DISPERSION IN THE WAKE
OF A MODEL INDUSTRIAL COMPLEX

by

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1. INTRODUCTION

Buildings and building complexes produce non-uniform flow fields and turbulence which can significantly modify the dispersion from a source in their vicinity. This study deals with the fate of contaminants released into the atmosphere from positions on and near the EOCR reactor building and surrounding silo and tank buildings at the Idaho National Engineering Laboratory.

1:200 scale models of the complex were put into the Meteorological Wind Tunnel at Colorado State University. Flow visualization used titanium-tetrachloride as a visible tracer gas. Concentration measurements were accomplished using ethane and propane as tracer gases, and gas chromatography techniques. The test program consisted of systematic releases from the base of the northwest face, center rooftop, and the stack. In each case the release rate was maintained at low rates such that no appreciable jetting or plume rise was present. The program was repeated for cases of moderately unstable, neutral, moderately stable, and stable conditions in the wind tunnel.

2. EXPERIMENTAL EQUIPMENT AND PROCEDURE

A complete discussion of physical modeling and scaling criteria applicable to this type of wind tunnel study is found in Cermak (1971) and Hatcher, et al. (1977). The experiment was conducted in the low speed Meteorological Wind Tunnel (MWT) at Colorado State University which is capable of reproducing atmospheric stabilities in both the stable and unstable ranges. Models were constructed from plastic, instrumented with release ports and pressure taps, and installed 15 boundary layer heights from the test section entrance in the deep surface shear layer. A sketch of the building and its entrance are shown in Figure 1. A complete description of the experiment is found in Hatcher, et al. (1977).

The experiment consisted of two phases. The first phase attempted to define the cavity and wake region leeward of the building using flow visualization. For 108 cases representing 4 stratifications, 8 wind directions, and 3 release heights still and motion picture photographs were taken of the smoke plumes. In addition, 16 surface oil film conditions were studied to delineate the influence of separation, reattachment, vortex shedding and auxilliary buildings on the building wake.

The second phase of the experiment consisted of concentration measurements made for the 108 cases. An air-propane-ethane mixture was emitted as a tracer gas. Samples were drawn into 48 sample bottles over a period of 5 minutes. Concentrations were obtained by transferring quantities of each sample to a flame ionization detector through a gas chromatograph column to separate gases emitted from different locations. For each case the concentration measurements were repeated with the buildings removed. Vertical profiles were also made on a number of downwind sampling arcs. Sample concentrations have been normalized as $\frac{\chi \bar{U} A}{Q}$, a dimensionsless dilution factor which may be compared to field values. These values are comparable to field concentrations measured in a non-meandering plume over a time period of 10 to 15 minutes.

3. RESULTS AND DISCUSSION

The objectives of this study were: 1) to obtain concentration distributions in the wake and downwind of the model industrial complex with different atmospheric stability categories, 2) to analyze these distributions to obtain information concerning the enhanced dispersion due to the presence of the building complex, and 3) to compare the plume characteristics with the predictions of several analytical and semi-empirical models currently in use.

3.1 Background Flow

To model the diabatic boundary layer bulk Richardson numbers were modeled with the corresponding 2-30 m layer in the field. Bulk Richardson numbers of -0.44, 0, +0.17, and +0.85 were obtained to correspond to Pasquill-Gifford stability categories B, C, E, and F respectively.

The atmospheric boundary layer was modeled to produce velocity profiles equivalent to the prototype flow with a roughness length equivalent to that of short grass ($z_o \sim 0.04$ m, prototype). Power law exponents were evaluated using linear regression analysis of the velocity profiles. Table I presents the comparison of all model and prototype conditions.

3.2 Flow Visualization

An oil film technique was used to determine the nature of the flow field at the surface around the building complex. To determine the effect of the auxilliary buildings on the wake size the technique was repeated without these buildings present. When the silo and tank buildings are directly upstream ($\theta = 0^o$) the flow pattern downstream of the complex is virtually unchanged from the case without these buildings present. This is also the case when the silo and tank buildings are directly downstream. For all other wind directions the auxilliary buildings serve to enhance the lateral extent of the wake, in some cases increasing it as much as 38 per cent.

To determine the movement of an effluent released in the vicinity of the building, titanium tetrachloride was released from each of the exit ports. This technique was repeated for each of the 8 wind directions, and 4 atmospheric stabilities. For ground level releases, all wind directions show smoke being well but not necessarily uniformly entrained into the cavity region. The effects of the auxilliary buildings are noticed for $\theta = 0^o$ when the ground release port is in the wake region of the silo building. In this case the smoke recirculates to the roof of the silo building and enters the tank wake. When the release is directly downwind ($\theta = 135^o$) the smoke is recirculated to the leading edge of the rooftop and becomes entrained into the wake of the stack and appears as stack downwash.

Building height releases also show entrainment into the cavity region for all 8 wind direction. For $\theta = 90^o$ and $\theta = 180^o$ the smoke shows a jetting action that hugs the rooftop and then becomes entrained into the cavity. This phenomenon only occurs when the flow is not disrupted by the presence of the auxilliary buildings. Other wind directions show the smoke being distributed on the roof, sometimes extending to the corners and the leading edge (the release port is in the center of the roof). The amount of effluent that enters the cavity region varies with wind direction for stack height releases. For $\theta = 0^o$, 270^o, and 315^o the smoke is well entrained into the wake, sometimes recirculating back up to the leading edge of the rooftop level. These cases show little differences from ground or building height releases. Building orientations of $\theta = 45^o$, 135^o, and 225^o show very little entrainment into the wake. Stack downwash is present in all cases except $\theta = 45^o$ and 135^o.

For different thermal stratifications dispersion patterns can vary significantly downstream from the buildings. Near the buildings, however, the dispersion is dominated by the mechanical turbulence generated by the building. The major difference noted for the strongly stable case is a "puddle" effect where the flow would lie almost stagnant on the floor showing very little movement. This occurred for $\theta = 0^o$, 225^o, and 270^o. However, the smoke that was recirculating into the wake region did not show significant differences from that of the neutral case.

4. CONCENTRATION MEASUREMENTS

All concentrations, for this study, were converted to the nondimensional concentration coefficient $K = \frac{\chi \overline{U} A}{Q}$. Figure 2 is a graph of nondimensional vertical plume spread, σ_z/h_B, versus nondimensional distance downstream, x/h_B, that compares the vertical dispersion with distance as a function of release height, stability and presence of the buildings. Values of σ_z/h_b tend to increase with decreasing stability for the cases without the buildings, although the rates (slopes) of dispersion are nearly equal. Data points are also compared to the standard Pasquill-Gifford curves for plume growth. The values vary with stratification and downwind distance in a similar manner. A regression curve is shown which best describes the neutral data; the expression for this curve is $\frac{\sigma_z}{h_b} = 0.08 \left(\frac{x}{h_B}\right)^{0.9}$. The data points indicate that the vertical growth of the plume is greatly enhanced by the presence of the building for cases of both ground and elevated releases.

Figure 3 shows the same comparison for values of the lateral plume spread, σ_y/h_B values of σ_y/h_B are substantially larger than the corresponding values of σ_z/h_B. As in the case of σ_z/h_B the values of σ_y/h_B tend to increase with decreasing stability for the cases without buildings present. For the ground level release the lateral growth of the plume is greatly enhanced while no such enhancement is noticed for the elevated release. A regression curve is included which best describes the neutral data; the expression for this curve is

$$\frac{\sigma_y}{h_b} = 0.16 \left(\frac{x}{h_b}\right)^{0.9} .$$

Comparing the curves for lateral and vertical plume spread is a convenient method to estimate stability categories.

Inspection of Figures 2 and 3 indicate that the slightly unstable case is indicative of stability class B, neutral conditons fall between C and D, while slightly unstable represents almost E type stability and strongly stable is between E and F.

Ln-Ln graphs of K versus x/h_B were produced to study the decay of concentration values with distance. For x/h_B greater than about 15 K decays as a power law exponent of -1.8. This slope shows little variation with wind direction and release port. The effect of stability in that region is to increase ground level concentrations for the stable categories while decreasing ground level concentrations for the unstable case. The enhanced turbulence for the unstable case tends to increase the dispersion capability of the layer, whereas for the stable case the turbulence is subdued and the maximum concentration remains close to the ground.

In the vicinity of the buildings dispersion is the result of the mechanical turbulence generated by the building. Ground level releases which emit nearly 100 per cent of the effluent directly into the cavity show highest concentrations, whereas stack level releases, where some effluent escape the cavity, show lower ground level concentrations. When ground level concentrations of the stack release approach those of the ground level release it is an indication that the elevated plume has diffused to the ground. This occurs generally by 8 building heights, however, for $\theta = 45^\circ$ and 315° it does not occur until 15 building heights.

Though in the wake of the building aerodynamic turbulence dominates, the effects of stratification are noticeable. Strongly stable stratification results in higher concentrations, a possible result of the "puddle" effect mentioned earlier and subdued dispersion in the vertical direction. Slightly lower concentrations resulted for the case of unstable stratifications.

5. COMPARISON WITH MODELS

Many methods have been used in the past for predicting ground level concentrations in the wake of buildings. Some of the simpler and more immediately applicable techniques are discussed and compared to the results of the present study in this section.

The basic Gaussian diffusion model, which provides the basis for most models which predict concentrations in building wakes is:

$$\frac{\chi \bar{U} A}{Q} = \frac{A}{\pi \sigma_y \sigma_z}$$

The object of most building wake diffusion models now is to make the denominator somehow larger either by adding a term or modifying values of σ_y and σ_z.

The simplest model is that by Gifford (1960) which suggests

$$\frac{\chi \bar{U} A}{Q} = \frac{A}{\pi \sigma_y \sigma_z + CA}$$

where values of C are intuitively suggested to range from 1/2 to 2. This model is based on Fuquay's (Slade, 1960) volume source model where the assumption is made that effluent mixes rapidly into a uniformly distributed volume and thus disperses as a volume source. However, Halitsky (1963) observed that the real concentration in the cavity was not uniformly distributed. Similar results are observed in this study, as discussed earlier. However, even with these failings Gifford's model (Equation above) does a reasonably good job in predicting ground level concentrations in the vicinity of the building from $1 < x/h_B < 10$. Comparison of this simple model to the present study will be made in later sections.

A model suggested by Halitsky modifies the standard values of σ_y and σ_z by complex functions of plume boundary and complex half widths. This model is more fully discussed in Halitsky (1975).

The third model is that suggested by Huber and Snyder (1975). It is similar to Halitsky's model in that it also modifies σ_y and σ_z. This model assumes that in the near wake ($x/h_b \le 10$) the dispersion is controlled by the high turbulence intensity close to the building. Since the wake turbulence decays rapidly, the dispersion in the far wake is controlled by the background atmospheric turbulence whose dispersion parameters are given by the standard Gaussian curves and are related to a virtual source a distance S upstream from the release point. Following the approach presented by Huber and Snyder, the model for this study would be

$$\frac{\sigma'}{h_B} = 0.45 + 0.06\left(\frac{X}{h_B} - 3\right) \quad \text{for } 3 \le X/h_B \le 10$$

and

$$\frac{\sigma'}{h_B} = 0.45 + 0.06\left(\frac{X}{h_B}\right)^{0.9} \quad \text{for } X/h_B \ge 10$$

Since for all the analytic models discussed above the assumption has been made that the effluent was well entrained into the wake, the appropriate cases selected for comparisons were ground, building, and stack height releases from a downwind face. Figure 4 compares the three models with the data and with standard Pasquill-Gifford curves. For ground level releases Gifford's model was most consistent when a value of C = 1 was used. Huber and Snyder's model also provided good correlation. Halitsky's model substantially underpredicted ground level concentrations. However, this latter model could probably suffice if the constants were adjusted. The only analytic model that can be related to elevated releases was that of Huber and Snyder. It did not appear to agree well with the observed data.

6. CONCLUSIONS

From this study the following conclusions can be made: 1) In the near wake region the presence of the buildings significantly alter the dispersion patterns from those without the buildings present. 2) At some distance downwind, generally by $x/h_B = 8$, the rate of dispersion is independent of release position and building orientation. 3) Minor additions to the building complex cause significantly altered flow and dispersion patterns. 4) In the cavity-wake region behind the building aerodynamic turbulence dominates over the atmospheric turbulence but the effects of the latter are still visible. 5) Further downwind the atmospheric turbulence dominates by $x/h_B = 15$. 6) The effects of stratification are to cause slightly higher concentrations for stable atmospheres while slightly lower concentrations are noticed for unstable stratifications. 7) The effect of the buildings is to enhance the dispersion (mostly in the horizontal) and cause lower concentrations. These lower concentrations may be accounted for by the use of simple models. 8) Ground level releases tend to enhance the dispersion in both the horizontal and vertical, while elevated releases enhance only the vertical in the presence of the building complex. 9) Minor additions to building complexes can significantly alter the effective wake size, increasing it by as much as 38%.

7. REFERENCES

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Table 1. Comparison of Modeling Parameters for Model and Prototype

Parameter	Model			Prototype		
z_o/h_B	0.0018			0.0018		
δ/h_B	10			13		
Re	12,000			10,000,000		
u_*/u_h	0.064			0.06		
h_s/h_B	0,1.0,1.2			0,1.0,1.2		
Power law exponent p (from data)	.12,.16,.22,.42			-,.15,.35,.52		
Sampling grid x/h_B	1.5-70			1.5-70		
ATMOSPHERIC STABILITY	*PG	Ri_B	h_B/L	*PG	Ri_B	h_B/L
stable	F-G	0.85	1.69	F-G	1.1	1.29
moderately stable	E	0.17	0.45	-	-	-
neutral	C-D	0	0	C-D	0	0
unstable	B	-0.44	-0.68	B	-0.63	-1.08

*Pasquill-Gifford stability category

8. ACKNOWLEDGMENTS

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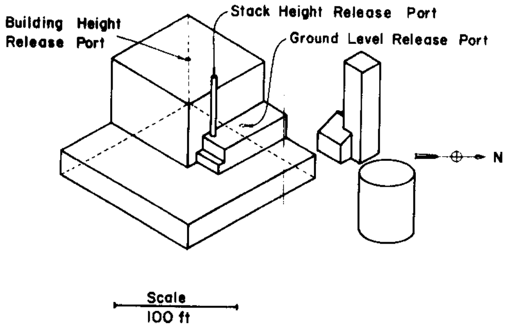

Figure 1. EOCR Reactor Complex

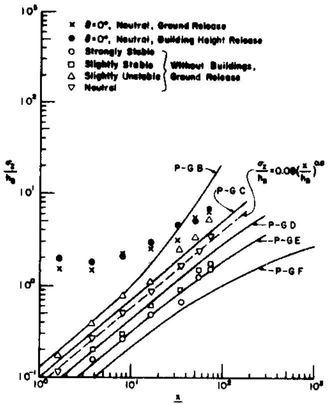

Figure 2.

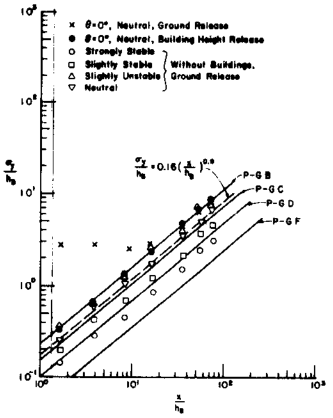

Figure 3.

Figure 2. Nondimensional Vertical Plume Spread Versus Distance Downstream

Figure 3. Nondimensional Lateral Plume Spread Versus Distance Downstream

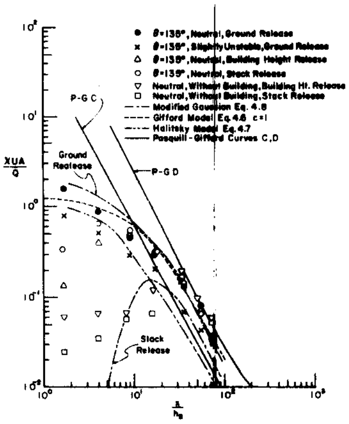

Figure 4. Comparison of Observed Data With Prediction Equations