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BLUFF-BODY AERODYNAMICS INFLUENCE ON TRANSPORT AND DIFFUSION OF HAZARDOUS GASES: Shelterbelts and Vapor Barrier Fences

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Abstract

Flow perturbations, recirculations and turbulence generated by buildings, obstacles, and other bluff bodies will often dominate the dispersion of flammable or toxic gases in the atmosphere. Flow over or through 2-dimensional barriers can result in plume lofting, pollutant stagnation in downwind recirculation zones, enhanced mixing in elevated shear zones, or increased deposition if the barrier is itself a water or steam curtain. Flow around 3-dimensional obstacles can produce regions of enhanced longitudinal vorticity, which can transport gases downward and sometimes extend plume concentrations to greater downwind distance. Under stratified conditions 2-dimensional objects can block ground-level flow; whereas, 3-dimensional obstacles can deflect or channel pollutants into unexpected areas.

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.

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

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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. During the 1988 Bluff Body Aerodynamics Conference in Kyoto, Meroney (1990) reviewed some forty-seven field and laboratory situations which related to the character of dispersion in the presence of bluff bodies of various shapes. Nine situations identified included companion sets of field and laboratory data. Eleven additional studies were only examined at full scale, and twenty-seven additional configurations were only examined in the fluid laboratory. The review identified which features of bluff body flow control scalar transport, summarized field and laboratory data, critiqued several semi-empirical models commonly used to predict the behavior of point-source releases of neutral density gases, and noted how bluff bodies can sometimes mitigate gaseous hazards.

In this review we will examine the interaction of dense gas clouds with bluff barriers and the ability of fluid or numerical modeling to illuminate the entrainment mechanisms further.

2.0 BUILDING AERODYNAMICS

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 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.

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 were intended 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.

2.1 Hazardous Gas Dispersion

Meroney (1982) reviewed the use of fluid modeling to evaluate the dispersion of dense gases. He noted 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) provided guidelines for using fluid modeling to generate Liquid Natural Gas (LNG) dispersion information. The second volume reviewed 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.

British Maritime Technology (Davies and Inman, 1986) 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.) The neutrally-stable wind-tunnel boundary layer adequately represented the dispersion in the more stable full-scale atmospheric conditions,

b.) The laboratory experiments reproduced field measurements of reductions in downwind dispersion distances due to vapor fences,

c.) No lower limit was detected for Reynolds number for trials involving sharp-edged mixing elements, such as buildings or fences,.

d.) Conservative simulations of continuous and instantaneous releases without obstacles present were obtained when Reynolds number ($U_{10m}*L_{Dm}/m$)exceeded 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).

2.2 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); 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). Neff and Meroney (1986) completed a pre-field-test wind tunnel series of the Falcon LNG vapor barrier test series, and Shinn and Meroney (1991) describe post-field wind-tunnel tests of the Falcon program..

British Maritime Technology (Davies and Inman, 1986), 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.

API (1989) modeled the dispersion of dense gas plumes over a variety of surface roughnesses. They examined point and area sources released over homogeneous surface roughness ranging from full-scale values of 3 to 50 cm, and generic tank farms and process units which produced effective roughness values ranging from 1 m to 17 m. As anticipated the effective roughness associated with bluff bodies like tanks, buildings, and process units enhances mixing and limits exposure to high concentrations downwind. Process units reduced concentrations from 8 to 25 times that produced over an unobstructed grassy plain. An extensive tank farm reduces concentrations downwind from 3 to 8 times. Fluid model measurements of vertical entrainment rates agreed with the values projected from solutions of codes like DEGADIS (Havens and Spicer, 1990) or SLAB (Ermak and Chan, 1986). Some dissension continues to exist about the appropriate modifications to the codes required to handle roughness which exceeds the depth of the dispersing plumes.

Confidence in the results provided by the roughness study led to further fluid model studies of the behavior of dense gas clouds influenced by vapor barriers and water-spray curtains (Petersen and Ratcliff, 1989; and Petersen *et al.,* 1992). The vapor barrier study examined the influence of different barrier mitigation strategies on hypothetical hydrogen-fluoride releases. Vapor barrier constructed around a process unit were found to delay downwind cloud arrival and reduce concentrations, but plume concentrations were found to return to values very close to those anticipated without the additional enclosure at distances further downstream. Thus, for gases which are hazardous at ppm levels, the barrier configurations were found to provide only minimal additional dilution far downwind. Water-spray curtains, on the other hand, did produce significant dilution and deposition. Once material was actually removed from the gas cloud, substantially lower concentrations were measured downwind.

3.0 FIELD AND LABORATORY DATA ON DENSE-GAS BLUFF-BODY AERODYNAMICS

Accidental releases of some hazardous and flammable gases 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 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, enhance cloud dilution, or remove the gas from a cloud by deposition were considered (Meroney et al., 1988). Field and laboratory experiments were analyzed to estimate the effectiveness of barrier devices. Conclusions drawn from these analysis and review follow.

3.1 Dilution Performance of 2-D 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.

<u>Water Spray Curtains: Removal Characteristics</u>

- Concentrations in a gas cloud couldl decrease abruptly as a result of chemical reaction and removal processes associated with reactive gases like 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/gas volume ratios, water droplet sizes and cloud concentrations.

<u>Water Spray Curtains: Dilution Characteristics</u>

- 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, constant water spray intensity, and constant 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.

3.2 Dilution Performance of 2-D Barriers in the Far-field Region

Gases like hydrogen fluoride (HF) are 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. 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.

- Peak concentrations measured during the experiments did not generally fall below 10,000 ppm of stimulant 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. 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 at distances greater than 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.

- 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.

3.3 Vertical Concentration Distributions

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

At elevated heights the cloud arrived and departed earlier for the enclosure cases than for the no-fence situation. Water spray curtain measurements produced very similar shape plumes to the fence scenarios; however, no elevated maximum occurred near the curtain.

3.4 ANOVA Regression Model

An analysis of variance (ANOVA) multilinear regression model was 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 C_w and C_{wo} are concentrations measured with and without fence present, $Fr = U^2/(g(SG - 1)L_c)$, $\underline{V}$ is dimensionless continous volumetric spill rate or $Q/(UL_c^3)$, Vol is total gas volume released, H is characteristic cloud height, L_c is characteristic length (typically 10 m), and x is downwind distance. The coefficient A, and exponents 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.

4.0 COMPUTATIONAL DENSE-GAS BLUFF-BODY AERODYNAMICS

Meroney (1992a) prepared a summary of the 1991 AIChE workshop on the dispersion of toxic gases over non-flat obstructed terrain. The workshop reviewed the capabilities of numerical and fluid models to predict scalar transport across complex flow fields. Panel members reviewed the capabilities of linear-perturbation models, finite-difference and finite-elemnt models, and the anticipated future effect of massively parallel computers on obstacle aerodynamics. Numerical prediction of the transport of hazardous gases around buildings or in the midst of an industrial complex is in its infancy. Calculations performed by Murakami (1990) revealed the limitations of various turbulence models when predicting flow around simple cubical buildings. Predictions by j-e, algebraic stress (ASM) and large-eddy simulation (LES) models were compared with wind tunnel measurements. ASM and LES models appear to reproduce laboratory measurements of streamline location, separation, reattachment, and turbulence magnitudes.

Currently there is no operational numerical model to predict diffusion around buildings suitable for regulatory purposes. The primary constraint seems to be the fine computational grid and resultant large memory required to resolve the smaller scales of motion found near building surfaces. Leone observed that the continued development of massively-parallel computers will allow a significant increase in model resolution, improved representation of flow physics, and real-time modeling of some emergency response situations (Meroney, 1992a).

The First International Computational Wind Engineering Symposium was sponsored by the University of Tokyo during summer 1992 (Murakami, 1992). This symposium focused on the use of numerical models to predict the flow around various bluff objects (houses, automobiles, bridges, terrain, etc.). Most of the presentations examined the efficacy of j-e (turbulent kinetic energy-dissipation) or LES (large eddy simulation) turbulence closure finite difference, finite volume or finite element models when applied to the prediction of bluff-body aerodynamic flows. These same models may soon be applied to the prediction of dense-gas behavior around obstacles. Indeed, Chen (1990) have already applied their FEM-3 finite-element model to the behavior of liquefied natural gas clouds of released near vapor barrier fences during the Falcon field tests.

Alternatively a less computationally complex approach to account for simple bluff-body interactions may be constructed by inserting appropriate entrainment models into volume-averaged, section-averaged or depth-averaged numerical models (Meroney, 1984a, 1984b, 1989, 1991, 1992; Shin, 1990; Lee and Meroney, 1988). As noted in the following sections very simple entrainment models suffice to predict the dominant effects of 2-dimensional objects such as vapor-barrier fences and spray curtains on transport and diffusion.

4.1 Proposed Entrainment Models

Given a volume- or section-averaged 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:

<u>Fence entrainment model:</u>

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

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

Water spray entrainment model:

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

where Q_s is 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).

4.2 Conclusions from Section and Volume Averaged Numerical Studies

Meroney and Neff (1985) examined the effect of a hypothetical water spray barrier on the Burro No. 8 LNG field tests. Meroney and Shin (1991) reported the impact of different fences and water spray barriers on the Goldfish No. 1 Hydrogen Fluoride field test.

Other dense gas spill configuration were proposed and tested in the API Publication No. 4491 (1989) to evaluate the relative impact of surface roughness on heavier-than-air dispersion. Two run cases from API No. 4491, Tests 29 and 30, simulated the release of heavy gas (SG = 1.4 and 4.0, respectively) at $Q = 11.14\ m^3/s$ from a small 5 m diameter area source over a surface roughness, $z_o = 0.03$ m, for a wind speed of $U_{10} = 5.6$ m/s. These conditions were chosen by Meroney (1992b) for further evaluation given the hypothetical addition of fence and/or water spray barriers. Numerical calculations were also performed for a reduced wind speed of $U_{10} = 3.0$ m/s.

Fence Barriers

- During numerical sensitivity tests reported earlier (Meroney and Shin, 1991) 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.

- 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 box model assumes that a logarithmic velocity profile exists, such that wind speed is determined by surface roughness and friction velocity. 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 residual dilution effect is small after about 200 fence heights. The cloud height approaches the cloud height in the absence of a barrier after 1000 meters or about 200 fence heights.

- 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 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. Model results suggest that the perturbation produced by a fence is constant, but the model fails to allow for a constant height wake region.

Meroney (1992b) compared the relative dilutions and plume growth of a 1.4 specific gravity plume for wind speeds of 3.0 and 5.6 m/s, barrier heights of 2, 4, and 6 m, and barrier porosities of 0 and 50 %. All barriers were located 20 m downwind of the source area.

- As before increases in wind speed and barrier height increase dilution. An increase in barrier porosity decreases plume dilution by one-third.

- The barriers diluted a denser plume of 4.0 specific gravity slightly more effectively, primarily because the increased entrainment acted over a greater surface area due to enhanced plume width at the fence location.

Water Spray Curtain Barriers

The box model was also used to predict the joint effects of water spray dilution and deposition on an HF cloud (Meroney and Shin, 1991).

- 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. Separate calculations considered the effect of varying curtain location from 30 to 400 meters downwind of the spill center. A nominal spray entrainment rate of 6 m/sec was chosen for these calculations.

- The concentrations predicted downwind of the spray location were very similar with just 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.

- Other calculations examined 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. Given a constant spray location, wind speed, and plume width, increased entrainment velocities result in proportional increases in dilution.

- Increased wind speed advects the gas plume through the spray zone more quickly. 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.

Meroney (1992b) also considered the relative dilution and plume growth behavior of a 1.4 and 4.0 specific gravity plume downwind of our generic small-area source spill for a wind speed of 3.0 m/s when a water spray with entrainment velocities of 0, 1, 2, and 5 m/s and deposition strengths of 0, 50 and 75 %. All water spray curtains were located 20 m downwind of the source area.

- An increase in water spray entrainment velocity increases dilution proportionally, and deposition results in a permanent shift of downwind concentrations to lower values. The mitigation devices are slightly more effective when interacting with a 4.0 specific gravity plume, primarily because the water spray curtain acts over a greater plume width at the spray location.

Joint Performance of Fence and Water Spray Barriers

Meroney and Neff (1985) previously described the effect of dual water spray barriers. Meroney and Shin (1991) reported the effect of dual water sprays including deposition.

- When both barriers operated with the same entrainment rates, the net effect of two such barriers located downwind of one another seems to be very close to the effect expected from one barrier with twice the entrainment velocity. The second barrier must also be wider in order to intercept over a wider plume; hence, greater water consumption may occur.

- Given the defined effect of a specified deposition on the plume a second spray produces a second shift to lower concentrations of equivalent width. The decrease in concentration persists at all subsequent downstream distances.

- Combining a fence and a water spray barrier located up- or downwind of one another on dilution and plume growth of a 1.4 specific gravity plume does not produce simple superposition effects.. Fences of 6 m height and 0 porosity were combined with water spray curtains which achieved entrainment velocities of 5 m/s and either 0 or 75 % deposition. The barriers were located alternatively at 20 m and 100 m downwind of the source area. In each case the downwind mitigation device reduces plume concentrations by only a modest amount. Certainly the first device encountered produces the majority of subsequent dilution.

- The fence is less effective downwind of a water spray curtain because at such a location the cloud height and advection velocities already exceed those at fence top. If the water spray is located within the wake of the fence, it may only add marginally to an already enhanced entrainment rate. Similar calculations performed for a 4.0 specific gravity plume produce very similar but somewhat larger dilutions.

Influence of Side-wall Barriers Around the Source Location

The effect of lateral fences located either side of the source area and extending downwind to a fence were examined using the depth-integrated program, FENCE. The same generic API spill conditions were utilized as before. Calculations were performed for a region extending about 40 m upwind and 700 m downwind of the source center. The fence was located 20 m downwind of the source downwind edge, and any lateral barriers were located 10 m apart. A continuous source of 1.4 specific gravity was released into a 5.6 m/s wind. A gravity head forms which eventually leaves the calculation domain downwind. Given the continuous nature of the source, the plume concentrations, height and width all eventually approach asymptotic values for all distances.

- A 6 m high fence of 0 % porosity produces dramatic plume growth at the fence followed by some density driven plume collapse; however, the plume widths for distances less than 600 m (100 h) are somewhat narrower. The greater fence height wind speeds excite greater dilution rates in the fence wake.

- The influence of lateral barriers about the source area which restrict initial lateral growth was considered. Plumes are mixed to about the same height; hence, dilution is only marginally reduced. By the time the plume reaches distances of 700 m (120 h) downwind, plume widths have asymptotically approached no-lateral-barrier conditions, and plume dilutions are essentially the same as without lateral barriers.

5.0 CONCLUSIONS

Fence and water spray curtain field effects on plume dilution have now been measured for a wide range of laboratory and field conditions. These measurements suffice to calibrate simple box and depth-integrated numerical models. Calculations with such models for a range of hypothetical barrier configurations permit the designer to estimate the probable value of alternative arrangements. Superposition of the dilutions produced by barriers acting far enough apart to be considered independent suggests that such geometries are not as efficient together as when installed alone. Dilutions will increase, but total dilutions will not equal the sum of each acting alone. These calculations do not, however, provide any guidance concerning the use of fences and sprays constructed directly next to one another. For example, a fence might be used effectively to divert a plume into a smaller but more energetic water spray curtain.

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