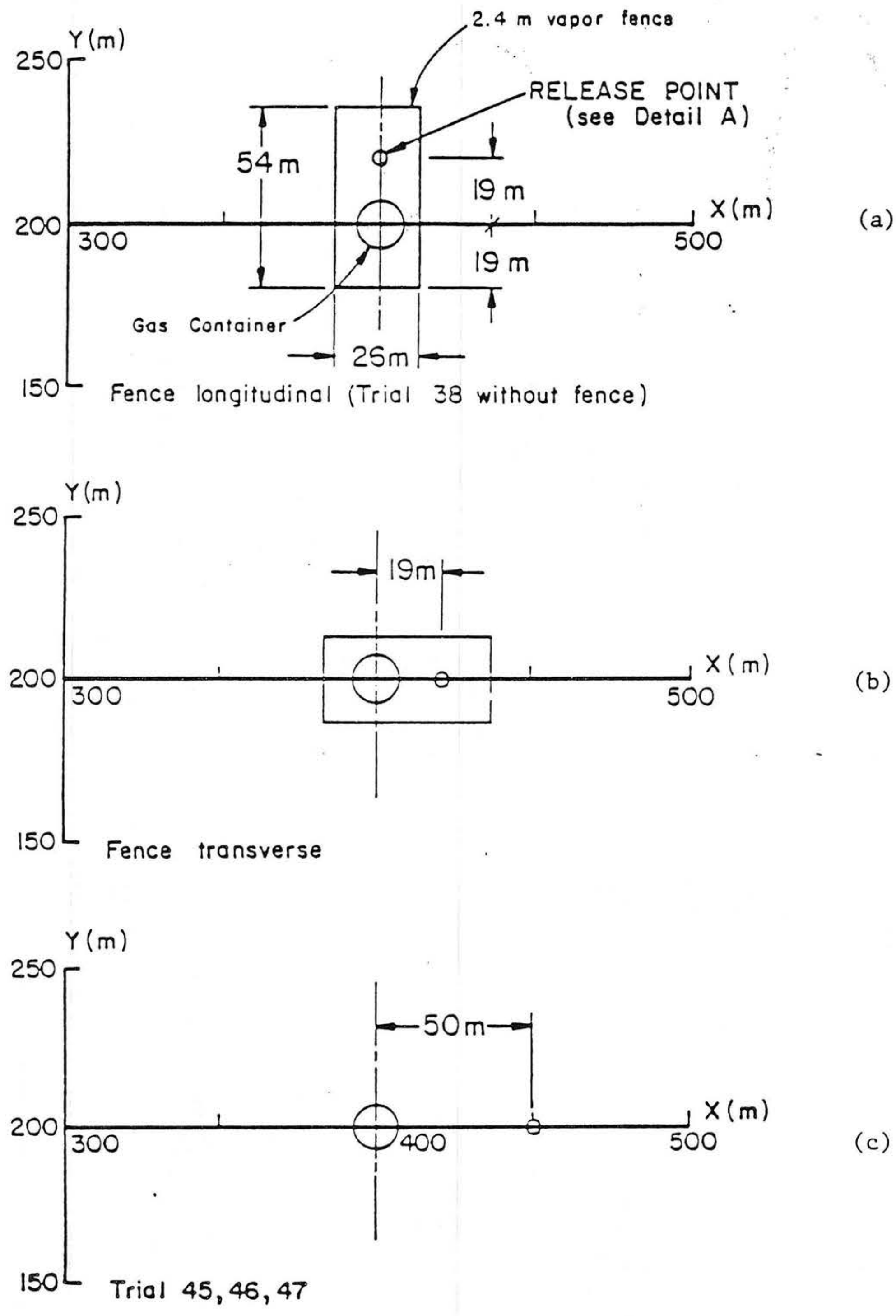
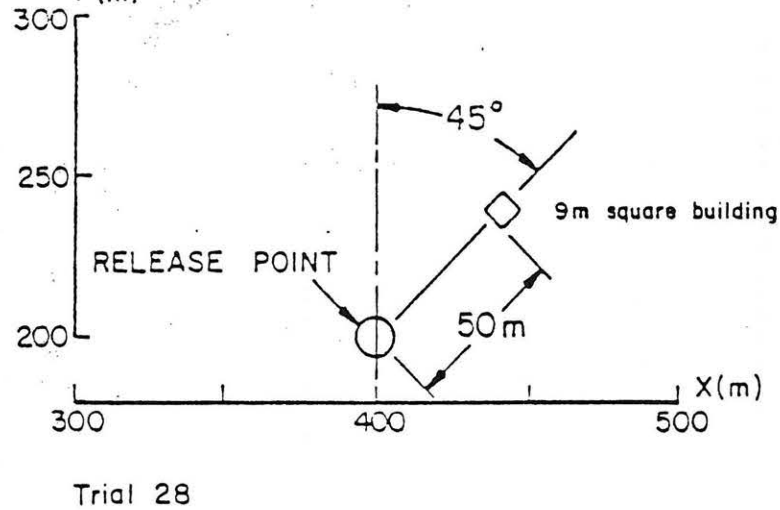
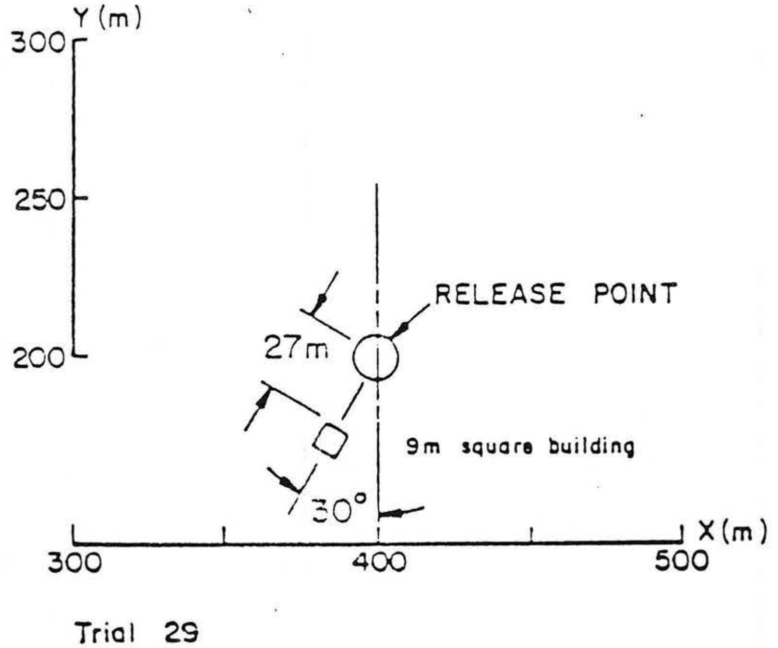


Fig. 4.6-2 Obstacle Arrangements, Phases II and III, Thorney Island Trials



(d)



(e)

Fig. 4.6-2 Obstacle Arrangements, Phases II and III, Thorney Island Trials

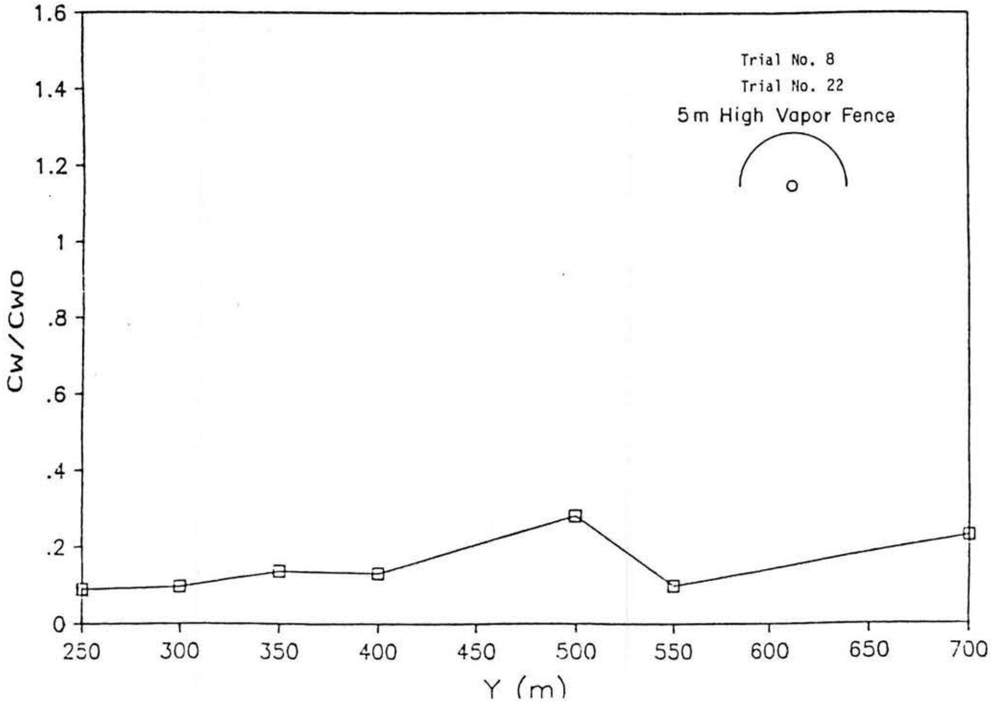


Fig. 4.6-3 Peak Concentration Ratio vs Downwind Distance, Thorney Island Trials 8 and 22

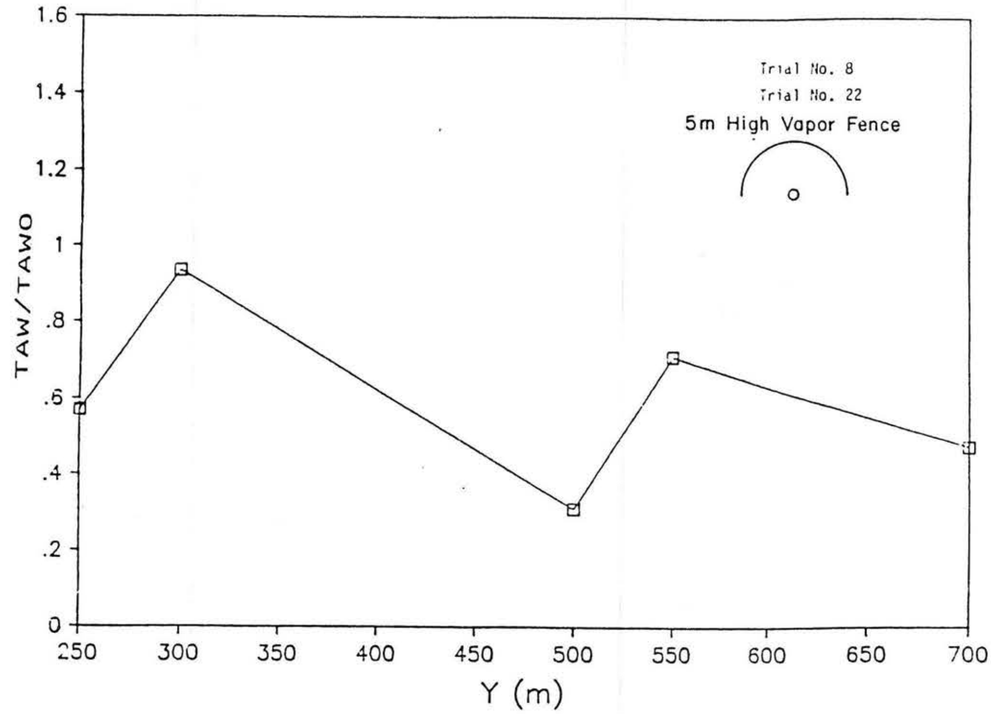


Fig. 4.6-4 Arrival Time Ratio vs Downwind Distance, Thorney Island Trials 8 and 22

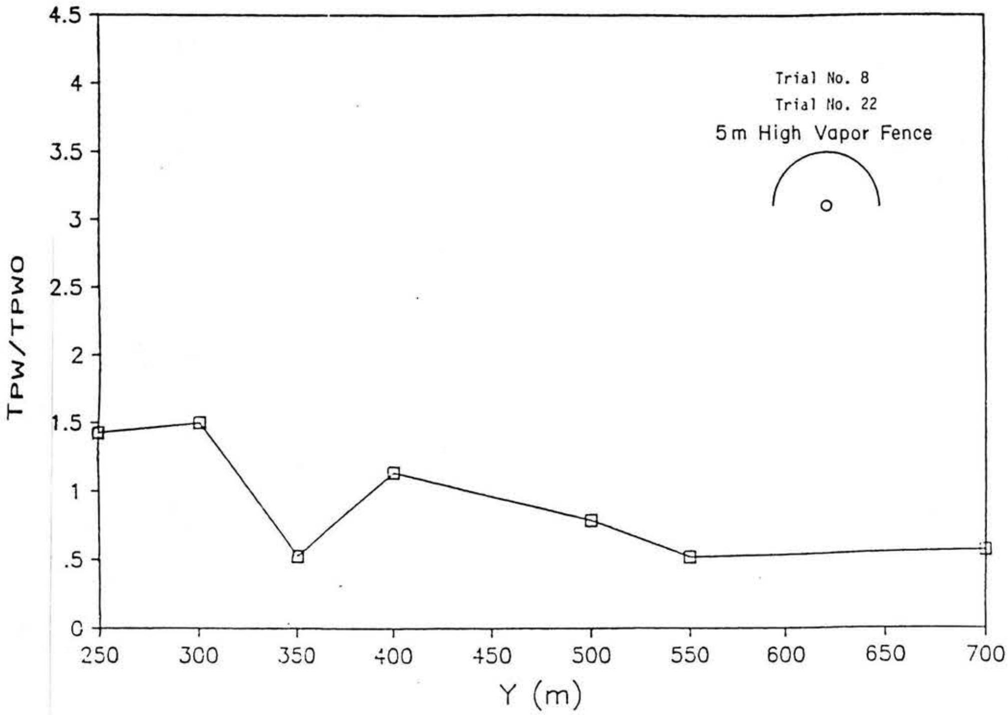


Fig. 4.6-5 Peak Arrival Time Ratio vs. Downwind Distance,.Thorney Island Trials 8 and 22

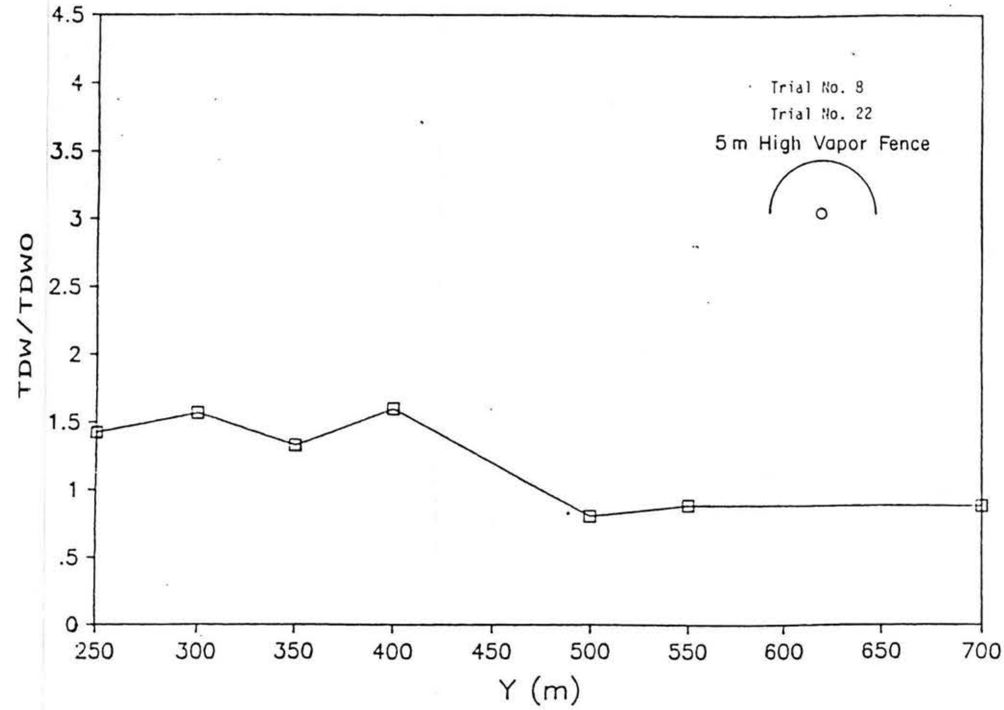


Fig. 4.6-6 Departure Time Ratio vs. Downwind Distance, Thorney Island Trials 8 and 22

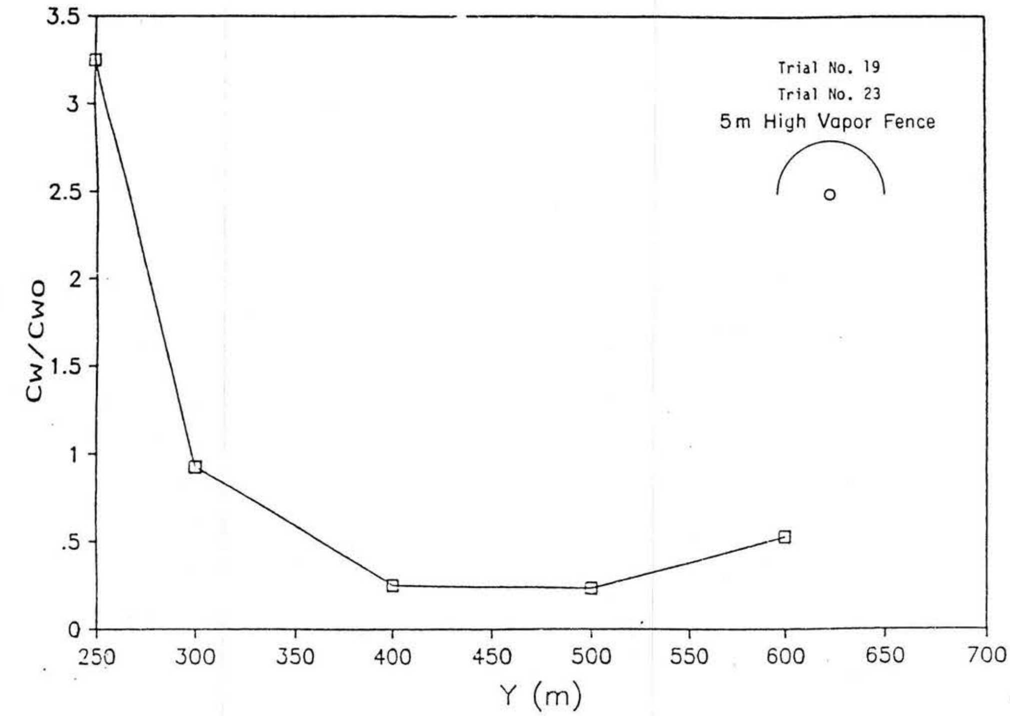


Fig. 4.6-7 Peak Concentration Ratio vs. Downwind Distance, Thorney Island Trials 19 and 23

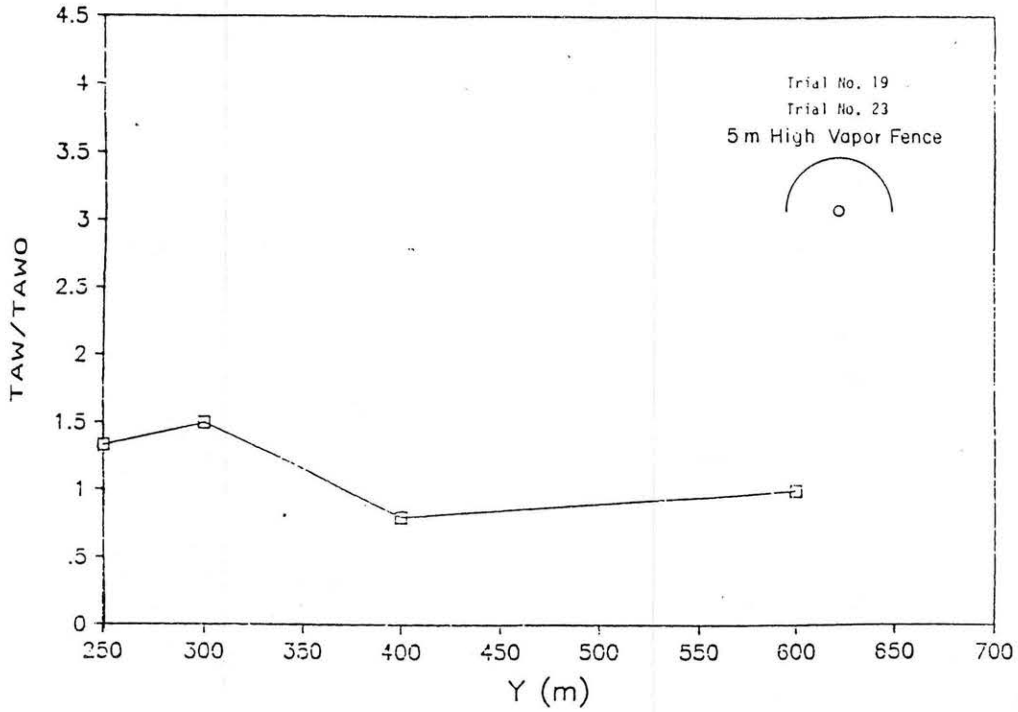


Fig. 4.6-8 Arrival Time Ratio vs. Downwind Distance, Thorney Island Trials 19 and 23

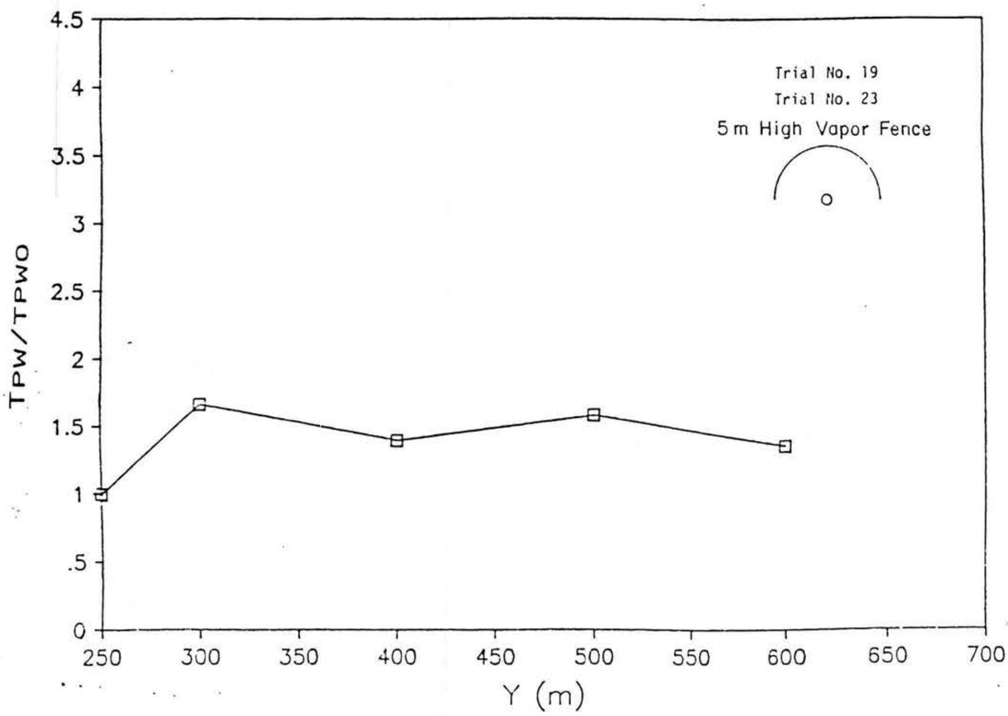


Fig. 4.6-9 Peak Arrival Time Ratio vs. Downwind Distance, Thorney Island Trials 19 and 23

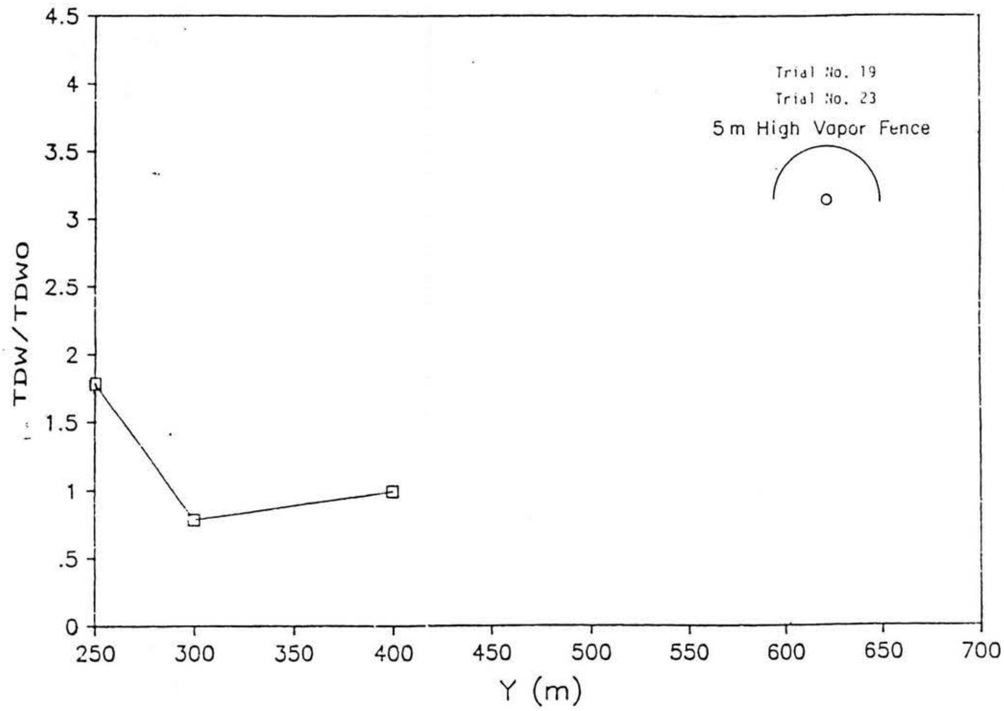


Fig. 4.6-10 Departure Time Ratio vs. Downwind Distance, Thorney Island Tirals 19 and 23

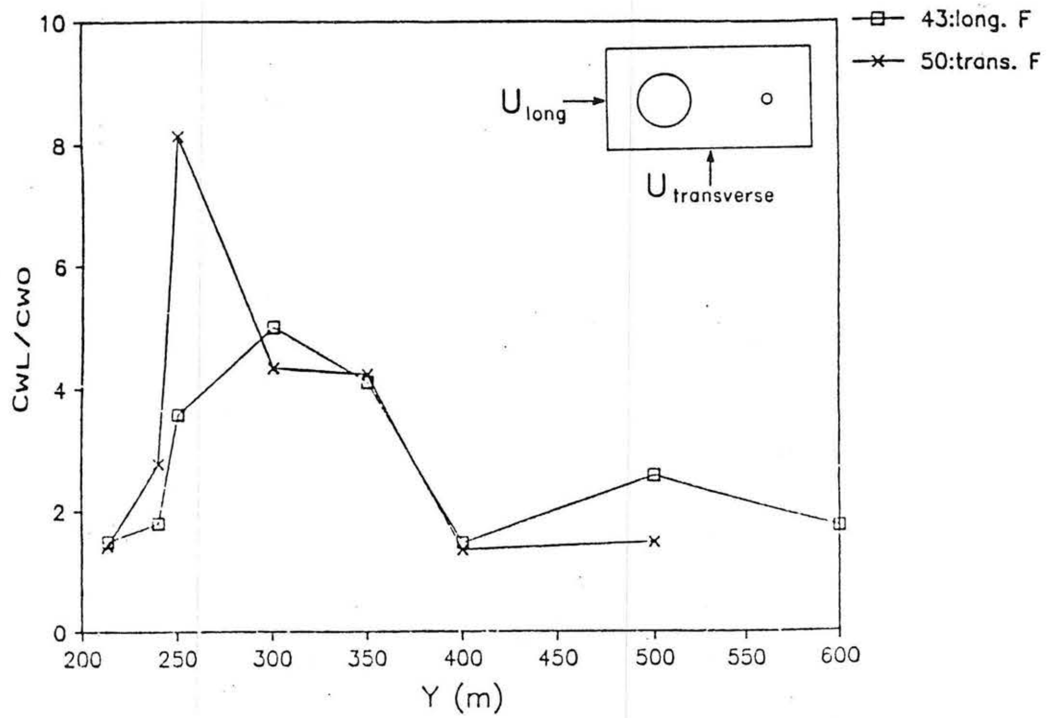


Fig. 4.6-11 Peak Concentration Ratio vs. Downwind Distance, Thorney Island Trials 43, 45 and 50

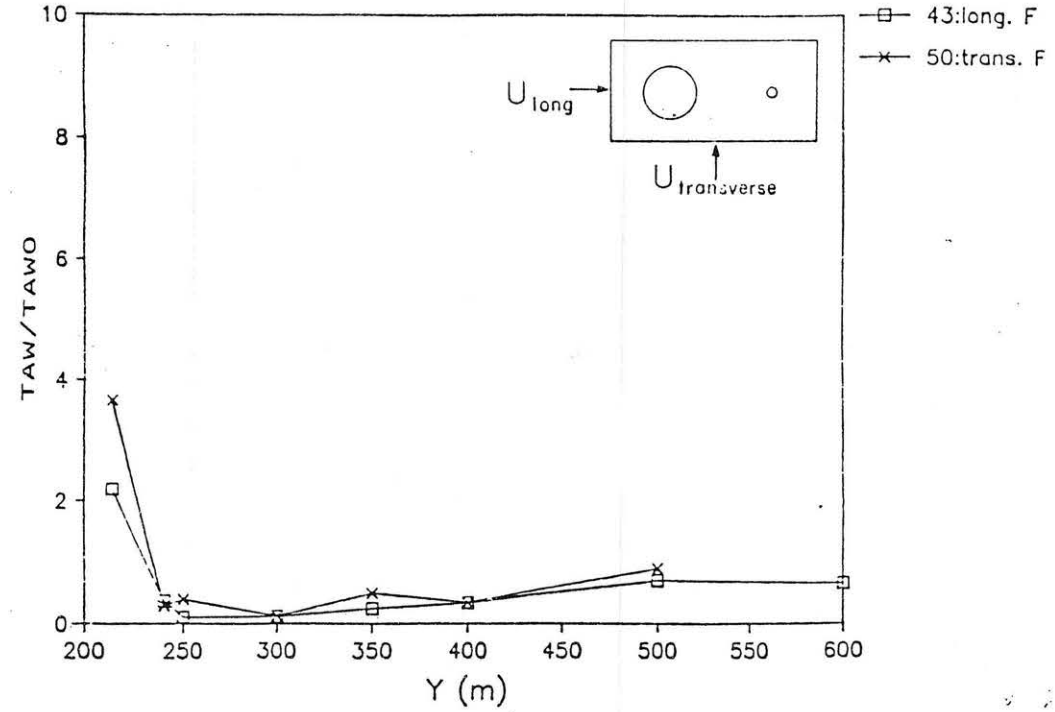


Fig. 4.6-12 Arrival Time Ratio vs. Downwind Distance, Thorney Island Trials 43, 45 and 50

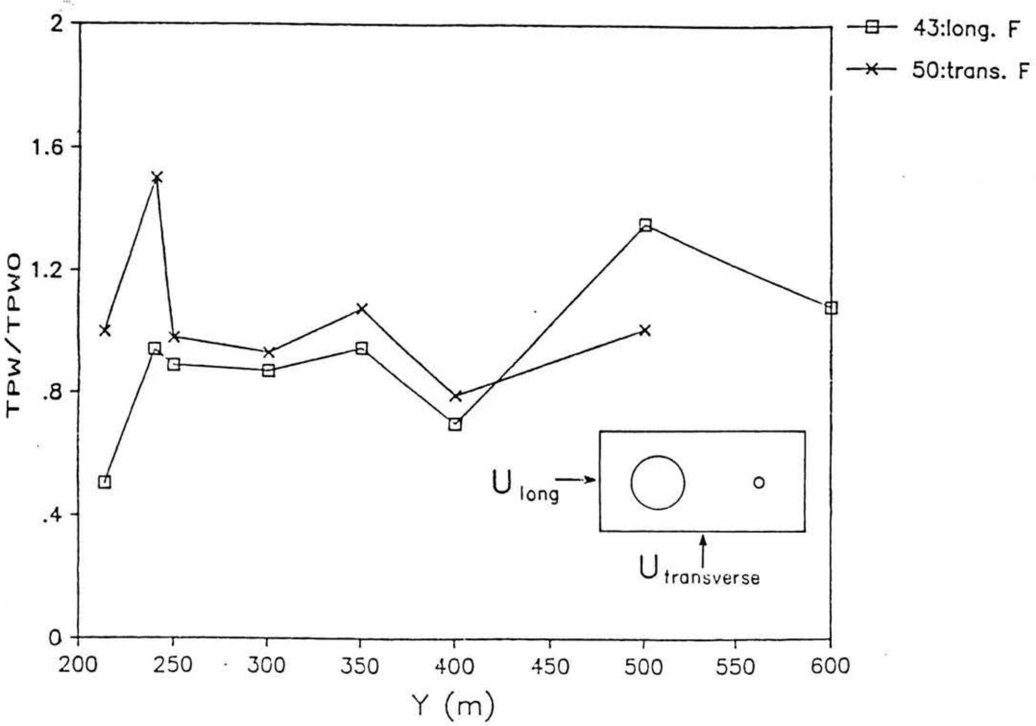


Fig. 4.6-13 Peak Arrival Time Ratio vs. Downwind Distance, Thorney Island Trials 43, 45 and 50

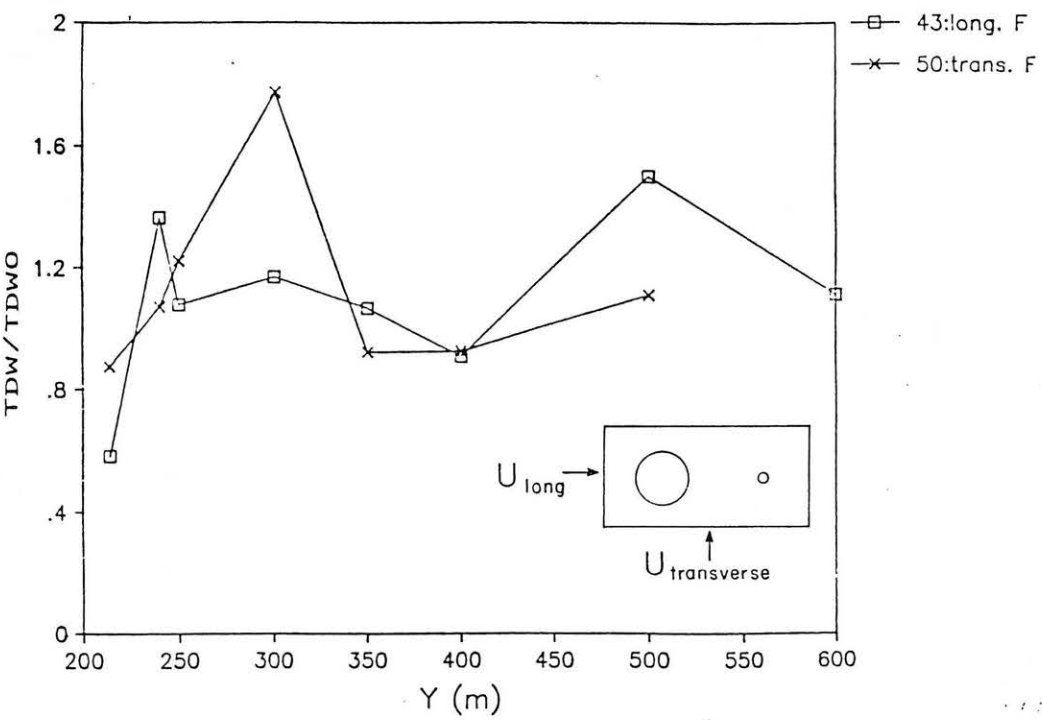


Fig. 4.6-14 Departure Time Ratio vs. Downwind Distance, Thorney Island Tirals 43, 45 and 50

4.7 "Wind Tunnel Modeling of the Thorney Island Heavy Gas Dispersion Trials," Davies and Inman, 1986

Experiment Configuration:

The purpose of the Davies and Inman (1986) wind-tunnel tests was to obtain a large data base of laboratory simulations over a range of model scales typical of those used in hazard studies on prototype installations. Scales ranging from 1:40 to 1:250 were used to simulate 34 trials from the Thorney Island HGDT project. A total of 86 laboratory cases were produced. Typically, 10 repetitions of each wind tunnel run were required to map the concentration field for each simulation and to provide point to point comparisons with the 10 to 20 "ground level" (0.4 m high) sensors used during the field trials.

The instantaneous spill cases of the HGDT project were simulated at scales of 1:40, 1:100, and 1:150 using a collapsing wall type container to simulate the prototype collapsing bag. A large grid of sensor locations were used in the laboratory to enable concentration contours to be prepared from the laboratory measurements. Concentration measurements were made in the laboratory with low-volume hot-wire aspirated katherometers. These instruments permitted measurement of concentration time series at each sensor location.

Davies and Inman provided some comparisons between their laboratory measurements and the Thorney Island field results. This report examines the data further by the Surface Pattern Comparison technique described by Meroney (1986b, 1987). The emphasis here is to analyze the results to establish the level of confidence which can be placed in laboratory simulations.

During the field study there were a large number of uncontrolled or poorly specified variables, which have effects on the resultant concentration field, that are not completely accounted for by either a physical or numerical model. The full-scale wind field is typically nonstationary, the source conditions are only approximately known, and the modeling method itself introduces errors. The Surface Pattern Comparison method estimates how much the predicted concentration contour pattern must be shifted in space to cover all of the observed values. This is done by comparing observed and calculated patterns over increments of decreasing spatial resolution. The result of such a comparison is knowledge of what percentage of observed concentrations are contained within increased areas of spatial resolution as specified by their angular displacement observed from the release location, delta theta.

Results of Comparison:

Table 4.7-1 lists the prototype and model conditions considered by Davies and Inman. The peak concentration contours at ground level measured at full scale and during the laboratory simulation are plotted together in the Davies and Inman report. These data were used to produce Figures 4.7-1 to 4.7-3 and Table 4.7-2. Figure 4.7-1 shows a typical plot of f-N, the percentage of field data predicted within a factor of N by the laboratory data, versus angular displacement, a measure of spatial resolution. All trials were regrouped for comparison as follows:

1. Unobstructed instantaneous releases (Figure 4.7-2c),
2. Instantaneous releases with wall or building (Figure 4.7-2d),
3. Continuous releases with fence enclosures (Figures 4.7-3a to 4.7-3c),
4. Unobstructed continuous releases (Figure 4.7-3d).

Scale ratios of 40, 100, 150, and 250 are denoted by ##/a, ##/b, ##/c, and ##/d, respectively on these figures.

Most laboratory scientists expect that as model scale ratio, LSR, increases the quality of the physical simulation may decrease. This decrease results from mismatch in turbulence size and strength, exaggerated dispersion due to microscopic transport, and mismatch between buoyancy and inertial forces in the model. Thus, one expects some evidence that the quality of simulation decreases as one changes model scale from 1:40 to 1:250 (from cases a to d). It would be valuable if one could quantify the loss of accuracy as a function of model scale.

Unfortunately, close inspection of the data reveals no consistent pattern of error variability with model scale. Tests 42a, b, c, and d; tests 8b and c, tests 38a, b, c, and d show the expected decline in model reliability. Yet tests 49a, b, and c; tests 30a, b, and c; tests 33 a, b, and c show the opposite trend! Other tests display an irregular rise and fall of accuracy with scale ratio. At this time it is not known whether this is evidence of normal statistical variability, experimental errors, or fallacies in the similarity theories.

On a positive note, most of the data compared within a factor of one for angular displacements of 15 to 20 degrees. Similar comparisons between field data and many numerical models require angular displacements exceeding 45 degrees. Also results from continuous spill experiments appear to compare somewhat better than the instantaneous spill experiments.

Conclusions:

Laboratory simulation of dense gas behavior near obstructions appear to be reliable in the sense that predicted concentration contours do not require major modifications to reproduce field data. Based on this Surface Pattern Comparison analysis no limitations could be placed on the largest model scales which might be used to simulate dense cloud behavior.

Table 4.7-1 Prototype and Model Conditions Compared from Thorney Island Field and Model Tests by Davies and Inman

INSTANTANEOUS RELEASES

TRIAL CONFIGURATION/NO.	SCALE RATIO	<SPECIFIC GRAVITY>f	<SPECIFIC GRAVITY>m	U10,f m/s	U10,m m/s	VOL. m³	RATE m³/min	D cm²/s	<Ri>B	<Pe/Ri>m	<Re>m	<Re*>m	PASQUILL STABILITY
UI/08	100.00	1.70	1.70	2.40	.24	2000.00	-	.08	15.50	269.00	1679.89	7.73	D
UI/08	150.00	1.70	1.70	2.40	.20	2000.00	-	.08	15.50	146.00	914.42	6.31	D
UI/12	100.00	2.30	2.30	2.60	.26	1950.00	-	.08	24.70	184.00	1804.59	8.37	E
UI/12	150.00	2.30	2.30	2.60	.21	1950.00	-	.08	24.70	100.00	982.30	6.84	E
UI/17	40.00	4.20	4.20	5.30	.84	1700.00	-	.08	12.50	2502.00	13890.88	26.98	D/E
UI/17	100.00	4.20	4.20	5.30	.53	1700.00	-	.08	12.50	633.00	3514.14	17.07	D/E
UI/17	150.00	4.20	4.20	5.30	.43	1700.00	-	.08	12.50	345.00	1912.86	13.93	D/E
UI/19	100.00	2.10	2.10	6.60	.66	2100.00	-	.08	3.50	3556.00	4635.46	21.25	D/E
UI/19	150.00	2.10	2.10	6.60	.54	2100.00	-	.08	3.50	1936.00	2555.88	17.35	D/E
SW-50/20	100.00	1.90	1.90	5.60	.56	1920.00	-	.08	3.50	2655.00	3866.78	18.03	C/D
SW-50/20	150.00	1.90	1.90	5.60	.46	1920.00	-	.08	3.50	1445.00	2104.81	14.72	C/D
SW-50/21	100.00	2.00	2.00	3.90	.39	2050.00	-	.08	9.00	807.00	2752.39	12.56	D/E
SW-50/21	150.00	2.00	2.00	3.90	.32	2050.00	-	.08	9.00	439.00	1498.21	10.25	D/E
SW-50/22	150.00	4.20	4.20	6.00	.49	1400.00	-	.08	7.80	500.00	2029.79	15.77	D/E
9B-50/28	100.00	2.00	2.00	9.00	.90	1050.00	-	.08	1.50	9918.00	6138.01	28.98	D
9B-50/28	150.00	2.00	2.00	9.00	.73	1050.00	-	.08	1.50	5399.00	3341.11	23.66	D
9B-27/29	100.00	2.00	2.00	5.50	.55	1950.00	-	.08	4.10	2264.00	3817.41	17.71	D
9B-27/29	150.00	2.00	2.00	5.50	.45	1950.00	-	.08	4.10	1232.00	2077.93	14.46	D
UI/34	40.00	1.80	1.80	1.40	.22	2110.00	-	.08	60.40	184.00	3943.30	7.13	F

CONTINUOUS RELEASES

TRIAL CONFIGURATION/NO.	SCALE RATIO	<SPECIFIC GRAVITY>f	<SPECIFIC GRAVITY>m	U10,f m/s	U10,m m/s	VOL. m³	RATE m³/min	D cm²/s	<Ri>B	<Pe/Ri>m	<Re>m	<Re*>m	PASQUILL STABILITY
FL/30	40.00	1.40	1.40	4.30	.68	1603.00	260.00	.08	.20	10700	947.94	21.89	E
FL/30	100.00	1.40	1.40	4.30	.43	1603.00	260.00	.08	.20	2700	239.81	13.85	E
FL/30	150.00	1.40	1.40	4.30	.35	1603.00	260.00	.08	.20	1500	130.54	11.31	E
FL/30	250.00	1.40	1.40	4.30	.27	1603.00	260.00	.08	.20	700	60.67	8.76	E
FL/33	40.00	1.60	2.50	2.80	.70	1870.00	340.00	.08	1.20	3100	1383.09	22.54	D/E
FL/33	100.00	1.60	2.50	2.80	.44	1870.00	340.00	.08	1.20	800	349.90	14.26	D/E
FL/33	150.00	1.60	2.50	2.80	.36	1870.00	340.00	.08	1.20	400	190.46	11.64	D/E
FL/33	250.00	1.60	2.50	2.80	.28	1870.00	340.00	.08	1.20	200	80.52	9.02	D/E
FL/36	40.00	1.60	2.00	2.40	.49	1963.00	310.00	.08	1.60	1600	998.33	15.77	F/D
FL/36	100.00	1.60	2.00	2.40	.31	1963.00	310.00	.08	1.60	400	252.56	9.98	F/D
FL/36	150.00	1.60	2.00	2.40	.25	1963.00	310.00	.08	1.60	200	137.48	8.15	F/D
FL/37	40.00	1.60	1.60	3.20	.51	1891.00	255.00	.08	.70	2900	809.85	16.29	E
FL/37	100.00	1.60	1.60	3.20	.32	1891.00	255.00	.08	.70	700	204.88	10.30	E
FL/37	150.00	1.60	1.60	3.20	.26	1891.00	255.00	.08	.70	400	111.52	8.41	E
FL/37	250.00	1.60	1.60	3.20	.20	1891.00	255.00	.08	.70	200	51.83	6.52	E
UC/38	40.00	1.60	1.60	3.80	.60	1867.00	280.00	.08	.50	4900	924.77	19.35	F
UC/38	100.00	1.60	1.60	3.80	.38	1867.00	280.00	.08	.50	1200	233.95	12.24	F
UC/38	150.00	1.60	1.60	3.80	.31	1867.00	280.00	.08	.50	7[illegible]	127.35	9.99	F
UC/38	250.00	1.60	1.60	3.80	.24	1867.00	280.00	.08	.50	300	59.19	7.74	F
FL/39	40.00	1.40	1.40	5.80	.92	1808.00	350.00	.08	.10	26200	1277.35	29.53	D
FL/39	100.00	1.40	1.40	5.80	.58	1808.00	350.00	.08	.10	6600	323.15	18.68	D
FL/39	150.00	1.40	1.40	5.80	.47	1808.00	350.00	.08	.10	3600	175.90	15.25	D
FL/39	250.00	1.40	1.40	5.80	.37	1808.00	350.00	.08	.10	1700	81.75	11.81	D
FL/40	40.00	1.20	1.20	3.10	.49	1860.00	310.00	.18	.20	3400	878.87	15.78	D
FL/40	100.00	1.20	1.20	3.10	.31	1860.00	310.00	.18	.20	900	222.34	9.98	D
FL/40	150.00	1.20	1.20	3.10	.25	1860.00	310.00	.18	.20	500	121.03	8.15	D
FL/40	250.00	1.20	1.20	3.10	.20	1860.00	310.00	.18	.20	200	56.25	6.31	D
FL/42	40.00	1.60	1.60	3.40	.54	1973.00	185.00	.08	.50	3500	711.03	17.31	D
FL/42	100.00	1.60	1.60	3.40	.34	1973.00	185.00	.08	.50	900	179.88	10.9[illegible]	D
FL/42	150.00	1.60	1.60	3.40	.28	1973.00	185.00	.08	.50	500	97.91	8.94	D
FL/42	250.00	1.60	1.60	3.40	.22	1973.00	185.00	.08	.50	200	45.51	6.92	D
FL/43	40.00	1.30	2.00	1.50	.43	1899.00	265.00	.08	2.50	1100	1051.98	13.94	F
FL/43	100.00	1.30	2.00	1.50	.27	1899.00	265.00	.08	2.50	300	261.07	8.82	F
FL/43	150.00	1.30	2.00	1.50	.22	1899.00	265.00	.08	2.50	200	142.11	7.20	F
UC/45	40.00	2.00	2.00	2.30	.36	1972.00	260.00	.08	2.60	700	693.29	11.71	E/F
UC/45	100.00	2.00	2.00	2.30	.23	1972.00	260.00	.08	2.60	200	175.39	7.41	E/F
UC/46	40.00	2.00	2.00	3.30	.52	1490.00	260.00	.08	1.00	1900	830.43	16.80	D
UC/46	100.00	2.00	2.00	3.30	.33	1490.00	260.00	.08	1.00	500	210.09	10.63	D
UC/46	150.00	2.00	2.00	3.30	.27	1490.00	260.00	.08	1.00	300	114.36	8.68	D
UC/46	250.00	2.00	2.00	3.30	.21	1490.00	260.00	.08	1.00	100	53.15	6.72	D
UC/47	40.00	2.00	2.00	1.50	.24	1938.00	250.00	.08	7.90	200	549.01	7.64	F
FT/49	40.00	1.60	2.50	2.50	.63	1907.00	260.00	.08	1.30	2200	1142.05	20.13	F
FT/49	100.00	1.60	2.50	2.50	.40	1907.00	260.00	.08	1.30	600	289.12	12.73	F
FT/49	150.00	1.60	2.50	2.50	.32	1907.00	260.00	.08	1.30	300	157.38	10.39	F
FT/49	250.00	1.60	2.50	2.50	.25	1907.00	260.00	.08	1.30	100	75.14	8.05	F
FT/50	40.00	1.40	2.00	1.74	.44	1800.00	270.00	.08	2.10	1100	971.60	14.01	F
FT/50	100.00	1.40	2.00	1.74	.28	1800.00	270.00	.08	2.10	300	245.80	8.86	F
FT/50	150.00	1.40	2.00	1.74	.22	1800.00	270.00	.08	2.10	200	135.80	7.23	F

Table 4.7-2 Summary of Surface Pattern Comparison Results for Thorney Island Trials

Configuration	Date	Trial Configuration/No.	Scale Ratio	(Density Ratio)F	(Density Ratio)M	Points Compared	Intercept of Theta, Degrees f-1	f-2	f-5
Thorney Island									
Field ( )									
Model	(1985)	UI/08	100	1.7	1.7	6	10	7.5	
		UI/08	150	1.7	1.7	7	27.5	7.5	
		UI/12	100	2.3	2.3	9	25	15	
		UI/12	150	2.3	2.3	8	15	12.5	
		UI/17	40	4.2	4.2	7	50	30	
		UI/17	100	4.2	4.2	8	32.5	15	
		UI/17	150	4.2	4.2	8	27.5	7.5	
		UI/19	100	2.1	2.1	10	20	7.5	
		UI/19	150	2.1	2.1	10	20	10	
		5W-50/20	100	1.9	1.9	6	15	5	
		5W-50/20	150	1.9	1.9	5	10	5	
		5W-50/21	100	2	2	5	20		
		5W-50/21	150	2	2	12	22.5	12.5	
		5W-50/22	150	4.2	4.2	6	25	17.5	
		9B-50/28	100	2	2	7	15	7.5	
		9B-50/28	150	2	2	6	15	10	
		9B-27/29	100	2	2	9	20	12.5	
		9B-27/29	150	2	2	8	27.5	12.5	
		FL/30	40	1.4	1.4	6	22.5	12.5	
		FL/30	100	1.4	1.4	6	40		
		FL/30	150	1.4	1.4	4	12.5	5	
		FL/30	250	1.4	1.4	4	17.5		
		FL/33	40	1.6	2.5	6	25		
		FL/33	100	1.6	2.5	6	17.5	12.5	
		FL/33	150	1.6	2.5	6	15	10	
		FL/33	250	1.6	2.5	6	25	12.5	
		UI/34	40	1.8	1.8	8	22.5		
		FL/36	40	1.6	2	9	30	7.5	
		FL/36	100	1.6	2	11	15	7.5	
		FL/36	150	1.6	2	10	30		
		FL/37	40	1.6	1.6	4	7.5	7.5	
		FL/37	100	1.6	1.6	4	22.5	0	
		FL/37	150	1.6	1.6	4	17.5	2.5	
		FL/37	250	1.6	1.6	4	15	0	
		UC/38	40	1.6	1.6	7	20	7.5	
		UC/38	100	1.6	1.6	8	25	10	
		UC/38	150	1.6	1.6	11	30	22.5	
		UC/38	250	1.6	1.6	10	27.5	15	
		FL/39	40	1.4	1.4	6	22.5	7.5	
		FL/39	100	1.4	1.4	6	20	10	
		FL/39	150	1.4	1.4	6	22.5	10	
		FL/39	250	1.4	1.4	6	17.5	5	
		FL/40	40	1.2	1.2	5	7.5	7.5	
		FL/40	100	1.2	1.2	7	15	0	
		FL/40	150	1.2	1.2	7	7.5	2.5	
		FL/40	250	1.2	1.2	6	10	10	
		FL/42	40	1.6	1.6	5	5	0	
		FL/42	100	1.6	1.6	5	7.5	0	
		FL/42	150	1.6	1.6	5	15	15	
		FL/42	250	1.6	1.6	5	12.5	7.5	
		FL/43	40	1.3	2	8		5	5
		FL/43	100	1.3	2	12		20	7.5
		FL/43	150	1.3	2	12		20	10
		UC/45	40	2	2	7	15	12.5	
		UC/45	100	2	2	14	22.5	15	10
		UC/46	40	2	2	5	22.5	5	
		UC/46	100	2	2	6	10	10	
		UC/46	150	2	2	6	17.5	10	
		UC/46	250	2	2	6	27.5	10	
		UC/47	40	2	2	15		15	2.5
		FT/49	40	1.6	2.5	14	20	2.5	2.5
		FT/49	100	1.6	2.5	14	27.5	10	
		FT/49	150	1.6	2.5	14	25	10	
		FT/49	250	1.6	2.5	15	27.5	10	
		FT/50	40	1.4	2	32.5	30	15	
		FT/50	100	1.4	2	17	32.5	20	
		FT/50	150	1.4	2	18	35	10	

UI = Unobstructed instantaneous release
5W-50 = 5m wall at 50m
9B-50 = 9m square bldg, 50m at 45 degree down range
9B-27 = 9m square bldg, 27m at 30 degree up range
FL = Fence longitudinal
UC = Unobstructed continuous release
FT = Fence traverse

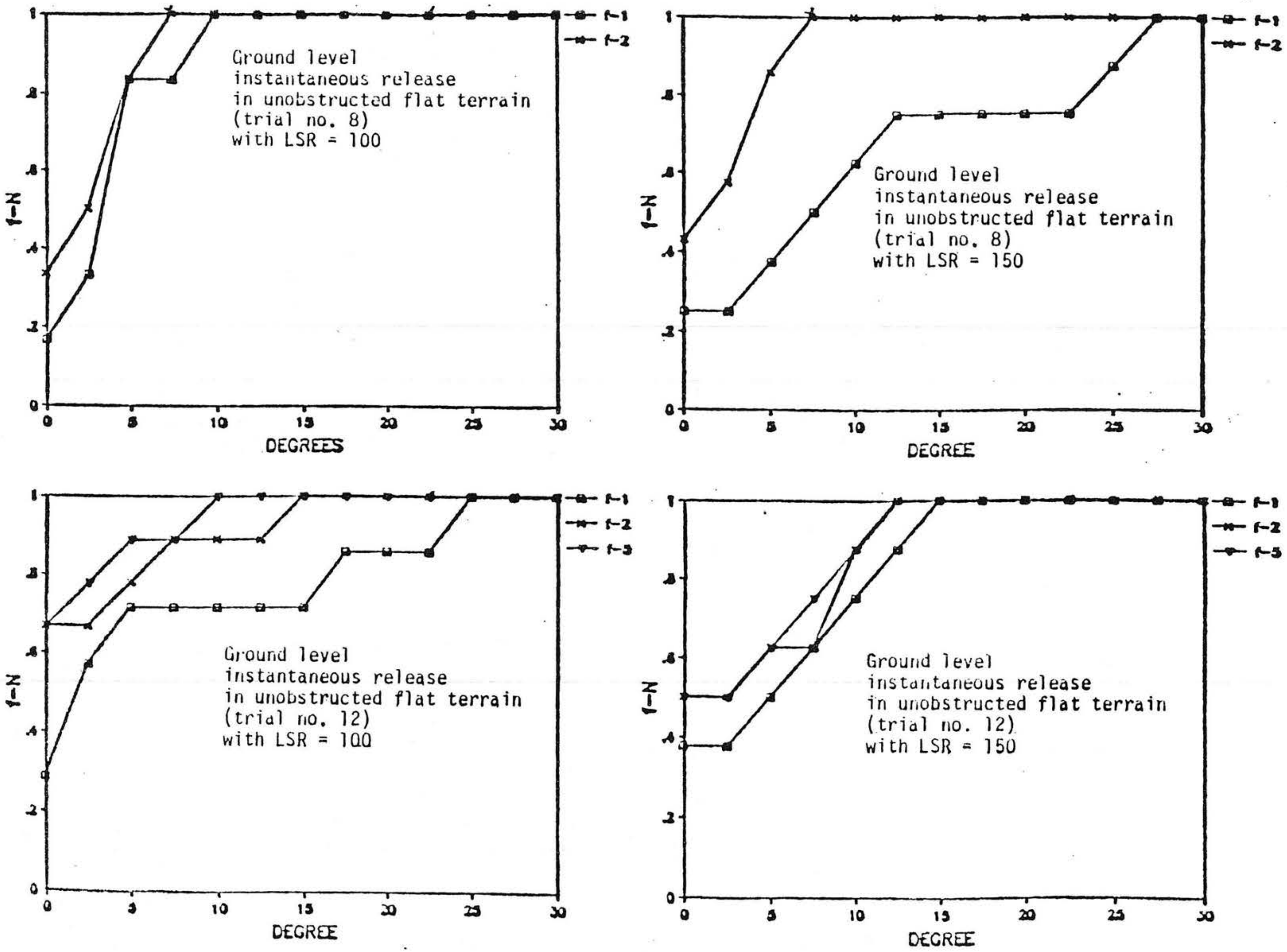


Fig. 4.7-1 Surface Pattern Comparison Results, f-N vs. Angular Displacement

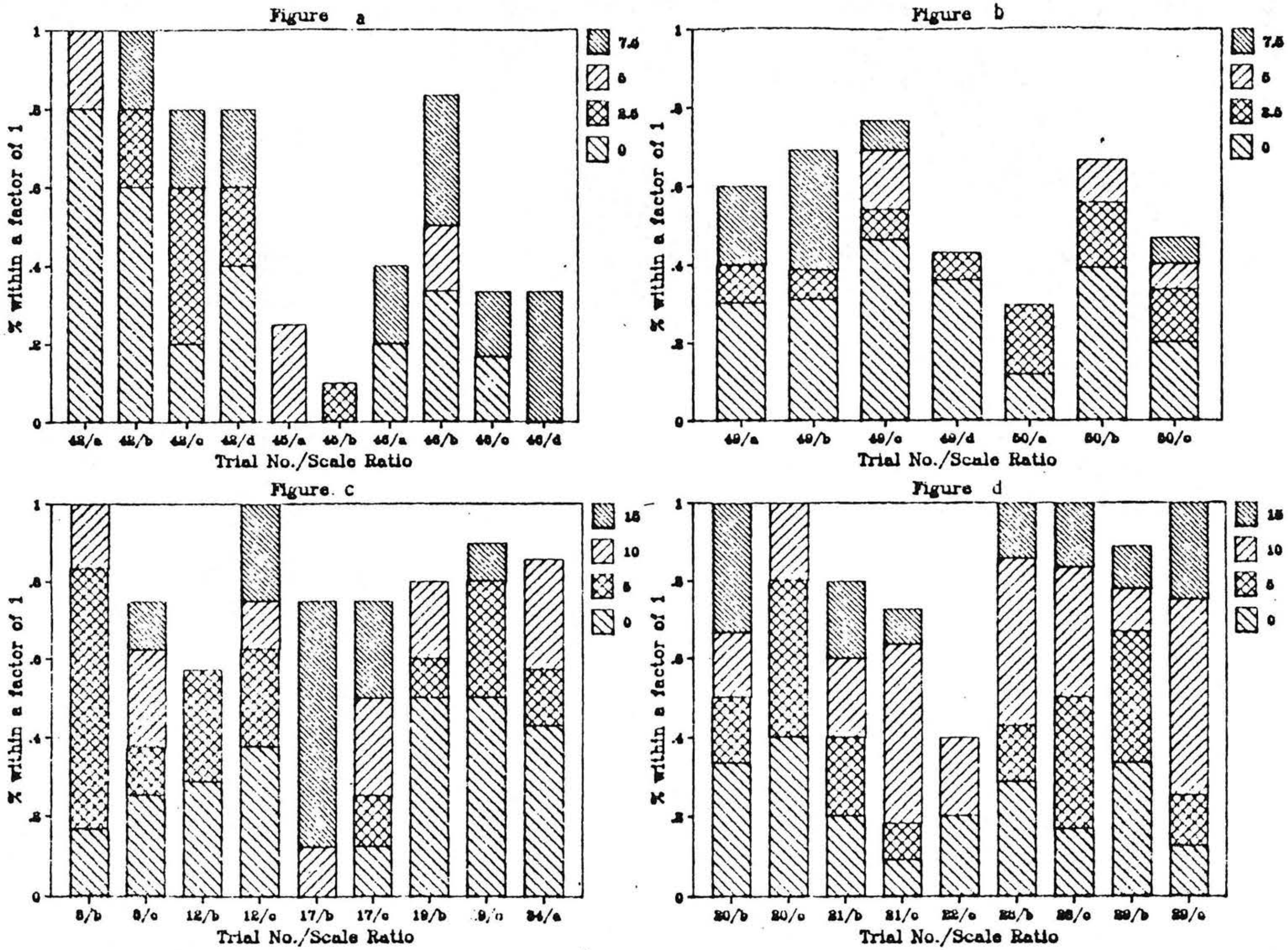


Fig. 4.7-2 Surface Pattern Comparison Results, Bar Charts of f-N vs. Angular Displacement

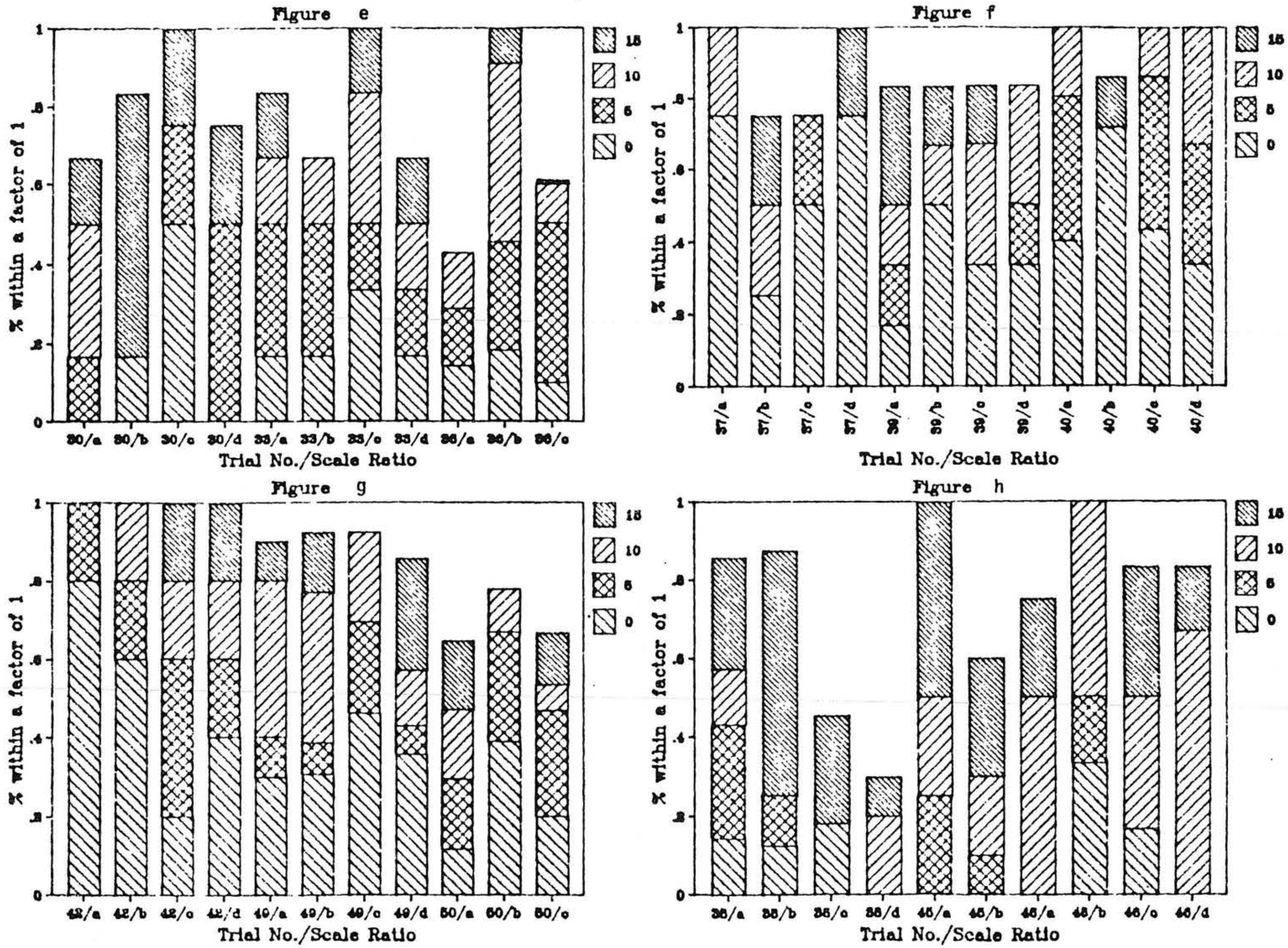


Fig. 4.7-3 Surface Pattern Comparison Results, Bar Charts of f-N vs. Angular Displacement

4.8 "LNG Vapor Barrier and Obstacle Evaluation: Wind-tunnel Prefield Test Results," Neff and Meroney, 1986

Experiment Configuration:

The experiments described by Meroney and Neff (1986) were performed to provide planning information to design the instrumentation grid used during the Falcon LNG Spill tests. The Falcon test series were performed by Lawrence Livermore National Laboratory during the summer of 1987 at the DOE Liquefied Gaseous Fuels Test Facility at Frenchman's Flats, Nevada. The pre-field laboratory tests were run at a model scale of 1:100 for a range of spill rates (10, 20, and 40 cubic meters/min of LNG), total spill volumes (50, 70 and 100 cubic meters of LNG), wind speeds (2, 3.5, and 5 m/sec), and four spill arrangements (no enclosure, 9.4 m fence only, and 9.4 or 14.1 m vortex generator added). A total of 17 tests were completed using a rake of aspirated hot-wire katherometer probes to obtain multiple replications of concentration times series at each measurement location.

The measurement grid included cross-wind sections at 15, 75, 200 and 400 m downwind with vertical profiles from ground level to a height of 28 m. Only a wind direction along the long axis of the enclosure was considered. The fence enclosure geometry and measurement grid are shown in Figures 4.8-1 and 4.8-2.

Results of Comparison:

Figure 4.8-3 considers the centerline variation of the peak concentration ratios for the fence enclosure alone and the two vortex generator additions. Notice that the peak ratio drops to a minimum value at 75 m, but thereafter all cases behave in a similar fashion and increase slowly with downstream distance. Apparently an upwind vortex generator acts to dilute gases before they pass over the downwind fence; hence, the tests with vortex generator installed produced minimum peak concentration ratios at 15 m rather than 75 m.

Figures 4.8-4 to 4.8-6 present arrival time, peak arrival time, and departure time ratios for the same conditions displayed on Figure 4.8-3. Cloud advection times are from 1.5 to 4 times larger than the no enclosure case in the immediate wake of the enclosure;however, by the time the cloud reaches 300 to 400 meters downwind, time ratios are reduced to one or less. This behavior is consistent with that observed for data from the Thorney Island tests discussed in Chapter 4.6.

Given a fence enclosure with a 14.1 m vortex generator upwind of the spill area and an LNG spill rate of 40 cubic meters/min then Figure 4.8-7 presents the influence of increase in total spill volume on peak concentration. Doubling the total spill volume appears to double ground level peak concentrations. Yet an increase in spill volume has less systematic effect on peak arrival time in Figure 4.8-8.

Similarly, Figure 4.8-9 shows that increasing spill rate while holding spill volume constant may increase peak concentrations, but the perturbations are much smaller. Increased spill rate produces only minor variations in peak concentration arrival time on Figure 4.8-10.

Figures 4.8-11 to 4.8-14 display vertical profiles of concentration, arrival, peak arrival, and departure times for a section 15 m downstream of the downwind enclosure fence. The fence clearly mixes the cloud to greater heights, and a peak in the concentration profile occurs just above fence height (13 m). The fence also delays the arrival and departure of the cloud in the wake region, but the cloud appears first near fence height.

By the time the cloud reaches 75 m downstream of the fence, the concentrations and arrival, peak arrival, and departure times are essentially constant with height as noted on Figures 4.8-15 to 4.8-18. Measurements at stations farther downstream look similar to the 75 m data sets, except that concentrations are less and times are larger.

Figures 4.8-19 to 4.8-22 and 4.8-23 to 4.8-26 display crosswind profiles of ground level concentrations and cloud times at distance of 15 and 75 m downstream of the fence, respectively. Lateral profiles for the no-enclosure release condition extend to significantly greater lateral distances than the enclosure conditions. Visual observations of the model and field enclosure spills revealed strong three dimensionality in the cloud. Longitudinal vortices generated at enclosure corners appeared to draw the cloud over the fence first at the corners. Nonetheless, concentration and cloud time data show a strong two-dimensionality in the cloud wake.

<u>Multilinear Regression by ANOVA of Pre-Falcon Wind Tunnel Data:</u>

Since the pre-Falcon data set were the most complete, reliable, and comprehensive available, the SAS-PC statistical package was used to estimate coefficients in a multilinear regression on the data. The ANOVA procedure was applied to the logarithmic form of simple power law formula, i.e.:

$$(1 - C_w/C_{wo}) = (A * Fr^a * \underline{V}^b * (Vol/L_c^3)^c * (H/L_c)^d * (x/L_c)^e),$$

$$(Ta_w/Ta_{wo} - 1) = (\quad " \quad),$$

$$(Tpa_w/Tpa_{wo} - 1) = (\quad " \quad), \text{ and}$$

$$(Tda_w/Tda_{wo} - 1) = (\quad " \quad),$$

where subscripts w and wo indicate measurements with and without the enclosure present. The coefficients A, a, b, c, d, and e were determined by the ANOVA procedure. Both Forward, Backward, and Maximizing versions of the multilinear regression procedures were employed. The regression was applied to data from Runs 1, 3, 4, 7, 8, 9, 13, 10, 16, and 17 from the Neff and Meroney data set. Data were always normalized by a no-enclosure reference value taken under the same spill rate and wind speed conditions.

The regression procedure revealed that inclusion of the Froude number term did not reduce the variance of the prediction equation significantly. This probably occurs because all data points are normalized by data with the same Froude number magnitude. The dominant terms were found to be volume spill rate and total volume spilled. The optimum expressions were determined to be:

$$(1 - C_w/Cwo) = (1.56\underline{V}^{0.051}*(Vol/L_c^3)^{-0.163}*(H/L_c)^{0.040}*(x/L_c)^{-0.035}),$$

$$(Ta_w/Ta_{wo} - 1) = (0.103*\underline{V}^{-1.035}*(Vol/L_c^3)^{0.681}*(H/L_c)^{0.212}*(x/L_c)^{-0.181}),$$

$$(Tpa_w/Tpa_{wo} - 1) = (0.027*\underline{V}^{0.438}*(Vol/L_c^3)^{1.267}*(H/L_c)^{-0.264}*(x/L_c)^{-0.275}), \text{ and}$$

$$(Tda_w/Tda_{wo} - 1) = (0.142*Fr^{-0.450}*(Vol/L_c^3)^{0.230}*(H/L_c)^{1.332}*(x/L_c)^{-0.419}).$$

These relations are the best four-variable expressions determinable by the ANOVA approach. Notice the analysis presumes all time ratio data is greater than one and all peak concentration ratio data is less than one.

Presuming a correct expression has been derived by the ANOVA procedure the peak concentration ratio formula was used to prepare Figures 4.8-27 and 4.8-28. A range of conditions were selected that might be encountered during an HF release. The first figure predicts peak concentration ratios versus downwind distance for a fixed spill rate and increasing spill volume. The second figure predicts peak concentration ratios versus downwind distance for a fixed spill volume and increasing spill rate. The second figure does not seem physically realistic, since, intuitively, a fence should be very efficient at low spill rates. Examination of the original data set reveals that the variations with spill rate are themselves irregular; hence, the unusual behavior in the final regression expression.

<u>Conclusions:</u>

Since each measurement was repeated several times during the pre-Falcon experiment, it is possible to focus on trends that occur with confidence. A fence enclosure around a transient dense gas spill will reduce downwind concentrations, reduce the lateral extent of the cloud near the source, and delay the arrival, peak arrival and departure of the cloud at downwind measurement stations. An increase in total spill volume released or spill rate is expected to increase peak concentrations. Vertical profiles along the plume centerline reveal a maximum in plume concentrations very near the fence, but further downwind the cloud is well mixed in the vertical.

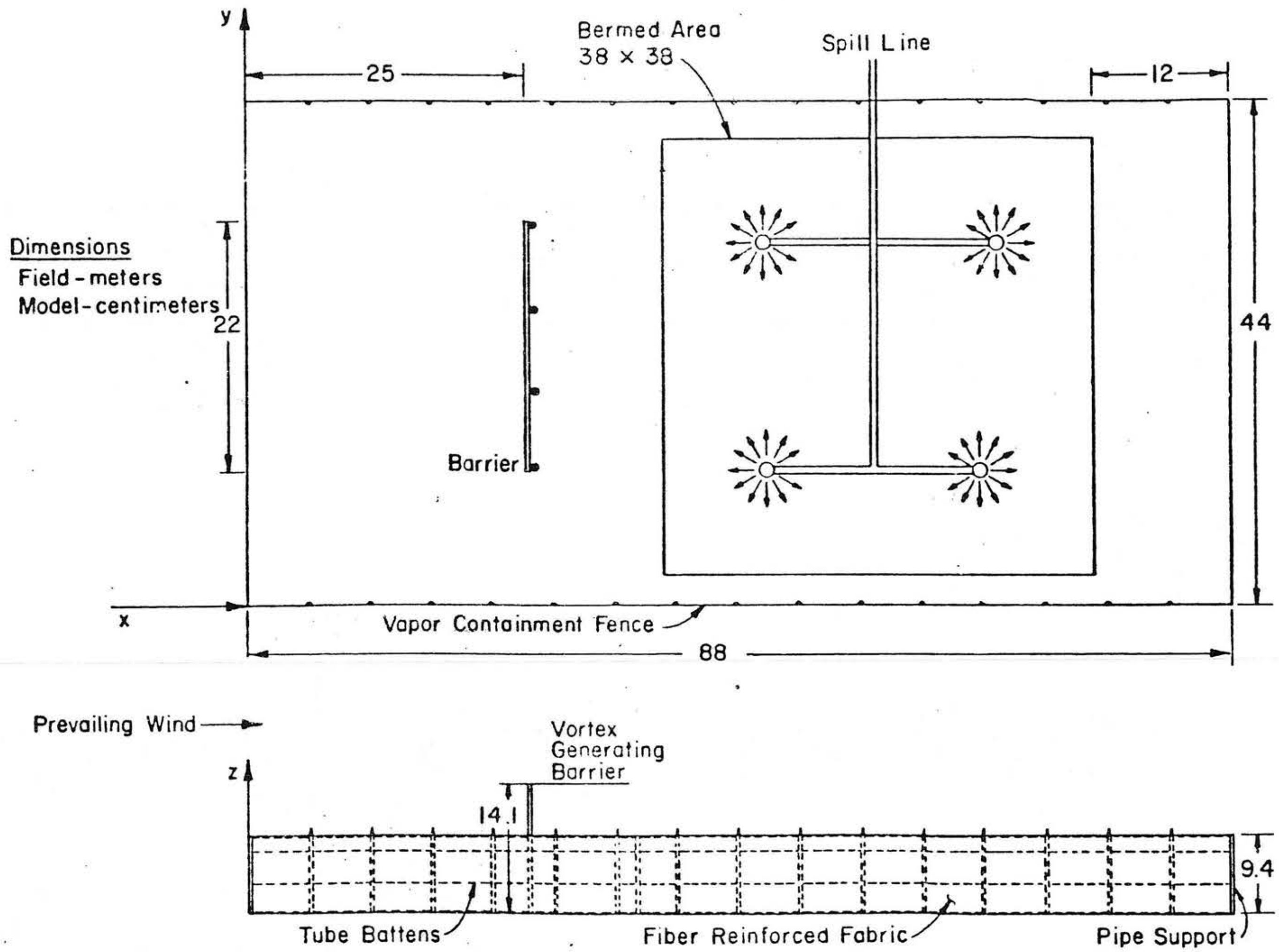


Figure 4.8-1 Fence Enclosure Geometry, Pre-Falcon Wind-tunnel Tests

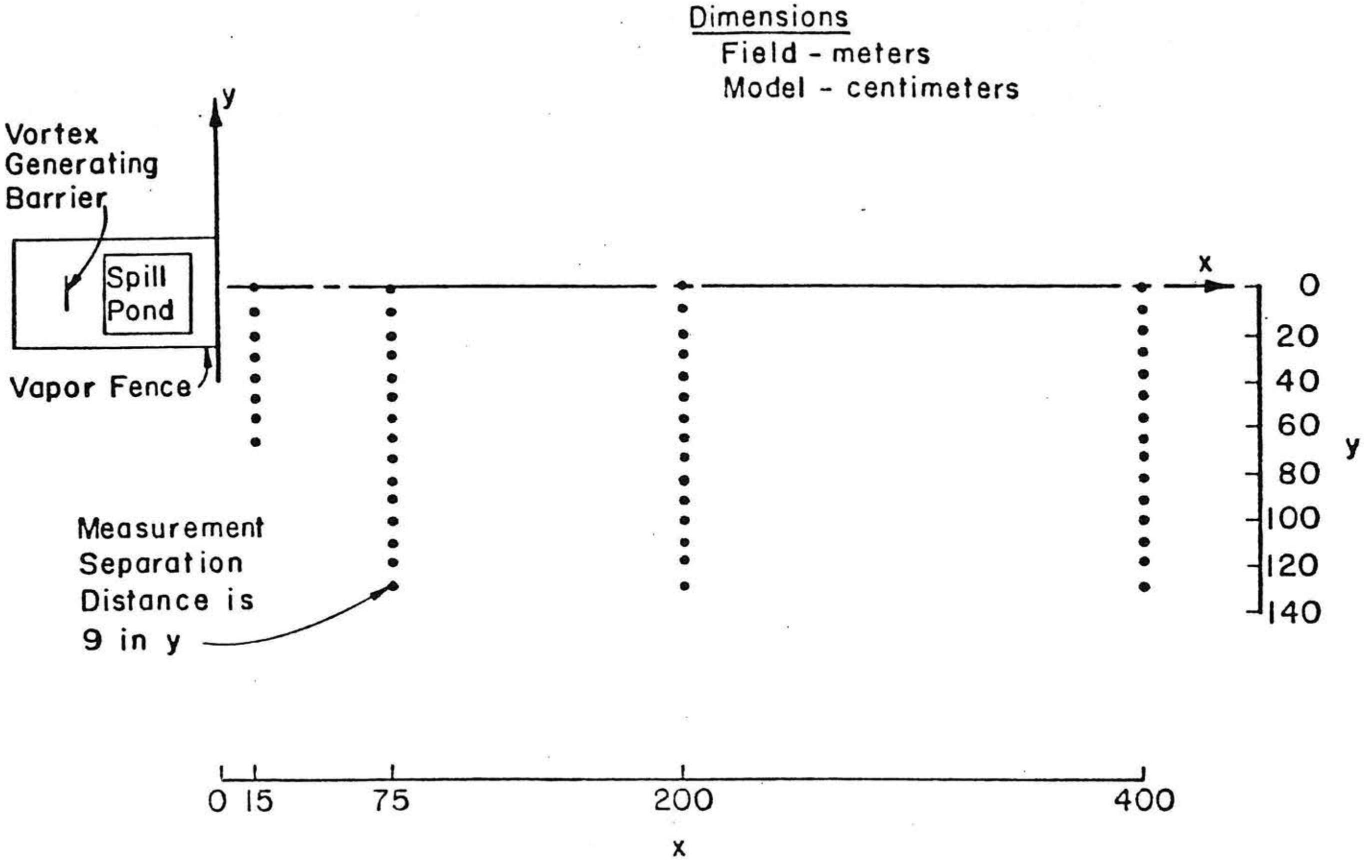


Figure 4.8-2 Measurement Grid, Pre-Falcon Wind-tunnel Tests

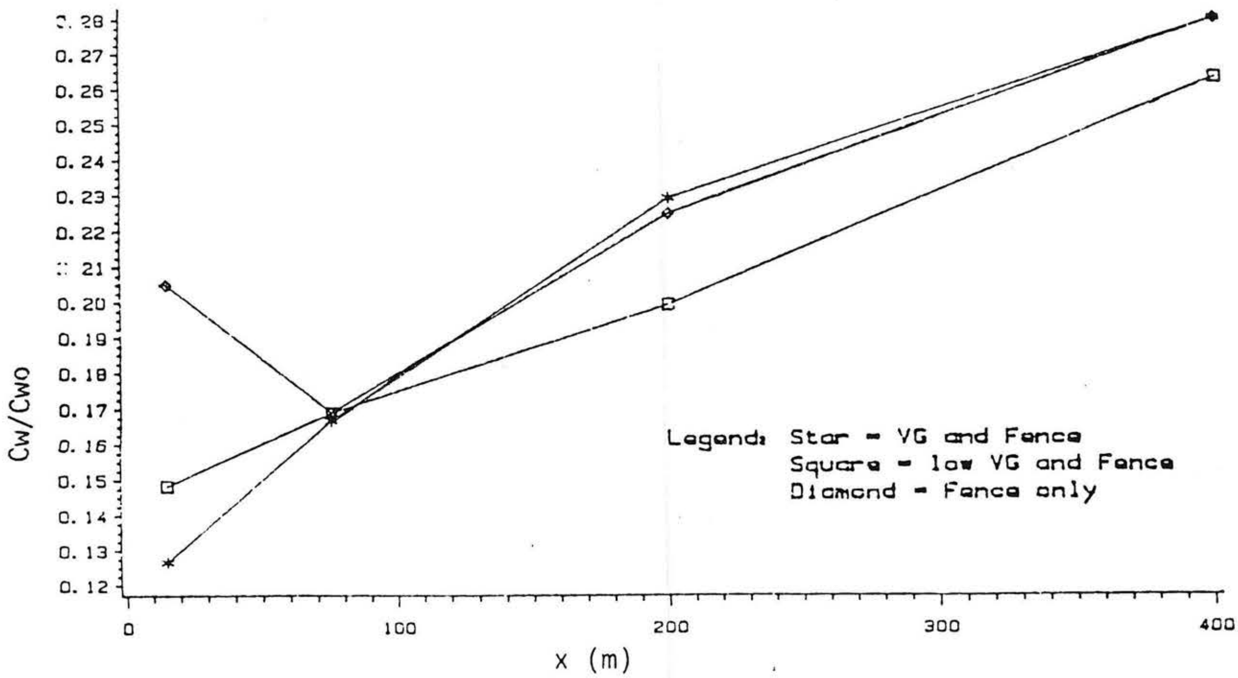


Figure 4.8-3 Peak Concentration Ratio vs. Downwind Distance, $V = 100\ m^3$, $Q = 40\ m^3/min$ LNG, Various Enclosure Arrangements

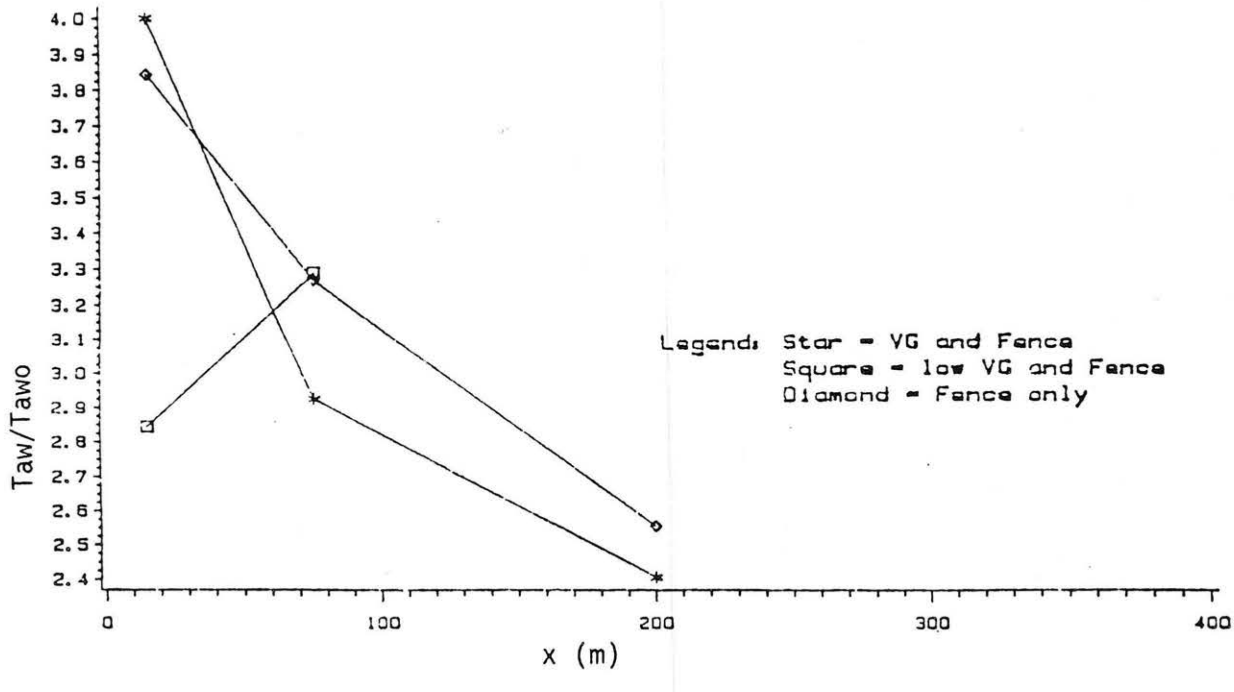


Figure 4.8-4 Arrival Time Ratio vs. Downwind Distance, $V = 100\ m^3$, $Q = 40\ m^3/min$ LNG, Various Enclosure Arrangements

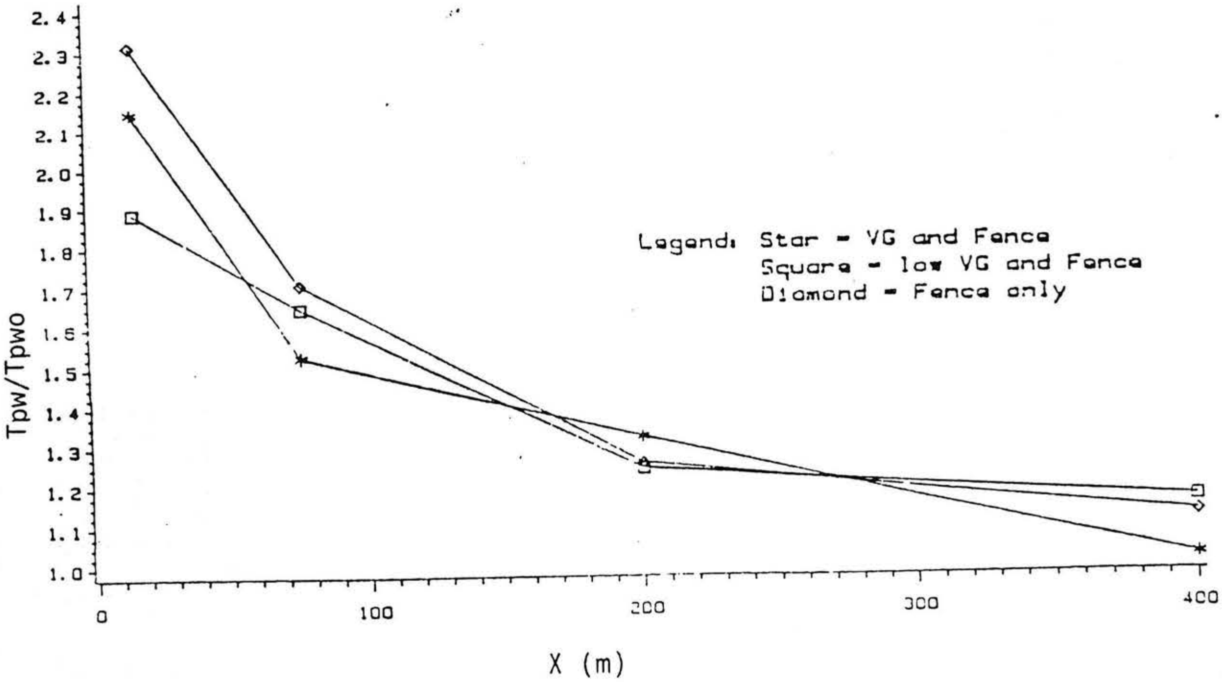


Figure 4.8-5 Peak Arrival Time Ratio vs. Downwind Distance, $V = 100\ m^3$, $Q = 40\ m^3/min$ LNG, Various Enclosure Arrangements

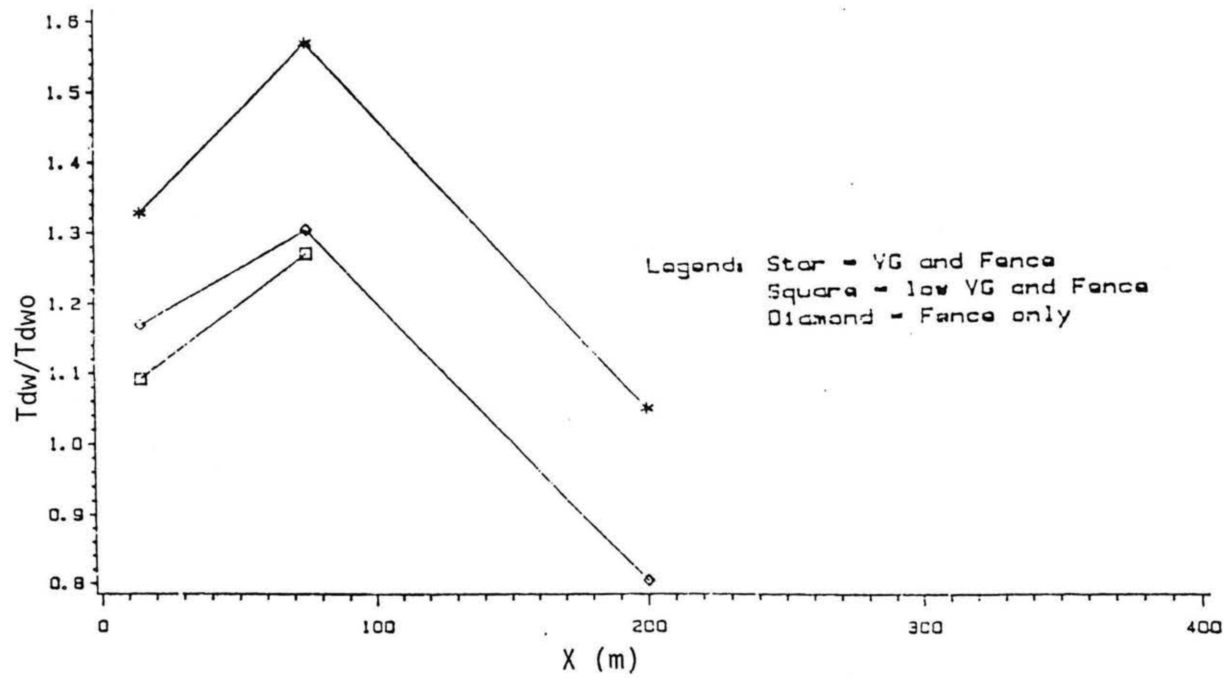


Figure 4.8-6 Departure Time Ratio vs. Downwind Distance, $V = 100\ m^3$, $Q = 40\ m^3/min$ LNG, Various Enclosure Arrangements

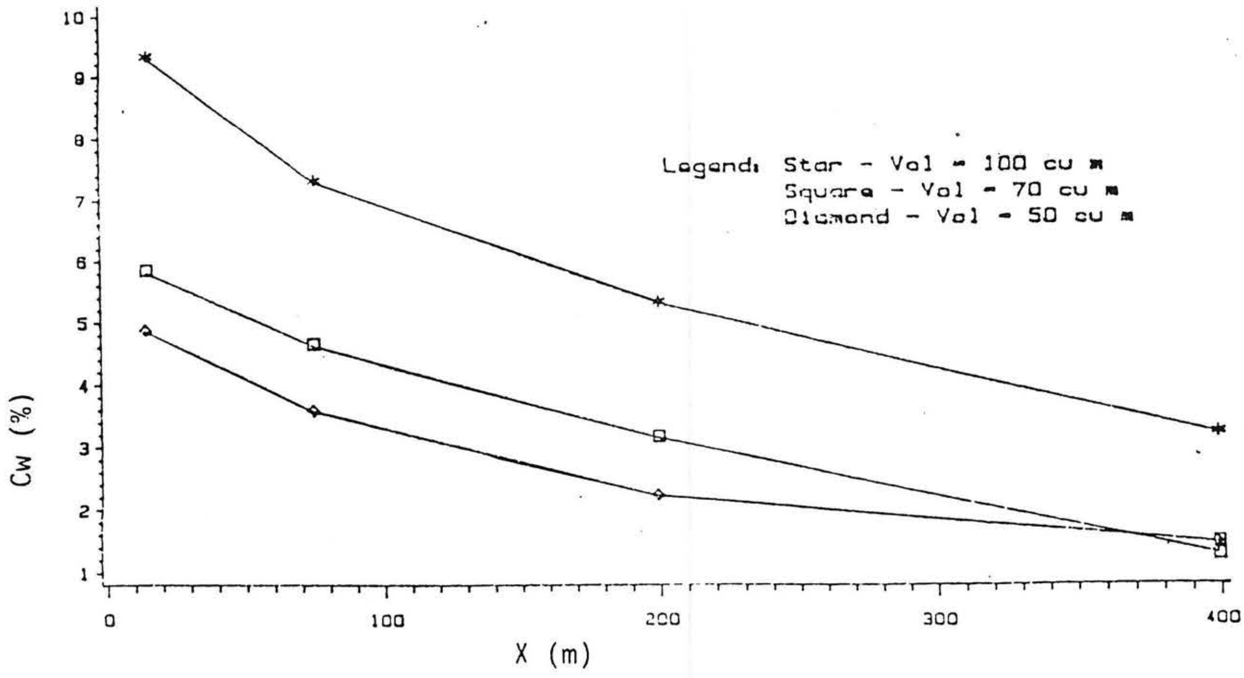


Figure 4.8-7 Peak Concentration vs. Downwind Distance, 14.1 m Vortex Generator and Fence, Q = 40 m^3/min LNG, Various Total Spill Volumes

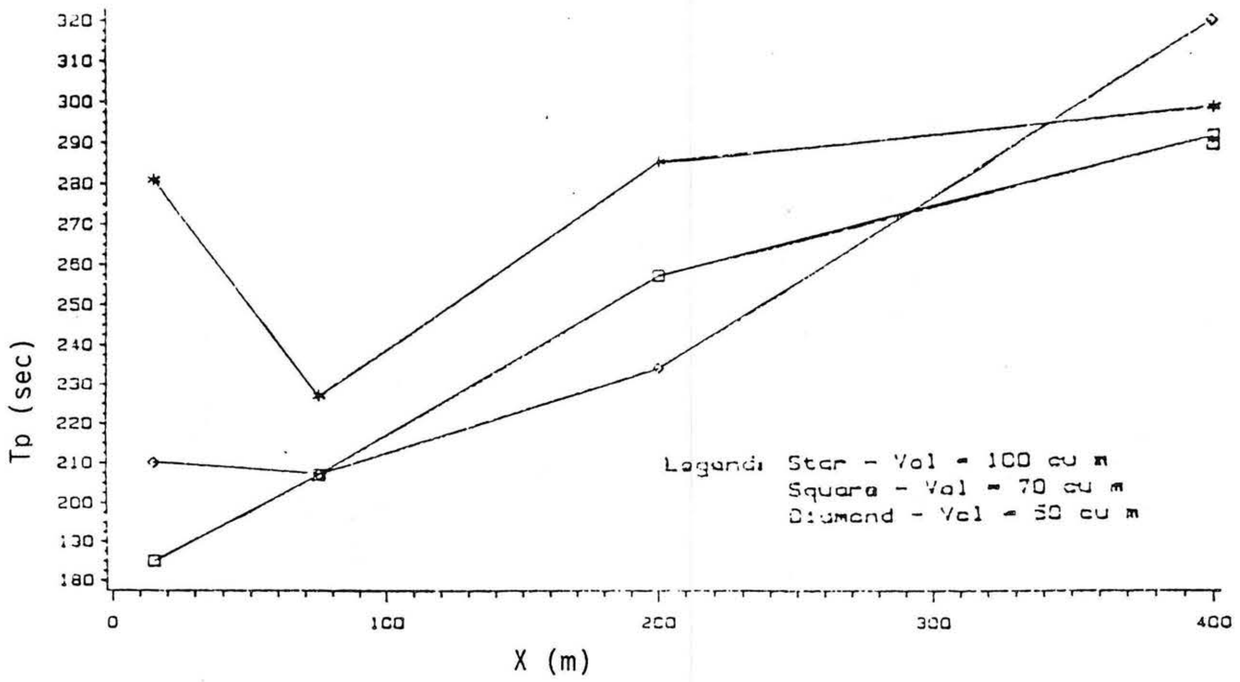


Figure 4.8-8 Arrival Time vs. Downwind Distance, 14.1 m Vortex Generator and Fence, Q = 40 m^3/min LNG, Various Total Spill Volumes

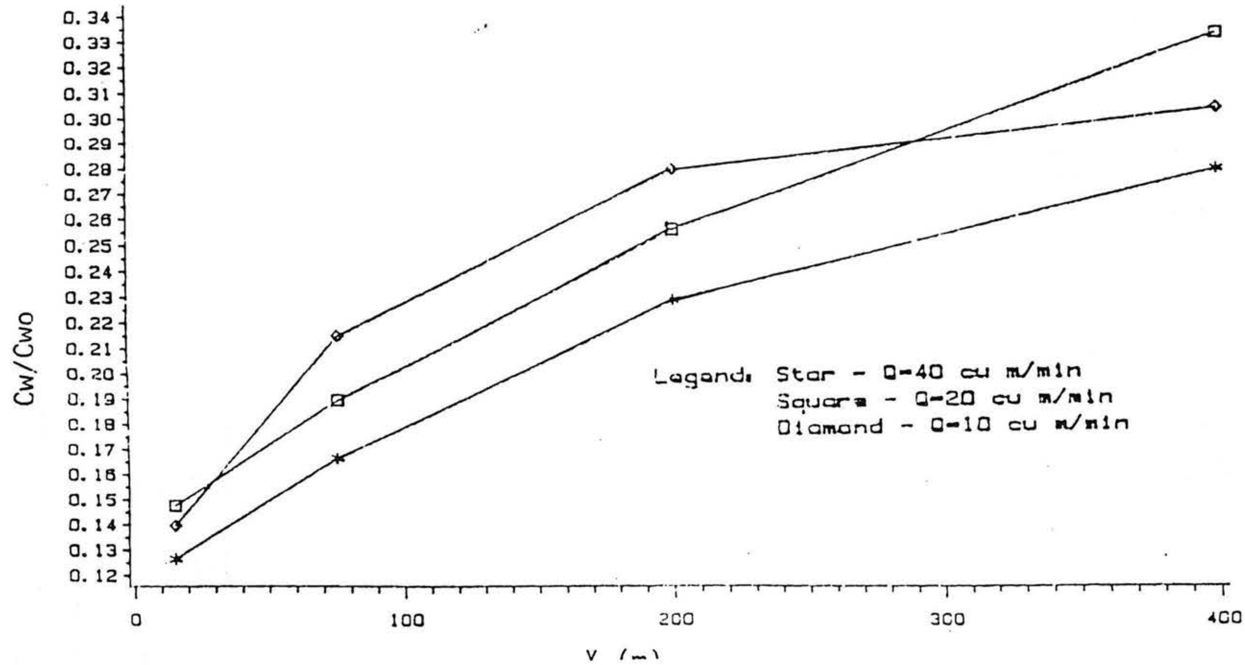


Fig. 4.8-9 Peak Concentration Ratio vs. Downwind Distance, 14.1 m Vortex Generator and Fence, V = 100 m^3 LNG, Various Spill Rates

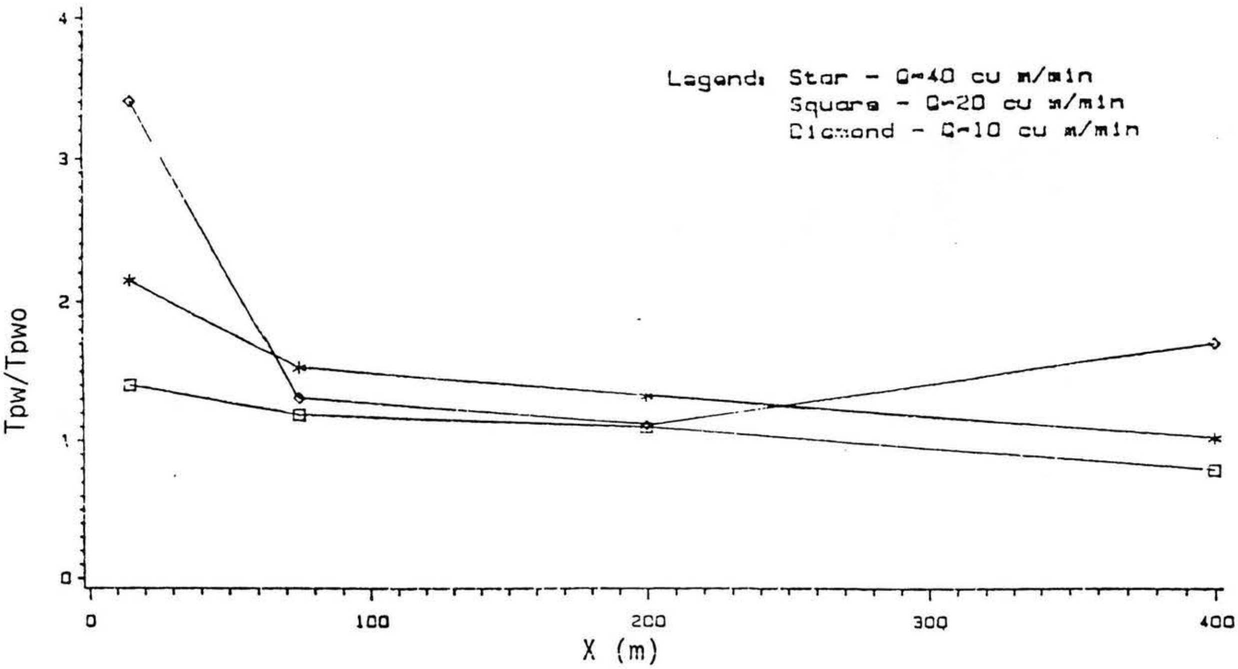


Fig. 4.8-10 Peak Time Ratio vs. Downwind Distance, 14.1 m Vortex Generator and Fence, V = 100 m^3 LNG, Various Spill Rates

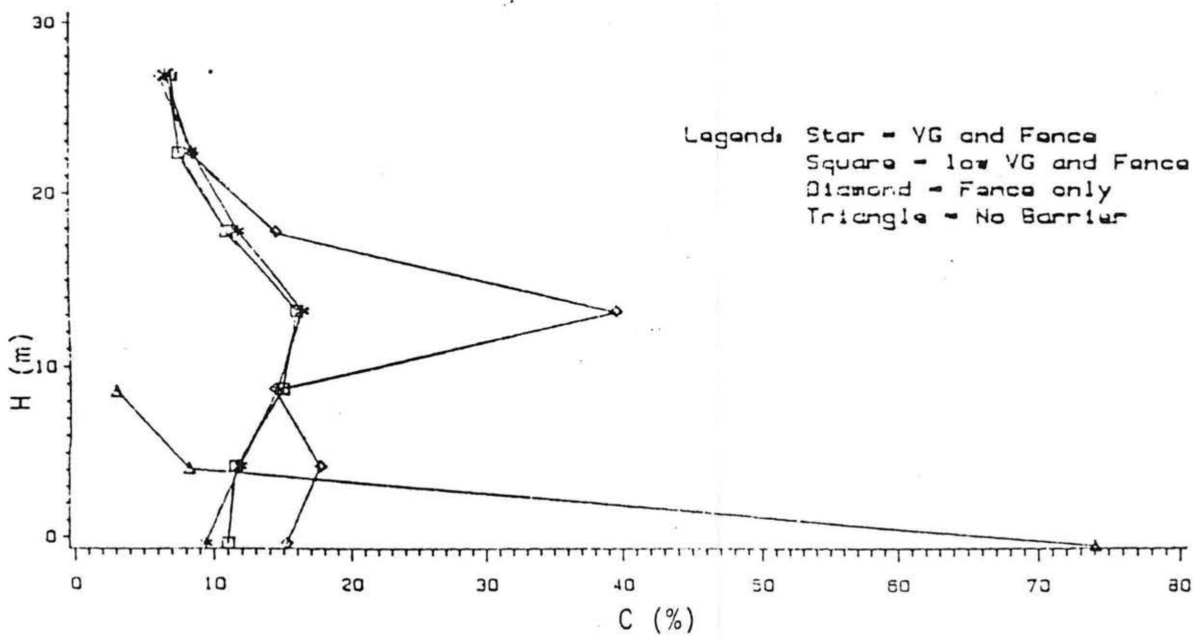


Figure 4.8-11 Peak Concentration vs. Height at X = 15 m, V = 100 m^3, Q = 40 m^3/min LNG, Various Enclosure Arrangements

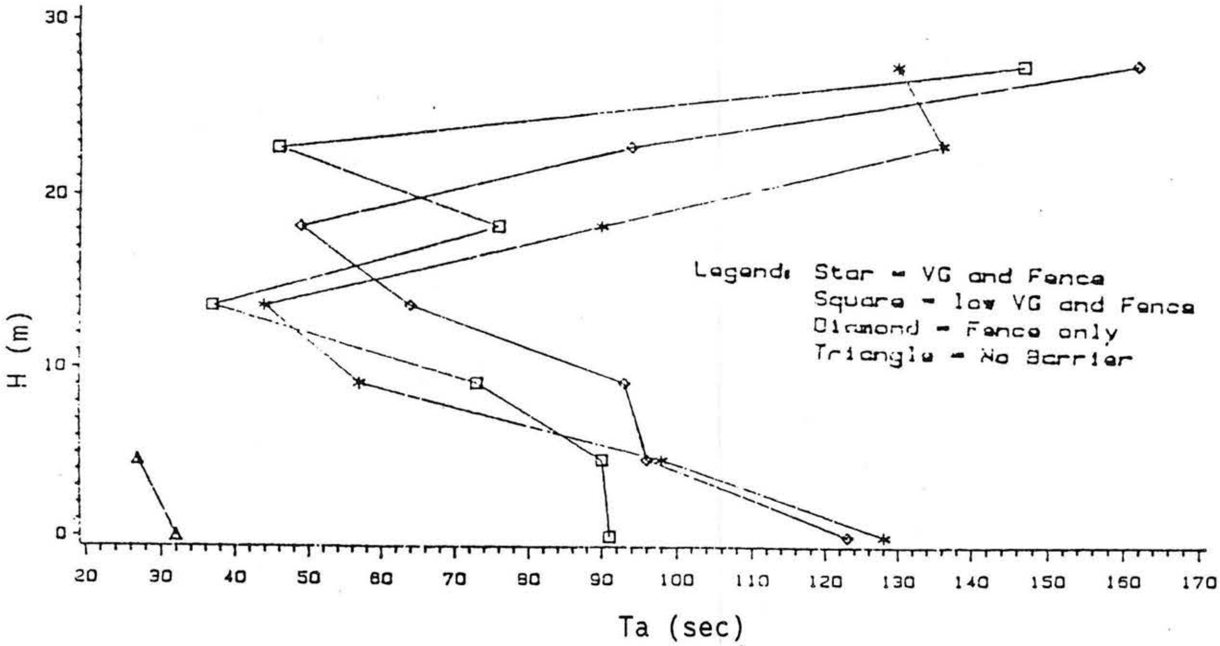


Figure 4.8-12 Arrival Time vs. Height at X = 15 m, V = 100 m^3, Q = 40 m^3/min LNG, Various Enclosure Arrangements

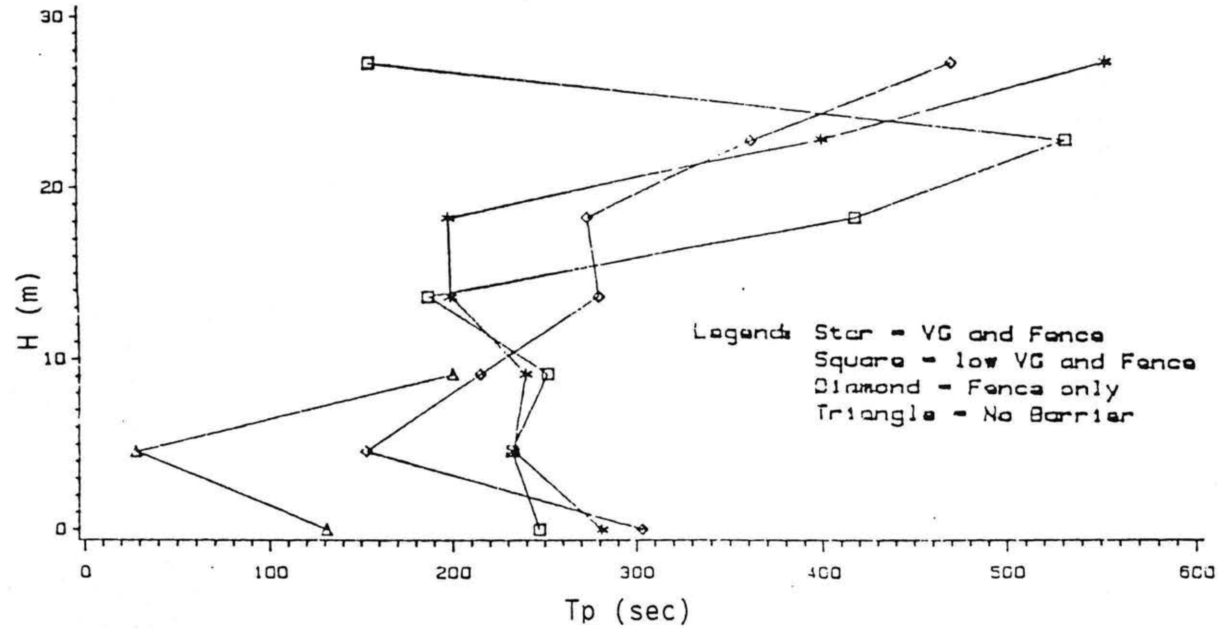


Figure 4.8-13 Peak Arrival Time vs. Height at X = 15 m, V = 100 m^3, Q = 40 m^3/min LNG, Various Enclosure Arrangements

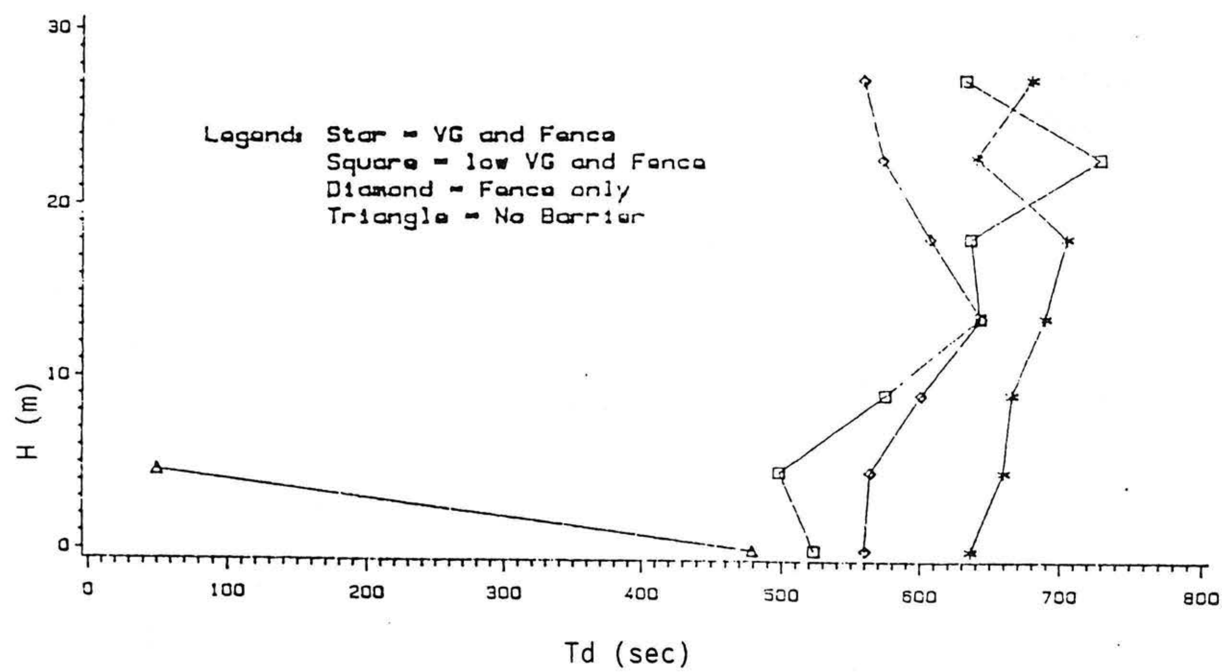


Figure 4.8-14 Departure Time vs. Height, at X = 15 m, V = 100 m^3, Q = 40 m^3/min LNG, Various Enclosure Arrangements

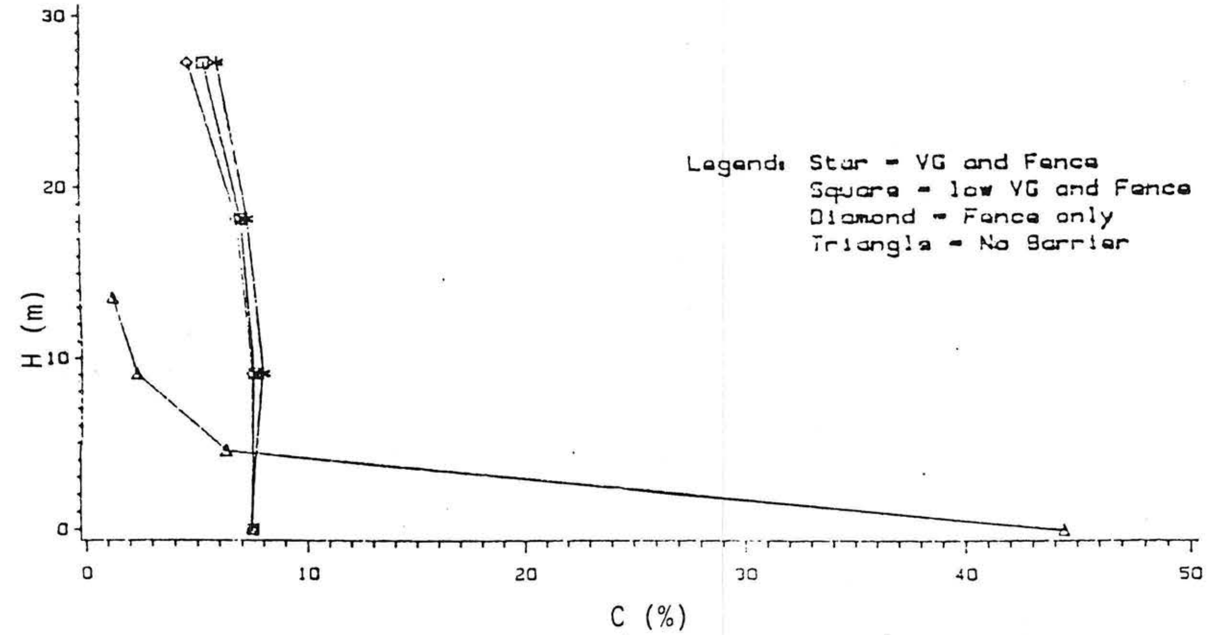


Figure 4.8-15 Peak Concentration vs. Height at X = 75 m, V = 100 m^3, Q = 40 m^3/min LNG, Various Enclosure Arrangements

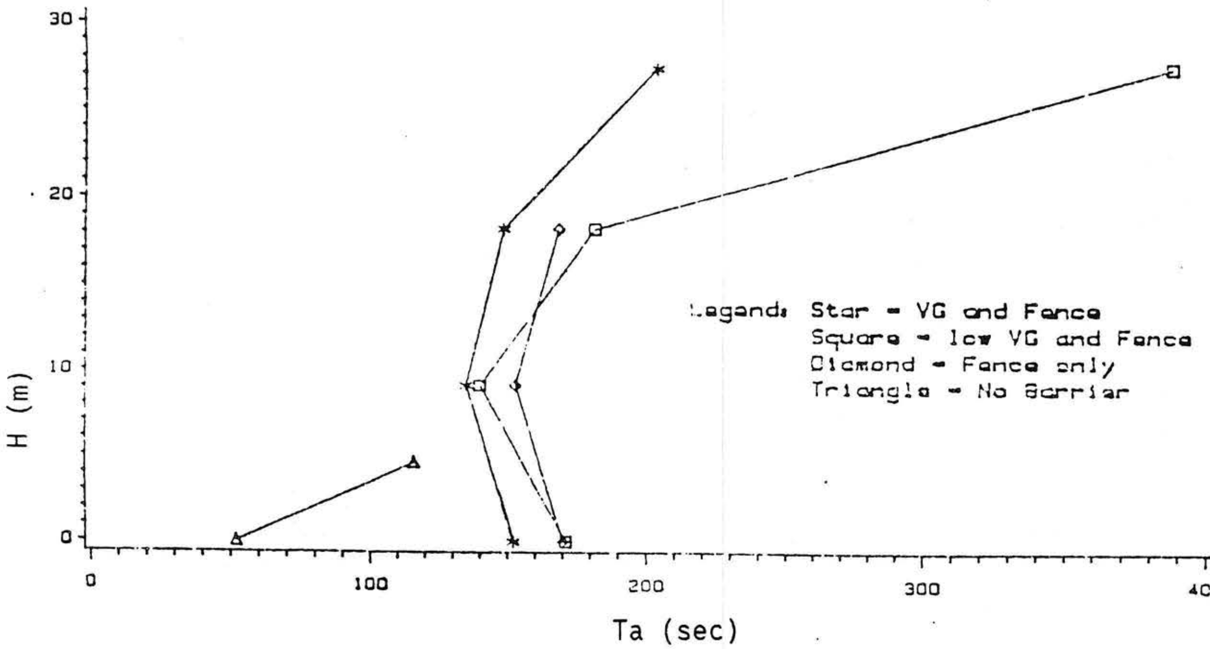


Figure 4.8-16 Arrival Time vs. Height at X = 75 m, V = 100 m^3, Q = 40 m^3/min LNG, Various Enclosure Arrangements

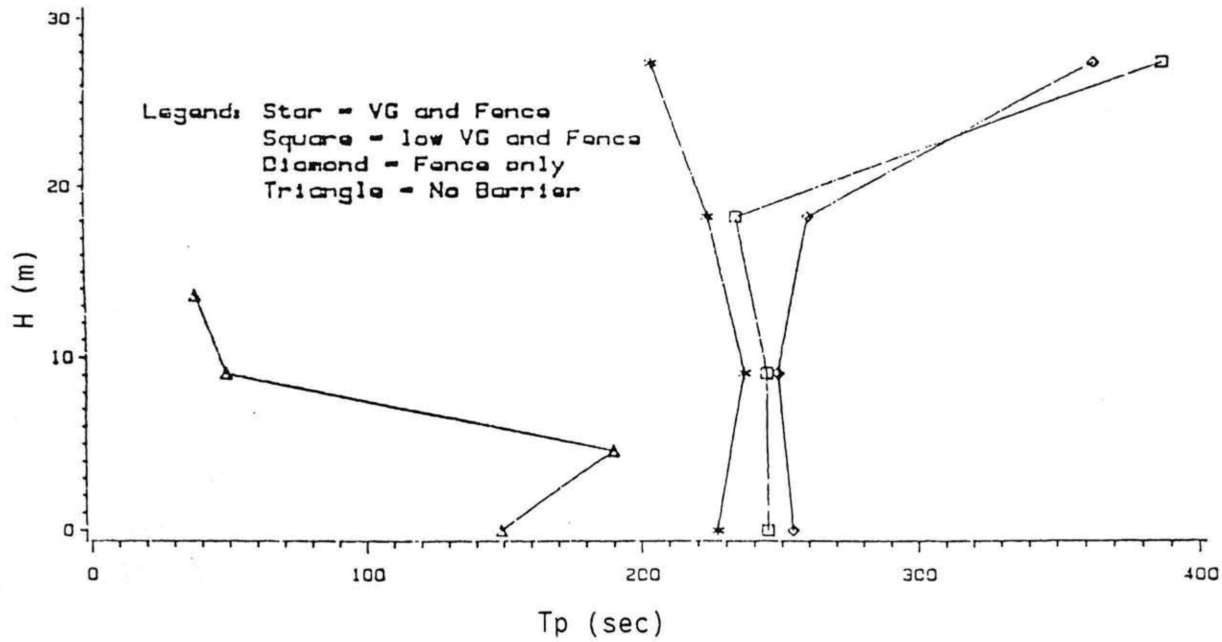


Figure 4.8-17 Peak Arrival Time vs. Height at X = 75 m, V = 100 m^3, Q = 40 m^3/min LNG, Various Enclosure Arrangements

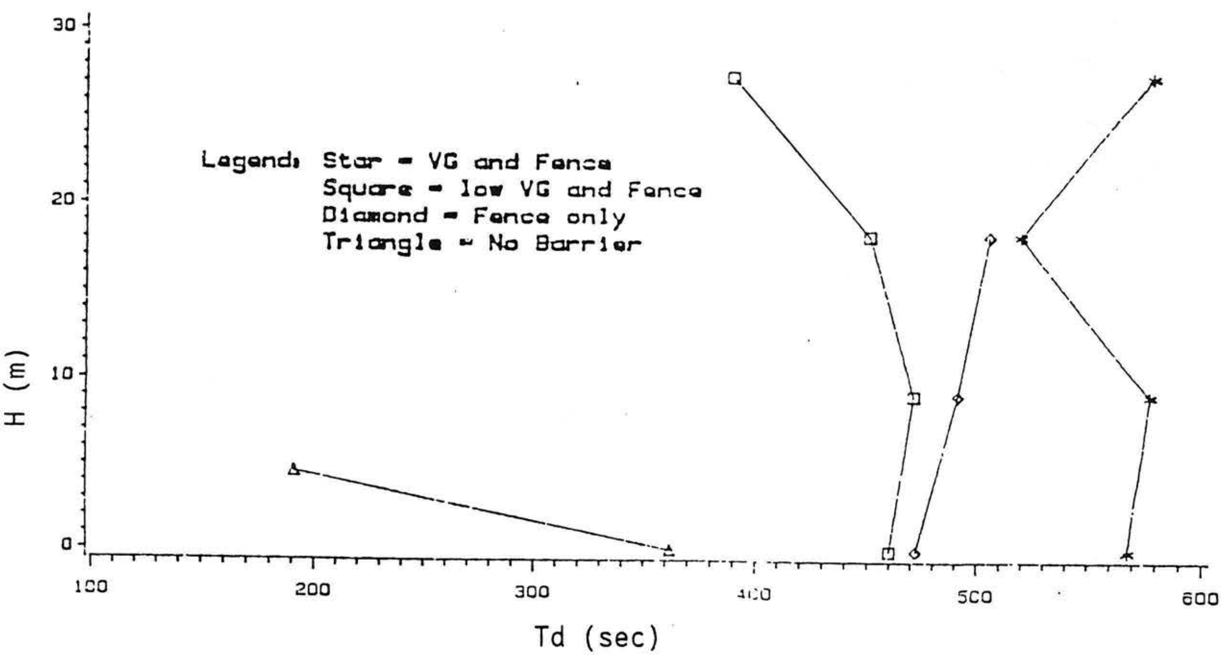


Figure 4.8-18 Departure Time vs. Height at X = 75 m, V = 100 m^3, Q = 40 m^3/min LNG, Various Enclosure Arrangements

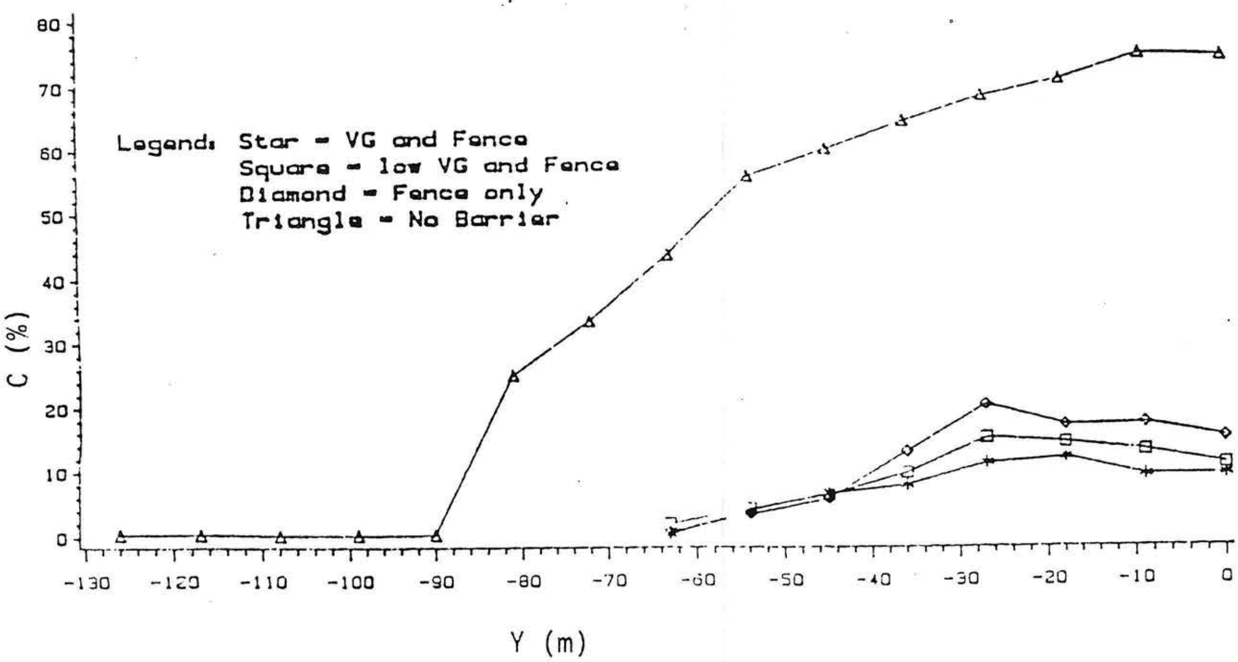


Figure 4.8-19 Peak Concentration vs Crosswind Distance at X = 15 m, V = 100 m^3, Q = 40 m^3/min LNG, Various Enclosure Arrangements

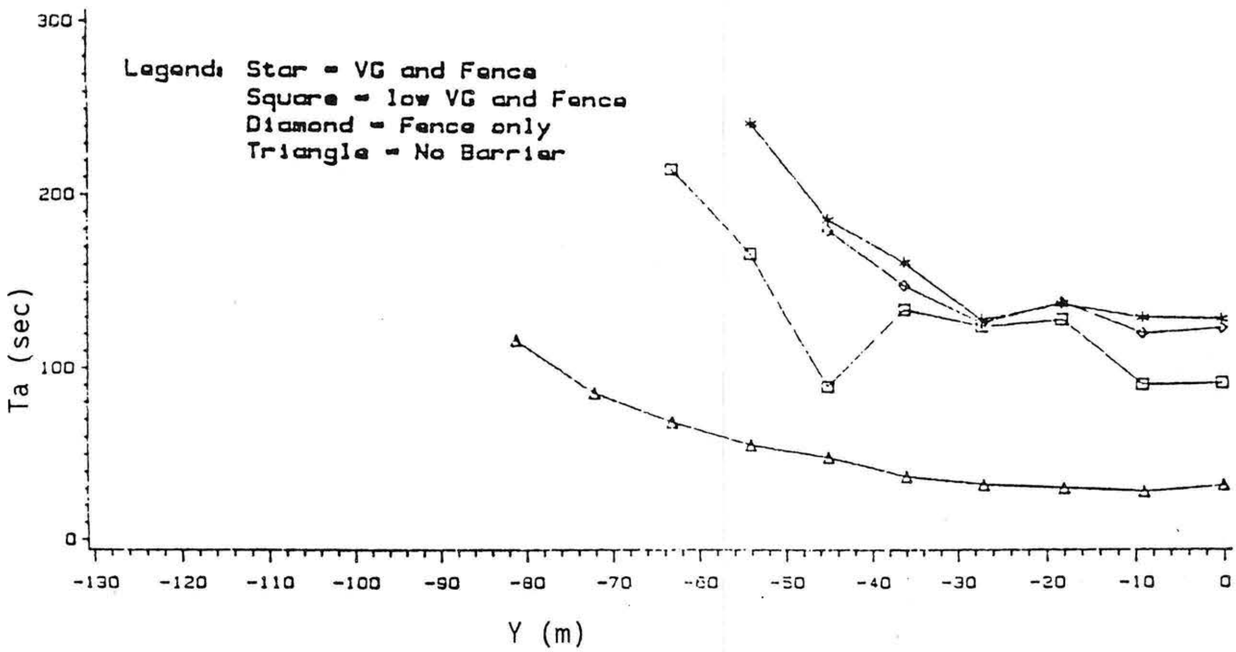


Figure 4.8-20 Arrival Time vs Crosswind Distance at X = 15 m, V = 100 m^3, Q = 40 m^3/min LNG, Various Enclosure Arrangements

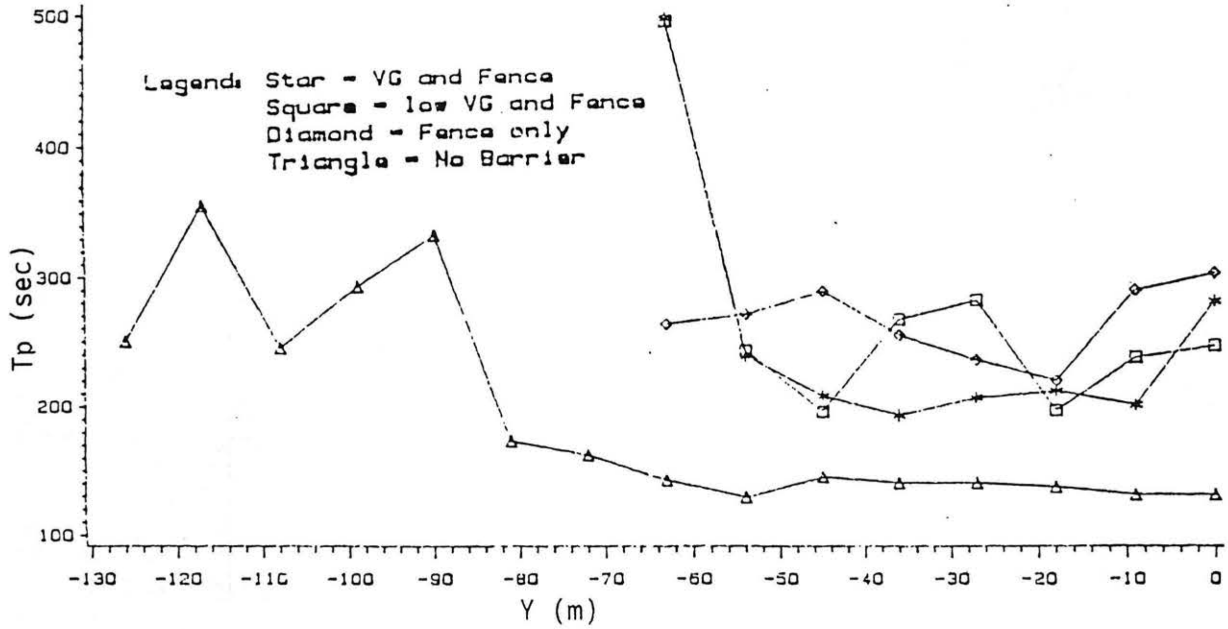


Figure 4.8-21 Peak Arrival Time vs Crosswind Distance at X = 15 m, $V = 100\ m^3$, $Q = 40\ m^3/min$ LNG, Various Enclosure Arrangements

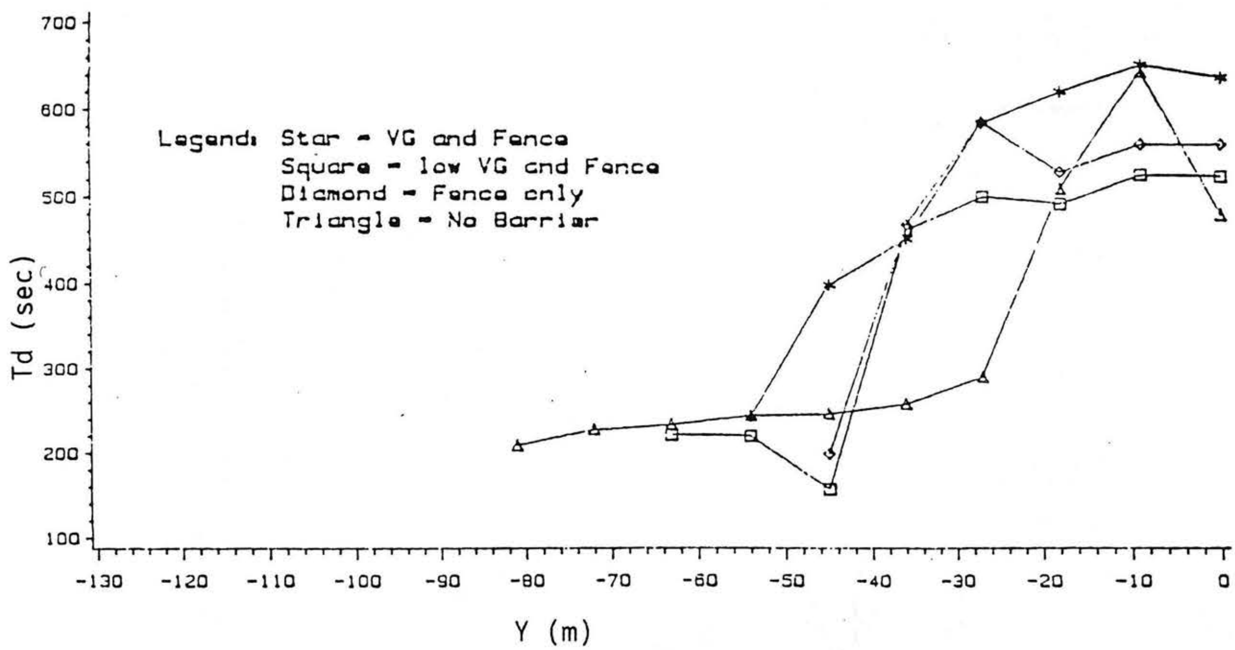


Figure 4.8-22 Departure Time vs Crosswind Distance at X = 15 m, $V = 100\ m^3$, $Q = 40\ m^3/min$ LNG, Various Enclosure Arrangements

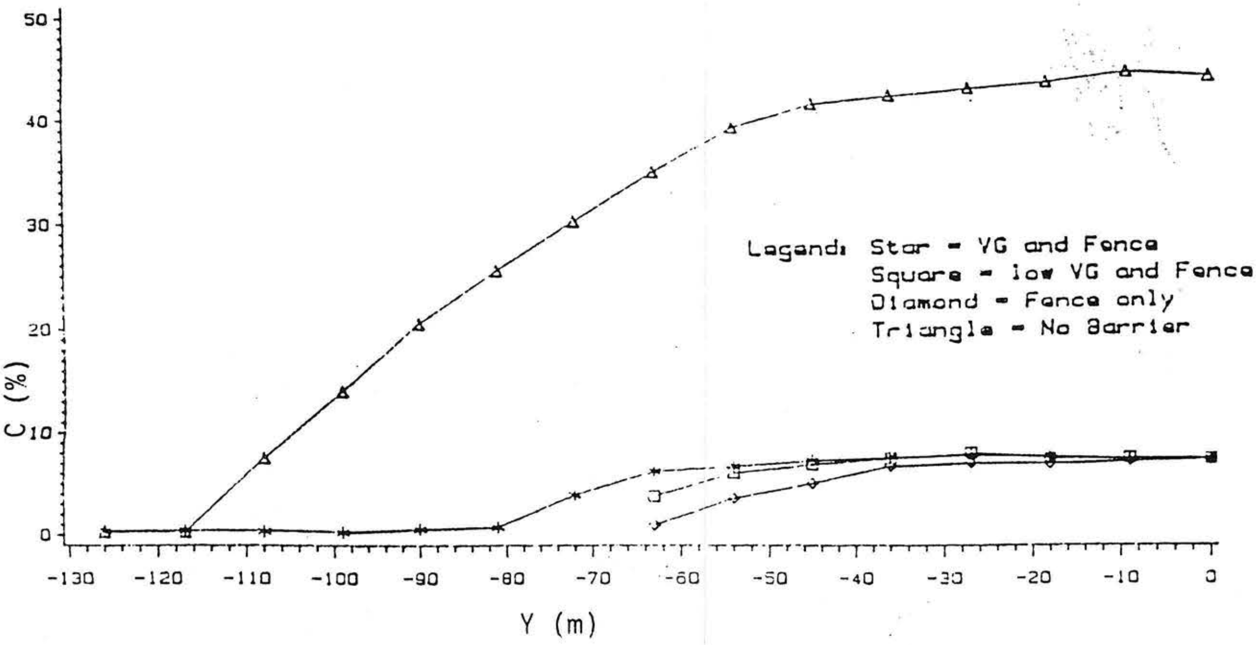


Figure 4.8-23 Peak Concentration vs Crosswind Distance at X = 75 m, $V = 100\ m^3$, $Q = 40\ m^3/min$ LNG, Various Enclosure Arrangements

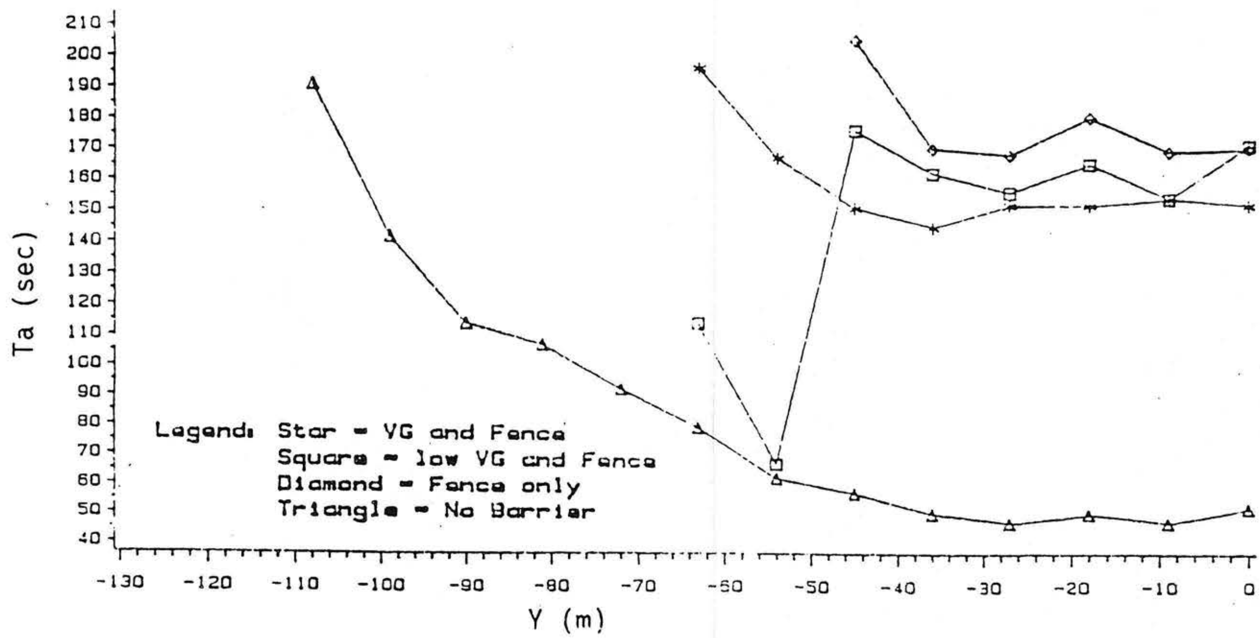


Figure 4.8-24 Arrival Time vs Crosswind Distance at X = 75 m, $V = 100\ m^3$, $Q = 40\ m^3/min$ LNG, Various Enclosure Arrangements

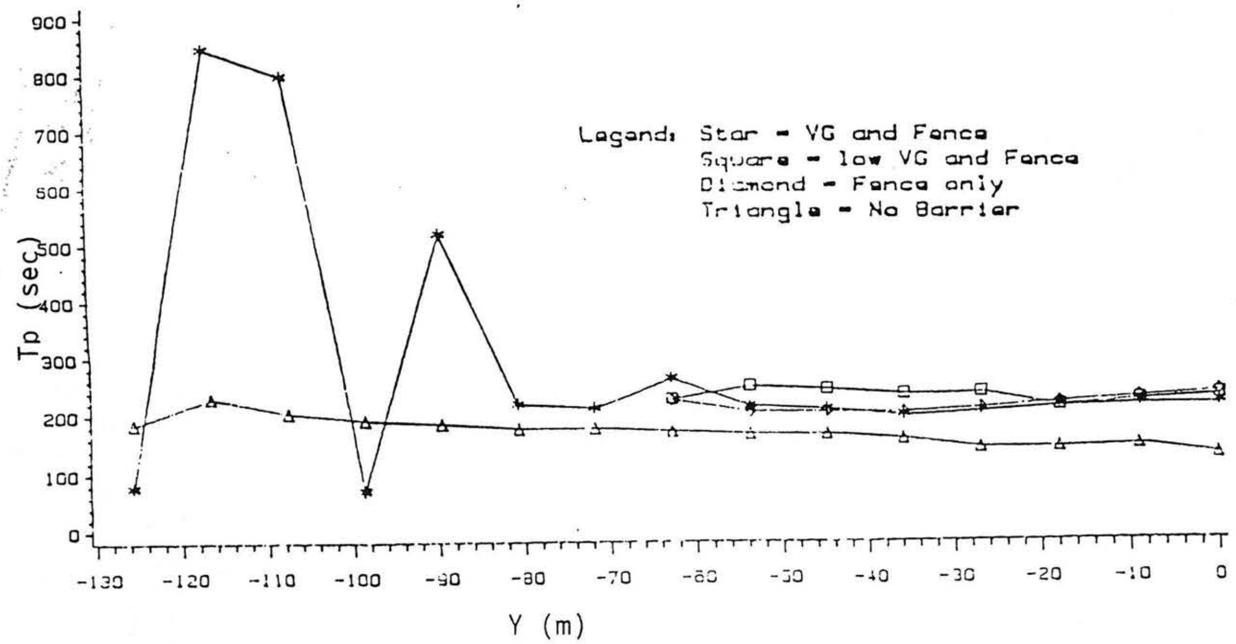


Figure 4.8-25 Peak Arrival Time vs Crosswind Distance at X = 75 m, $V = 100\ m^3$, $Q = 40\ m^3/min$ LNg, Various Enclosure Arrangements

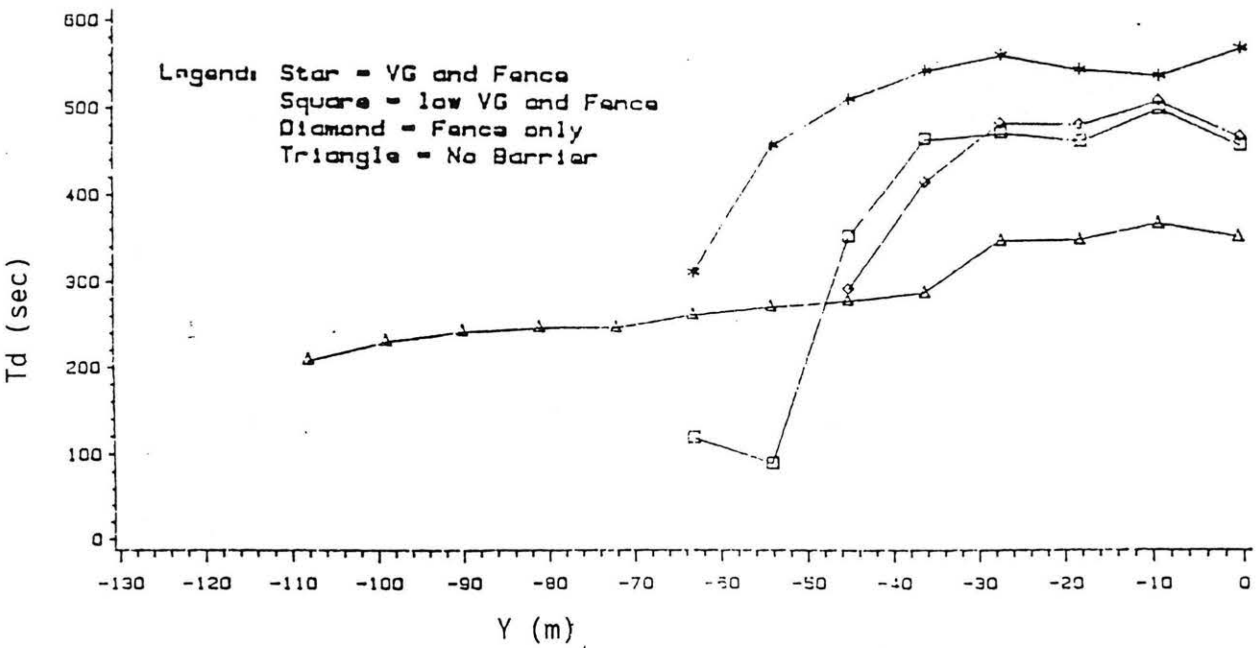


Figure 4.8-26 Departure Time vs Crosswind Distance at X = 75 m, $V = 100\ m^3$, $Q = 40\ m^3 min$ LNG, Various Enclosure Arrangements

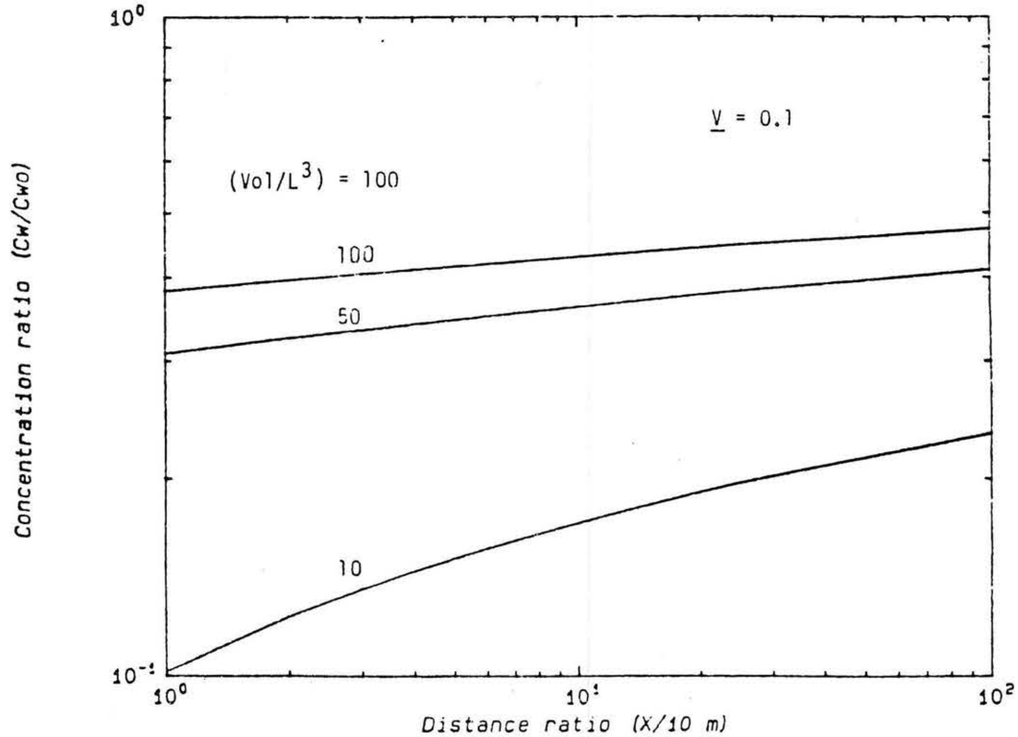


Figure 4.8-27 Peak Concentration Ratio vs. Downwind Distance, Volume Flux Ratio = 0.1, Total Volume Ratio = 10, 50 and 100, Predicted by ANOVA Relation

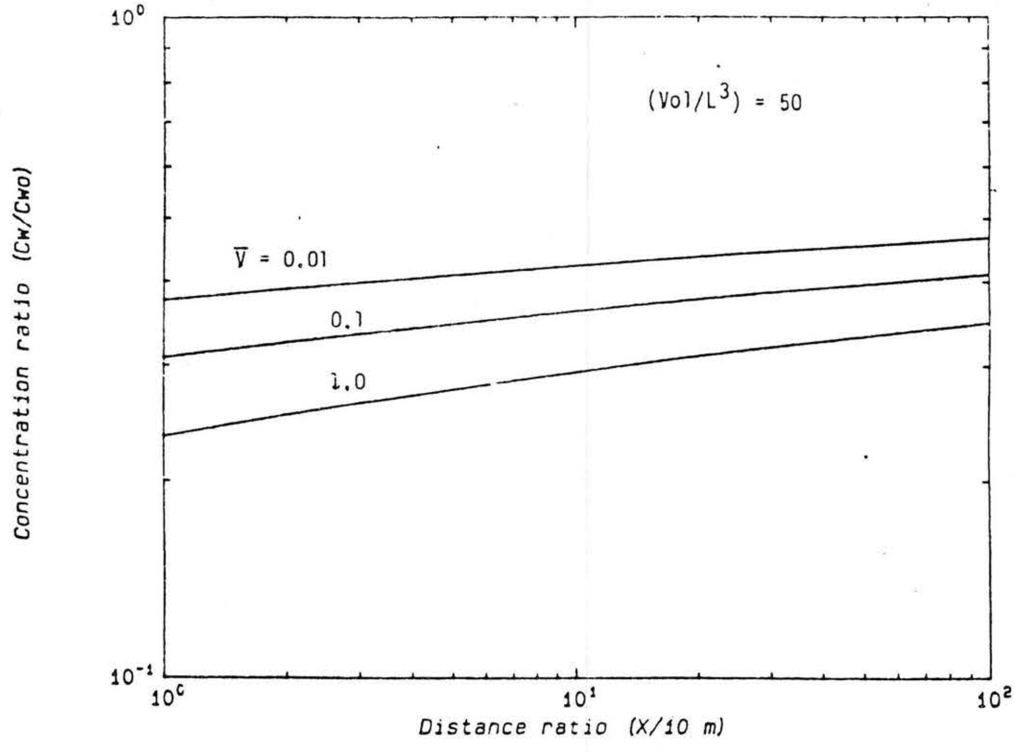


Figure 4.8-28 Peak Concentration Ratio vs. Downwind Distance, Total Volume Ratio = 50, Volume Flux Ratio = 0.01, 0.1 and 1.0, Predicted by ANOVA Relation

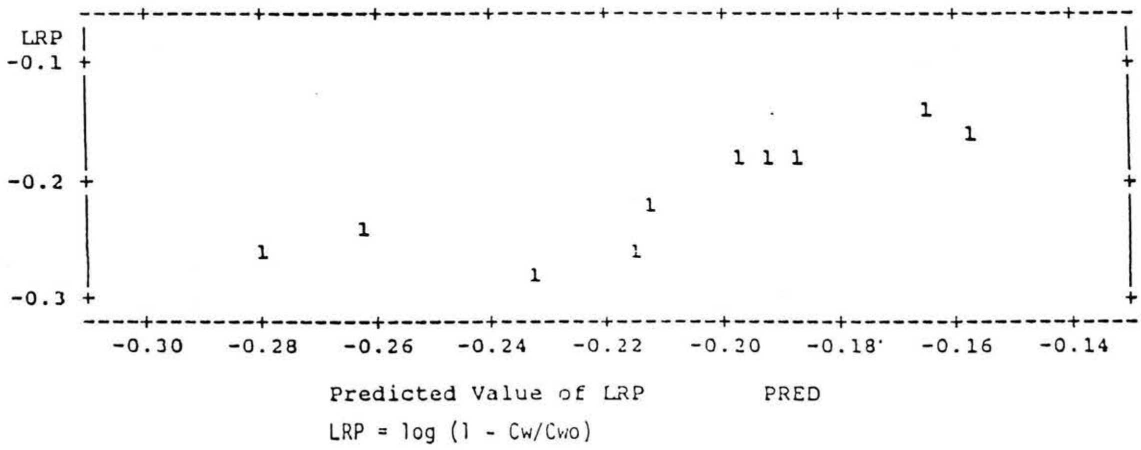


Figure 4.8-29 Measured vs Predicted Values of the Logarithmic Ratio in Concentrations with and without Vapor Fence for Falcon Test Series

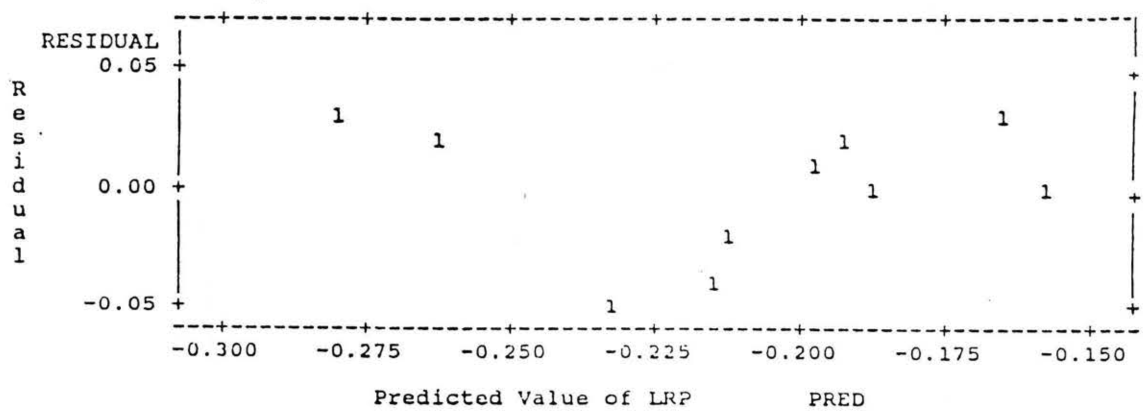


Figure 4.8-30 Residual vs Predicted values of the Logarithmic Ratio in Concentrations with and without Vapor Fence for Falcon Test Series

4.9 "Wind Tunnel Modeling of Density Current Interaction with Surface Obstacles," Koenig and Schatzmann, 1986

Experiment Configuration:

The data of Koenig and Schatzmann (1986) are unique in that they display the potential for some obstructions to reduce spread, inhibit mixing and increase surface concentrations. To validate their simulation approach and instrumentation methodology they also recreated the conditions of Thorney Island Trial No. 20 at model scales. Trial No. 20 released 2000 cubic meters of dense gas instantaneously from a collapsing tank. Fifty meters downwind of the tank the flow was obstructed by a 5 m tall semicircular fence. Koenig and Schatzmann used an aspirated hot-wire katherometer to measure concentration time series. They replicated each measurement several times to establish mean, rms, and peak concentration values.

Koenig and Schatzmann determined that the largest concentrations would occur downwind when the approach wind speed equaled the characteristic gravity spread of the source cloud. Hence, they performed most tests at their characteristic speed, i.e., Ucc = characteristic speed for continuous releases or Uci = characteristic speed for instantaneous releases, and U = 0 for calm conditions. Their study was planned to determine the influence of industrial complex and urban obstructions on the transport and dispersion of a hazardous gas cloud. They released both instantaneous cylindrical volumes (generated in a similar manner to the Thorney Island trials) and continuous area sources of dense gas. They considered the effects of undistorted and distorted simulant gas specific gravity on the cloud behavior.

Their final report discusses nine obstruction scenarios, and the authors provided additional time-series data to Colorado State for the purpose of this review. The situations considered include:

Thorney Island Trial No. 20 An instantaneous release of 2000 cubic meters of dense gas (Specific gravity 1.41 or 4.18) placed 50 m upwind of a 5 m high semicircular solid fence,

Test H1 An infinite height wall oriented in the streamwise direction to one side of a release point,

Test H2 A finite height wall oriented in the streamwise direction to one side of a release point,

Test H3 A street canyon of finite width and infinite height oriented in the streamwise direction,

Test H4 A street canyon of finite width and finite height oriented in the streamwise direction,

Test H9 A street canyon of finite width and infinite height oriented at 45 degrees to the streamwise direction, Test H6 A street canyon intersection of finite width and infinite height with one street oriented in the streamwise direction, and

Test H8 A ditch or depressed roadway oriented perpendicular to the streamwise direction and downwind from the release point.

Measurements were taken both along the wind and transverse to the wind to evaluate cloud asymmetries.

Results of Comparison:

Figures 4.9-1 to 4.9-4 display the influence of a 5 m fence upon peak concentration ratios and cloud times during the simulated Thorney Island Trial 20 experiment. Data from trials using both distorted and undistorted density scaling are shown. (Distorted scaling refers to the practice of using an exaggerated model gas density while adjusting the model wind speed upward to maintain Froude number equality.) Field data from Trials 20 and 16 are also compared on the same figures as dotted lines. Since the laboratory data points are average values from several realizations, the difference between the dotted and solid lines reveal the deviations observed when a single experimental realization is considered.

Figures 4.9-5 to 4.9-13 examine the influence of the obstacles described above on instantaneous gas clouds, and Figures 4.9-14 to 4.9-23 examine the influence of the same obstacles on plumes released continuously from a similar size area source. The downwind distance, x, is scaled by a characteristic length, $L_{ci} = (\text{Volume})^{1/3}$, for instantaneous spills and by a second characteristic length, $L_{cc} = (Q/g(SG - 1))^{1/5}$, for continuous releases.

Figures 4.9-5 and 4.9-14 consider the effect of an infinite height wall under calm conditions upon the two spill types. Transverse concentrations are only slightly perturbed, but along wall concentrations are increased by a factor of about 2 to 3 due to cloud reflection. Figures 4.9-6 and 4.9-15 consider the effect of infinite and finite height walls on the longitudinal distribution of concentrations along the wall. Concentrations may be increased from 1.5 to 2 times. Transverse to an infinite wall downstream concentrations may be increased by factors from 2 to 4 as the plume reflects laterally, but the effect of a finite height wall is less, see Figures 4.9-7 and 4.9-16.

Figures 4.9-8 and 4.9-17 reveal the effect of constraining cloud dispersion within a street canyon. For an instantaneous plume the concentrations are increased by factors of 2 to 4 for both finite and infinite height walls, but for a continuous plume the gas escapes over the finite height wall and the peak concentration ratio decreases toward 1 with downstream distance.

When the canyon is oriented at 45° as shown in Figures 4.9-9 and 4.9-18 concentrations are often greater along the upwind side of the canyon than along the downstream side of the canyon. Although the instantaneous source produced peak ratios greater than 1, the continuous source produced peak ratios less than one along both canyon walls.

Given a crosswind intersection in the canyon, and a spill in the middle of the intersection, Figures 4.9-10 and 4.9-19 show that longitudinal concentration ratios increase for the windless case, but the peak ratio remains the same or decreases with wind. Figures 4.9-11 and 4.9-20 show the variation of concentrations in the cross street. Again concentration ratios increase for the windless case, but fall toward zero with winds.

When a ditch or depressed roadway crosses the plume path as noted in Figures 4.9-12 and 4.9-21 the ditch decreases the transverse concentrations for both calm and windy situations. This occurs because the ditch traps a substantial part of the plume and diverts it along the ditch axis for a calm situation and introduces additional turbulence in the windy situation, see Figures 4.9-13 and 4.9-22.

As noted on the final Figure 4.9-23 even a three-fold increase in continuous source strength does not change the effect of a ditch on the dispersing cloud.

Conclusions:

The data set prepared by Koenig and Schatzmann demonstrates that some obstacle arrangements act to increase concentrations rather than reduce them. Urban areas and industrial complexes abound with narrow street canyons between tall buildings, walls, ditches, and intersections. Such configurations may multiply concentration hazards by factors ranging from 2 to 8. In addition the barriers may delay dispersion, and cause the hazard to persist for longer times. A cross-wind ditch acts effectively to reduce downwind concentrations and delay cloud transit times.

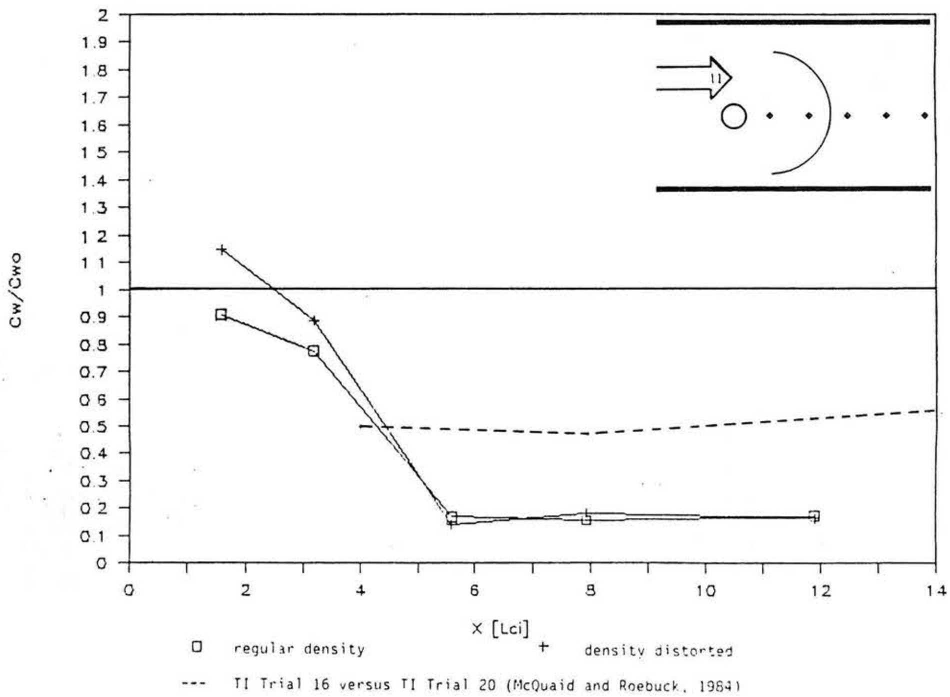


Figure 4.9-1 Peak Concentration Ratio vs. Downwind Distance, Thorney Island Trial 20 Model Simulation

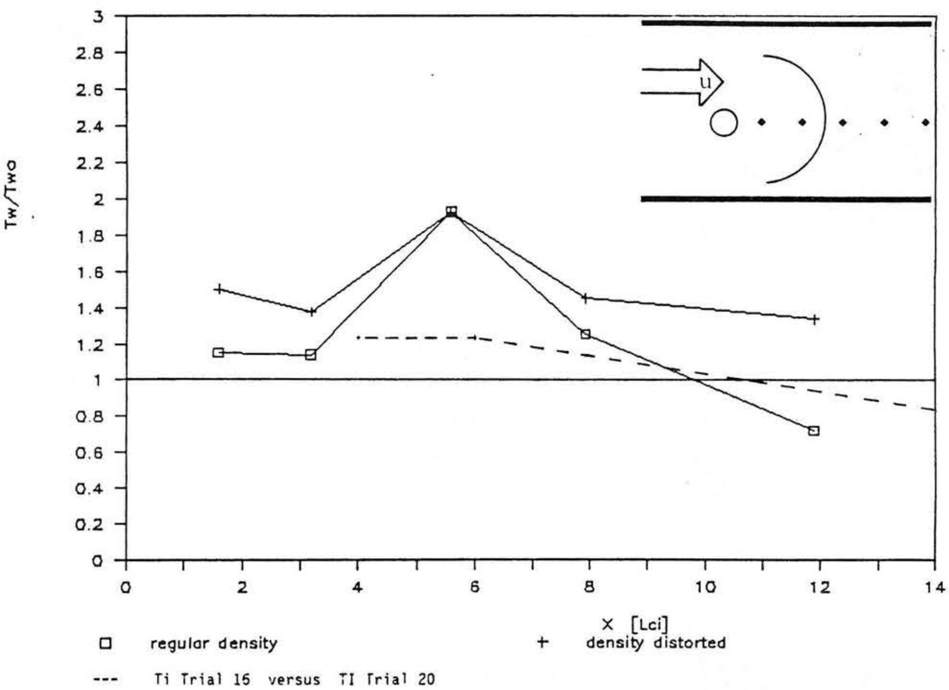


Figure 4.9-2 Arrival Time Ratio vs. Downwind Distance, Thorney Island Trial 20 Model Simulation

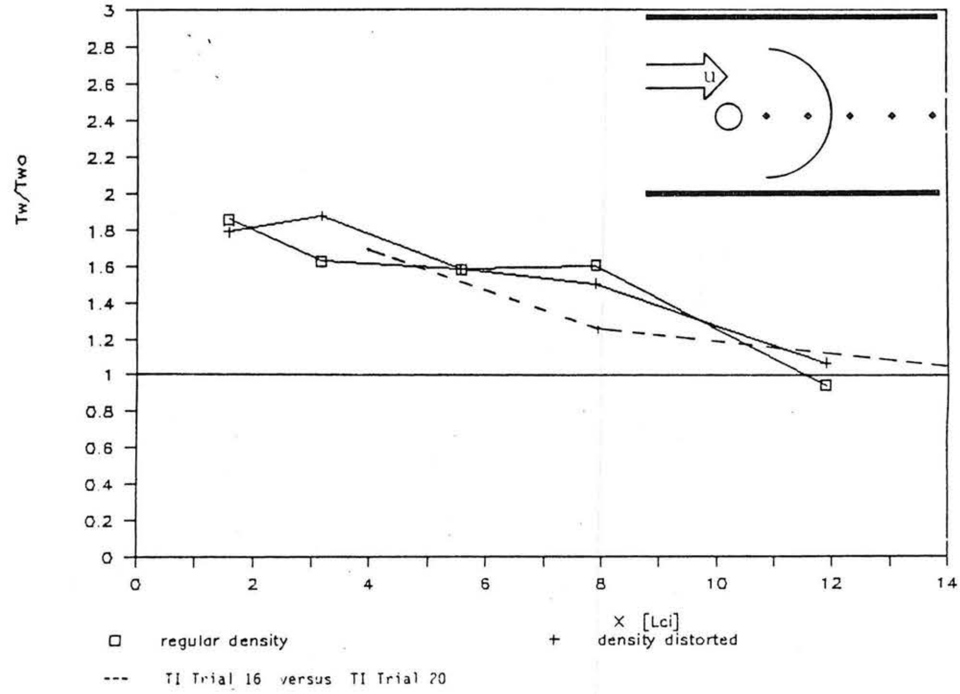


Figure 4.9-3 Peak Arrival Time Ratio vs. Downwind Distance, Thorney Island Trial 20 Model Simulation

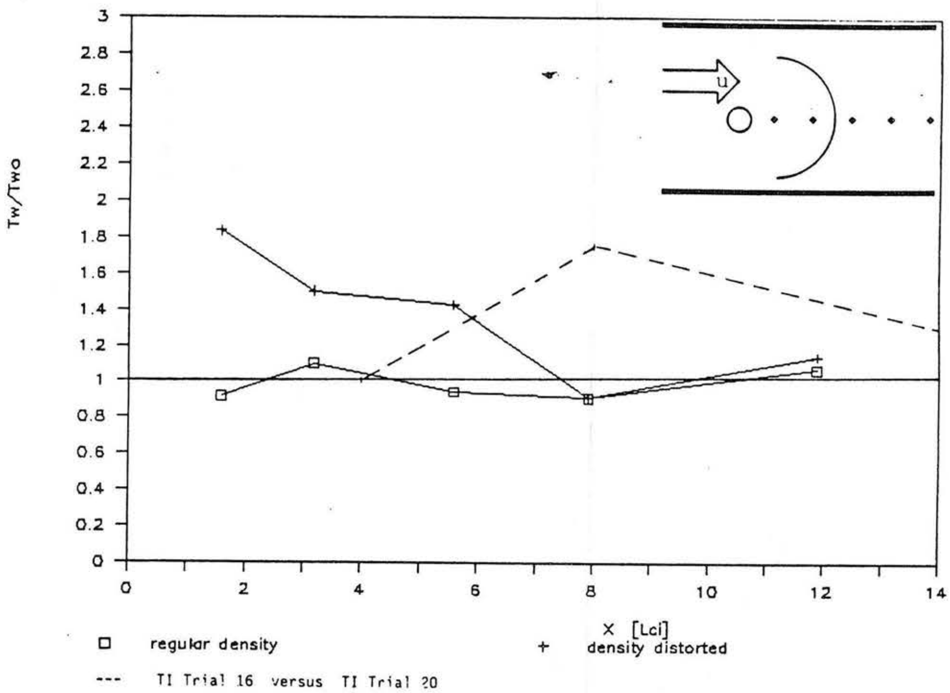


Figure 4.9-4 Departure Time Ratio vs. Downwind Distance, Thorney Island Trial 20 Model Simulation

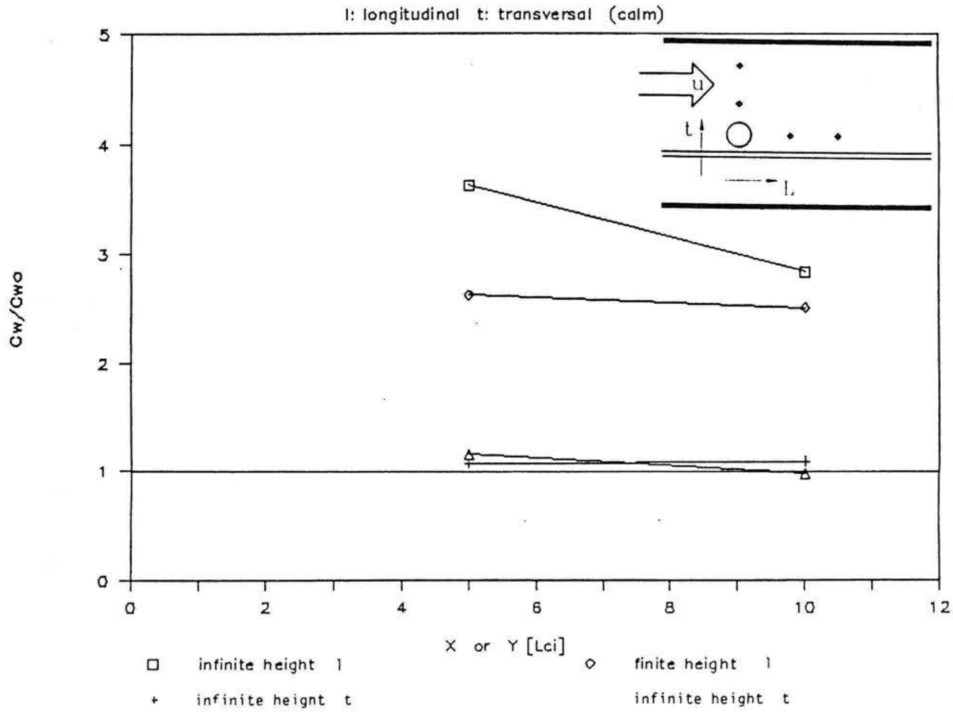


Figure 4.9-5 Peak Concentration Ratio vs. Downwind or Transverse Distance, Finite and Infinite Walls, Calm Conditions, Instantaneous Spill

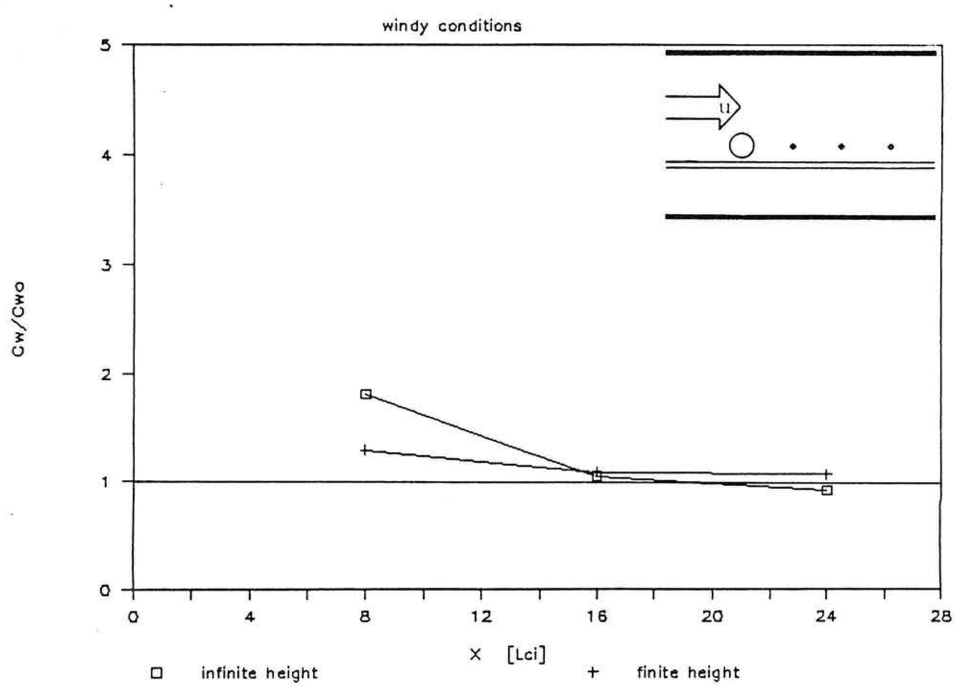


Figure 4.9-6 Peak Concentration Ratio vs. Downwind Distance, Finite and Infinite Walls, Windy Conditions, Instantaneous Spill

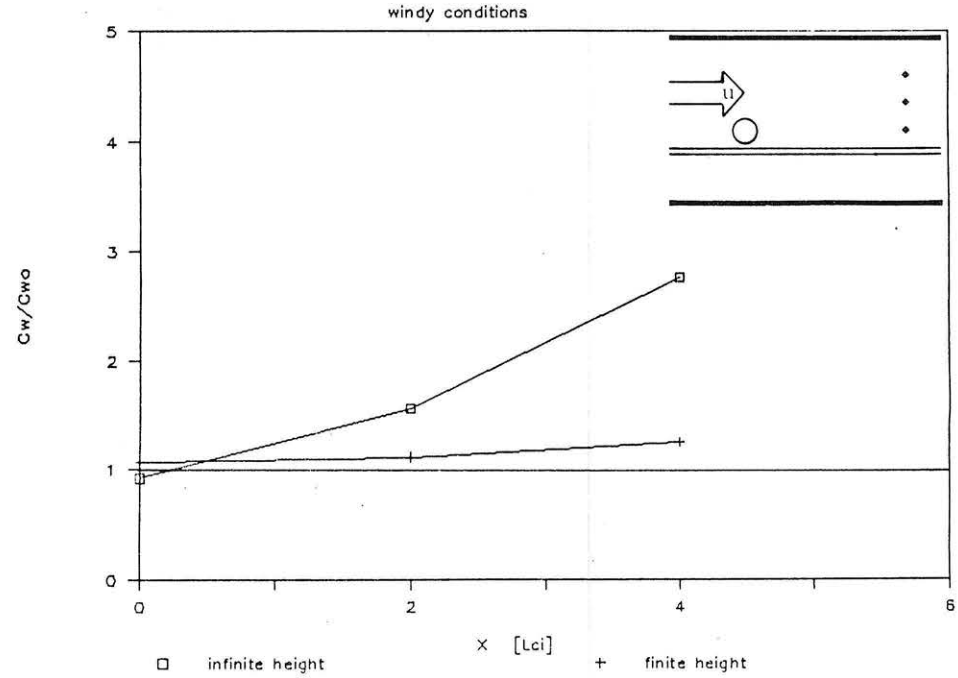


Figure 4.9-7 Peak Concentration Ratio vs. Transverse Distance, Finite and Infinite Walls, Windy Conditions, Instantaneous Spill

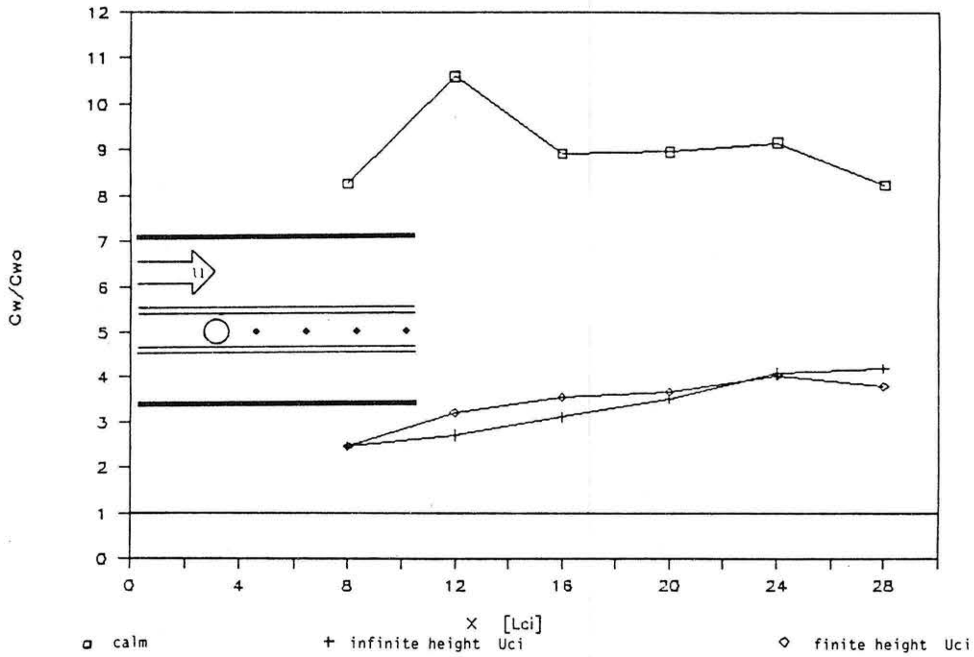


Figure 4.9-8 Peak Concentration Ratio vs. Downwind Distance, Finite and Infinite Canyon Walls, Instantaneous Spill

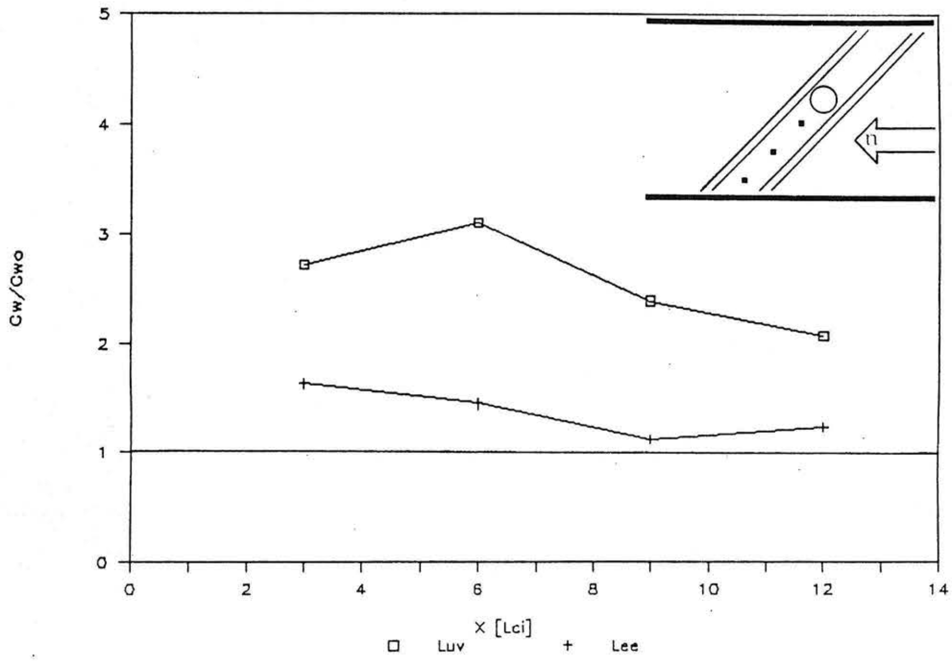


Figure 4.9-9 Peak Concentration Ratio vs. Downwind Distance, Infinite Canyon Walls, 45° Orientation, Instantaneous Spill

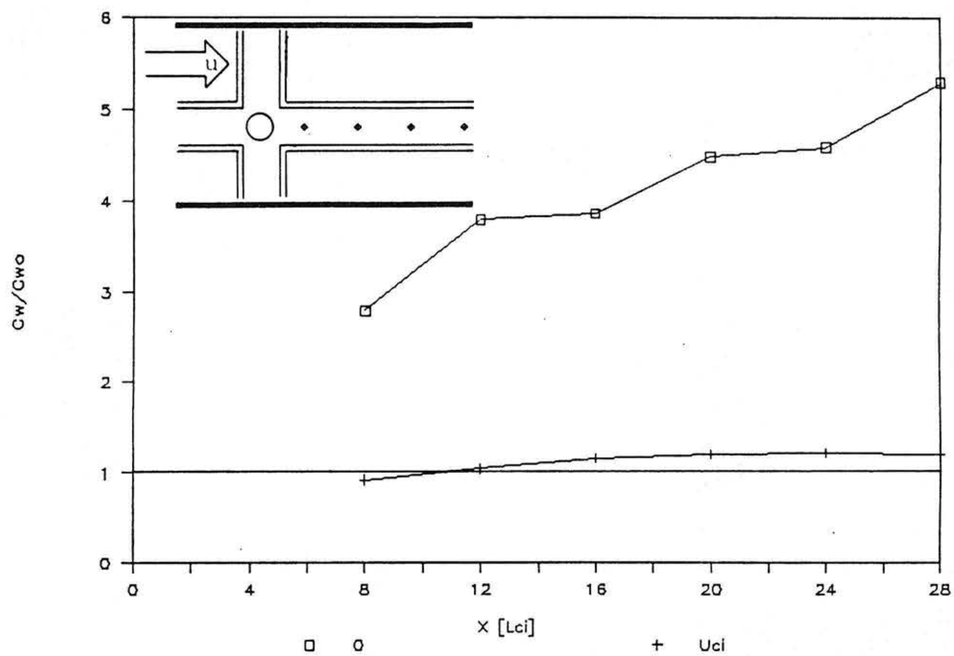


Figure 4.9-10 Peak Concentration Ratio vs. Downwind Distance, Canyon Intersection, Instantaneous Spill

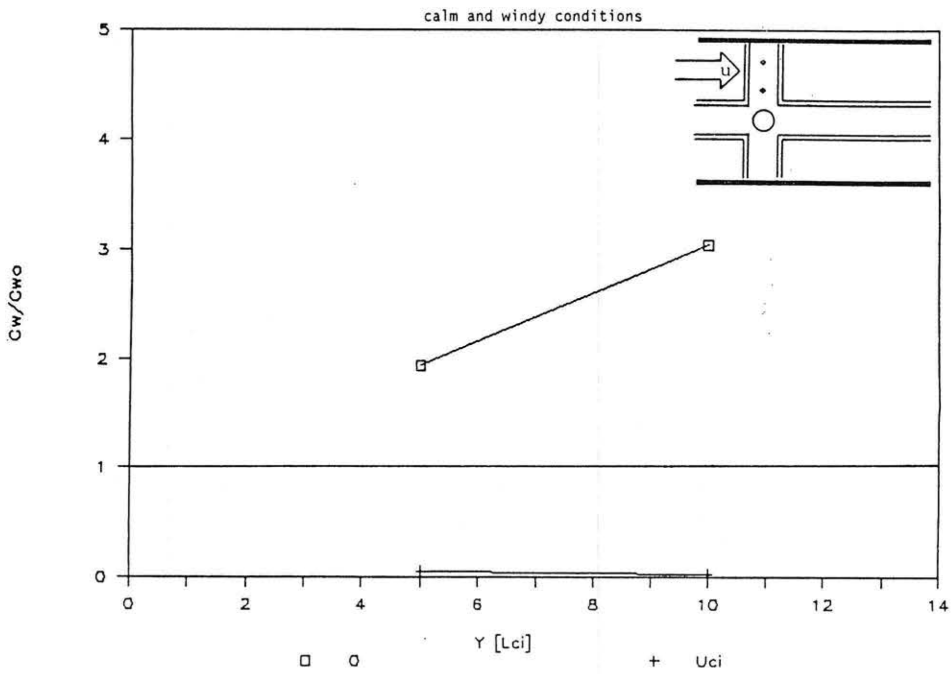


Figure 4.9-11 Peak Concentration Ratio vs. Transverse Distance, Canyon Intersection, Instantaneous Spill

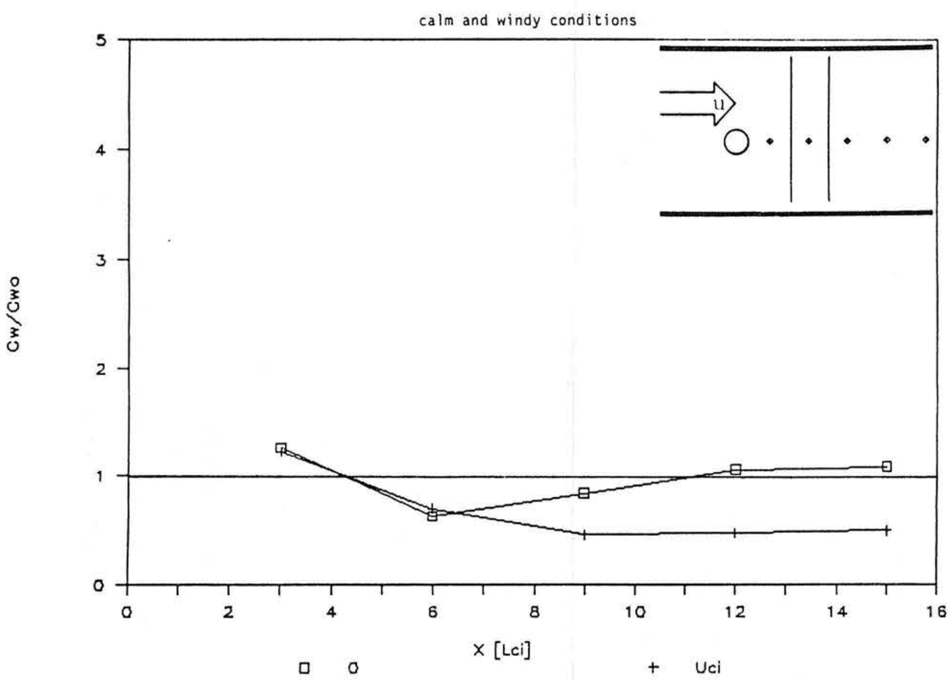


Figure 4.9-12 Peak Concentration Ratio vs. Downwind Distance, Crosswind Ditch, Instantaneous Spill

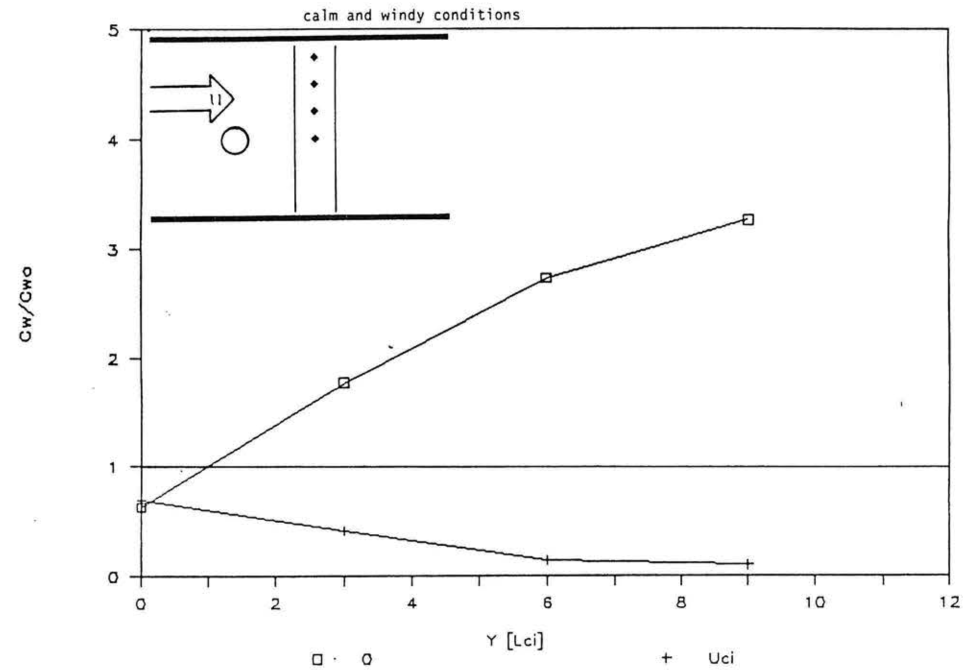


Figure 4.9-13 Peak Concentration Ratio vs. Transverse Distance, Crosswind Ditch, Instantaneous Spill

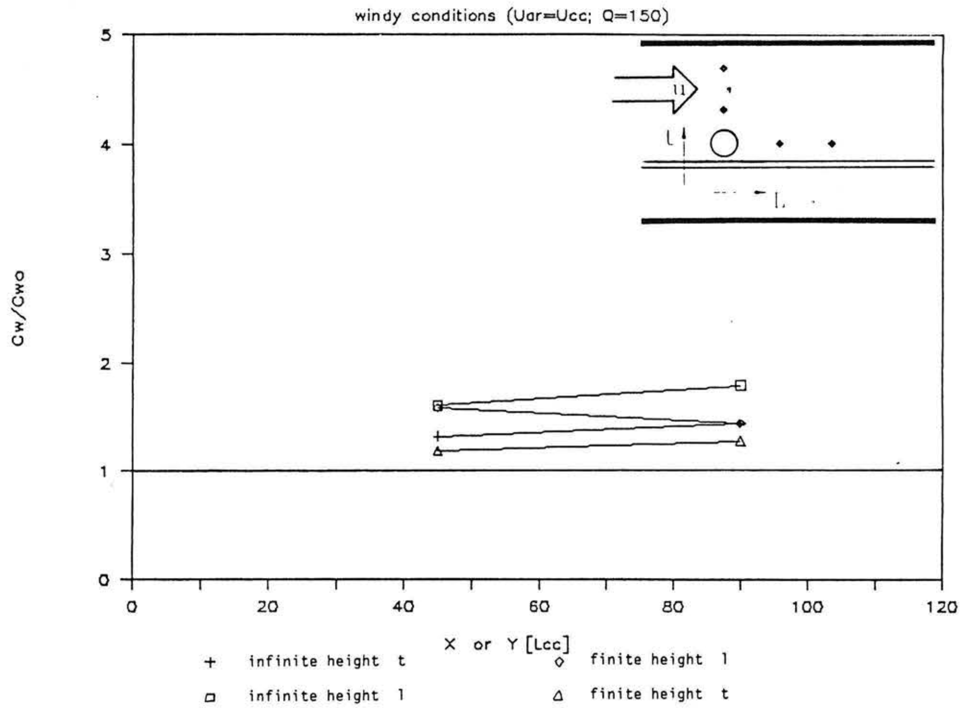


Figure 4.9-14 Peak Concentration Ratio vs. Downwind or Transverse Distance, Finite and Infinite Walls, Calm Conditions, Continuous Spill

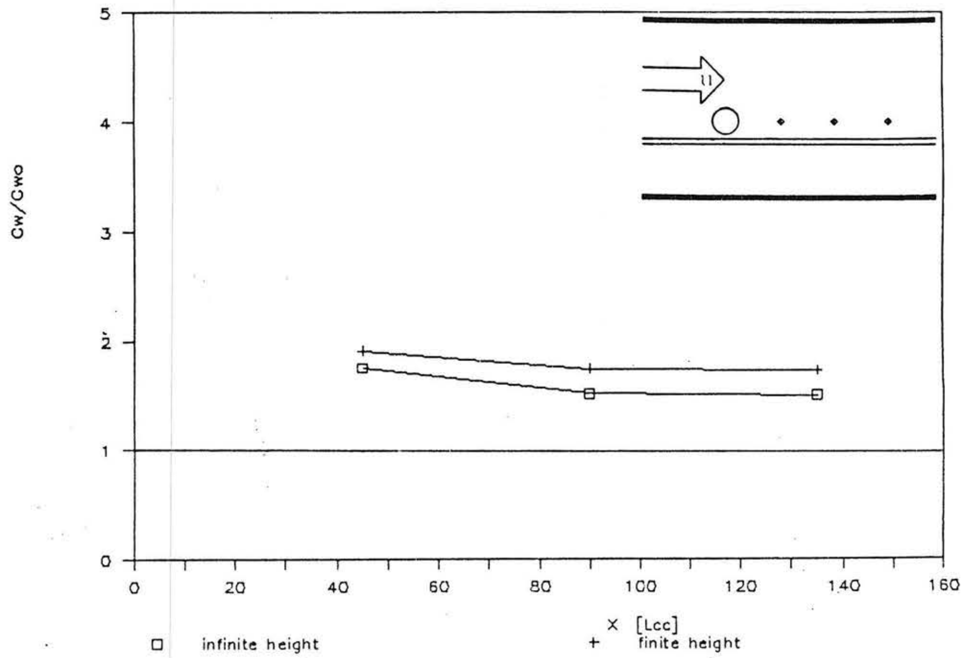


Figure 4.9-15 Peak Concentration Ratio vs. Downwind Distance, Finite and Infinite Walls, Windy Conditions, Continuous Spill

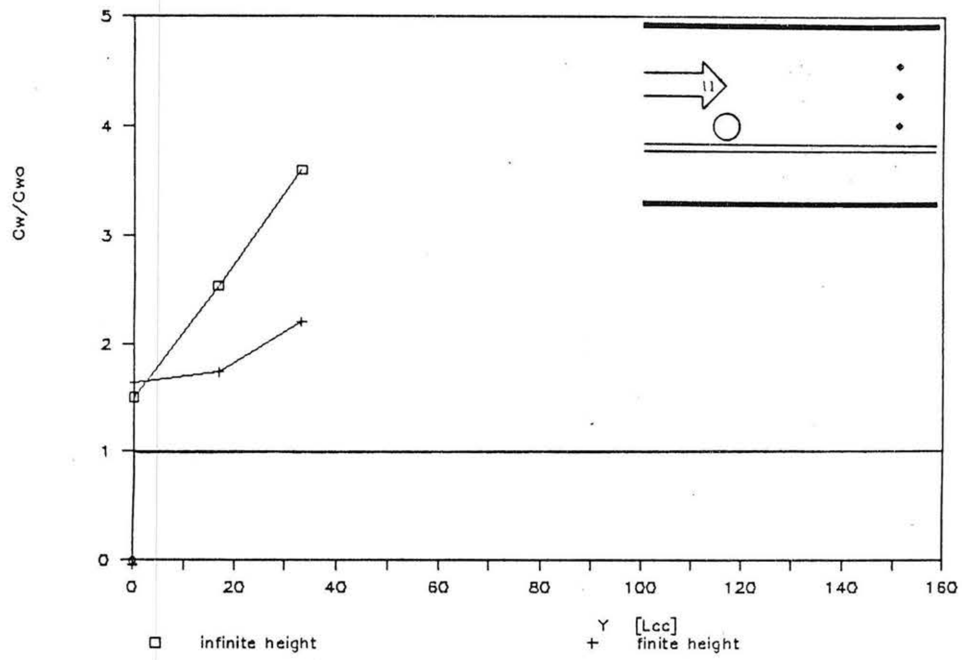


Figure 4.9-16 Peak Concentration Ratio vs. Transverse Distance, Finite and Infinite Walls, Windy Conditions, Continuous Spill

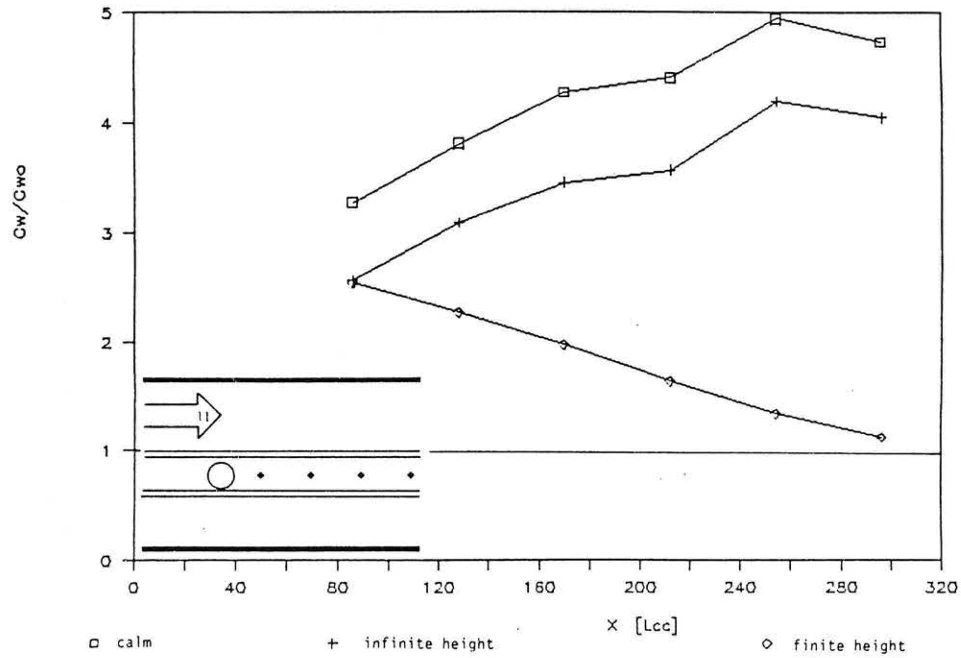


Figure 4.9-17 Peak Concentration Ratio vs. Downwind Distance, Finite and Infinite Canyon Walls, Continuous Spill

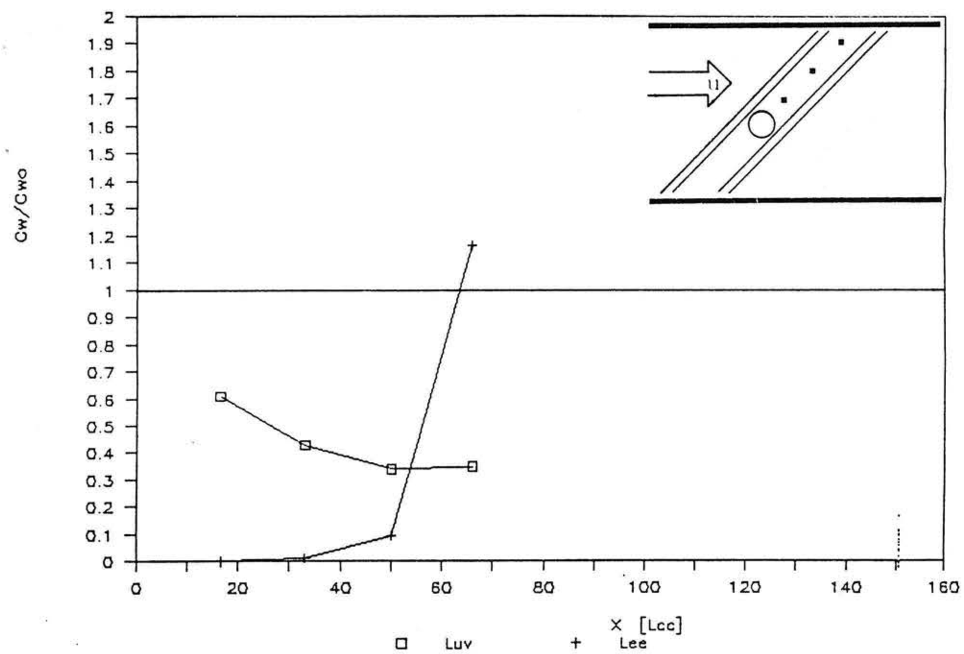


Figure 4.9-18 Peak Concentration Ratio vs. Downwind Distance, Infinite Canyon Walls, 45° Orientation, Continuous Spill

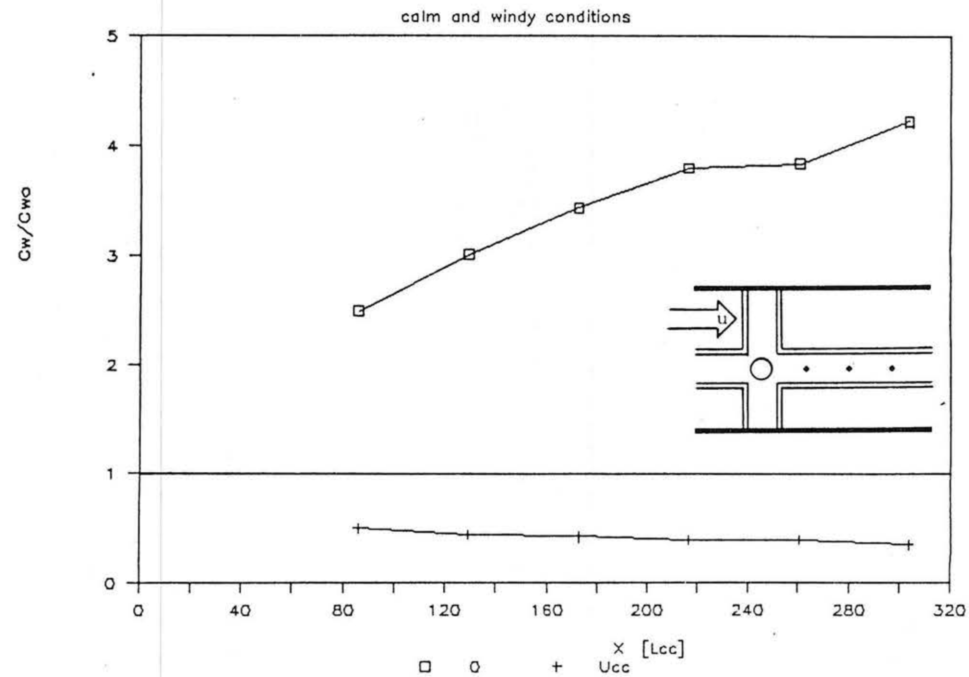


Figure 4.9-19 Peak Concentration Ratio vs. Downwind Distance, Canyon Intersection, Continuous Spill

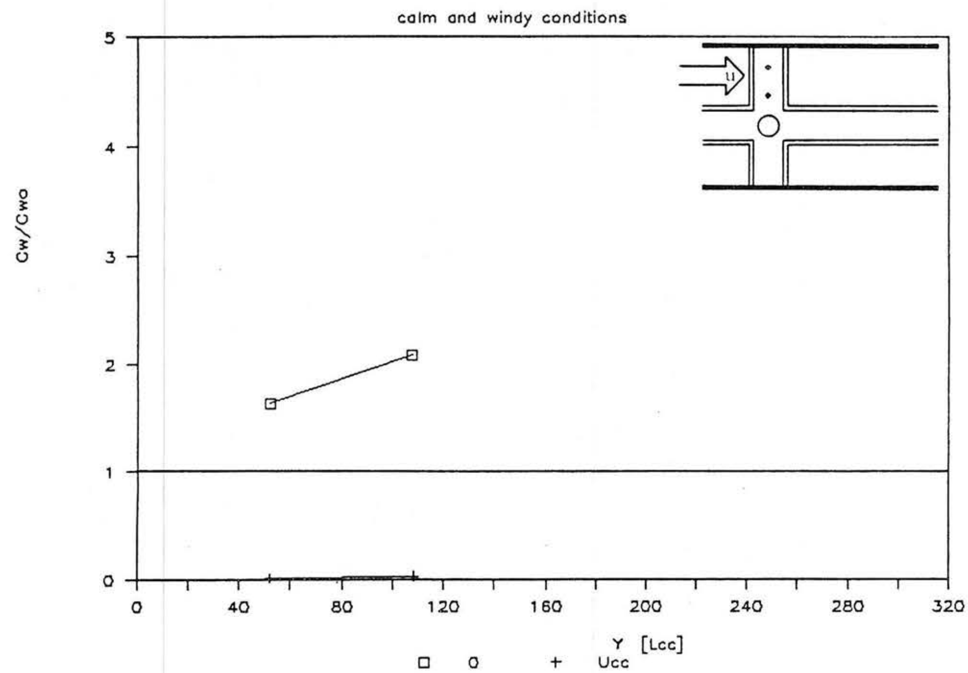


Figure 4.9-20 Peak Concentration Ratio vs. Transverse Distance, Canyon Intersection, Continuous Spill

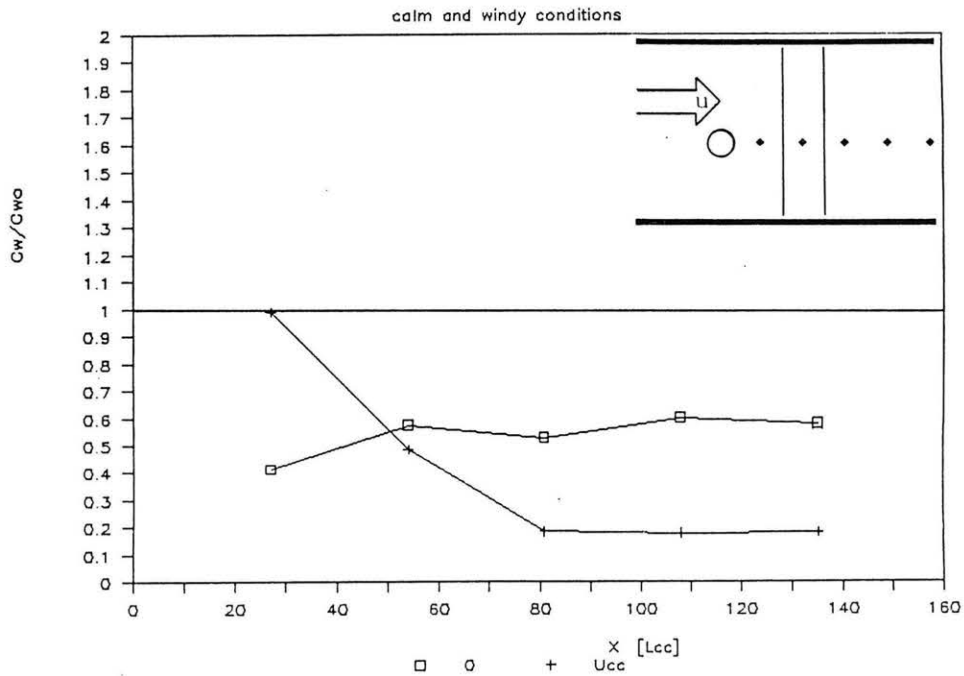


Figure 4.9-21 Peak Concentration Ratio vs. Downwind Distance, Crosswind Ditch, Continuous Spill, Q = 150 l/h

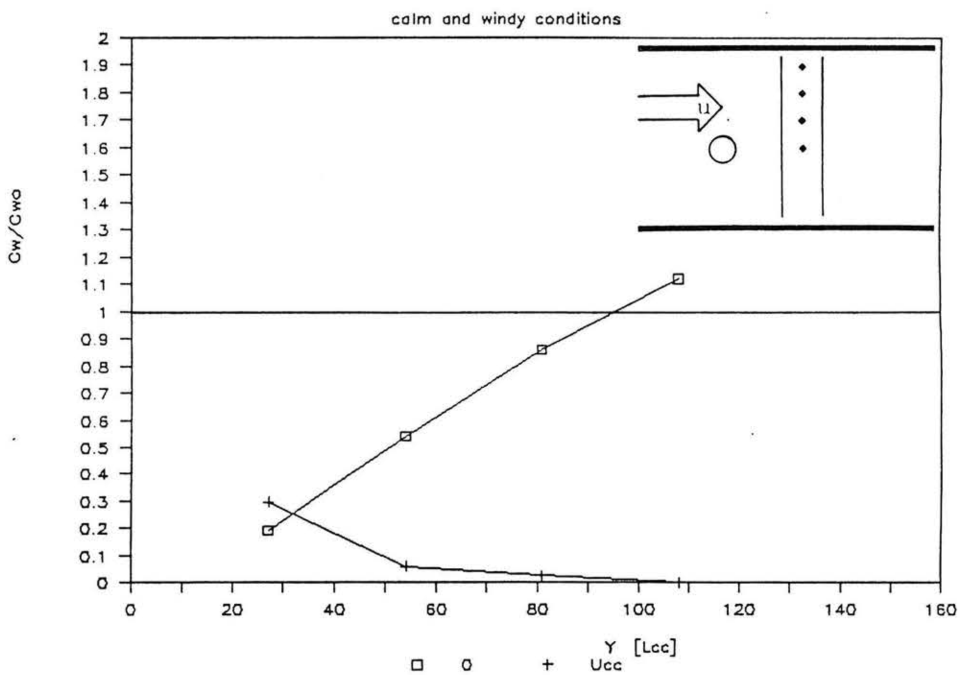


Figure 4.9-22 Peak Concentration Ratio vs. Transverse Distance, Crosswind Ditch, Continuous Spill, Q = 150 l/h

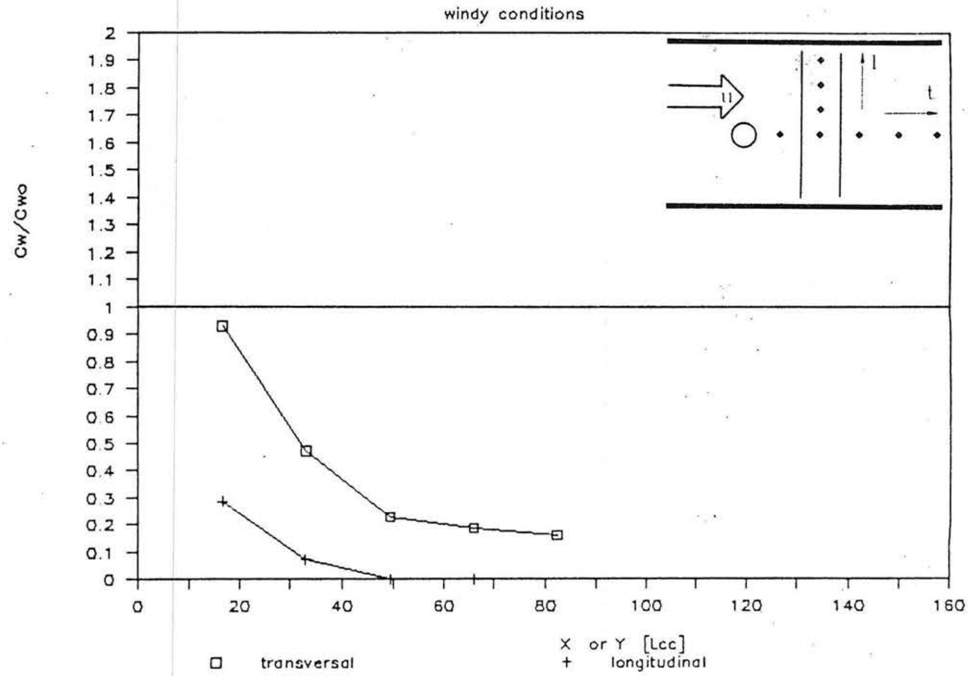


Figure 4.9-23 Peak Concentration Ratio vs. Downwind Distance, Crosswind Ditch, Continuous Spill Q = 500 l/h

5..0 EVALUATION OF NUMERICAL MODELS PROPOSED FOR WATER SPRAY AND VAPOR BARRIER DILUTION EFFECTS

As proposed in Chapter 2.4 two existing numerical models were equipped with entrainment algorithms which allow for the enhanced dilution caused by water spray curtains and vapor barrier fences. A continuous source box model (DENS6) created by Meroney (Andriev et al., 1983) was previously modified to incorporate the presence of an idealized water-spray curtain (SPRAY6A, SPRAY6B, Meroney and Neff, 1985). During this study the box model was modified further to facilitate sensitivity analysis of HF/water spray arrangements (SPRAY62), and additional subroutines were prepared to examine the behavior of HF/vapor fence arrangements (FENC62). Another version was prepared to include the effects of HF reduction by water/HF reaction and deposition (SPRAY65). These models have been compared against sets of selected data using the entrainment models described in Chapter 2.4.

A depth-averaged or slab type model developed by Meroney (DENS23, Meroney and Lohmeyer, 1982; Meroney, 1984; Meroney, 1985) was previously modified to incorporate the presence of an idealized water-spray curtain (SPRAY21, Meroney and Neff, 1985). During this study the slab model was modified further to facilitate sensitivity analysis of HF/water spray arrangements and include the effect of HF removal by deposition (SPRAY23), and additional subroutines were prepared to examine the behavior of HF/vapor fence arrangements (FENCE23). These models were used to evaluate the influence of barriers upon arrival, peak concentration, and departure time ratios.

5.1. Comparison of Numerical Models with Goldfish Trials Data

Blewitt, Yohn, and Ermak (1987b) compared the box model SLAB developed by Ermak et al. (1985) and the slab model DEGADIS developed by Havens and Spicer (1985) against Goldfish Trials No. 1, 2, and 3. A transient version of SLAB predicted experimental data within a factor of two. Averaging time ambiguities in the DEGADIS model led to difficulties in the interpretation of the predictions. The authors remained uncertain as to the value of these particular models when extrapolated to an industrial setting to accurately predict low concentrations in the far-field region. Nonetheless, such models provide a framework within which to examine the viability of various mitigation devices.

DENS62 predictions of Goldfish Trials No. 1, 2 and 3 were calculated using an ideal gas with molecular weight equal to 20, source temperatures of 20°, 20°, and 10° K, respectively, and molar specific heat capacities of 0.83, 0.83 and 0.9 times that of air, respectively. As noted in Chapter 2.2 these values are necessary to reproduce the HF density behavior predicted by the Schotte equations. A value for surface rougheness over the desert area of 0.005 m was assumed for all calculations presented here. Figures 5.1-1, 4, and 5 compare centerline concentration decay of the HF plume with measured values and the SLAB predictions by Blewitt et al. (1987b). The comparison Figure 5.1-6 shows that these predictions reproduce measurements in the near-field within 50% and in the far-field within 20%.

Lateral plume concentrations at the 300 and 1000 meter distances downwind of the source for Goldfish Trial No. 1 are shown in Figures 5.1-2 & 3. Lateral concentration distributions were calculated from the predicted peak concentration and plume width incorporated into an algebraic relation suggested by Meroney (1984). The model does not predict concentrations reach the 8 meter height; hence, comparisons are not provided at this level.

The HF was released as a horizontal jet during the Goldfish trials. Intense mixing occurred near the source, which resulted in rapid dilution to cloud densities below 2.0 kg/cubic meter. The use of a pure HF source or a diluted HF gas to initiate the model has little effect upon initial plume dynamics since the model conserves buoyancy. Reduction in initial source density is compensated for by an increase in effective source volume. Comparisons were made between calculations for a pure HF and a dilute HF source (mass ratio = 4) for Goldfish Trial No. 1. These conditions produced less than 10% differences in concentrations, densities, plume dimensions and temperatures at distances farther than 100 m downwind.

The DENS62, SPRAY62, FENC62 model series seem to predict the Goldfish Trials adequately; hence, the programs were used to evaluate barrier behavior.

5.2 Calibration of the Vapor Barrier Fence Entrainment Model

Data from the pre-Falcon model tests performed by Neff and Meroney (1986) were used to calibrate the vapor barrier fence entrainment model proposed in Chapter 2.4. The behavior of the peak concentration ratios downwind of the 9.4 m fence during continuous spills of LNG simulant were slightly different when an upwind vortex generator was installed. In the absence of such upwind generators the peak concentration ratio reaches a minimum at about 75 meters downwind of the spill point, and then it increases linearly further downwind. Since the numerical model does not include the effect of an upwind vortex generator Run No. 5 (9.4 m fence enclosure alone) was selected to compare with Run No. 10 (no enclosure). These two tests simulated a liquid spill rate of 40 cubic meters/min for 2.5 minutes onto a water pond. The gas was assumed to flash immediately into a gas released over the 44 m x 44 m area of the water pond. Wind speeds simulated equaled 3.5 m/sec at a 2 meter height. Simulant concentrations were converted to equivalent LNG vapor concentrations.

Figure 5.2-1 compares the results of calculations by FENC62 when the coefficient $C_D = 0.1$. The source center was assumed to be about 60 m upwind of the fence to allow for the 88 m total longitudinal length of the fence enclosure and its tendency to move the virtual source upwind. Centerline measurements were used to negate the 3-dimensional effects of the enclosure corners. Model measurements at distances 15, 75, 200, and 400 meters downwind of the fence (or 75, 135, 260, and 460 meters from the virtual source) are plotted on the figure. Variations in virtual distance between 60 and 44 m, and variations in the entrainment coefficient over a two-fold range did not significantly improve agreement. Best agreement occurred for Trial No. 10 data when the initial source width without a fence was set to 44 meters. A small dike existed about the model water spray pond, which may have inhibited lateral spread at the source.

Calculations of the peak concentration ratio from the numerical results at various downwind distances reproduce the minimum in the ratio noted at the 75 meter measurement station. Given a spill not constrained laterally at the source the numerical program predicts that peak concentration ratios may even exceed one near the source. Such a behavior was noted during the Thorney Island tests near the fence (See Chapter 4.6).

5.3 Calibration of the Vapor Removal Model

Blewitt et al (1987c) discuss the removal of HF by water sprays measured during Goldfish Trials No. 4, 5, and 6. Measurements of centerline concentrations were made with and without the water sprays on at 300 and 1000 m. Deposition measurements suggested that the water sprays removed 10-25%, 44%, and 47% of the HF during Trials 4, 5, and 6, respectively. The water spray systems were designed to produce small droplets to enhance chemical reactions, rather than strong dilution. SPRAY23 was used to predict cloud concentrations with the reduction mode on but water spray entrainment set to zero.

Figures 5.3-1 and 5.3-2 compare program predictions of cloud concentrations against measured values for Goldfish Trials No. 1 and 3.

The Appendix discusses the additional reduction in plume concentrations which may occur as a result of increased air entrainment induced by the water spray curtains.

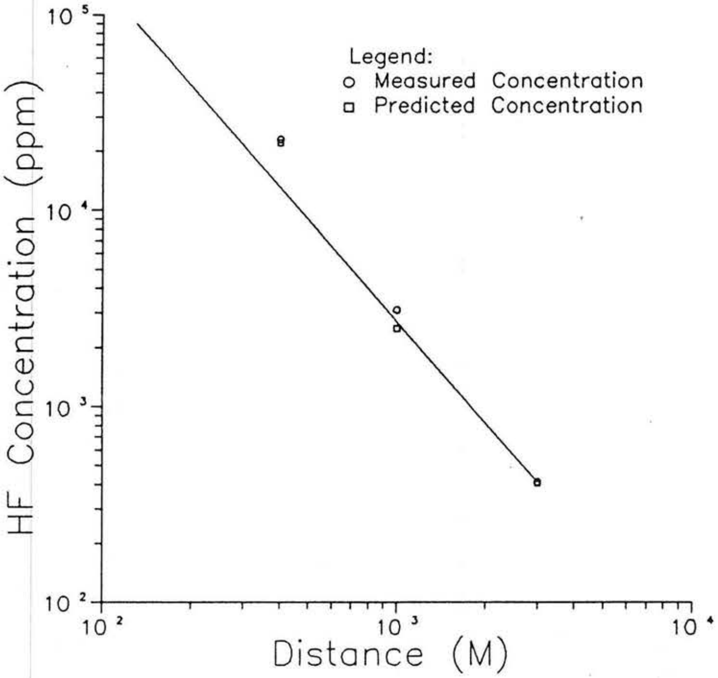


Fig. 5.1-1 Comparison of Observed, SLAB and DENS62 Predicted Plume Centerline Concentrations for Goldfish Test No. 1

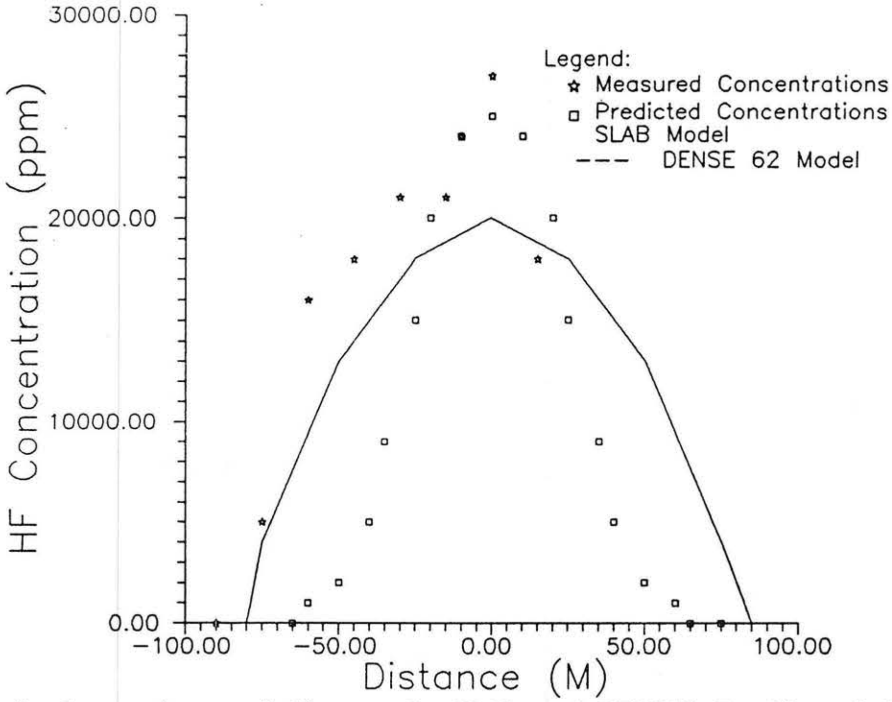


Fig. 5.1-2 Comparison of Observed, SLAB and DENS62 Predicted Crosswind Concentrations at 300 m for Goldfish Test No. 1

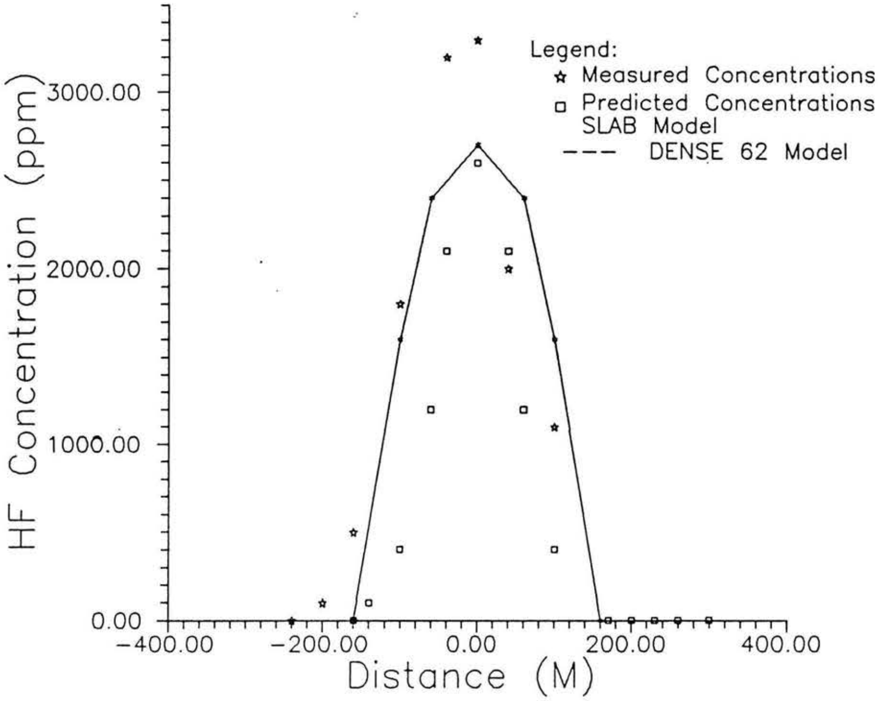


Fig. 5.1-3 Comparison of Observed, SLAB and DENS62 Predicted Crosswind Concentrations at 1000 m for Goldfish Test No. 1

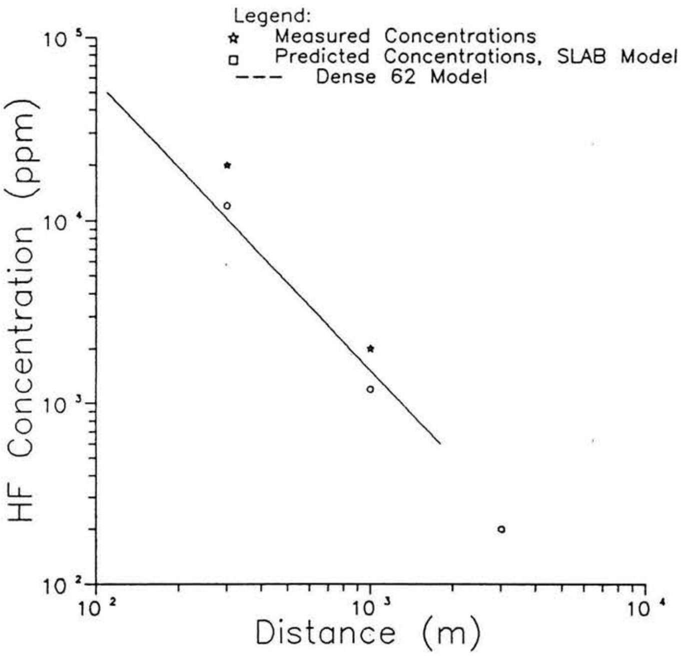


Fig. 5.1-4 Comparison of Observed, SLAB and DENS62 Predicted Plume Centerline Concentrations for Goldfish Test No. 2

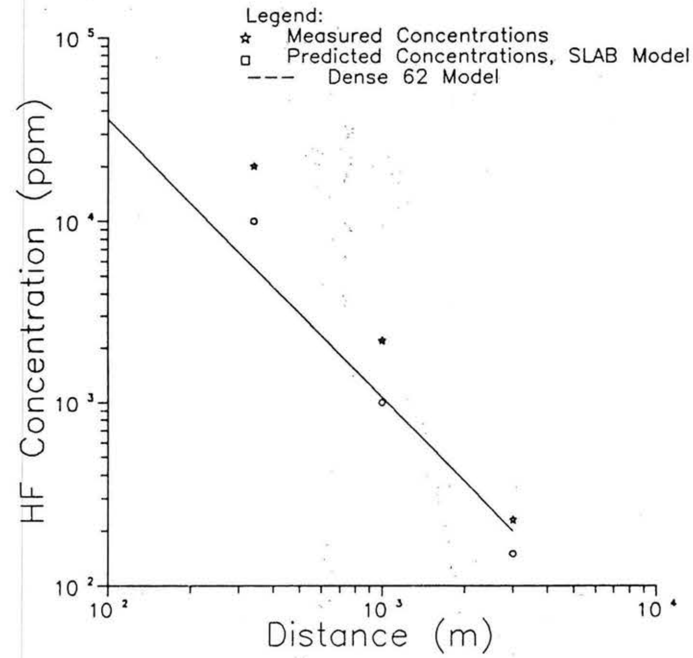


Fig. 5.1-5 Comparison of Observed, SLAB and DENS62 Predicted Plume Centerline Concentrations for Goldfish Test No. 3

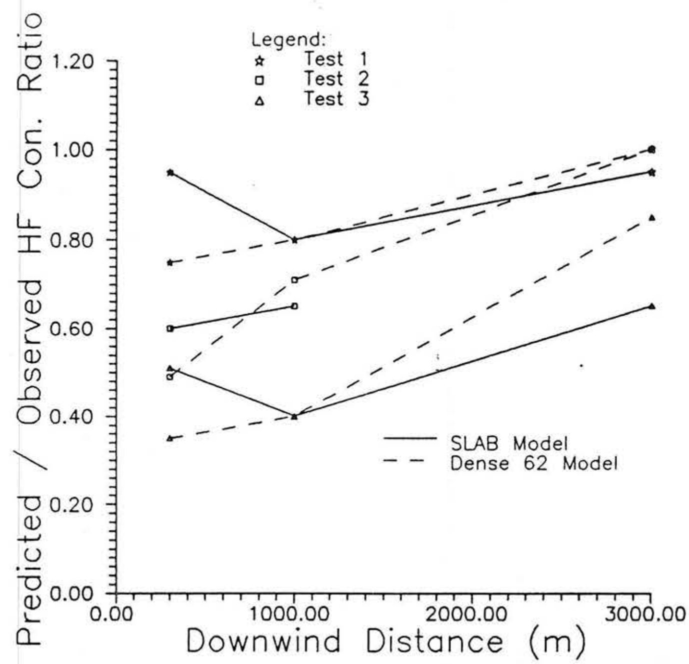


Fig. 5.1-6 Comparison of Ratios of Observed to SLAB and DENS62 Predicted Plume Centerline Concentrations for Goldfish Tests No. 1, 2, and 3

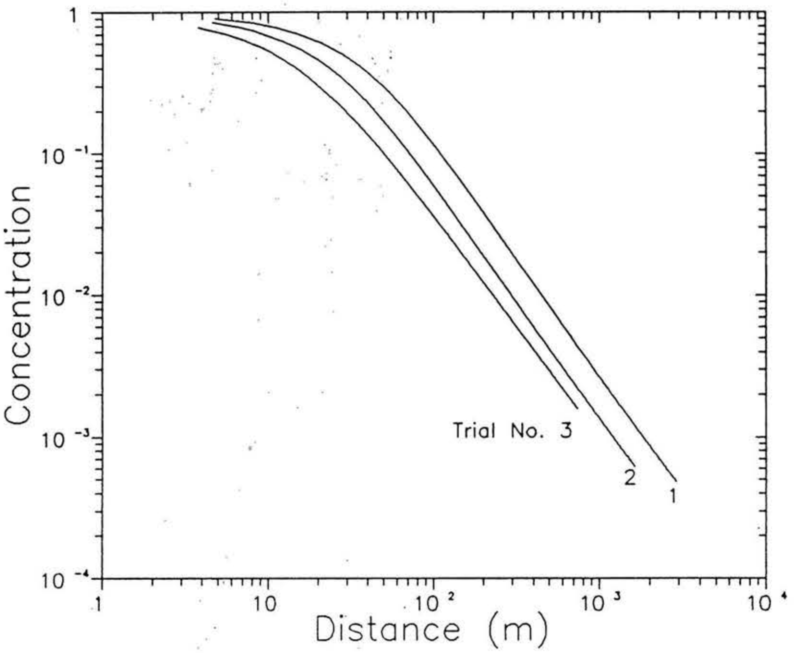


Fig. 5.1-7 Predicted Plume Centerline Concentrations for Goldfish Tests Nos. 1, 2, and 3 by DENS62

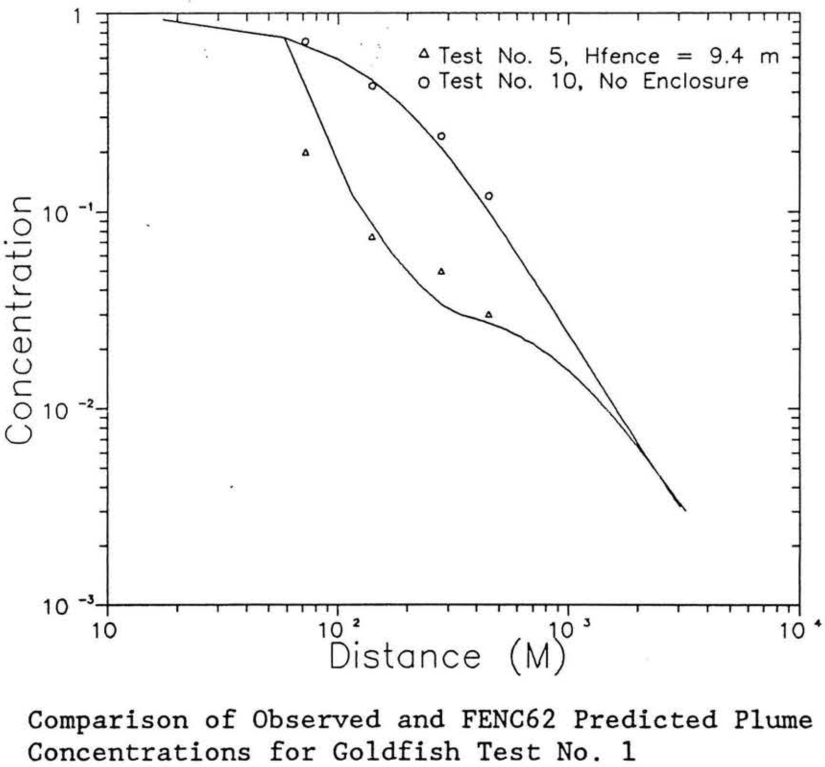


Fig. 5.2-1 Comparison of Observed and FENC62 Predicted Plume Centerline Concentrations for Goldfish Test No. 1

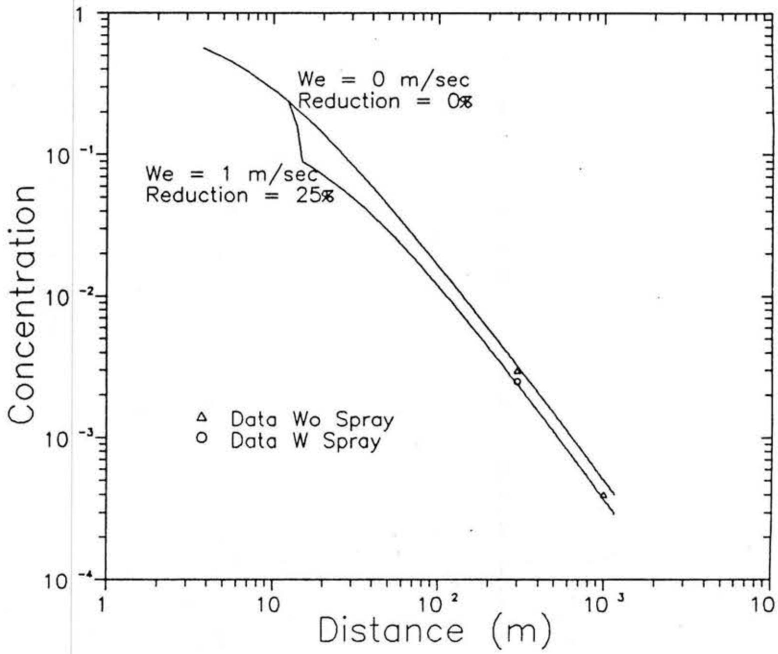


Fig. 5.3-1 Comparison of Observed and SPRAY65 Predicted Plume Centerline Concentrations for Goldfish Test No. 4

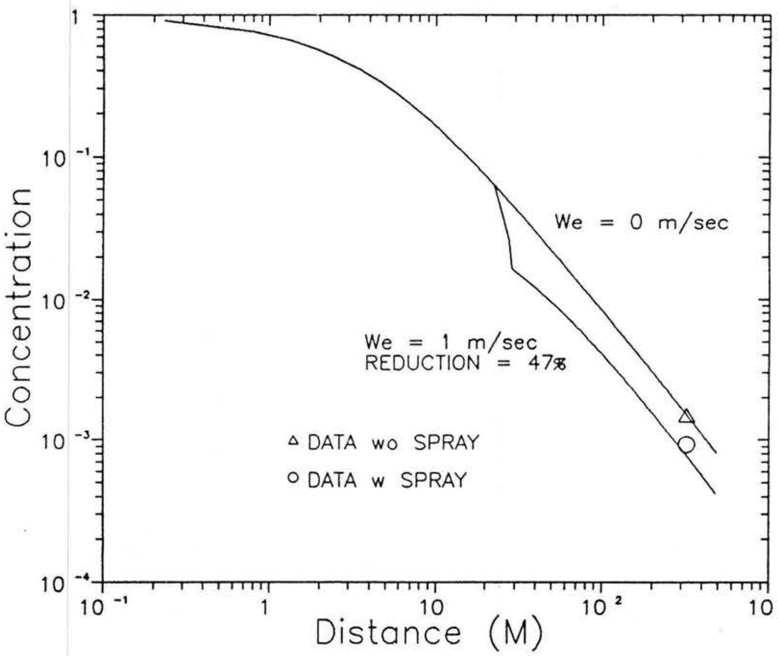


Fig. 5.3-2 Comparison of Observed and SPRAY65 Predicted Plume Centerline Concentrations for Goldfish Test No. 6

6.0 PREDICTION OF HYDROGEN FLUORIDE DILUTION

The conditions selected for design variations are equivalent to those observed during Test No. 1 of the Goldfish Trials performed at the DOE Liquefied Gaseous Fuels Test Facility by Blewitt et al. (1987). The HF source was assumed to arise from a 7 meter wide source at a rate of 469.2 gallons/min of liquid HF (28.33 kg/sec or 2.325 cubic meters/sec of gas). (This source configuration was also used by Blewitt et al. in their numerical calculations.) The ambient air temperature was set at 310° K, the wind speed of 5.6 m/sec at two meters was assumed to produce a friction velocity of 0.374 m/sec over a surface roughness of 0.005 meters. The source gas molecular weight was set at 20 and the source temperature was set to 20° K to reproduce the density mixture behavior predicted by Schotte for such conditions.

The Goldfish Test No. 1 conditions were chosen for barrier sensitivity tests because they relate to an actual HF release, even though the observed surface roughness is not typical of a refinery or chemical complex setting. The larger background turbulence levels associated with a "rough-boundary" refinery area will reduce the downwind distance over which vapor-barrier or water spray dilution significantly influence centerline concentration magnitudes. (The reader should consult the results of work in progress by Petersen and Radcliff of CPP for the American Petroleum Institute which examines the influence of roughness on dense plume dispersion.) Water spray removal of HF will not be affected by variations in surface roughness. The Goldfish HF Trials were designed to examine hypothetical release scenarios being evaluated by industry.

The humidity and the surface heat transfer in the models were set to zero so that adiabatic entrainment of air would reproduce the density mixture behavior predicted by Schotte. The molar specific heat capacity of the source gas was chosen to be 0.83 times that of air.

In DENS62, SPRAY62, and FENC62 the increments of downwind distance are automatically determined by various buoyancy scaling criteria and the need to maintain numerical stability. Thus, fence and spray locations varied somewhat when different wind speeds were investigated; however these variations were still small compared to the total plume trajectory examined.

In SPRAY23 and FENC23 only 100 longitudinal grid locations are available; hence, a nested set of calculations were performed as the cloud advected out of the initial calculation domain. The primary adjustment made was to the source size and source velocity. As the grid expands the effective source area increases and the source velocity decreases proportionately (the Flux Froude number and Volume Flux ratio are kept constant); thus, some irregularities are noted at locations where the grids overlap.

6.1 Goldfish Trial No. 1 with Vapor Barrier Fences

No tests were actually carried out during the Goldfish Trials in the presence of vapor barrier fences; however, calculations to show the effect of hypothetical fences are interesting. These calculations are representative of the entrainment resulting from straight sharp-edged fences, where separation occurs at a the fence top. Fences are assumed to be transverse to the wind direction. The effect of barrier height and wind speed are examined below. Calculations were performed with the fence entrainment model discussed in Chapters 2.4 and 5.4 and an entrainment coefficient $C_D = 0.1$.

Effects of Fence Location

The effects of fence location were determined to be similar to that of water spray curtain location. Fences are more effective in terms of initial dilution, when they are placed nearer the source. Fence dilution effects did not persist beyond 1000 m, when the fence was placed less than 400 m downwind of the source.

Effects of Fence Height

The fence entrainment model permits the entrainment velocity to increase with fence height velocity. Since wind profiles increase with height, then the dilution rate should increase with fence height. The FENC62 model assumes that a logarithmic velocity profile exists, such that wind speed is determined by surface roughness and friction velocity. Figure 6.1-1 displays a set of curves for fence heights ranging from 3 to 12 meters. The entrainment velocity does not turn off abruptly like the water spray model, but decreases linearly out to a distance of 30 fence heights. The resulting displacement of the concentration profile is cusp shaped rather than triangular, and the dilution effect is small after about 200 fence heights.

The effect of fence height on cloud height is displayed in Figure 6.1-2. The cloud height approaches the cloud height in the absence of a barrier after 1000 meters or about 200 fence heights.

Effects of Wind Speed

Increased wind speeds result in larger entrainment rates, but this is compensated by the tendency for the plume to pass through the fence wake more quickly. Given a constant fence height of 3 meters located 100 meters downwind of the source, Figure 6.1-3 and 4 suggests that, for a range of wind speeds varying from 1 to 8 m/sec, the increased entrainment and shortened time in the wake balance out to produce no net change in dilution rate. Plume height also remains constant. These calculations agree with other experiences in building aerodynamics where it is found that perturbation of gas plumes by obstacles seems to be velocity independent. Concentrations decay at higher wind speeds inversely with the speed, but this is an independent effect of source dilution by the ambient wind, not an effect of a fence.

Cloud height downwind of an obstacle is expected to be independent of wind speed, since a sharp edged geometry will produce similar streamline patterns over a range of velocities. Figure 6.1-4 suggests that the perturbation produced by a fence is constant, but the model fails to allow for a constant height wake region.

6.2 Goldfish Trial No. 1 with Water Sprays

As noted in Chapter 5.3 water spray curtain tests were performed during the Goldfish Trials No. 4, 5, and 6. These tests included chemical reactions between the HF and the water spray and subsequent deposition of the HF on the ground. Goldfish Trial No. 1 conditions are used below to examine the effect of various spray placement and water spray reduction and entrainment rate alternatives. The influence of added air entrainment induced by the water spray curtains is discussed in the Appendix.

Water Spray Effects on HF Reduction

SPRAY65 was used to predict the joint effects of water spray dilution and deposition on an HF cloud. Figure 6.2-1 displays the effect of placing a single spray which produces 80% deposition at 100m followed by a second spray of similar strength at 300 m. Notice that spray deposition produces a parallel shift of the concentration decay curve. A second spray produces a second shift of equivalent width. The decrease in concentration persists at all subsequent downstream distances.

Figure 6.2-2 depicts the effect of joint dilution and depletion. In this case it is assumed that $(w_e)_{spray} = 6$ m/sec and HF reduction is again 80%. Reductions in plume concentration produced by the water spray alone do not persist, but combined dilution and reduction produce large local reductions and concentration followed by a shift in the concentration curve downward.

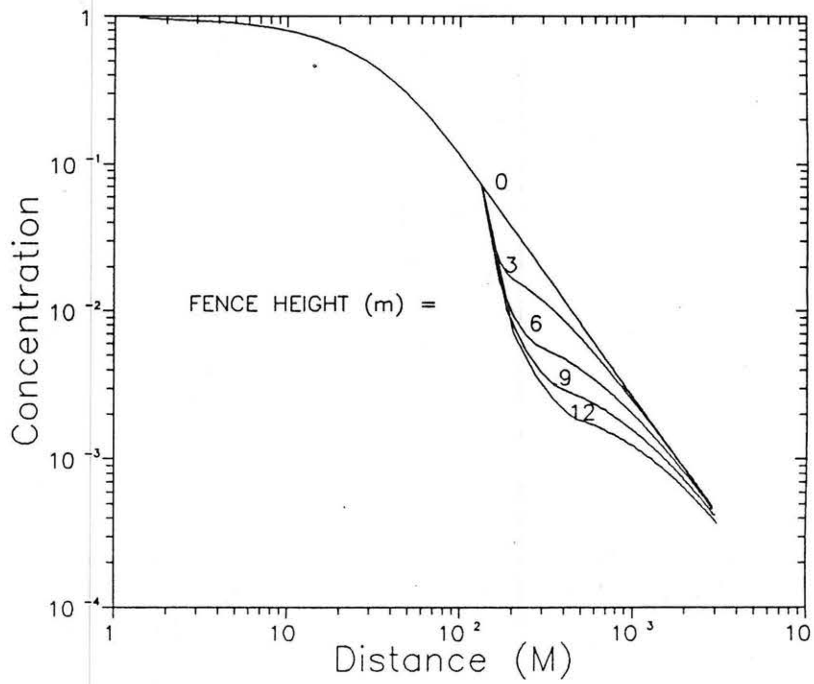


Fig. 6.1-1 FENC62 Predicted Plume Centerline Concentrations for Goldfish Test No. 1, Fence heights = 0, 3, 6, 9 and 12 m at X = 100m

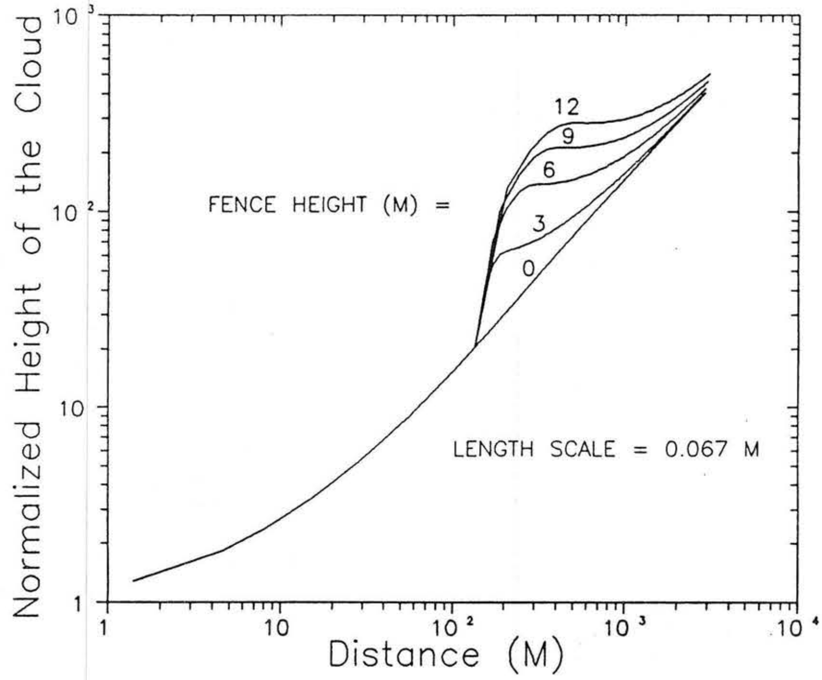


Fig. 6.1-2 FENC62 Predicted Plume Heights for Goldfish Test No. 1, Fence Heights = 0, 3, 6, 9 and 12 m at X = 100 m

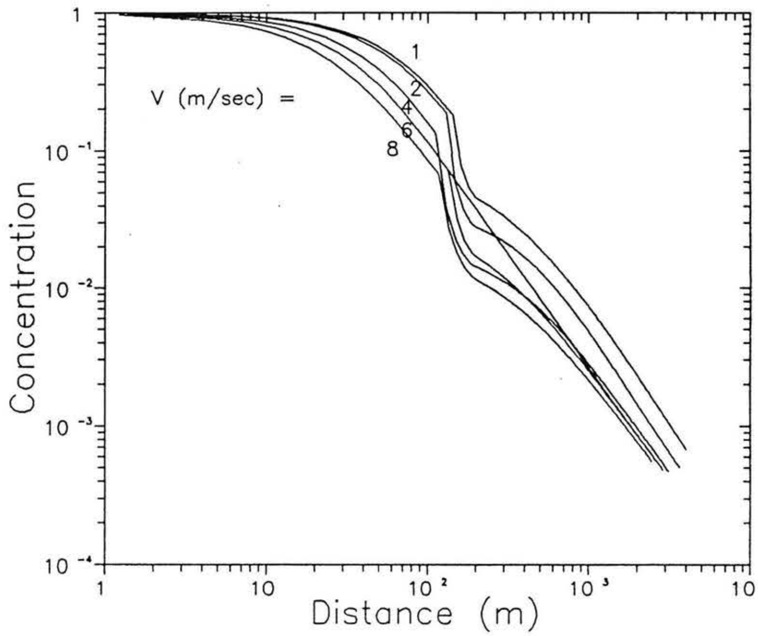


Fig. 6.1-3 FENC62 Predicted Plume Centerline Concentrations for Goldfish Test No. 1, Fence Height = 3m, X = 100 m, U = 1, 2, 4, 6, and 8 m/sec

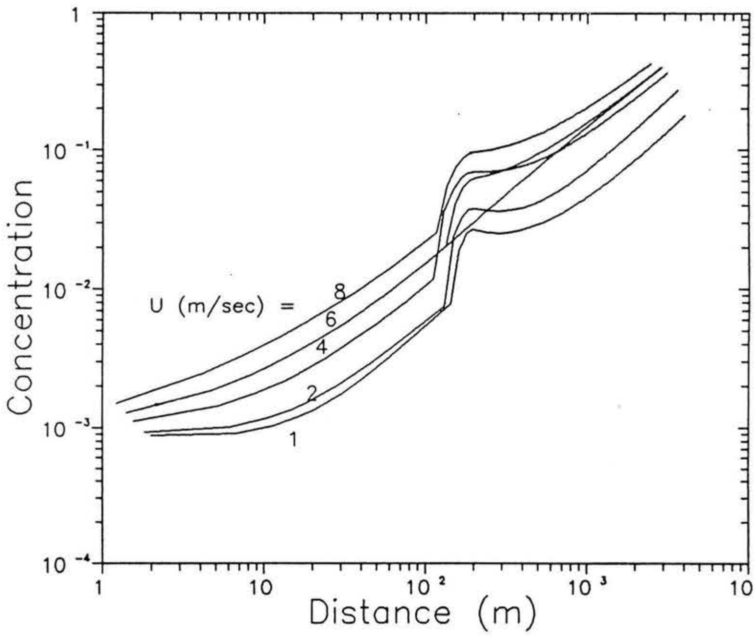


Fig. 6.1-4 FENC62 Predicted Plume Heights for Goldfish Test No. 1, Fence Height = 3 m, X = 100 m, U = 1, 2, 4, 6, and 8 m/sec

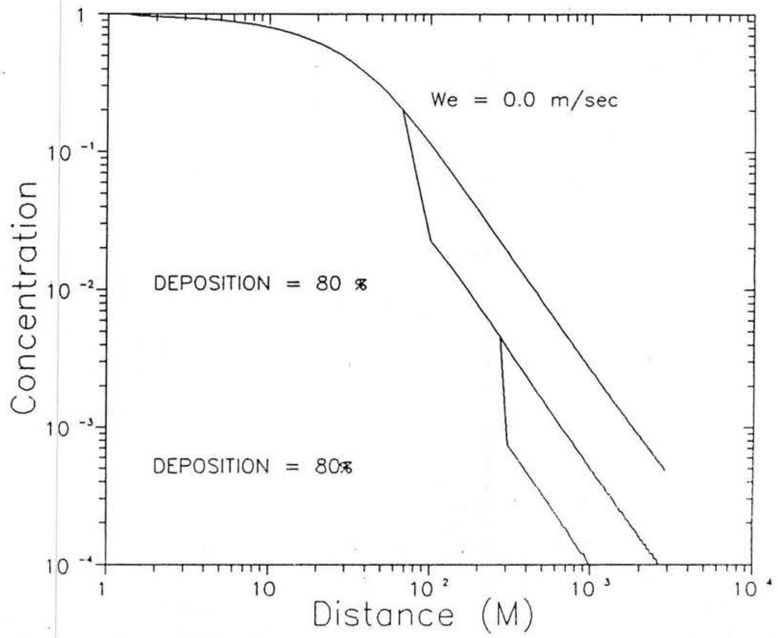


Fig. 6.2-1 SPRAY65 Predicted Plume Centerline Concentrations for Goldfish Test No. 1, 80% HF Removal by Water Spray at X = 100 m and X = 300 m

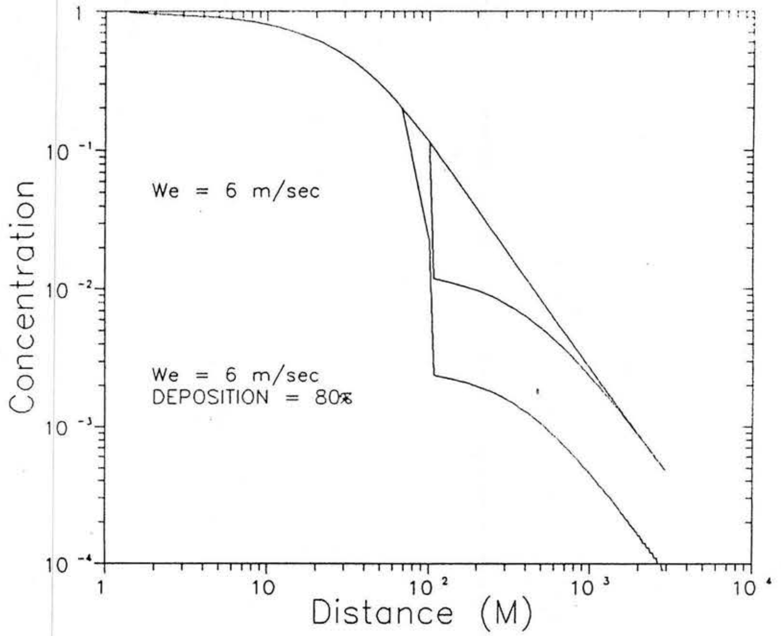


Fig. 6.2-2 SPRAY65 predicted plume centerline concentrations for Goldfish Test No. 1, 80% HF removal and W_e = 6 m/sec by a water spray at X = 100 m.

7.0 REMARKS ABOUT LABORATORY SIMULATION OF A HYDROGEN FLUORIDE SPILL

Measurements of the behavior of simulated hydrogen fluoride gas clouds dispersing over small-scale models placed in meteorological wind tunnels provide an opportunity to evaluate relative merits of various mitigation techniques and the associated hazards of the gas cloud in a controlled environment. Two systems at different geometric scales will exhibit similitude if a one to one correspondence exists in space and time between fluid particle kinematics (locations, velocities, accelerations and rotations) caused by fluid particle dynamics (pressures, gravity, Coriolis forces, viscous forces, etc.), when properly scaled by characteristic scales of fluid properties, force, length and time. To achieve this similarity, however, is not trivial. The specification of dimensionless parameters which guarantee similarity has historically been the subject of much discussion and debate.

The capabilities and limitations of physical modeling techniques for dense gas clouds were summarized by Meroney (1986a), and a formal set of guidelines were proposed by Meroney (1986b) to assure credible physical modeling for the prediction of behavior of dense gas clouds. This section discusses the specific range of HF spill conditions suitable for credible modeling, the need for special corrections applied to measured model concentrations, and the potential for modeling the reactive character of an HF cloud.

7.1 Wind Tunnel Performance Envelope for HF Spills

The viability of a given simulation scenario is not only a function of the governing flow physics but the availability of a suitable simulation facility and the measurement instrumentation to be employed. It is appropriate, therefore, to suggest bounds for the range of field situations which can reasonably be treated by physical modeling.

The major practical limitations of accurate wind tunnel simulation of HF cloud dispersion are (1) operational constraints, particularly the inability of most facilities to obtain a steady wind profile, or to accurately simulate atmospheric turbulence at the lowest wind speeds of interest, and (2) Reynolds number constraints (as yet somewhat ill-defined) associated with the proper scaling of the mixing turbulence and the frontal velocities. When these considerations are combined with estimates of the restraint to plume expansion by wind tunnel side walls, these considerations permit the development of performance envelopes for particular wind tunnel facilities.

Different performance envelopes result depending upon whether experimental focus is placed upon the behavior of pure HF and its associated high initial specific gravity (circa 10-14) or pre-diluted HF found in the region following jet mixing and its associated low specific gravity (circa 1.3). Two envelopes are considered below, one appropriate to the simulation of pure HF using an SF_6 simulant, and one appropriate to the simulation of dilute HF after it is mixed to a mass ratio of lbm air/lbm HF equal to 5.0. In the latter case it is assumed that the simulant gas has a specific gravity equal to 1.29.

It is instructive to consider the operational constraints on meteorological wind tunnels to determine those field situations which may be exactly simulated or only marginally simulated. Operational limitations used to construct Figures 7.1-1 and 7.1-2 include:

1. Most large wind tunnels are unable to function satisfactorily at very low wind speeds (< 0.1 m/sec). At low wind speeds the wind tunnels become sensitive to small disturbances, both external and internal, which lead to unrealistic perturbation of the mean flow.

2. The associated inability to maintain large Reynolds number.

   a. When the characteristic obstacle Reynolds number ($Re = UL_c/\nu$) falls below 3300, wake turbulence no longer remains similar to field conditions. Figure 7.1-1 and 7.1-2 consider the limiting effect of a prototype obstacle ten meters tall.

   b. When the wall roughness Reynolds number ($Re_* = u_* Z_o/\nu$) falls below 2.5, the near-wall region will not behave in a fully turbulent manner. This turbulence level will govern HF mixing in the far-field region. Since HF vapor is hazardous at ppm levels, the correct simulation of this parameter is more critical than for flammable gases where cloud mixing drops below the flammability limit in the near-field region. Figures 7.1-1 and 7.1-2 show a curve presuming the field roughness length is 10 centimeters.

3. A minimum spatial resolution for concentration measurements of 2.0 mm is likely in the laboratory. Minimum pertinent vertical resolution required in the field to define vertical concentration profiles may be 0.25 m for a shallow HF cloud.

4. Mixing rates associated with molecular diffusion exaggerate dilution at low wind speeds. Molecular dispersion becomes significant for unobstructed flows (or after water spray or vapor barrier turbulence has diminished) when the Peclet/Richardson number ratio, Pe/Ri, is less than 1500, or Pe_*/Ri_* is less than 0.2. This effect may be particularly important for HF predictions, since the error produces concentrations which are too low.

5. Lateral interference with a spreading dense plume by wind tunnel walls. Interaction conditions may be calculated using the spread formula proposed and tested against laboratory and field spills by Britter (1980). Since the constraint this effect produces would be typically smaller than Reynolds number limitations for most meteorological wind tunnels (> 2 m wide), this curve is not shown on Figures 7.1-1 or 7.1-2.

6. Meteorological wind tunnels typically produce turbulent eddies no larger than the simulated boundary layer thickness. This results in model turbulent integral scales near 2 to 3 m, but atmospheric turbulence which dominates mixing in the far-field region supports ground level integral scales near 100 m. Thus, models with length scale ratios (LSR) smaller than about 33 should not be used in most meteorological wind tunnels.

Prototype velocities (U_p) plotted on Figures 7.1-1 and 7.1-2 are related to Length Scale Ratios (LSR) through equality of the Froude number parameter introduced in Chapter 4.0. An HF cloud has a source specific gravity near 10, and the densest isothermal simulant used in the laboratory is SF_6 with a specific gravity equal to 5.1. Thus increased laboratory wind speeds through distorted scaling of density is not possible, indeed model wind speeds are required significantly lower than for simulation of LNG, propane, chlorine, or other hazardous gases.

The final region for reliable simulation of HF dispersion down to ppm levels lies in a triangle between the Re* > 2.5 line and the Min Integral Scale line. Accurate scaling of far-field dispersion at prototype wind speeds below 5 m/sec or with model LSR above 100 is unlikely. Near field simulation of the influence of vapor barriers and water spray curtains is likely down to prototype wind speeds of 2 m/sec and model scales below 150. The quantitative penalty for working outside these envelopes is not very well defined. Many of the laboratory experiments discussed in Chapter 4.0 fall in the region to the right of the minimum wind speed criteria and below the minimum resolution criteria, but the experimentalists were focusing on near source plume behavior.

7.2 Conversion of Model Concentrations to HF Concentrations

The local molar concentrations, measured in the model and the prototype will be directly proportional to the actual number of moles released at the source. Most plume studies measure the concentration magnitudes at distances far downwind from the source; hence Snyder (1981) encourages analysts to evaluate source volume flux rates at ambient (not stack or source) temperatures. At long distances, the effect of volume flux ratio distortion and source gas temperature differences between a model and prototype are corrected by this approach. Unfortunately, correct simulation of the kinematics of dense plume motion and initial mixing near the source does require similarity of the volume flux ratio. Consideration of the molar concentrations, volume flux ratio effects, and source temperature distortions produces the following relation which relates prototype and model concentrations.

$$C_p = C_m/(C_m + (1 - C_m)(\underline{V}T_{amb}/T_s)_m/(\underline{V}T_{amb}/T_s)_p),$$

where $\underline{V} = Q/(U^*L_c^2)$ is the Volume Flux Ratio. Thus, whenever the Volume Flux Ratio is not simulated, or there are different source temperatures used in the model and prototype, the model concentrations must be corrected to field values. Of course this relation presumes that plume kinematics and dynamics are correctly simulated in all other respects. Note that if $\underline{V}_m = \underline{V}_p$ and $(T_{amb}/T_s)_m = (T_{amb}/T_s)_p$, then $C_p = C_m$.

Assuming that the Volume Flux Ratio is exactly scaled between model and prototype and that an isothermal simulant at 300° K is used in the model, then for a pure HF gas released at the effective source temperature of 20° K, low prototype concentrations will be about 15 times larger than model measurements. Figure 7.2-1 displays the nature of the concentration correction over a wide range of molar concentrations. Given a model concentration measurement system accurate to 1 ppm, then 15 ppm HF levels can be predicted in the field; however, if the instrument is reliable to say 100 ppm, then only 1500 ppm HF levels can be predicted in the field.

Fortunately, an alternative approach which simulates plume behavior after it has diluted to the minimum temperature levels may be satisfactory. In this case concentration corrections may be quite small (See Figure 7.2-1). The only drawback to this procedure is the absence in the laboratory model of some source dynamics very close to the release point.

7.3 Potential for Laboratory Simulation of a Reactive Hydrogen Fluoride Plume

Water spray/HF measurements by Allied Corporation reported by Blewitt et al. (1987c) suggest that water sprays might remove 78% or more of the HF from a plume through chemical reaction and deposition. It would be desirable to simultaneously model the removal and dilution influence of water spray curtains and fences in a wind tunnel. Unfortunately, it is likely that the reaction rate response times, the heat transfer convection and conduction time constants, and the time constants associated with turbulent mixing will be mismatched during the typical model experiment. This has been found to be the case during model tests of the dilution of cryogenic gas clouds (See Andriev et al., 1983). Buitjles (1981) performed exploratory model tests with a NO plume and a tunnel flooded with ozone, O_3. The gas interaction involves a first-order chemical reaction; however, the measurements were not very extensive, and application of the technique seems limited.

The chemical reaction that occurs between HF gas and water requires large surface areas. Thus droplet sizes recommended in field experiments were less than 500 micrometers but larger than 100 micrometers to permit gravitational settling. To maintain an equivalent surface area ratio during model tests droplets at a length scale ratio of 100 must be less than 5 micrometers, but then little deposition would occur in the model experiment.

One must conclude that a study of a chemically reactive cloud in the wind engineering laboratory should be a subject for basic research and is not suitable for an environmental impact analysis at this time.

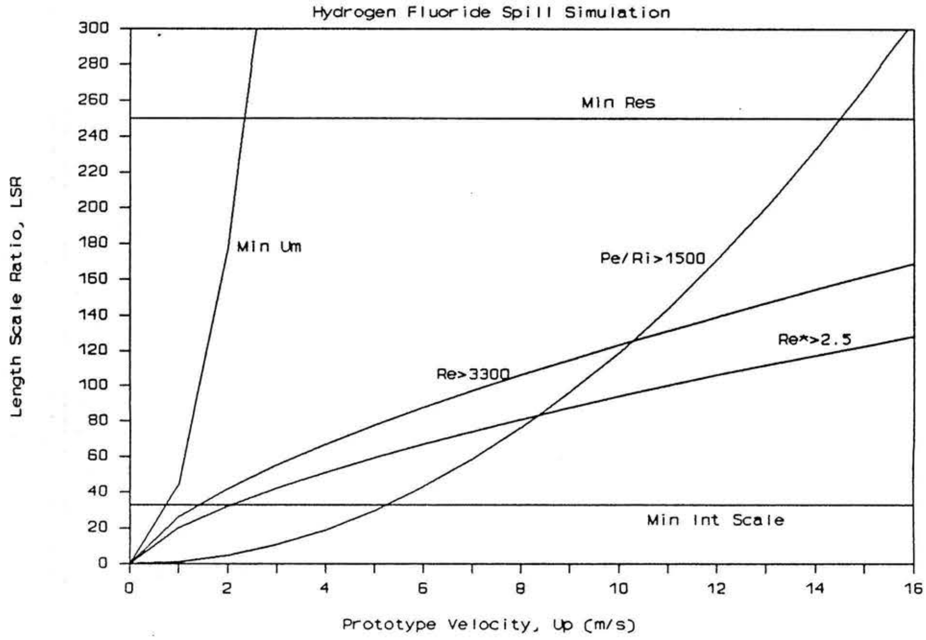


Fig. 7.1-1a Performance Envelope for Simulation of HF Spills in Meteorological Wind Tunnels, S.G. = 1.29

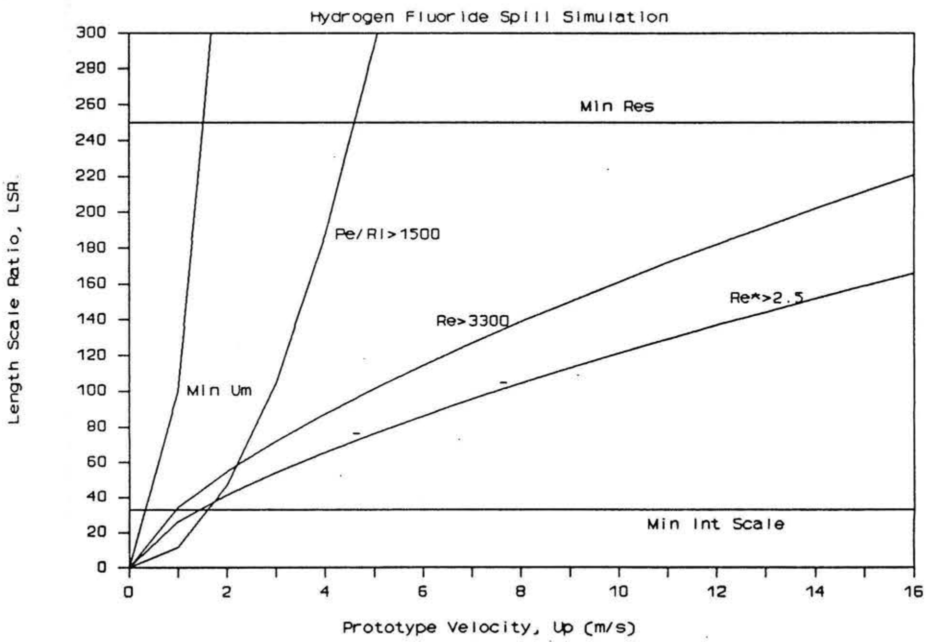


Fig. 7.1-1b Performance Envelope for Simulation of HF Spills in Meteorological Wind Tunnels, S.G. = 5.05

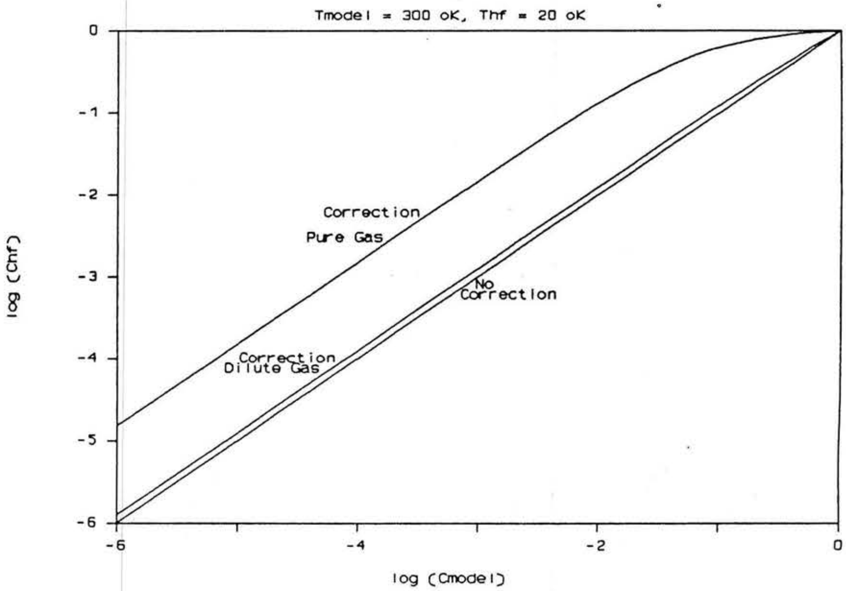


Fig. 7.1-2 Conversion of Model Concentrations to HF Concentrations, Corrections for Pure Gas and Dilute Gas Model Scenarios .

8.0 CONCLUSIONS

Accidental releases of Hydrogen Fluoride (HF) can result in initially dense gas clouds that will typically contain a mixture of gases, aerosols and droplets which can be transported significant distances before lower hazard levels of HF concentration are reached. The potential for hazard mitigation through the use of containment fences, vapor barriers or water-spray curtains to hold-up or delay a gas cloud expansion, elevate plume trajectories downwind of barriers, and enhance cloud dilution or remove HF gas from a cloud by deposition were considered in this report. Previous related field and laboratory experiments were analyzed to estimate the effectiveness of barrier devices. Conclusions drawn from these analysis and review follow.

8.1 Dilution Performance of Vapor Barriers in the Near-field Region

Eleven data sets from field and laboratory experiments dealing with the influence of vapor barrier fences and water spray curtains on the dispersion of dense gas clouds were examined. Tests were paired into sets of data which reflected the dilution of the cloud with and without the barriers present. Peak concentration ratios, cloud arrival time ratios, peak arrival time ratios, and departure time ratios were calculated for each test pair. Consideration of the regions immediately downwind from the fences and sprays (distances less than 300 m downwind of the barriers) reveals that:

<u>Vapor Barrier Fences:</u>

@ Concentrations directly downwind of a vapor fence may be slightly higher or lower than for plumes released in the absence of the fence. The concentrations then diminish to a minimum peak concentration ratio dependent upon source strength, spill volume, wind speed and fence height.

@ An additional fence or vortex generator located upwind of the source tends to reduce the likelihood of an increased concentration ratio directly downwind of the downwind fence.

@ Additional dilution occurs downwind of the fence as the turbulence produced by the shear at the top of the fence persists for about 30 fence heights.

@ A fence tall enough to hold up a dense gas cloud will produce a broader cloud immediately downwind of the barrier; thus concentrations to the sides of the cloud centerline will actually increase substantially above values found in the absence of the barrier.

@ Given comparable spill situations the decrease in concentration ratio is not strongly dependent upon Froude number magnitude or wind speed. ANOVA calculations suggest the most important variables are spill volume, and spill rate.

@ The peak concentration ratio is not significantly influenced by wind speed. Although the turbulence levels at fence top are expected to increase with wind speed, the cloud residence time in the fence wake decreases with increasing wind speed. The net effect is minimal variation in fence performance with wind speed.

@ Taller fences are more effective than shorter fences. The top of tall fences are at levels where higher wind speeds act. Taller fences also have longer wake regions.

@ Cloud arrival time, peak arrival time, and departure time ratios often increase directly downwind of a fence because lower winds in the wake advect the cloud more slowly. However, farther downwind the cloud arrives earlier because once the cloud leaves the wake region it is transported downwind with the greater depth averaged velocities associated with the increased cloud height. As the cloud height asymptotes to the no-fence conditions even farther downwind no change in arrival time will be observed.

Water Spray Curtains: Removal Charactersitics

@ Concentrations in a gas cloud will decrease abruptly as a result of chemical reaction and removal processes associated with HF and water spray interaction, even when accelerated entrainment associated with the water spray curtain is not considered. The removal efficiency will be a function of water/HF volume ratios, water droplet sizes and cloud concentrations.

Water Spray Curtains: Dilution Characteristics

@ Concentrations in a gas cloud will decrease abruptly by factors ranging from 2 to 80 depending upon barrier location, wind speed, water spray intensity, and spray/cloud intercept area.

@ Water spray curtains are more effective at low wind speeds. Given a constant curtain entrainment velocity, the dilution performance varies inversely with wind speed.

@ Water spray curtains are more effective closer to the source. As the water curtain is placed further downwind the dilution rate decreases; however for constant wind speed, water spray intensity, and intercept area the resultant concentrations downwind of the curtain are about equal.

@ A strategic combination of droplet size, spray pattern, and nozzle orientation can improve curtain performance by a factor of 2 to 5.

@ Cloud height directly downwind of a water spray curtain will increase proportional to the dilution obtained in the curtain.

- Turbulence and mixing motions generated by the spray curtain do not appear to persist downwind of the curtain location.

8.2 Dilution Performance of Vapor Barriers in the Far-field Region

HF is hazardous at ppm levels. Thus, far-field concentrations are of interest in evaluating mitigation strategies. Most laboratory and field experiments were originally constructed to consider the behavior of flammable gases; hence, measurements were only taken at distances out to 1000 m downwind or less. Consideration of the regions modestly far downwind of barriers and spray curtains (300 m to 1000 m) reveals that:

Vapor Barrier Fences:

- Entrainment levels return to pre-fence levels at distances greater than 30 to 50 fence heights downwind of the fence location. After that point the concentrations asymptote to levels found in the absence of the fence or barrier about 2000 m downwind of fences placed between 10 and 100 meters downwind of the spill site.

- Again peak concentrations measured during the experiments did not generally fall below 10,000 ppm of simulant or 150,000 ppm HF over the measurement domain. The one exception was data from the unperturbed Goldfish HF Trials where peak concentrations as low as 200 ppm HF were measured at 3000 m downwind of the spill site. Again it appears that plausible height fences (5 to 10 m) would produce dilutions that would asymptote to levels found in the absence of the fence 2000 m downwind.

Water Spray Curtains: Removal Characteristics

- The reduction in HF cloud concentrations induced by water spray/cloud deposition processes persists at all downwind distances.

Water Spray Curtains: Dilution Characteristics

- Vertical entrainment rates return to pre-curtain values just downwind of the curtain location; hence, concentrations initially decay with distance at a rate lower than that found without spray curtains. The concentration levels asymptote to unperturbed plume levels about 2000 m downwind of curtains placed between 10 and 100 meters downwind of the spill site.

- Peak concentrations measured during the experiments did not drop below 10,000 ppm of simulant or 150,000 ppm HF over the measurement domain. It appears, however, that intersection of the original plume concentrations and the perturbed plume concentrations would occur about 1000 m downwind at levels near these values.

- @ In the far-field, but before the cloud asymptotes to no-curtain sizes, cloud arrival time, peak arrival time, and departure time ratios are less than without curtains. Again this is associated with higher depth-averaged velocities which advect the deeper clouds faster.

8.3 Vertical Concentration Distributions

Vertical concentration distributions were available from the data taken during the pre-Falcon Trials vapor barrier tests (Chapter 4.8) and the water spray curtain tests (Chapter 4.5).

Close to the fence ($x/H < 2$) during the pre-Falcon Trials elevated concentration maximums occurred as the plume flowed over the fence. However, at all other downwind distances the maximum occurred at ground level. Vertical concentrations indicated a well mixed plume existed to heights above the measurement domain. Vertical concentration profiles measured without a fence present displayed the characteristic of shallow plumes decaying exponentially with height observed for dense gas clouds.

At elevated heights the cloud arrived and departed earlier for the enclosure cases than for the unperturbed situation.

Water spray curtain measurements produced very similar shape plumes to the fence scenarios; however, no elevated maximum occurred near the curtain.

8.4 ANOVA Regression Model

The ANOVA multilinear regression model was only applied to the pre-Falcon data set, since this data was the most complete, reliable, and comprehensive available.

The ANOVA procedure was applied to the logarithmic version of a simple power law formulae, i.e.

$$(1 - C_w/C_{wo}) = A*Fr^a*\underline{V}^b*(Vol/L_c^3)^c*(H/L_c)^d*(x/L_c)^e,$$

where A, a, b, c, d, and e are constants to be determined by the ANOVA procedure. Since the peak concentration ratios were prepared from comparable data pairs, it was quickly found that inclusion of the Froude number term did not reduce variance significantly. The dominant terms were volume spill rate and total volume spilled. The optimum relation found was:

$$C_w/C_{wo} = 1 - 1.55*\underline{V}^{0.051}*(Vol/L_c^3)^{-0.163}*(H/L_c)^{0.04}*(x/L_c)^{-0.035}.$$

This expression applies only to a spill completely surrounded by a fence enclosure of aspect ratio 2 to 1 with wind flowing along the longitudinal dimension of the enclosure. The method is also limited to the data range near to that used to determine the coefficients.

8.5 Proposed Entrainment Models

Given a box or depth-integrated type numerical model simple expressions to account for the increased entrainment associated with water spray curtains or fence barriers may be used with confidence. These models do not account for chemical reactions, deposition, gravity current reflection, rapid flow speed up through a porous barrier, or the presence of a hydraulic jump downwind of a barrier. Both the initial dilution and post-barrier concentration decay are predicted well. The essence of the entrainment models are:

Fence entrainment model:

$$(w_e)_{fence} = 0.1\ U(H)(1 - P)(1 - (x - x_f)/(30\ H)),$$

where U(H) is the wind speed at fence height, P is fence porosity, H is fence height, x is distance downwind of the spill point, x_f is the fence location. Note that $(w_e)_{fence}$ exceeds background entrainment rates only to 30H downwind of the fence, after which it is set to zero.

The entrainment velocities above should be added to the values available calculated for entrainment from turbulence in the background atmospheric flow.

Water spray entrainment model:

$$(w_e)_{spray} = \frac{Q_s(T_{amb}/T_s)(1 - C_{spray}/C_{no\ spray})}{C_{spray}N(\pi * d_g^2/4)},$$

where Q_s is HF source strength, N is the total number of spray nozzles, and d_g is the spray intercept diameter with the cloud. This equation does somewhat presume the answer desired; however, other expressions related to the dynamics of the water spray nozzles themselves are available (Moodie, 1985).

8.6 Laboratory Simulation of a Hydrogen Fluoride Spill

The capabilities and limitations of physical modeling techniques for HF gas clouds were reviewed. Performance envelopes were constructed to illustrate the constraints of facilitiy size and gravity spreading. The following conclusions were made:

@ Laboratory simulation of a pure HF release with an isothermal simulant is not recommended. Reliable simulations would be limited to prototype wind speeds greater than 5 m/sec at scales less than 1:100. Model concentrations must be adjusted upward by a factor of 15 in the far downwind regions.

@ Laboratory simulation of a pre-diluted HF cloud can be accomplished. Reliable simulations should be possible at all distances for prototype wind speeds greater than 5 m/sec at scales less than 1:100.

@ Reliable simulations of pre-diluted HF clouds should be possible in the near-field of barriers and sprays for prototype winds speeds greater than 2 m/sec and at scales less than 1:150. The quantitative penalty for working outside these ranges is not well defined.

@ The laboratory simulation of a water spray curtain and a reactive hydrogen fluoride plume cannot be recommended without further basic research. Basic studies of how reactive plumes disperse in the presence of humidity, reactants, turbulence, and compressibility effects should be supported.

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APPENDIX: Numerical Simulation of Water Spray Dilution of Gas Plumes

A.1 Entrainment due to a water-spray barrier

The presence of a water spray barrier results in a local increase in entrainment rate. McQuaid and Fitzpatrick (1981) hypothesized a finite increase in local entrainment without specifying how the numbers would be related to nozzles used or their location; however, McQuaid (1975) derived a semi-empirical relationship for conical sprays which gives the rate of entrainment of air as a function of water flow, water pressure and size of spray. Of course, $(w_e)_{spray} = Q_e/A_i$, where Q_e is the flux of air entrained and A_i is the area of intersection between cloud and spray. Heskestad et al. (1976) also predicted a range of entrainment rates in terms of water flow, spray type, spray angle and distance from the nozzle. Values of entrainment rate velocity ranged from 5.0 to 34.0 m/sec when nozzle diameters ranged from 1 to 25 mm, spray angles ranged from 30 to 130°, and cloud intersection distance varied from 0.25 to 4.0 m.

Water spray entrainment can be included in the numerical models by either using a multiplicative factor with the normal entrainment rate, i.e.,

$$(w_e)_{total} = MR \times w_e,$$

or an additive factor, i.e.

$$(w_e)_{total} = w_e + (w_e)_{spray}.$$

The additive factor approach must be considered more realistic; however, there are circumstances where a multiplicative methodology might be more convenient if shown to be nominally effective. The area of interaction, A_i, is specified by the downwind interval, S, over which the spray intersects the plume. To ensure good mixing, McQuaid (1977) suggested a minimum velocity of air in the spray of $(w_e)_{spray} > 6$ m/sec at the plane where the spray meets the gas. In a 3 m/sec wind, a typical level of entrainment due to shear mixing alone would be 0.2 m/sec; hence, the multiplicative factors will range from 25 to 170.

The interval of spray interaction, S, should relate to lateral nozzle separation, L_s, and impact circle diameter, d_g, by the equation

$$S = \pi * d_g^2/(4L_s).$$

The effective entrained air velocity may be estimated from actual field or laboratory data from

$$(w_e)_{spray} = \frac{Q_s(T_{amb}/T_s)(1 - C_{spray})/C_{no\ spray})}{C_{spray} N(\pi * d_g^2/4)},$$

where N is the total number of spray nozzles. Alternatively one must estimate entrainment velocities from methods proposed by McQuaid (1975) or Heskestad (1976).

These models for water spray interaction with dense gas clouds have been validated by comparison with extensive laboratory measurements (Meroney and Neff, 1985).

A.2 Calibration of the Water Spray Entrainment Model

In a paper by Meroney and Neff (1985) extensive comparisons were made of the water spray algorithms proposed in Chapter 2.4 and the laboratory water spray tests discussed in Chapter 4.5. As shown in Figures A.2-1, 2, and 3 the use of an additive specified water spray entrainment velocity over the intercept region of the gas cloud faithfully reproduces measurements. The comparisons were made over a 5-fold range of water spray intensity and a 2.5-fold range of wind speed. Note that increased wind speed tends to decrease the diluting effect of the water spray curtain. This result occurs because at higher wind speeds the gas cloud parcels spend a shorter time within the spray curtain.

An additive water spray entrainment factor which is proportional to water volume flow rate, droplet size, and spray angle will adequately predict the initial dilution of a gas cloud passing through a spray curtain. The numerical model also satisfactorily reproduces the post spray curtain concentration decay rates.

A.3 Goldfish Trial No. 1 with Water Sprays

As noted in Chapter 5.2 water spray curtain tests were performed during the Goldfish Trials No. 4, 5, and 6. These tests included chemical reactions between the HF and the water spray and subsequent deposition of the HF on the ground. Goldfish Trial No. 1 conditions are used below to examine the effect of various spray placement and water spray entrainment rate alternatives.

Effects of Spray Barrier Location

In these calculations, only the location of the spray curtain was changed: from 30 to 50 to 100 to 400 meters downwind of the spill center. A nominal spray entrainment rate of 6 m/sec was chosen for these calculations. Figure A.3-1 displays box model predictions. The post spray concentrations are very similar with slightly lower concentrations when the spray is further downwind. The magnitude of the reduction in concentrations when the barrier is farther from the source is not large and any advantage in final concentrations would be outweighed by the greatly increased water consumption as the spray curtain width increases over the wider plume. Note that none of the spray curtains manage to dilute the peak concentrations significantly beyond 1000 m, yet concentrations still exceed 2000 ppm, which is far above the TLV for HF.

Figure A.3-2 displays the effect of a water spray curtain on plume height when activated at various downwind distances. Near the source cloud height is increased 25-fold; whereas further downwind the same spray curtain only causes a 2.5-fold increase in height.

Effects of Spray Entrainment Rate

Calculations were performed for a ten-fold range of spray entrainment velocity. Given a constant spray location (100 m), wind speed (5.6 m/sec), and plume width, increased entrainment velocities result in proportional increases in dilution. As noted in Figure A.3-3 a fairly substantial entrainment rate of 10 m/sec will result in about a ten-fold dilution for these conditions.

Plume height also increases at a rate proportional to water spray entrainment velocity in Figure A.3-4.

Effects of Wind Speed

Increased wind speed advects the gas plume through the spray zone more quickly. Figures A.3-5 and 6 exhibit the marked effects of wind speed on dilution effectiveness. Given a constant water spray entrainment rate of 6 m/sec, then a plume moving slowly through the spray curtain at 1 m/sec will receive about 12.5 times more dilution than a plume traveling at 10 m/sec. Cloud height increases by the same ratio.

Water Spray Effects on Arrival, Peak Concentration and Departure Times

SPRAY23 was used to estimate the influence of a water spray barrier on the downwind arrival of a transient gas cloud. A base case of a spray curtain located 100 m downwind of the source operating with the Goldfish Test No. 1 atmospheric and spill conditions and a water spray entrainment velocity of 1 m/sec was considered. Cloud arrival and departure were determined by two separate techniques. In Figure A.3-7 the arrival and departure of the could based on cloud height are shown. The cloud is seen to arrive and depart in a wave like manner with a sudden rise and fall in height. Note that the cloud arrives and departs earlier in the presence of the water spray curtain. In Figure A.3-8 the arrival and departure times are based on the arrival and departure of the 10% of peak concentration levels. The peak arrival time was chosen to be when the local concentration reaches 90% of the maximum level. This value was chosen since the peak in the time trace was sometimes rather flat.

The decrease in arrival, peak arrival, and departure times result from the lofting of concentration to greater heights by the spray curtain. The raised portion of the cloud travels at greater velocities since the boundary layer permits wind velocity to increase with height. Downwind the cloud disperses downward to the ground resulting in shorter arrival, peak arrival, and departure times.

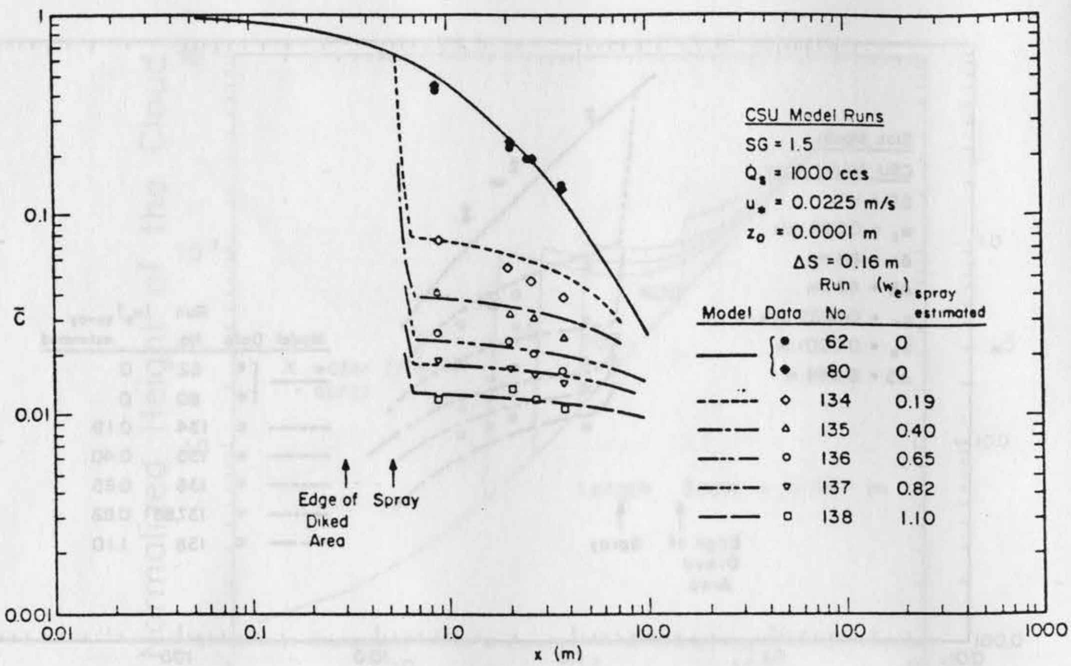

Fig. A.2-1 Comparison of Observed and SPRAY62 Predicted Plume Centerline Concentrations for Colorado State Water Spray Tests

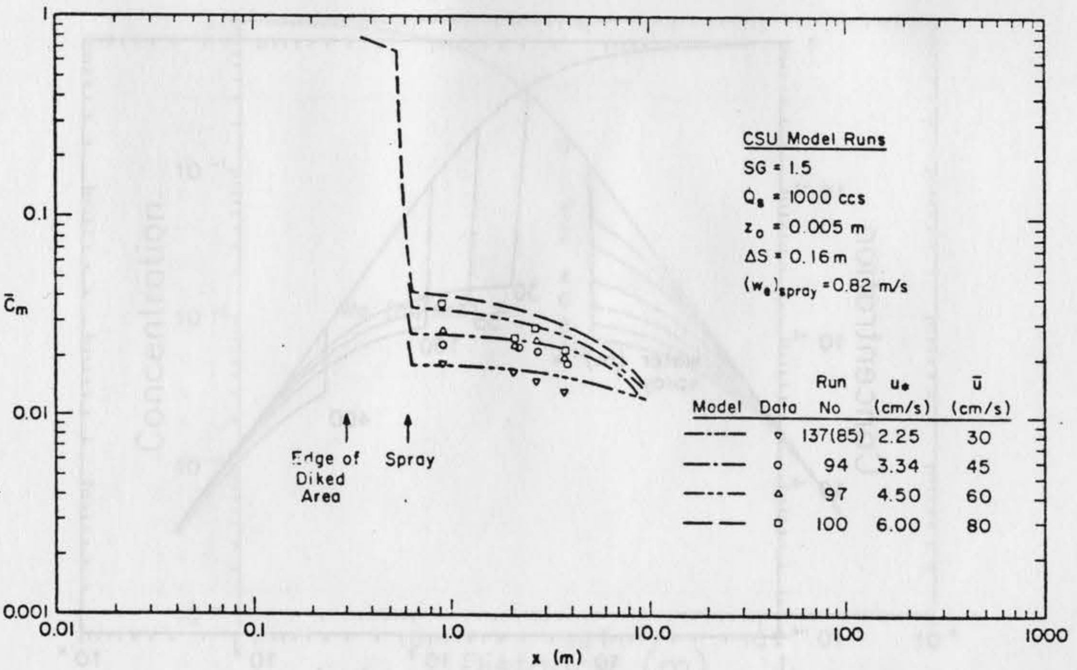

Fig. A.2-2 Comparison of Observed and SPRAY62 Predicted Plume Centerline Concentrations for Colorado State Water Spray Tests

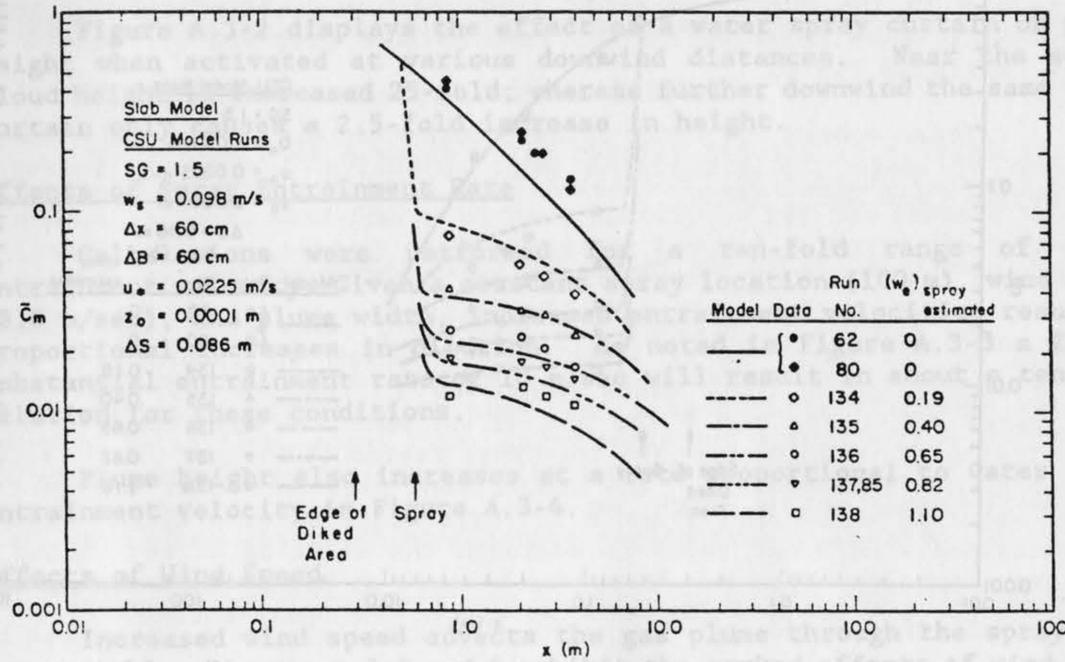

Fig. A.2-3 Comparison of Observed and SPRAY23 Predicted Plume Centerline Concentrations for Colorado State Water Spray Tests

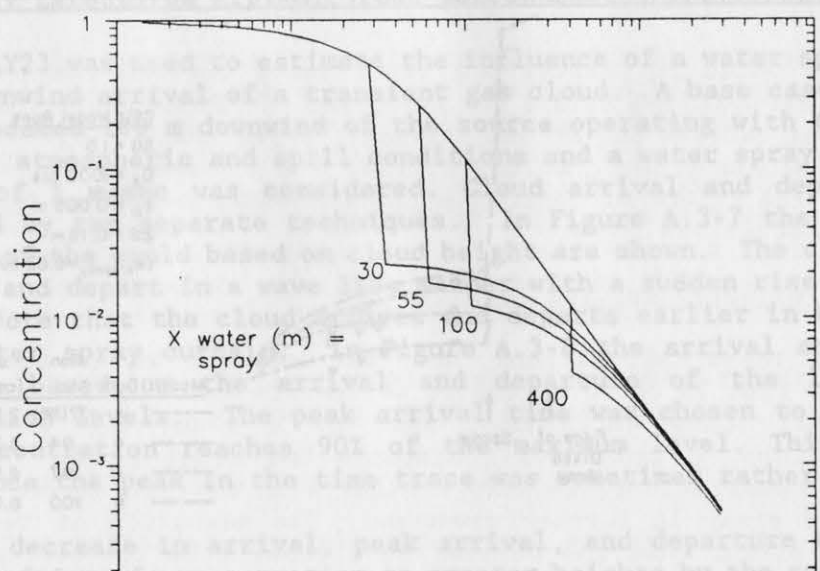

Fig. A.3-1 SPRAY62 Predicted Plume Centerline Concentrations for Goldfish Test No. 1, Water Spray Placed at X_{spray} = 30, 55, 100, and 400 m

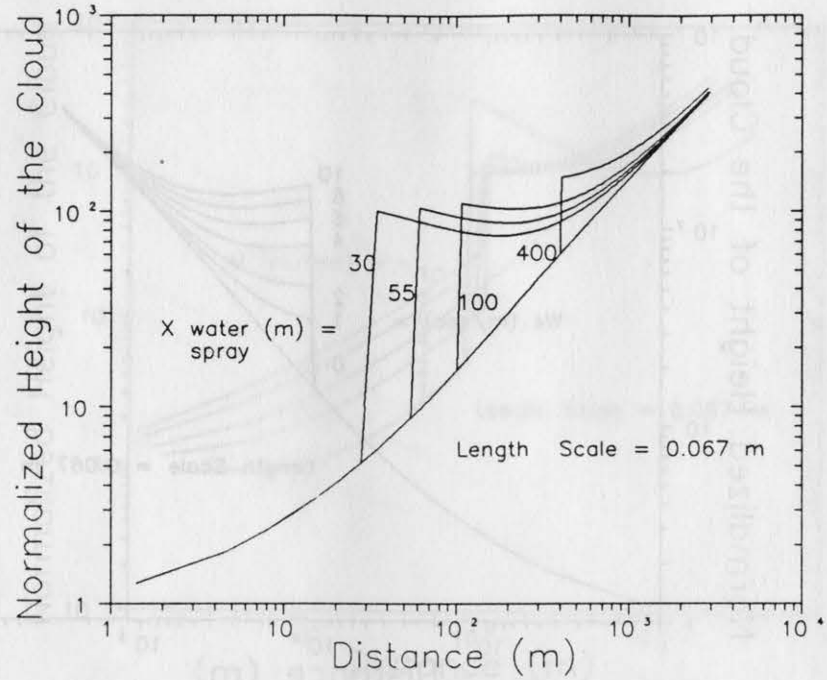

Fig. A.3-2 SPRAY 62 Predicted Plume Heights for Goldfish Test No. 1, Water Spray Placed at X_{spray} = 30, 55, 100, and 400 m

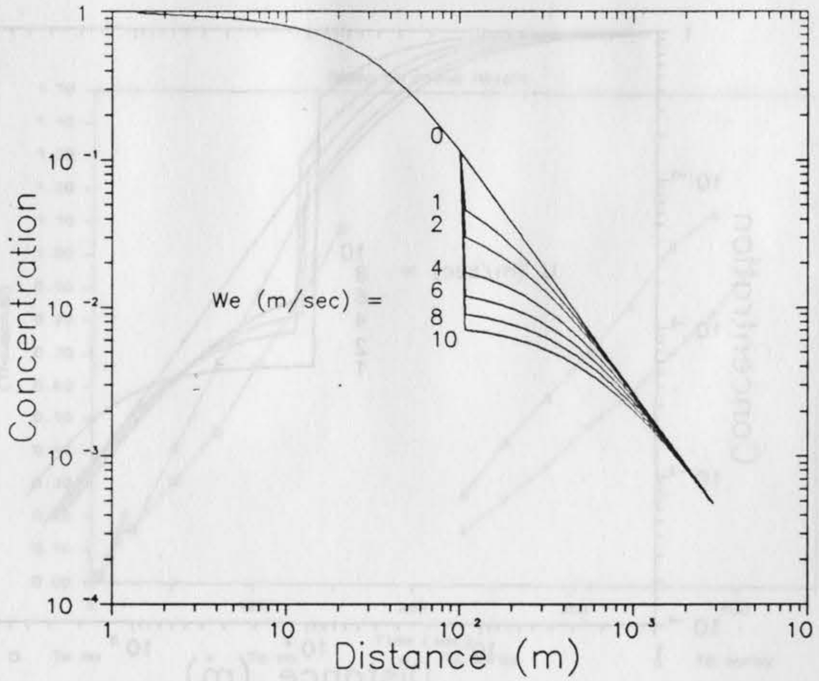

Fig. A.3-3 SPRAY62 Predicted Plume Centerline Concentrations for Goldfish Test No. 1, X_{spray} = 100 m, w_e = 1, 2, 4, 6, 8, and 10 m/sec

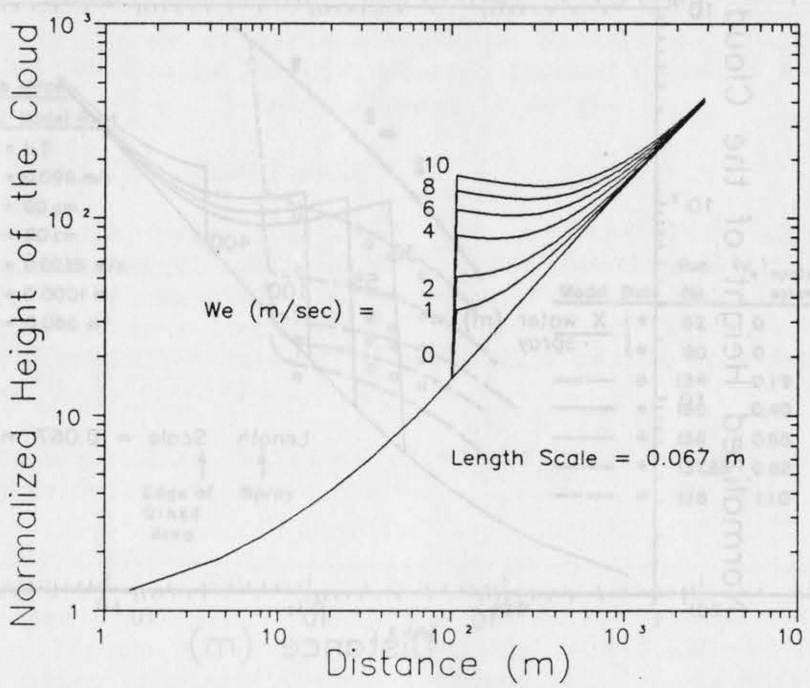

Fig. A.3-4 SPRAY62 Predicted Plume Heights for Goldfish Test No. 1, X_{spray} = 100 m, w_e = 1, 2, 4, 6, 8, and 10 m/sec

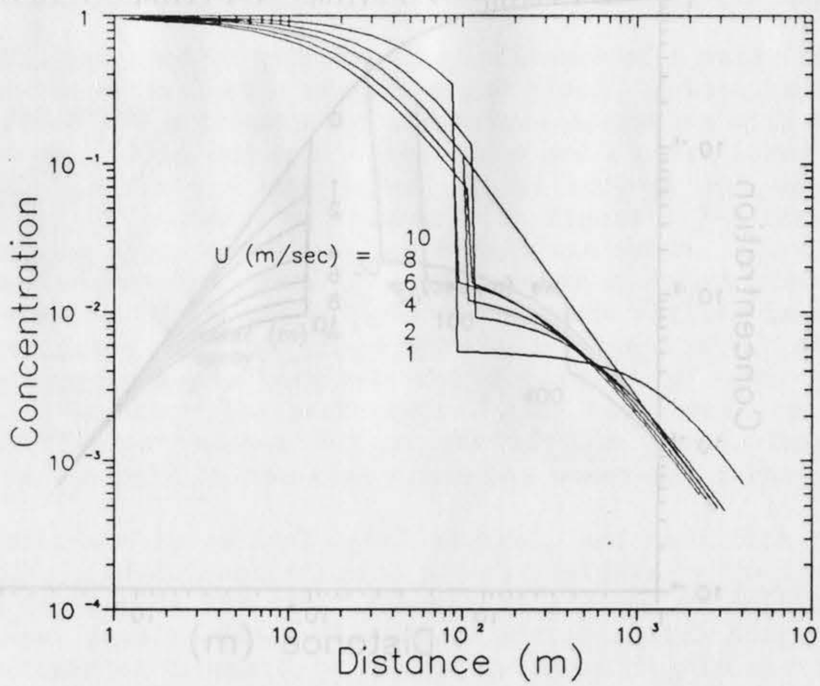

Fig. A.3-5 SPRAY62 Predicted Plume Centerline Concentrations for Goldfish Test No. 1, X_{spray} = 100 m, w_e = 6 m/sec, U = 1, 2, 4, 6, 8, and 10 m/sec

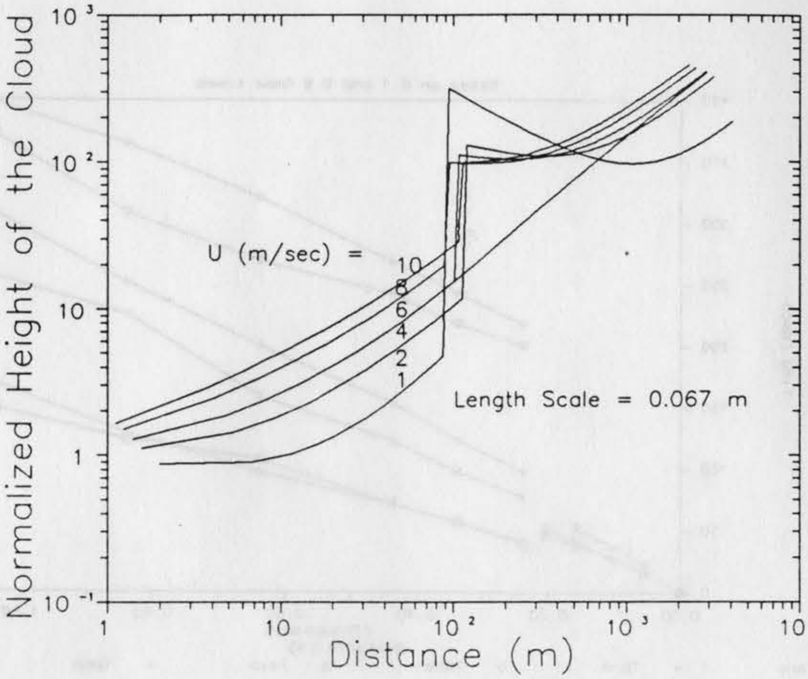

Fig. A.3-6 SPRAY62 Predicted Plume Heights for Goldfish Test No. 1, X_{spray} = 100 m, w_e = 6 m/sec, U = 1, 2, 4, 5.6, 8, and 10 m/sec

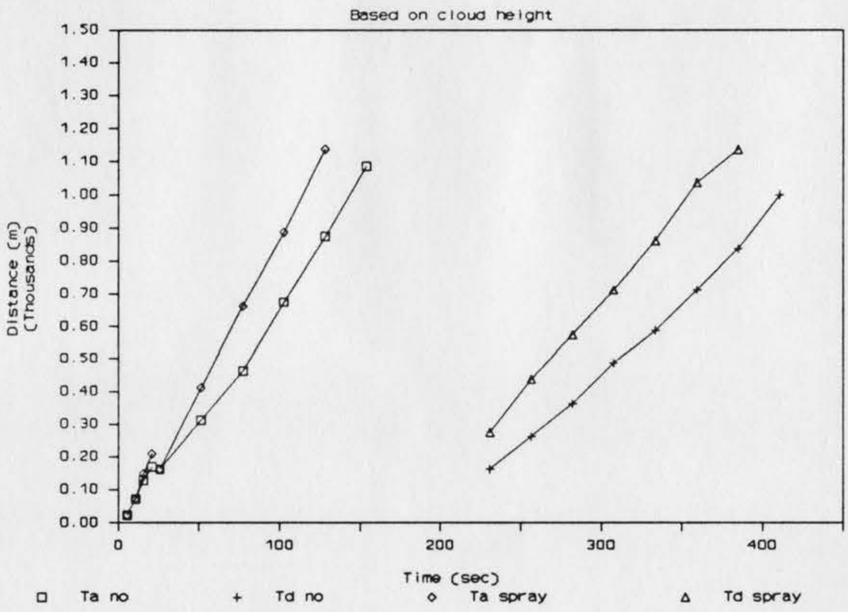

Fig. A.3-7 SPRAY23 Predicted Cloud Arrival and Cloud Departure Times for Goldfish Test No. 1, X_{spray} = 100 m (Based on predicted cloud heights)

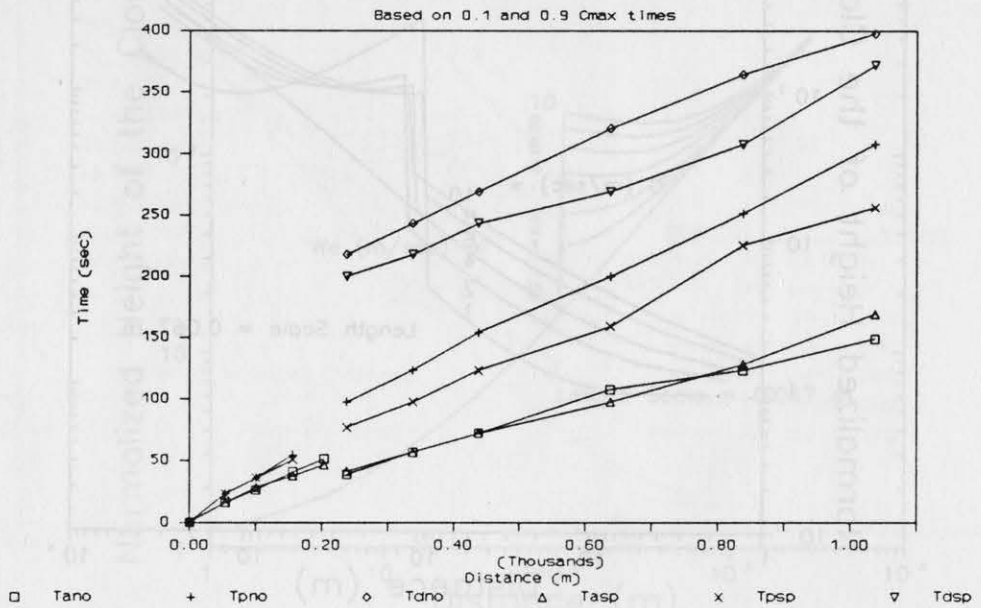

Fig. A.3-8 SPRAY23 Predicted Cloud Arrival and Cloud Departure Times for Goldfish Test No. 1, X_{spray} = 100 m (Based on predicted cloud concentrations)