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DISPERSION FROM LOW LEVEL SOURCES IN THE WAKE OF A TAILINGS POND DIKE

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ABSTRACT

The interaction between the turbulent wake, created by a tailings pond dike and the low level emissions at the Syncrude Tar Sands Plant has been investigated using wind tunnel model simulation. At the large Reynolds numbers experienced by model and full-scale dike the flow remains attached to the downwind side of the dike, with no recirculation zone. The effects on dispersion of three dike heights are compared to the flat terrain case for one typical low level source in the dike wake. By increasing the dike height, a small reduction in ground level concentration results, which is consistent with the observed increase in cross-wind plume spread relative to vertical spread. Simple Gaussian plume model predictions are compared to wind tunnel observations, and are shown to be accurate estimates of ground level concentrations.

At the Syncrude plant site the tailings pond containment dike is located about 1.2 km north of the main stack. This containment dike may in time reach a height of 50 meters, about 25 percent of the main stack height and about the same height as the low level sources. Eventually, the dike will become the predominant topographical feature in the neighborhood of the plant site. The effect of this dike on the dispersion of material from low level sources within the plant site forms the basis for the present investigation.

A single wind direction was considered in the investigation, namely that from due plant north. In this case the tailings pond dike lay perpendicular to the wind, and the turbulent wake behind it passed directly over the low level plant sources.

Why a Wind Tunnel Simulation?

The complex interaction between local terrain features and plume dispersion has not yet been successfully modeled mathematically. For this reason, the only viable alternative was an experimental simulation (using a physical model of the tailings pond dike) of atmospheric dispersion in the neighborhood of the plant. This study was carried out in the large atmospheric boundary layer wind tunnel of the Department of Mechanical Engineering at the University of Alberta. The advantage of such a laboratory simulation is that it is possible to generate any terrain feature that may exist in the future. At the same time, the simulated atmospheric conditions are easily reproducible from day to day, allowing the relative effects of various parameters such as wind speed, dike height, and source location to be easily evaluated. A further advantage of wind tunnel simulation is that the events in the wind tunnel occur several hundred times more rapidly than their full scale counterparts. This acceleration of events in the physical model allows long time averages to be generated in a relatively short period of time.

Atmospheric Wind Simulation

The first objective in this study was to accurately simulate in 800:1 geometric scale a neutrally stable atmospheric boundary layer typical of the Mildred Lake plant site. The data for selecting this typical profile were reported by Murray and Morrow (1977), who carried out full scale site tests using single theodolite balloon tracking techniques. They found that for an unbounded atmosphere, a power law (n = 0.19 and Z_{ref} = 183 m) well represented the data. Their data analysis indicated that the value of the index n increased with increasing values of the reference height Z_{ref}. In addition, they found that low level jets, in which the wind speed decreased with increasing distance above the height of the jet core, occurred 46% of the time. For this reason, considerable caution must be used when applying the adjective "typical" to any power law wind profile chosen for wind tunnel simulation.

Figure 1 shows the configuration of truncated triangular vortex generators, a ground based barrier, and surface roughness elements used in the present study to generate the correct atmospheric wind profile.

The comparison in Table 1 shows excellent agreement between simulated and full scale atmospheric boundary layers with one notable exception. The simulated boundary layer appears to have a deficiency in cross-wind fluctuation levels as evidenced from the low values of the ratio $(\overline{v^2}/\overline{u^2})^{0.5}$ and the high value of the structure function $\overline{uw}/(\overline{u^2} + \overline{v^2} + \overline{w^2})$. To some extent low values of the cross-wind fluctuation level are expected in any wind tunnel model because the tunnel side walls prevent the development of low frequency wind direction fluctuations which contribute to long term turbulent diffusion. In the present case, however, the value of the cross-wind turbulence level is somewhat lower than would be expected even when considering the influence of the tunnel side walls. Fortunately, these lower values of turbulence intensity did not appear to have any significant influence on vertical and cross wind plume spread, as will be seen later.

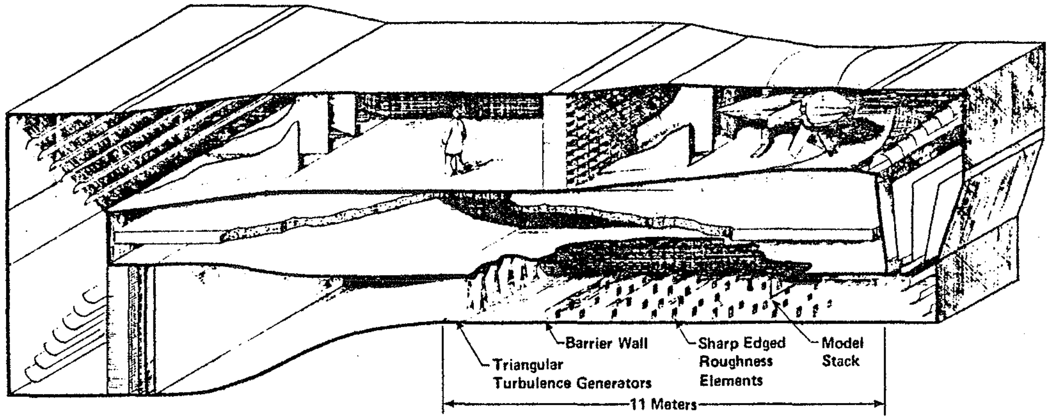
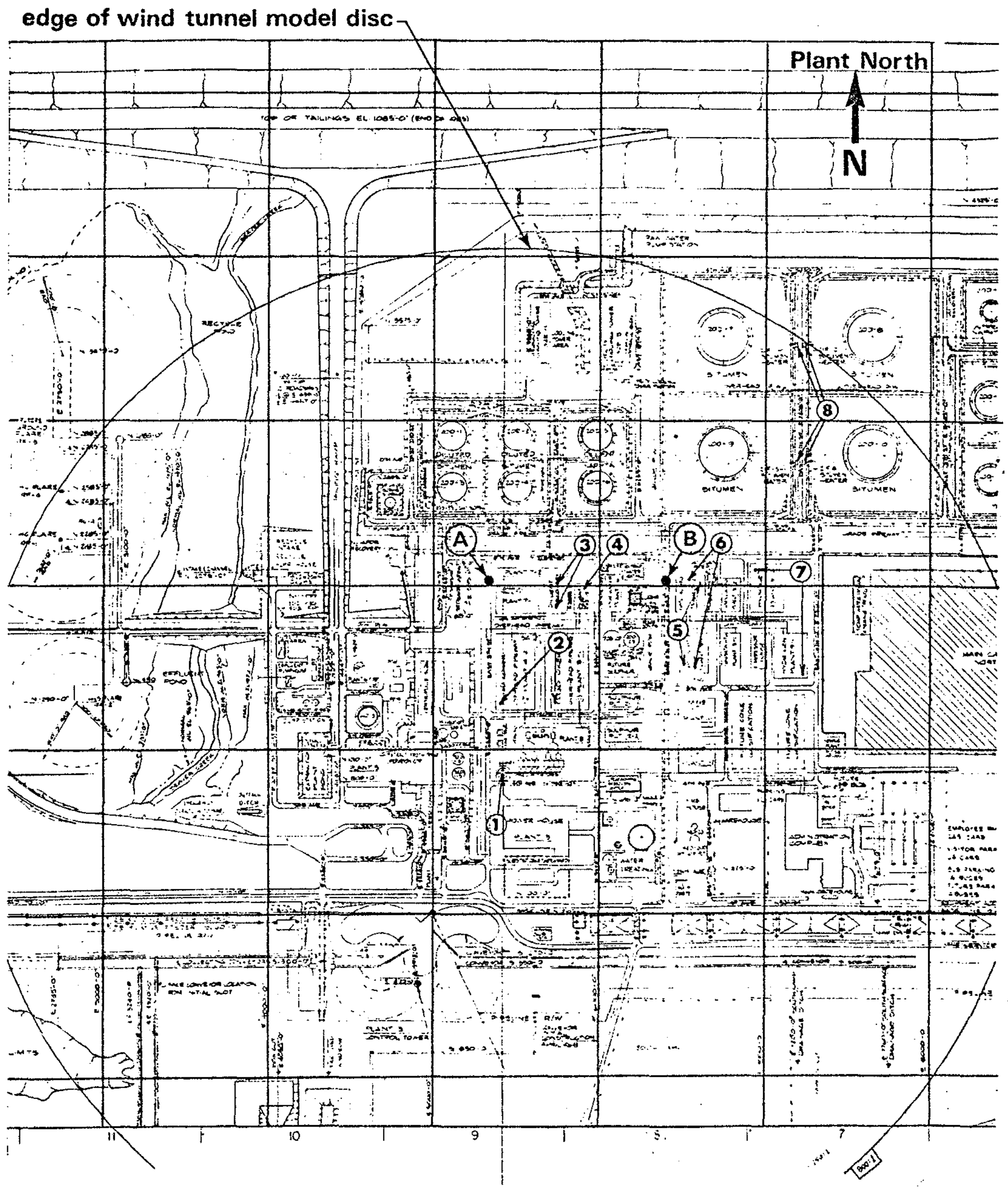


Fig. 1



grid spacing 1000′ intervals

Fig. 2

TABLE 1

COMPARISON OF WIND TUNNEL BOUNDARY LAYER
WITH FULL SCALE ATMOSPHERIC DATA OF COUNIHAN (1975)

Parameter	Wind Tunnel 800:1 Scale	Full Scale Neutral Stability with same Z_0
Roughness height, Z_0	0.4m	Fixed at 0.4m
Mean velocity power, n	0.18 $Z < 160$m 0.30 $Z > 160$m	0.20 ± 0.03
Boundary layer thickness, δ	650 - 750m	600m (approx.)
$\left(\frac{\overline{u^2}}{\overline{uw}}\right)^{0.5}$ @ 30m	1.94	1.9
$\left(\frac{\overline{v^2}}{\overline{u^2}}\right)^{0.5}$ @ 30m	0.53	0.75 ± 0.15
$\left(\frac{\overline{w^2}}{\overline{u^2}}\right)^{0.5}$ @ 30m	0.41	0.50 ± 0.1
$\frac{C_f}{2} = \frac{\overline{uw}}{U_\delta^2}$ @ 30m	0.00236	0.00251 ± 0.0005
$\frac{\sqrt{\overline{u^2}}}{U}$ @ 30m	0.17	0.20 ± 0.03
Integral Scale, Λ_x	150m @ $Z = 30$m 180m @ $Z = 160$m	130m $\pm$ 50 200m $\mp$ 50
$\frac{\overline{uw}}{\overline{u^2} + \overline{v^2} + \overline{w^2}}$ @ 100m	0.17	$0.14^* \pm 0.01$

* - Data from Hinze (1975) p. 643, p. 729.

Concentration Measurements

The low level sources shown on the map in Fig. 2 were not simulated individually. Instead, two typical low level sources A and B were located a distance of 366 m upwind from the main stack, as shown in Fig. 2. These source locations were selected so as to experience the greatest effect of the dike wake. A standard source height of $h_s = 30.5$ m was selected to represent a typical low level source.

The actual sources consisted of a 0.378 cm I.D. tube bent parallel to the flow. Pure helium tracer gas was emitted horizontally to avoid momentum rise. The tunnel speed at source height $h_s = 3.81$ cm (30.5 m full scale) was set at $U_h = 9.0$ m/s. This high tunnel operating speed was chosen to minimize the effects of buoyancy rise. As we shall see later, this large tunnel speed did not completely suppress the rise of the helium tracer gas, which reached an effective height of about h = 5 to 5.5 cm (40 to 44 m). In spite of the added buoyancy rise, the tests were typical of dispersion from a non-buoyant source, whose only non-dimensional parameter should be $CU_h h_s^2/Q$.

All wind tunnel tests were carried out at constant speed which was maintained using a reference pitot tube located upstream from the turbulence generator spikes. At the two locations A and B, both the turbulence and the mean wind speed can be affected by the presence of the tailings pond dike. With a constant wind speed approaching the dike the effects of both of these parameters were automatically included in the observed concentration profiles.

The concentration of tracer gas in the diffusing plume was measured by aspirating a sample from selected points within the plume and passing it through a heated element four-arm thermal conductivity bridge of the same type used in gas chromatographs. To compensate for background concentration levels a reference sample was drawn simultaneously from a point 1 m upwind of the edge of the plant site model and at a height roughly corresponding to the height of the source. The imbalance of the thermal conductivity detector bridge was displayed continuously on a chart recorder, and averaged over 100 second intervals using a low-noise bridge amplifier coupled with a voltage-to-frequency converter and counter. By using this long averaging time, and periodically turning off the tracer gas at the source to obtain zero drift readings, a high level of accuracy in the concentration readings was maintained. Average concentrations were reproducible to within $\pm 5\%$.

Converting From Model to Full-Scale

The turbulence structure in the approaching wind was adjusted to match the plant site model length scale factor of 800:1. This factor can be applied to any of the measured length parameters in the model study, such as x, y, z, σ, h. For non-buoyant sources there is no direct time scale ratio between model and its full-scale counterpart. To determine the full-scale averaging time corresponding to the 100 second wind tunnel measurements, it is necessary to compare the measured plume widths to full-scale values determined for various averaging times. We will see later that there is considerable uncertainty in determining the full-scale averaging times, which leads to uncertainty in interpreting the full-scale averaging time corresponding to the wind tunnel measurements.

The dimensionless variable $\frac{C_o U h^2}{Q}$ should be constant for non-buoyant plumes which disperse in strong wind conditions. Then, the model (m) and full-scale (f) concentrations are related by

$$\left.\frac{C_oU_h}{Q}\right|_f = \left.\frac{C_oU_h}{Q}\right|_m \cdot \left(\frac{h_m}{h_f}\right)^2 = 64 \times 10^4 \left.\frac{C_oU_h}{Q}\right|_m$$

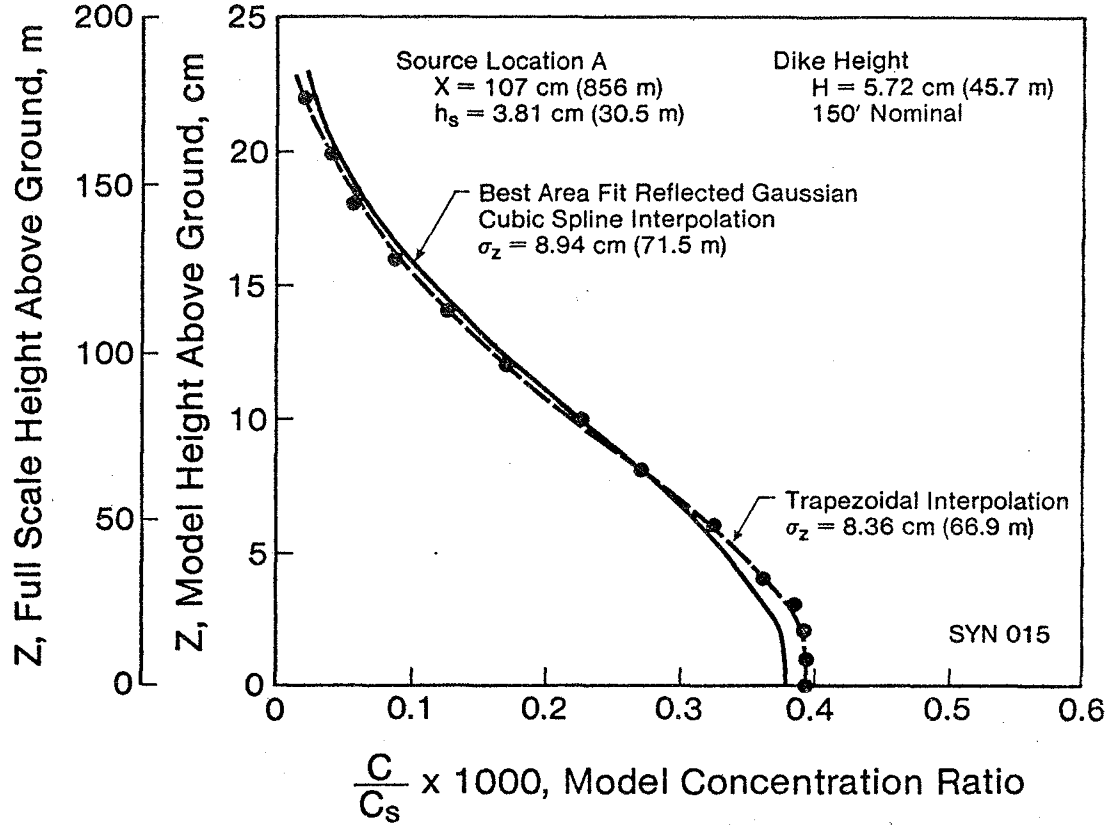
Because changes in the ground level concentration values are of interest and not the value of the concentration itself, all concentrations will be given in terms of those measured in the wind tunnel.

Vertical and Crosswind Concentration Profiles

Vertical profiles of concentration and crosswind concentration profiles at ground level were measured at the single downwind distance X = 107 cm (856 m full-scale) from source A. The vertical profiles were obtained by a motor-driven probe traversing the plume in the vertical plane. Crosswind profiles were obtained simply by moving the sampling probe along the y-axis at ground level. The sampling point was selected so as to avoid interference by nearby structures. In addition, the sampling point was located where the ground level concentration profile along the x-axis showed a monotonic decrease (downwind from the point of maximum ground level concentration).

Vertical and crosswind profiles were obtained without dike, and for two dikes of height 22.9 and 45.7 m. Figure 3 shows typical concentration profiles obtained for a dike height of 45.7 m. Plume spreading rates σ_y and σ_z were determined by fitting ground-reflected equivalent Gaussian distributions (same area) to the data. As can be seen, the Gaussian distributions are in agreement with the observed concentration profiles.

The plume spreading ratio σ_z/σ_y at X = 107 cm (856 m full-scale) for source A was approximately 0.67, which is in agreement with the


Source Location A
X = 107 cm (856 m)
hs = 3.81 cm (30.5 m)
Dike Height
H = 5.72 cm (45.7 m)
150' Nominal
Best Area Fit Reflected Gaussian
Cubic Spline Interpolation
σz = 8.94 cm (71.5 m)
Trapezoidal Interpolation
σz = 8.36 cm (66.9 m)
SYN 015
Z, Full Scale Height Above Ground, m
Z, Model Height Above Ground, cm
C/Cs x 1000, Model Concentration Ratio

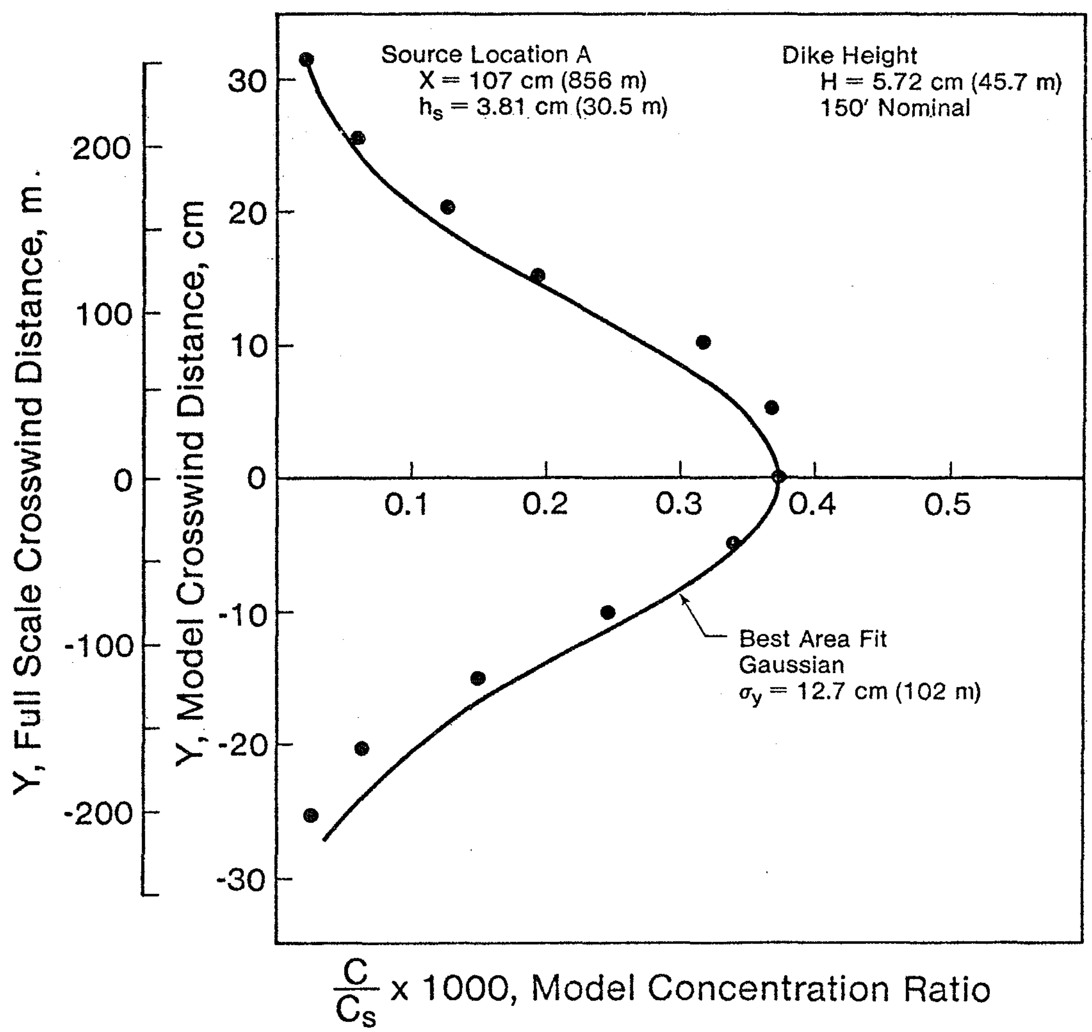

Source Location A
X = 107 cm (856 m)
hs = 3.81 cm (30.5 m)
Dike Height
H = 5.72 cm (45.7 m)
150' Nominal
Best Area Fit
Gaussian
σy = 12.7 cm (102 m)
Y, Full Scale Crosswind Distance, m.
Y, Model Crosswind Distance, cm
C/Cs x 1000, Model Concentration Ratio

Fig. 3

Brookhaven data of Singer and Smith (1966) who found a value of 0.69 for neutrally stable atmospheric conditions. Values of σ_z and σ_y and their ratio are presented in Table 2, and compared with full-scale values in Table 3. Intense turbulence near the ground creates plume dimensions which are significantly larger than those predicted for an elevated release, where turbulence is less pronounced.

Effective Source Height

Table 2 shows values of vertical and crosswind spreading rates obtained from Gaussian fits to the measured concentration profiles. In addition, using the measured plume spreading ratio σ_z/σ_y and the experimental value of the maximum concentration the effective source heights can be computed from the reflected Gaussian distribution as follows:

$$h = \left[\frac{2}{\pi e} \left(\frac{Q}{C_{O_{max}} U_h} \right) \left(\frac{\sigma_z}{\sigma_y} \right) \right]^{0.5} \qquad (1)$$

This equation requires that the plume spreading ratio σ_z/σ_y remains constant at all X locations. Effective source heights computed from Eq. (1) are shown in Table 2, and we may conclude that although the plume was emitted at a height of 3.81 cm above ground, initial buoyancy caused it to rise an additional 1.69 cm. The corresponding final rise in full-scale conditions is 44 m.

Using Briggs' formula (1975) a second estimate for the buoyant rise may be obtained:

$$\Delta h = 1.6 \frac{F^{1/3} X^{2/3}}{U_h}$$

Taking the final rise to occur 10 source heights downwind, a plume rise

TABLE 2

VERTICAL AND CROSSWIND PLUME SPREAD

Source Location A

X = 107 cm (2808 ft, 856 m)

h_s = 3.81 cm (100 ft, 30.5 m)

Dike Height H	σ_z** cm	σ_y cm	$\frac{\sigma_z}{\sigma_y}$	Experimental $\frac{C_{o_{max}} U_h}{Q}$ cm^{-2}	Effective source height h Eq 1 cm
No Dike	7.84	11.65	0.673	.0052*	5.51*
H = 22.9 m (2.86 cm)	7.98	12.05	0.662	.00515	5.49
H = 45.7 m (5.72 cm)	8.34	12.70	0.657	.0050	5.55

*Data from Location B has maximum concentration levels about 20% higher and, if σ_z/σ_y is the same, values of h $\cong$ 5.0 cm, 10% lower than those shown for Location A

**computed using effective source height h = h_s = 3.81 cm

TABLE 3

COMPARISON OF MODEL AND FULL SCALE PLUME

SPREADS FOR LOW LEVEL SOURCES WITH NO DIKE

Source Location A

X = 107 cm (2808 ft, 856 m)

Parameter	σ_z m	σ_y m	$\frac{\sigma_z}{\sigma_y}$
Wind Tunnel scaled up 800:1	62.7	93.2	0.673
Singer and Smith(1966) Brookhaven 1 hour averages	42.6	62.0	0.688
Alberta Dispersion Guidelines (1978) 3 min averages	45.0	74.2	0.606
Alberta Dispersion Guidelines (1978) 1 hour averages	45.0	135.0	0.333

Full Scale Values in Meters

Singer and Smith (1966) for 1 hour averages — $\sigma_z = 0.22\ X^{0.78}$, $\sigma_y = 1.45\ \sigma_z$

Alberta Dispersion Guidelines (1978) for 3 min averages — $\sigma_z = 0.456\ X^{0.68}$, $\sigma_y = 0.195\ X^{0.88}$

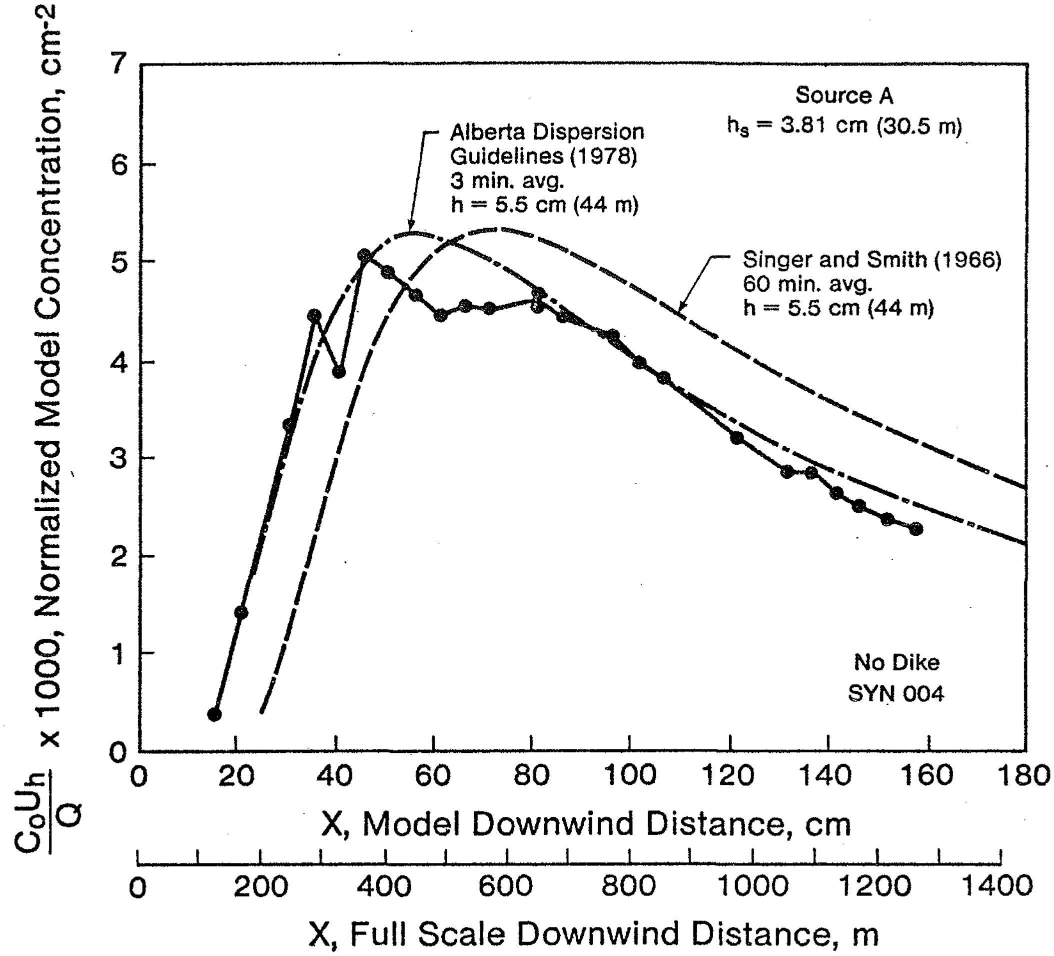
for 1 hour averages — σ_z, unchanged, , $\sigma_y = 0.355\ X^{0.88}$

of 0.61 cm is predicted. This value is less than half of that predicted by Eq. (1). However, because Briggs' formula was developed from full-scale data, it may not apply to model scale systems. Therefore, the effective source height is in our case better represented by Eq. (1).

The assumption in Equation (1) that the ratio σ_z/σ_y remains constant with downwind distance was relaxed by assuming different power laws for σ_z and σ_y. Plume dimensions recommended by the Alberta Environment (1978), and given in Table 3, were used to predict the effective source height. This more complicated approach gave values within a few percent of the effective source heights predicted by the much simpler approach.

Ground Level Concentration Without Dikes

Ground level profiles were measured by positioning a movable sampling probe at ground level downwind from each of the source locations. Figure 4 shows the ground level measurements along a line directly downwind from the source. All profiles showed variations in the mean concentration at locations near the maximum concentration. The data in Fig. 5, obtained with a model dike in place, show that these variations are reproducible, and cannot be attributed to experimental error. The probable source of these variations is a crosswind displacement of the plume axis, which exposes the sampling probe to lower off-axis concentration levels. The dips in ground level concentrations appeared to occur most often when the plume passed near a large building. To account for this plume meandering, the maximum ground level concentrations were determined from the envelope to the maximum observed concentrations, with


Source A
hs = 3.81 cm (30.5 m)
Alberta Dispersion Guidelines (1978)
3 min. avg.
h = 5.5 cm (44 m)
Singer and Smith (1966)
60 min. avg.
h = 5.5 cm (44 m)
No Dike
SYN 004
CoUh/Q x 1000, Normalized Model Concentration, cm-2
X, Model Downwind Distance, cm
X, Full Scale Downwind Distance, m

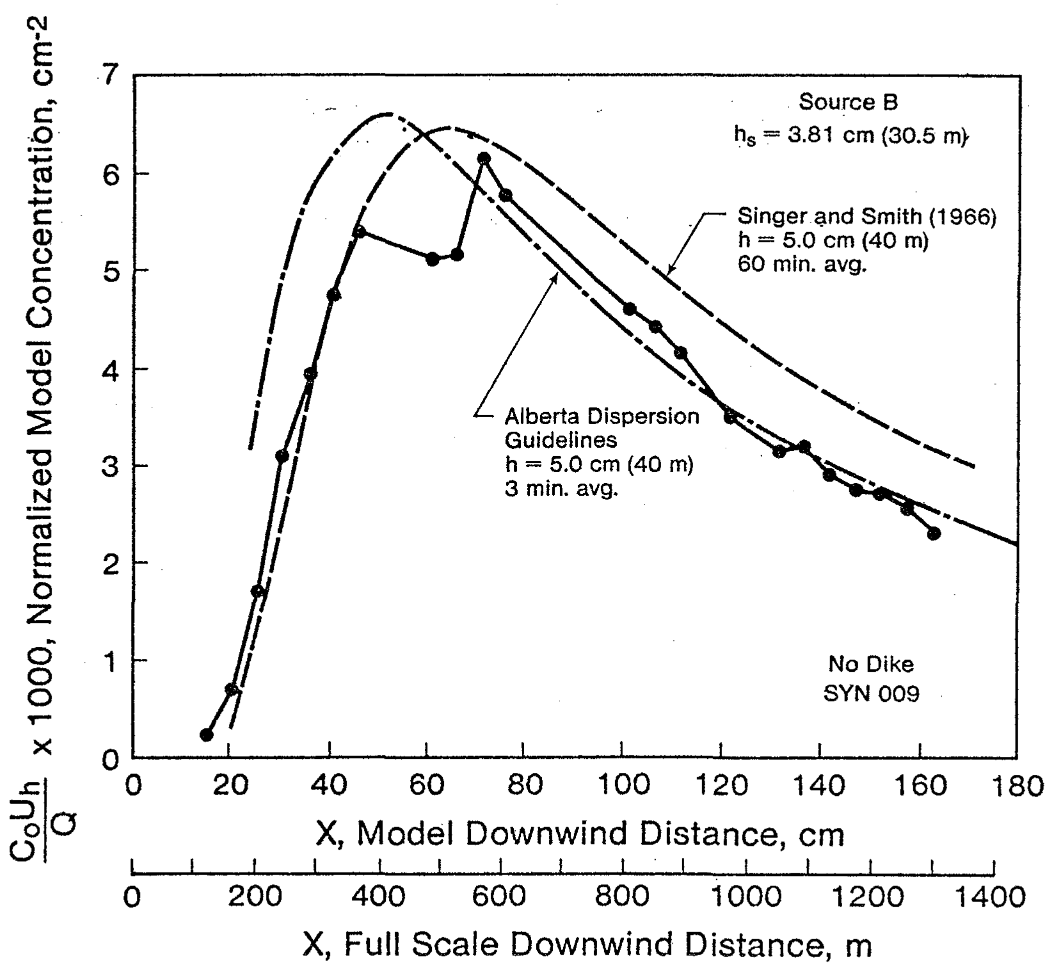
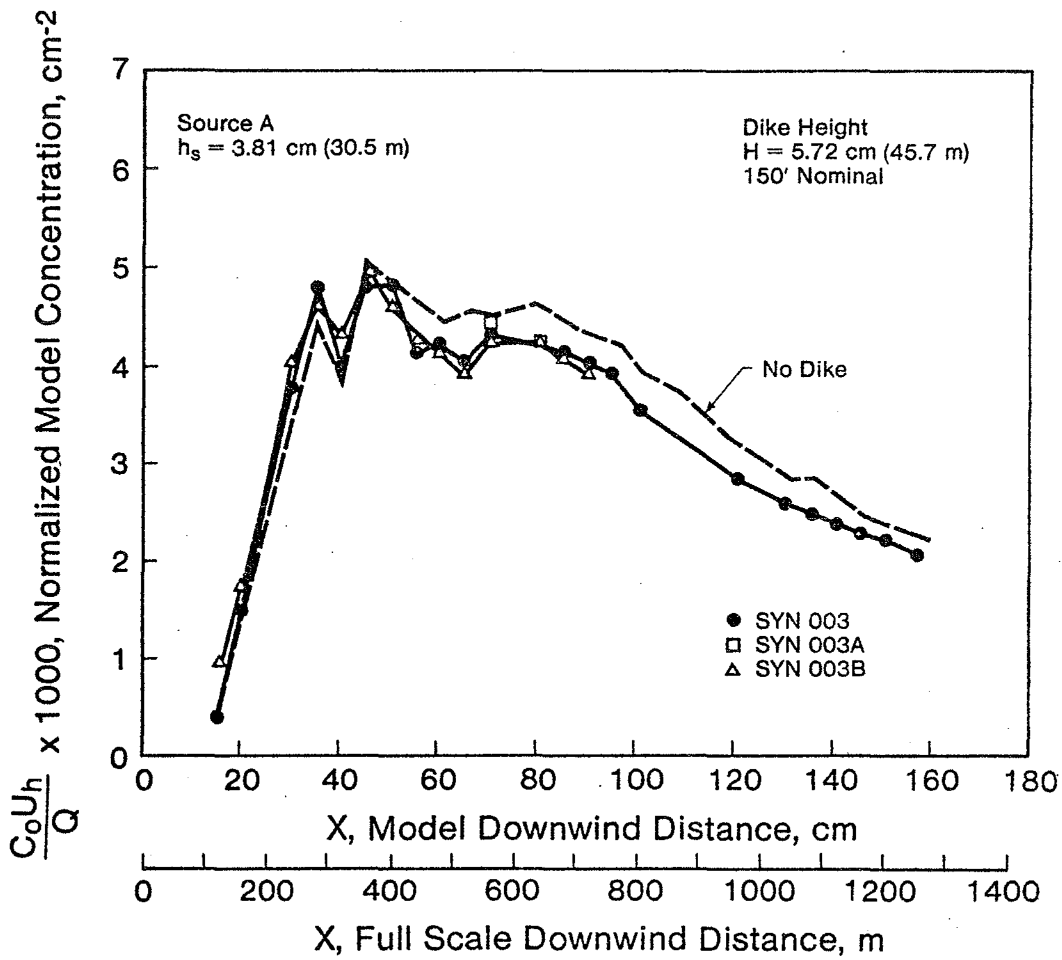

Source B
hs = 3.81 cm (30.5 m)
Singer and Smith (1966)
h = 5.0 cm (40 m)
60 min. avg.
Alberta Dispersion Guidelines
h = 5.0 cm (40 m)
3 min. avg.
No Dike
SYN 009
CoUh/Q x 1000, Normalized Model Concentration, cm-2
X, Model Downwind Distance, cm
X, Full Scale Downwind Distance, m

Fig. 4


Source A
h_s = 3.81 cm (30.5 m)
Dike Height
H = 5.72 cm (45.7 m)
150' Nominal
No Dike
SYN 003
SYN 003A
SYN 003B
$\frac{C_o U_h}{Q}$ x 1000, Normalized Model Concentration, cm-2
X, Model Downwind Distance, cm
X, Full Scale Downwind Distance, m

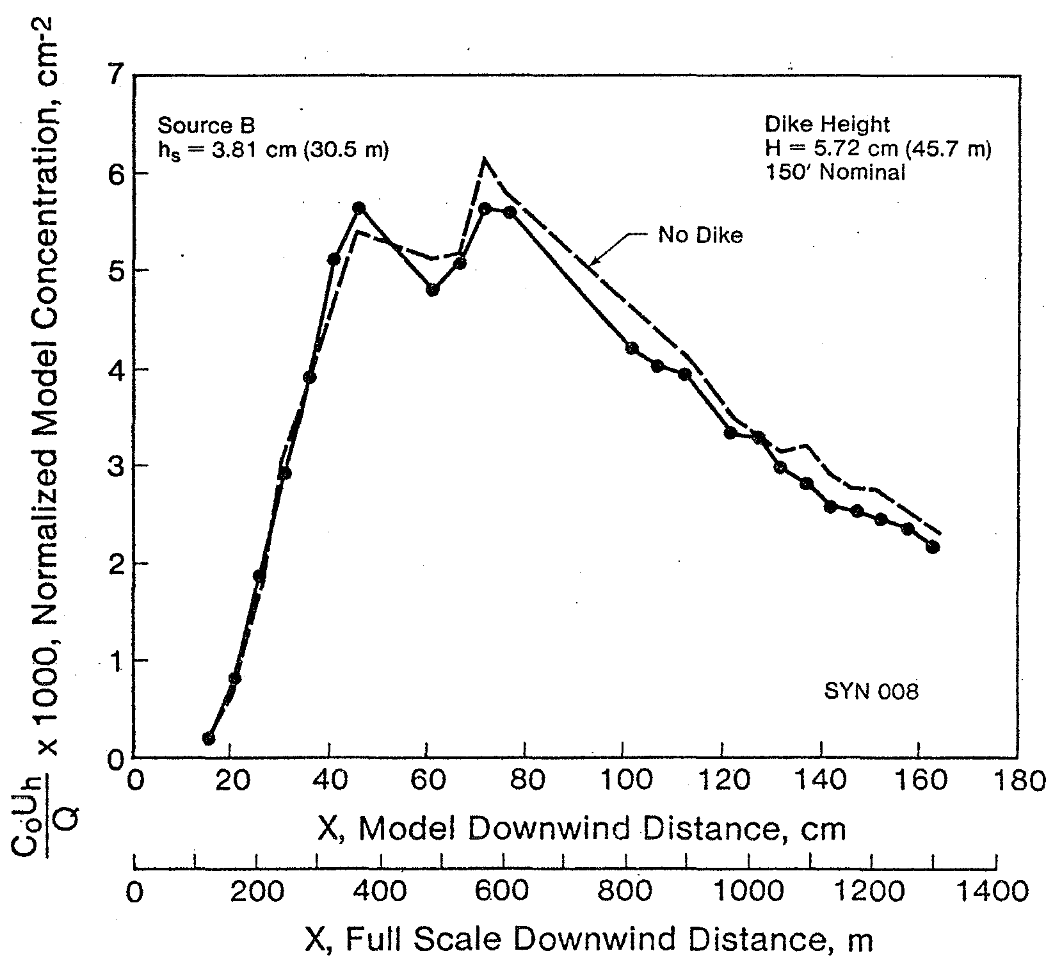

Source B
h_s = 3.81 cm (30.5 m)
Dike Height
H = 5.72 cm (45.7 m)
150' Nominal
No Dike
SYN 008
$\frac{C_o U_h}{Q}$ x 1000, Normalized Model Concentration, cm-2
X, Model Downwind Distance, cm
X, Full Scale Downwind Distance, m

Fig. 5

the dips and valleys in the observed profile assumed to represent values off the projected plume centerline.

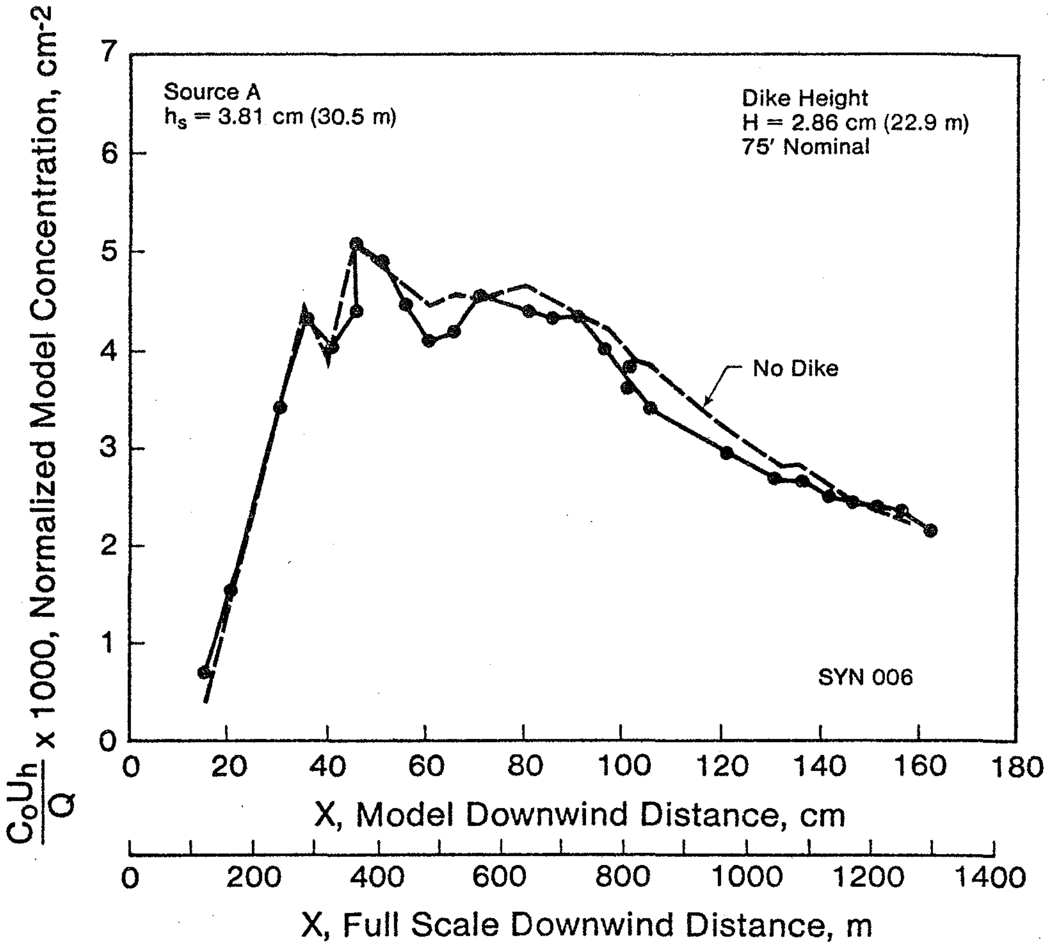
Although the two source locations A and B produced the same qualitative trends in their results, the maximum concentrations caused by location B were about 20 percent higher than those due to location A. Because the buoyancy rise can only partly explain the observed effective source height, it is plausible that the plume from source A may have been deflected upward by about 0.5 cm relative to the plume from source B. This slight additional plume rise for source A would account for the difference in both magnitude and downwind location of the observed ground level concentrations. Another plausible explanation is that the plume from source A had a larger crosswind spread σ_y than the plume from source B. No direct measurements were made of crosswind spread to support this hypothesis, however it was observed that several large structures, including the main power plant building, lie close to the location for the maximum ground level concentration attributable to source A. These buildings may have locally increased the crosswind plume dimension and/or caused the plume axis to deviate so that the sensor was not placed on the line of maximum concentration.

Gaussian model predictions were made for ground level concentration profiles using dispersion coefficients given by Singer and Smith (1966), and Alberta Dispersion Guidelines (1978). (These Guidelines use σ_y values from Gifford (1968) and σ_z values from Smith's correlations reported by Pasquill (1975), adjusted to surface roughness Z_o = 100 cm.) The predictions in Fig. 4 show remarkably good agreement with the experimental values, considering that the effective source heights were adjusted to give the correct value for the maximum ground level concentration. The most remarkable aspect in these predictions is the use of widely different averaging times in each case. The Alberta Dispersion Guidelines require the plume spreads to be 3 minute averages, while those of Singer and Smith are 1 hour averages. Clearly, both of these averaging times cannot be correct. The Alberta Dispersion Guidelines (1978) suggest that only the crosswind spread depends on averaging time, according to the relationship $\sigma_y \propto t^{-0.2}$. If the 3 minute crosswind spread is adjusted to the 60 minute value using this relationship then the ground level concentrations decrease by about a factor of 2. The measured ratios of σ_z/σ_y shown in Table 2 do not help to resolve this dilemma, because the no dike value of 0.67 agrees reasonably well with both the claimed 3 minute and 60 minute averaging times.

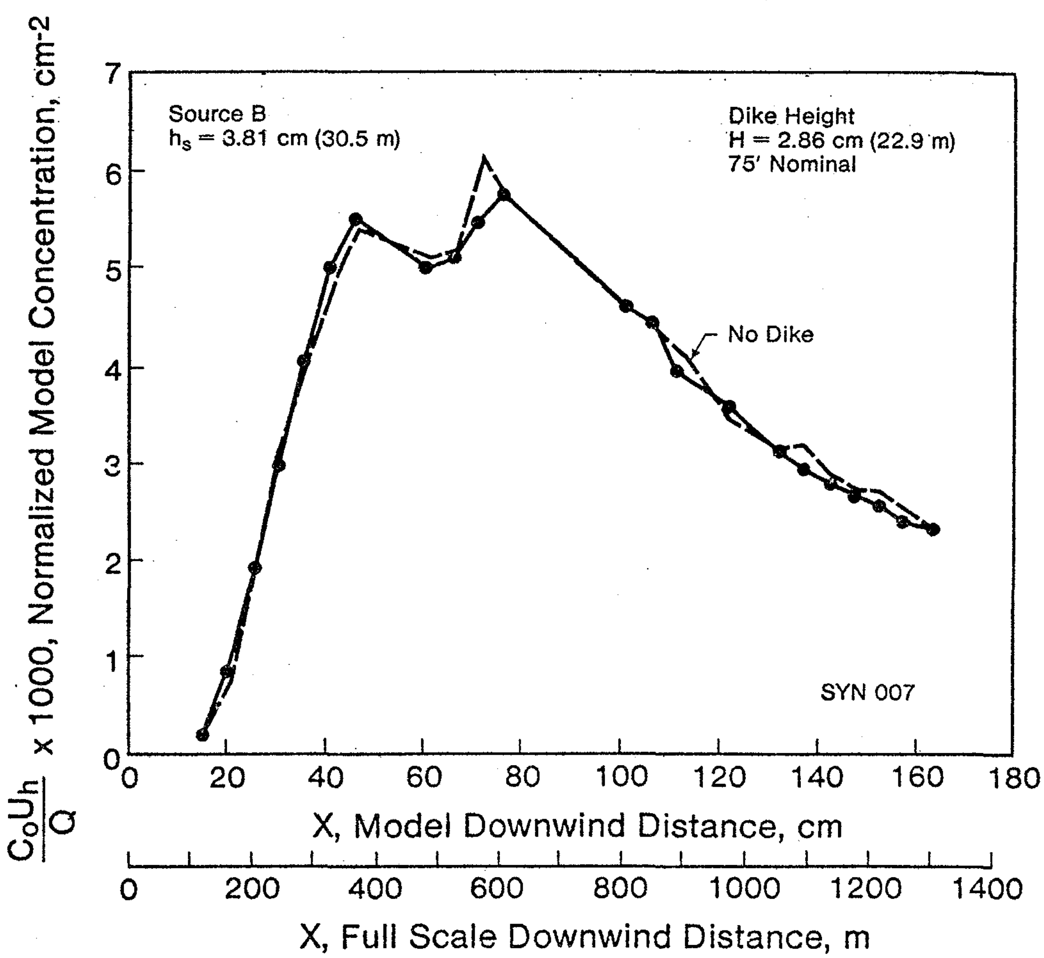
Effect of Dikes on Ground Level Concentration

Ground level profiles for both source locations are shown in Figs. 5, 6, and 7 for dike heights H = 22.9, 45.7, and 94 m. For all dike heights the ground level concentrations exhibited the same variations with downwind distance that were observed with no dike present. Fig. 5 for the 45.7 m dike height shows that these variations are reproducible from day to day, and are almost certainly due to crosswind deflection of the plume axis by nearby structures on the plant site model.

Both source locations showed consistent trends, with increasing dike height causing a slight decrease in the maximum ground level concentration. Concentrations close to the source tended to increase slightly, while concentrations downwind from the ground level maximum position showed a significant decrease with increasing dike height. These two observations indicate that the position of the maximum concentration moves somewhat

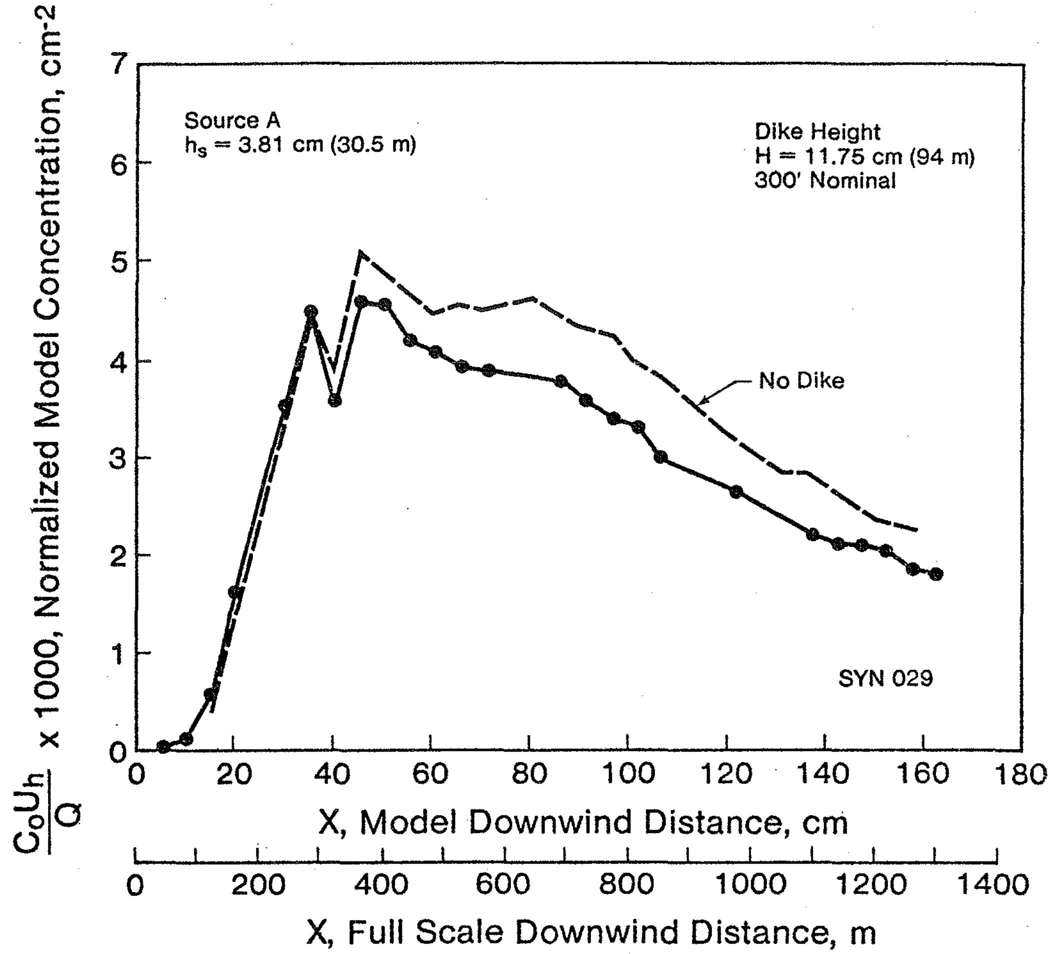


Source A
h_s = 3.81 cm (30.5 m)
Dike Height
H = 2.86 cm (22.9 m)
75' Nominal
No Dike
SYN 006
$\frac{C_o U_h}{Q}$ x 1000, Normalized Model Concentration, cm-2
X, Model Downwind Distance, cm
X, Full Scale Downwind Distance, m



Source B
h_s = 3.81 cm (30.5 m)
Dike Height
H = 2.86 cm (22.9 m)
75' Nominal
No Dike
SYN 007
$\frac{C_o U_h}{Q}$ x 1000, Normalized Model Concentration, cm-2
X, Model Downwind Distance, cm
X, Full Scale Downwind Distance, m

Fig. 6


Source A
h_s = 3.81 cm (30.5 m)
Dike Height
H = 11.75 cm (94 m)
300' Nominal
No Dike
SYN 029
$\frac{C_o U_h}{Q}$ x 1000, Normalized Model Concentration, cm^{-2}
X, Model Downwind Distance, cm
X, Full Scale Downwind Distance, m

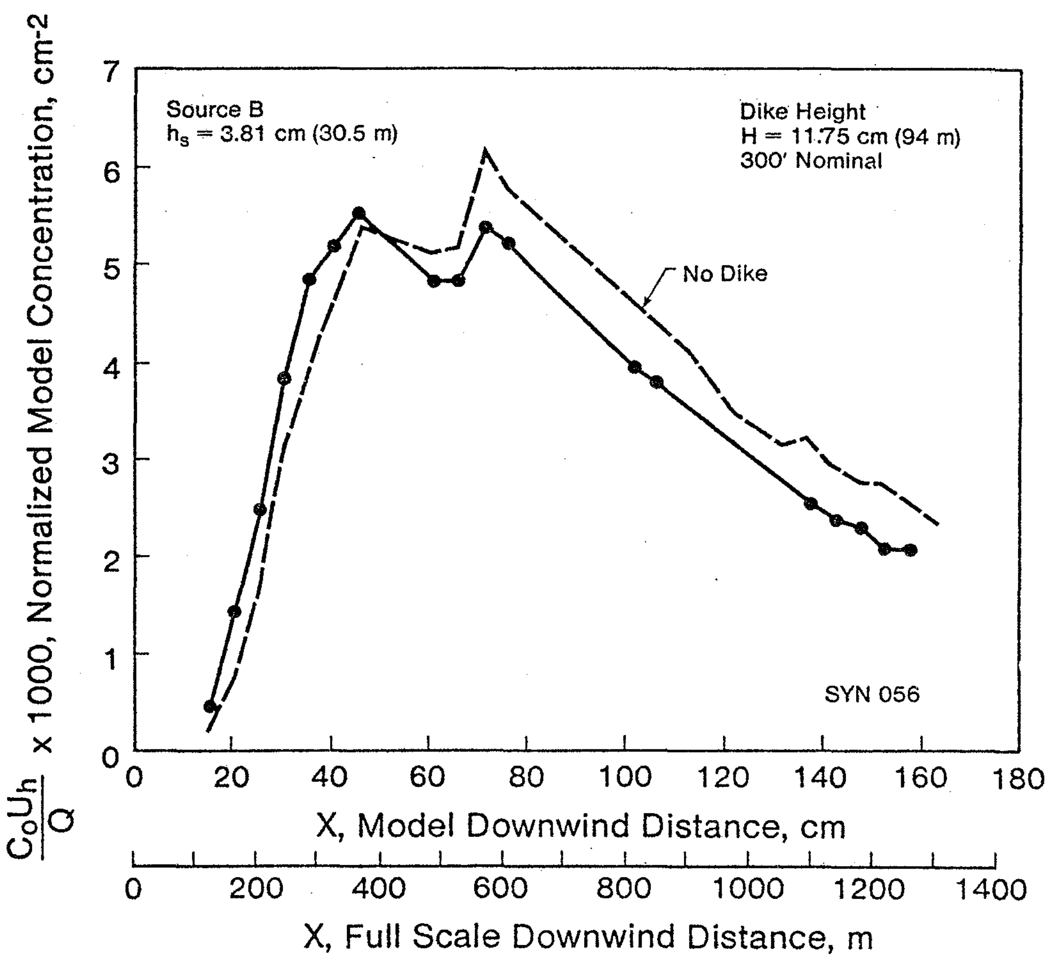

Source B
h_s = 3.81 cm (30.5 m)
Dike Height
H = 11.75 cm (94 m)
300' Nominal
No Dike
SYN 056
$\frac{C_o U_h}{Q}$ x 1000, Normalized Model Concentration, cm^{-2}
X, Model Downwind Distance, cm
X, Full Scale Downwind Distance, m

Fig. 7

closer to the source as dike height increases. This trend, however, must be inferred, because variations in the concentration distribution make it difficult to accurately locate the point of the maximum concentration. Nevertheless the trend is consistent with a high rate of vertical plume spread σ_z which occurs when the dike reinforces the turbulence in its wake (see Table 2).

The Gaussian plume model provides a rational explanation for all of the observed effects of the dike wake on ground level concentrations. Equation (1) may be written in the form:

$$\frac{C_{o_{max}} U_h h^2}{Q} = \frac{2}{\pi e} \left(\frac{\sigma_z}{\sigma_y}\right)$$

The decrease in maximum ground level concentration observed in the dike wake implies that the turbulence generated by the dike produces a larger increase in crosswind spread σ_y than it does in the vertical spread σ_z.

The most remarkable observation of the effect of the dike on the source is not that it causes a change in concentration, but how little effect it has. Even for the 94 m dike height, Fig. 7 shows that the sources located about 10 dike heights downwind experience only a 10 percent change in their maximum ground level concentration due to the dike wake turbulence. Even more surprising is the observation that this change represents a decrease and not an increase in concentration.

Characteristics of the Dike Wake

The key to understanding the reason for the small influence of the dike on downwind sources lies in the flow pattern over the dike. For all heights the dike had 3:1 upwind and downwind slopes with 10.8 m wide road along its crest. A study by Wilson, Winkel, and Neiman (1979) using tracer gases to map regions of flow separation showed that the flow remains attached to the downwind slope at sufficiently high Reynolds number. For this dike configuration the flow remained attached when the momentum thickness Reynolds number $U_\delta \Theta/\nu$ of the approaching wind exceeded about 1.5×10^5. Because the wind tunnel tests were carried out above this critical value, no flow recirculation zone was present on the lee side of the dike, and wake turbulence was greatly reduced.

Because Reynolds numbers for the full-scale dike are 100 to 1000 times greater than those in the wind tunnel, there should also be no flow separation from the full-scale dike. Full-scale measurements of Eliseev (1973) on a hill with slopes about 10 to 20 percent steeper than the tailings pond dike showed only a small separation zone at the base of the lee side. This lends support to the prediction that little or no flow separation should occur on the full-scale dike.

Conclusions and Recommendations

The following conclusions can be drawn from the wind tunnel experiments using low level sources in the wake of the tailings pond dike:

1. The effect of increasing the tailings pond dike height, if any, will be to lower the ground level concentration from low level sources. This is consistent with an increased crosswind spread caused by turbulence in the dike wake.
2. Simple Gaussian models, such as that recommended in the Alberta Dispersion Guidelines, are capable of providing an accurate prediction of the ground level concentration when care is taken to properly estimate the effective source height. For low-level

sources it is particularly important to determine the plume rise, because this can represent a significant fraction of the total effective source height.

3. Full-scale correlations of plume spread are not consistent in their specification of averaging time. The Alberta Dispersion Guidelines (1978) and the Brookhaven correlations of Singer and Smith (1966) both predict the same value of the maximum ground level concentration. However, the Alberta Dispersion Guidelines claim that this concentration represents a 3 minute average, while the Brookhaven spreading rates claim that the average is for 60 minutes. Further investigations of full-scale plume spreading rates are required to resolve this discrepancy.

Acknowledgements

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Nomenclature

C_f	=	surface wind shear coefficient
C_o	=	ground level volume concentration of pollutant along plume axis (m^3/m^3air)
C_{omax}	=	maximum ground level volume concentration (m^3/m^3air)
h	=	effective source height $h_s + \Delta h$ (m)
h_s	=	source height (m)
Δh	=	plume rise (m)
n	=	mean wind speed power law in $\frac{U}{U_{ref}} = \left(\frac{Z}{Z_{ref}}\right)^n$
Q	=	volume release rate of pollutant (m^3/s)
t	=	averaging time for concentration samples (s)
u,v,w	=	turbulent velocity fluctuations in x,y,z (m/s)
U_{ref}	=	wind speed at height Z_{ref} (m/s)
U_δ	=	wind speed at edge of boundary layer (m/s)
U_h	=	wind speed at source height h_s (m/s)
$\overline{uw}$	=	Reynolds stress (m^2/sec^2)
x,y	=	distances from source along-wind, crosswind (m)
z	=	height above ground (m)
Z_o	=	surface roughness in log law for mean velocity (m)
Z_{ref}	=	reference height for power law mean velocity profile (m)
δ	=	boundary layer thickness (m)
Λ_x	=	along-wind integral scale of turbulence (m)
θ	=	boundary layer momentum thickness (m)
ν	=	kinematic viscosity of air (m^2/s)
σ_y	=	crosswind Gaussian plume spread (m)
σ_z	=	vertical Gaussian plume spread (m)

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