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PEAK-TO-MEAN CONCENTRATION RATIOS FROM GROUND-LEVEL SOURCES IN BUILDING WAKES*

W. T. HINDS†

Battelle Memorial Institute, Pacific Northwest Laboratory, Richland, Washington, U.S.A.

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Abstract—A short series of tests was conducted to determine whether ground level point sources at the upwind stagnation point of a large building yielded peak-to-mean concentration ratios that were significantly different than those observed for ground level point sources in unobstructed flow. Time-average concentrations over test periods of 6–15 min were measured to delineate the spatial extent of the plume for both types of flow conditions. Also, 5-sec averages of concentration at a point near the centerline of the plume were measured to indicate the time history of concentration. The results indicated that there was no detectable difference between peak-to-mean ratios measured in unobstructed flow and in the lee of a building with a point source near the upwind stagnation point. Because of the strong dependence of wake diffusion on source location, no conclusions were possible concerning peak-to-mean ratios from sources located at sites other than the upwind stagnation point.

INTRODUCTION

IN RECENT years, a significant amount of work has been devoted to studying the effect of flow around obstacles on atmospheric diffusion. Both wind tunnel and field tests have shown that strong effects can be introduced by the wake flow near the obstacle, and that wind tunnel tests can provide a good basis for predicting wake diffusion in the real atmosphere. However, little discussion of concentration variability, particularly that in the rather complicated flow immediately in the lee of an obstacle, has been published. The object of the preliminary study described here was to determine if first order differences in peak-to-mean concentration ratios may be introduced by flow around obstacles.

After a brief examination of previous work concerning diffusion in building wakes and the variation of concentration in point source plumes, the experiments are described, and the implication for peak-to-mean concentration ratios in wakes is discussed.

WAKE STRUCTURE AND CONCENTRATION VARIABILITY

There are several descriptions of the formation and structure of wakes available in the literature (BIRKHOFF *et al.*, 1957; HALITSKY *et al.*, 1963; MARTIN, 1965) so only a brief definition of terms is required here. Of most importance in the present discussion is the displacement zone and the cavity. The *displacement zone* is the region near the building that is characterized by streamline curvature around the obstruction. The inner portion

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† Research Scientist, Environmental and Radiological Sciences Department, Pacific Northwest Laboratory, operated by Battelle Memorial Institute for the United States Atomic Energy Commision, Richland, Washington.

of the displacement zone is marked by a rather stationary series of vortices generated by severe flow distortion at the building edges and corners. The characteristics of these vortices are dependent upon the free stream speed and direction relative to the obstacle; changes in direction, especially, cause the vortices to be shed from their sites and carried downwind, to be replaced by a new system of vortex placement depending upon the new wind condition. The shifting geometry of the vortices provides a mechanism by which material originally outside the wake streamlines can become enmeshed in the *cavity*, the stationary eddy attached to the downwind side of the building. The cavity is marked by a weak upwind flow, a decrease in wind speed, and an increase in turbulent intensity (MUNN and COLE, 1963, ISLITZER, 1965).

One assumption made by many workers is that the contaminant is rapidly spread throughout the wake once entrainment has begun (BARRY, 1965). DAVIES and MOORE (1964) apparently were successful in verifying that this is a rather good approximation in field conditions. However, even if the pollutant were well mixed, a steady concentration is unlikely, since turbulence is enhanced by the wake. Few data are available which would define the variance of concentration in the wake; only MARTIN (1965) quotes any, and his were taken well outside the cavity. Because of the close relation between concentration variation and turbulence, wind tunnel measurements of peak-to-mean ratios will be difficult, unfortunately.

Two types of peak concentration can be defined. One, discussed theoretically by GIFFORD (1960) and CSANADY (1967), considers variability of concentration in relation to plume centerline, that is, due to plume meander. Another results from averaging the time history of concentration at a point over differing time intervals, that is, considering the concentration to be a random function of time, the observed peak concentration will be a decreasing function of increased smoothing interval. This bifurcation is useful, although somewhat arbitrary. GIFFORD (1960) also presented a number of data from several workers indicating the effect of increasingly smoothing concentration measurements. A fairly well defined power law dependence was shown by his plot, with the index a function of displacement from the plume centerline. SINGER (1961) also presented a summarization of data that indicate a power law dependence on smoothing interval. In a later paper, SINGER *et al.* (1963) reported a summarization of a nearly independent set of data from a number of workers, again indicating a power law dependence of peak-to-mean ratio on smoothing interval. Recognizing that the peak concentration can be specified in terms of the standard deviation of the distribution of concentration observed through time (see CSANADY, 1967), SINGER and his co-workers (1963) hypothesized that a power law connected variance and smoothing interval.

Not all results indicate a strict power law. In another paper (HINDS 1968*a*), this point is discussed in more detail, and an equation is derived that indicates the rather restricted conditions to which a strict power law applies. FAORO (1965) presented data indicating the index may be a function of smoothing interval, and GENIKHOVICH and GRACHEVA (1965) (an untranslated report) derived a sum of exponential, inverse-linear, and inverse-square terms for the decrease of variance with smoothing interval.

EXPERIMENTAL METHODS

The techniques used in this series of diffusion tests were evolved from rather well-known methods previously used in larger scale experiments carried out at Hanford and other sites (Barad and Fuquay, 1962). The atmospheric tracer material used during these experiments was the fluorescent pigment, zinc sulfide, U.S. Radium Corporation designation No. 2210. It is a very fine particulate that fluoresces green under u.v. light and radiation. The particle size distribution is nearly log normal with a geometric mean diameter of about 4 μ and a standard deviation of logarithms of the diameter of 0.70. The density of the zinc sulfide particles is 4.1 g cm^{-3}.

Ordinarily, the tracer is suspended in water for dispersal at a constant rate through high volume insecticidal foggers. In the present case, the use of water as the suspension agent was considered impractical, since some travel distances of the order of only a few meters were used, which might well preclude complete evaporation of the droplets. A dry cleaning solvent, trichloroethane, was substituted; this liquid has a very high vapour pressure at normal temperatures, and evaporates completely within a meter. A small backpack type of herbicide dispenser (manufactured by Solo Kleinmotoren), which uses a high speed air flow to break up the tracer suspension into small droplets, proved to be a satisfactory low flow dispenser.

Two types of air sampling were conducted during this series of tests: time-integrated concentrations and time history of concentration. The time-integrated concentrations were comparable to the standard measurements as made in nearly all diffusion experiments, whereas the time history measurements were relatively new. In both cases, the measurements were made directly within the cavity, rather than in the wake proper where the mean wind direction had been re-established.

Air flow within the cavity was unsteady, since each change in wind direction caused a new orientation of the building with respect to the prevailing wind, and thus a different equilibrium shape and position of the cavity. Wind directions within the cavity thus showed a remarkable variability at any given point, often going full circle in less than a minute. Since the efficiency of any sampler, whether aspirated or not, is a function of the relative direction of sampler port and wind direction (Green and Lane, 1957) and is nearly zero when the wind is against the back of the sampler, some means of assuring wind flow into the face of the sampler was required. The air sampler units were thus provided with a large tail that assured proper orientation with minimum over-shoot and an adequate turning moment in light winds, and were dubbed SOS (Self-Orienting Sampler). The air sampler itself was identical with that used in previous tests (Barad and Fuquay, 1962), a membrane filter aspirated by gasoline engine powered vacuum pumps through calibrated critical flow orifices.

The measurement of time history of concentration was made with a Self-Orienting Real Time Sampler (SORTS), a Real Time Sampler (RTS) (Nickola *et al.*, 1967) mounted with a tail similar to the SOS. The RTS used the phosphorescence of u.v. irradiated zinc sulfide to activate a photomultiplier, and reliably yielded concentration measurements in the range from about 3×10^{-7} to 3×10^{-3} g/m^3. Although no precise measurement of the time constant of the RTS was available, it was estimated by the travel time through the sampler and the recorder speed. The time to traverse the sampler was about 0.8 sec, and the full scale response time of the recorder was 0.5 sec. Thus, to assure adequate accounting of instrument smoothing of the real concentration, average concentrations over 5-sec periods were chosen as the minimum time resolution for data reduction.

Other sampling errors, such as deposition and anisokinetic flow, were neglected. The anisokinetic error was not large, at most 20 per cent, and probably about 10 per cent (SEHMEL, 1966). The short internal distances involved in this series did not allow time for significant amounts to deposit.

DESIGN OF THE SAMPLING GRIDS

Two separate sampling grids were used in this study. One, the control grid, was laid out around the Hanford 400-ft meteorological tower to indicate the history of concentration variation from an unobstructed point source. A second, the wake grid, was laid out around a fairly large rectangular building (24 × 35 × 11 m) with a fetch of about a kilometer to provide data showing the difference, if any, in concentration history in the lee of a building. The source height was set at 1 m for both grids, avoiding, at this stage, the complications of elevated sources. Source point placement was at the center of concentric arcs for the control tests and at the upwind stagnation point for the wake tests.

The control grid consisted of three arcs of 11 samplers at each of the distances 30, 50, and 100 m from the source point, with arcs 85° in azimuth range. The wake grid consisted of arcs of 14 samplers at 30 m and 10 samplers at each of the distances 50 and 100 m from the center of the building. The arcs were considerably greater in angular coverage than the control grid, because large shifts in wake position were expected with changing wind direction. The inner arc covered 310°, the middle arc 270°, and the outer arc 200°. To avoid introducing confusion, the SORTS was placed at a point on the expected centerline before tracer release. This position was not changed during the test period.

THE DATA

Four tests (two each for the control and wake grids) were successful in all respects. Although an attempt was made to keep the two series exactly comparable in test conditions, release times were not identical: 10 and 15 min for the control tests and 6 and 15 min for the wake tests. Atmospheric stability was near neutral, with wind speed about 5–7 m sec^{-1} for all tests. The average concentration isopleths for the tests are shown in FIG. 1, in terms of exposure, E, (g sec m^{-3}) normalized to source strength, Q_T (g). The asymmetrical patterns observed for the wake tests were apparently caused by the mean stagnation point being slightly off the source point. The position of the SORTS is indicated for each test.

The SORTS data are tabled fully in HINDS (1968*b*).

ANALYSIS

There are two important points for examination: the distribution of concentrations in time, and the peak-to-mean concentration ratios observed during the tests as a function of smoothing (averaging) interval. Although too few tests were successful enough to allow definitive statements, some guidance is possible, and the direction for future investigation is clearly indicated.

Frequency distribution of concentrations

The position of the SORTS with respect to centerline was a most important factor for determining both the time distribution of concentration and the peak-to-mean ratios that were observed. The position of the SORTS in each test has already been indicated in plan view in FIG. 1, and in FIG. 2, the position of the SORTS along a cross wind transect of the plume through the SORTS position is shown. TABLE 1 lists the SORTS position with respect to the standard deviation of the mode in which the

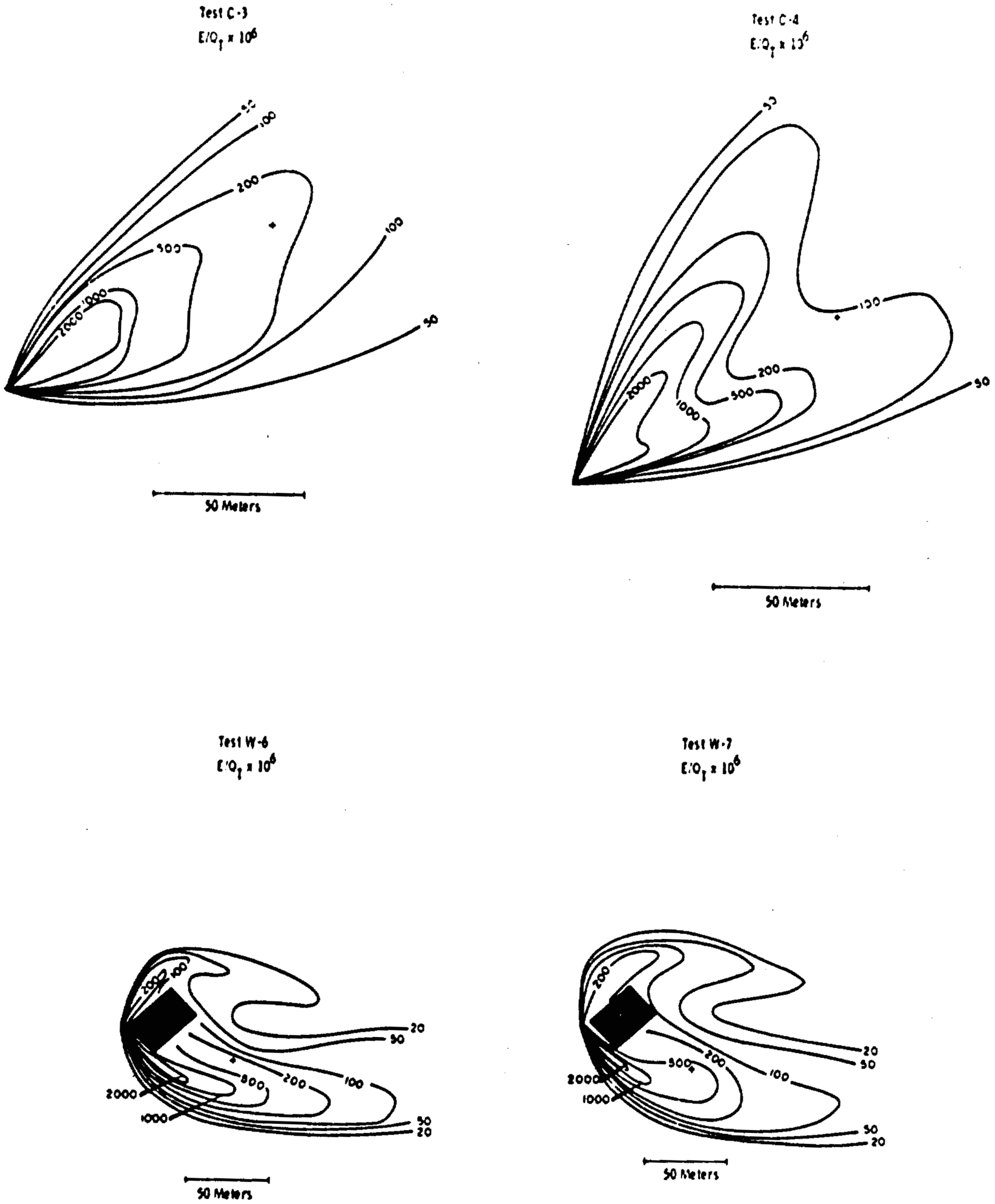

FIG. 1. Isopleths of exposure (normalized to source strength) for the test series, with position of the Self-Orienting Real Time Sampler (SORTS) indicated by +

SORTS was located (the standard deviation of the total distribution would yield misleading values, particularly in wake tests where modes were widely separated).

Clearly, centerline characteristics could be well represented by only two tests, C-3 and W-7.

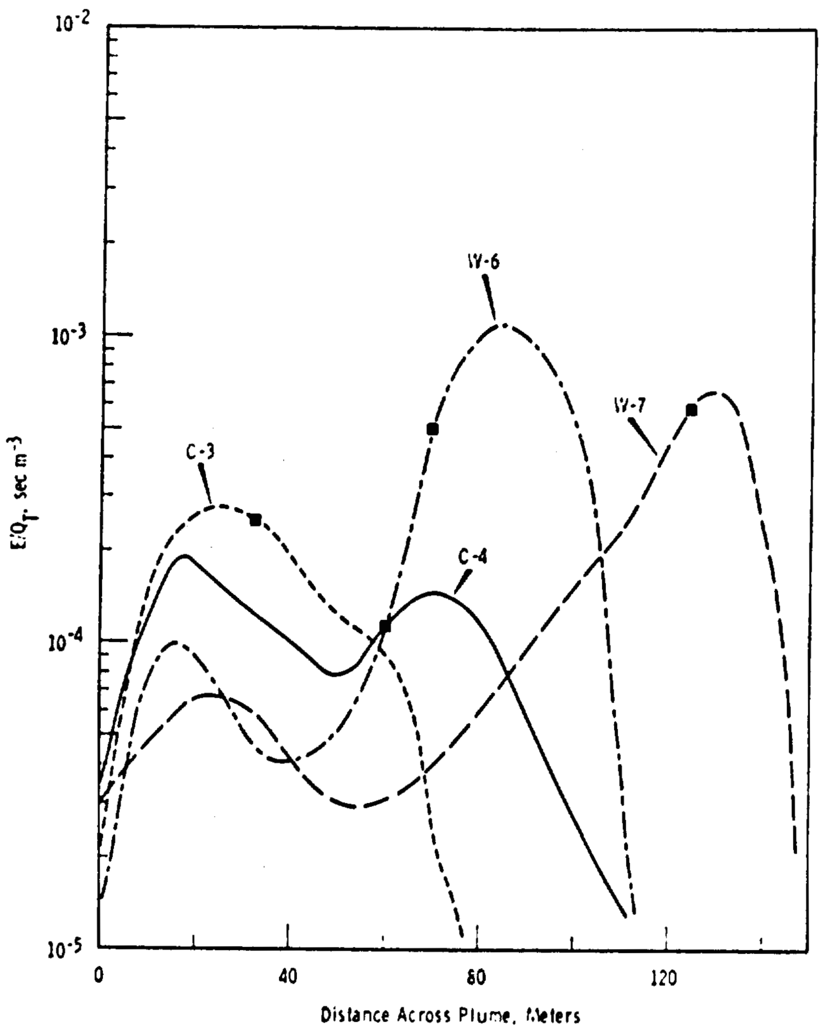

FIG. 2. Crosswind distributions of exposure (normalized to source strength) for the test series. The distributions are along a line normal to the free wind direction through the SORTS position (■).

As seen in FIG. 2, the cross-sections of wake tests are essentially the same as the bimodal point source test C-4; in this sense a wake provides no inherently different diffusive regime. One characteristic quality of bimodal distributions is a relatively high degree of intermittency, that is, the instantaneous plume centerline is not often at or near the point in question. Measures of intermittency are not standardized to any extent, but the intermittent character of the tests can be seen in FIG. 3, where the cumulative frequency of concentration levels is shown. Intermittency is indicated in

TABLE 1. SORTS POSITION WITH RESPECT TO NEAREST PLUME MODE

Test	σ_y, m (mode containing SORTS)	Distance from nearest mode centerline (in units of σ_y of the mode)
Control C-3	11	~0.6
Control C-4	14	~0.9
Wake W-6	10	~1.4
Wake W-7	10	~0.6

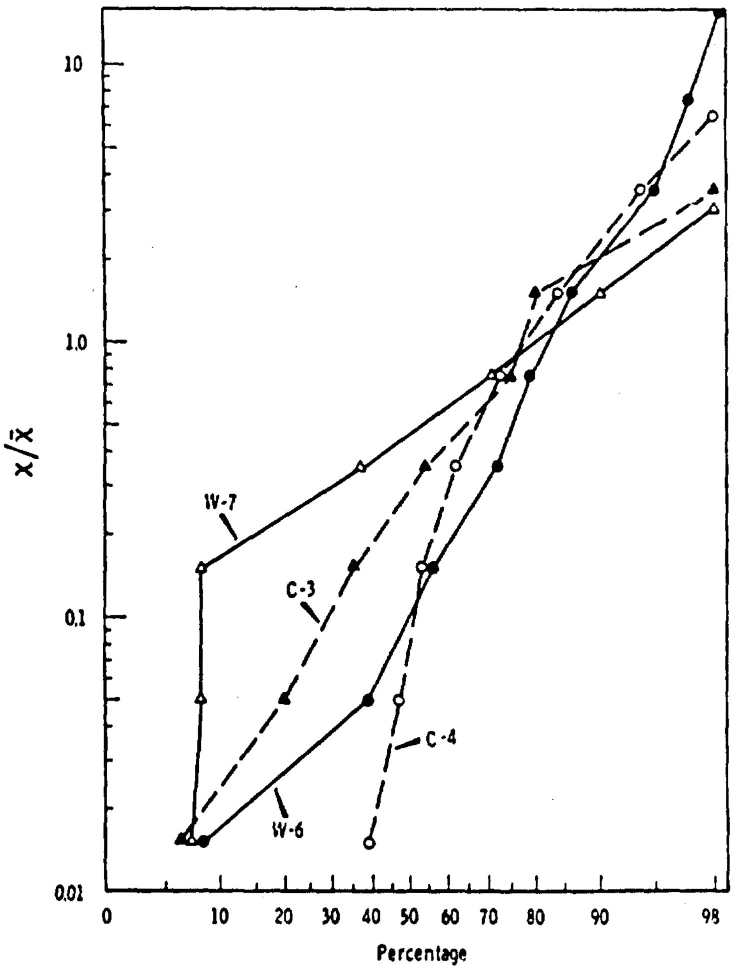

FIG. 3. Cumulative concentration distribution normalized to average concentration over whole release time.

FIG. 3 by a displacement of the lower concentrations toward high percentages of occurrence, typified by the bimodal test C-4. Thus, test W-6 was more intermittent in nature than C-3, and test W-7 was not at all intermittent in nature. Other factors remaining constant, an increase in intermittency will act to increase peak-to-mean ratios because of the increased proportion of low concentrations.

The time distribution of concentration near the center of a plume has on occasion been likened to a Poisson distribution; that is, the standard deviation of the distribution has been assumed equal to the mean (whereas for the Poisson distribution, the variance equals the mean). An equality between the standard deviation and the mean

TABLE 2. MEAN, VARIANCE AND STANDARD DEVIATION OF TIME HISTORY OF CONCENTRATION FOR CONTROL TESTS (C) AND WAKE TESTS (W), g m^{-3}

Test	Mean ($\times 10^{-4}$)	Variance ($\times 10^{-8}$)	Standard deviation ($\times 10^{-4}$)
C-3	0.656	0.878	0.937
C-4	0.310	0.358	0.598
W-6	4.83	167.0	12.9
W-7	0.817	0.760	0.872

has indeed been demonstrated for tube flow (see CSANADY, 1967). TABLE 2 shows the relation between the mean, variance, and standard deviation for the concentration distributions observed during the control and wake tests.

The Poisson distribution itself is inappropriate for distributions such as concentrations observed in the atmosphere, because each of the observations forming a Poisson distribution must have the same (small) expected value, a condition in conflict with the finite "memory" of the atmosphere. However, the assumption of equality between the standard deviation and the mean has some merit, at least for the rudimentary calculations that are possible at this writing; as indicated in TABLE 2, the ratio of the standard deviation to the mean varied from ~1 to ~2.6 for the four tests.

Peak-to-mean ratios

The peak-to-mean concentration ratios observed during the tests are shown in FIG. 4, along with the lines suggested by GIFFORD (1960) as representative of the dependence of peak-to-mean ratios on sampling time. The plot is based on plotting

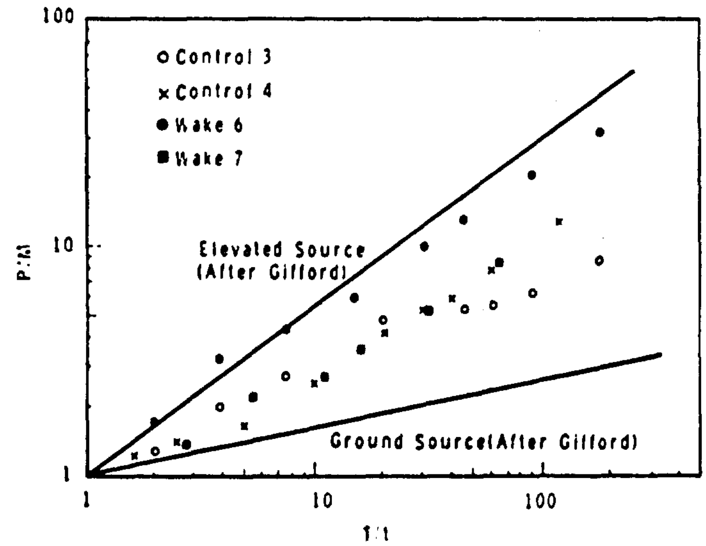

FIG. 4. Peak-to-mean concentration ratios (P/M) measured by the SORTS as a function of the time of release (T) and averaging interval (t).

peak-to-mean ratios against the ratio of total sampling time, T, to the smoothing interval over which the peak concentration was observed, t. Thus, as t approaches T, the peak-to-mean ratio must approach unity. There is no implication that this plot is universal; it is simply a straightforward method of demonstrating the dependence of peak-to-mean ratio on sampling and averaging times. GIFFORD (1960) proffered the two lines shown in FIG. 4 to represent peak-to-mean ratio behaviour at the centerline of the plume (the lower line) and below the centerline (the upper line). In our present state of knowledge concerning peak-to-mean behaviour, the upper line may be considered as the suggested expectation of peak-to-mean ratios observed at points displaced from the centerline either in the vertical or the horizontal. The data used by Gifford were taken from elevated sources up to 100 m above the ground, and from ground level sources, and the data were measured at distances from the source between 100 and 400 m. (There is no reliable way of determining a "typical" distance from the centerline to which the upper line applies.) Although GIFFORD (1960) pointed out that the suggested lines could be expected to hold only for the times of release and distances for which the data were measured, at present no better standard of comparison is available.

As can readily be seen, the data from the control tests do not lie near the line suggested by GIFFORD (1960) for near-centerline positions, and there is very little difference between the two control tests, even though the SORTS for test C-4 was nearly one standard deviation from the local mode of a bimodal distribution, while for C-3 the SORTS was about one-half standard deviation from the centerline of a single mode distribution. Wake test W-7 yielded data lying very near the data from the control tests, apparently a result of the very wide separation of the modes in the cross-section of this test (FIG. 2) and the proximity of the SORTS to the center of the major mode. Wake test W-6 yielded peak-to-mean ratios very much higher than any of the other tests, but the SORTS was significantly farther removed from the centerline of the local mode in W-6 than for any other test. To separate the effects due to displacement from

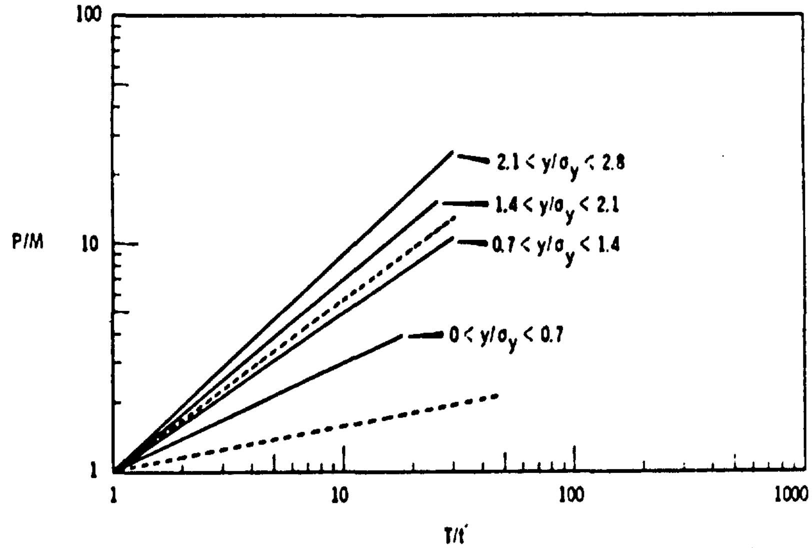

FIG. 5. Tentative dependence of peak-to-mean concentration ratios on displacement from centerline (y) in units of σ_y of the mode containing the SORTS.

the local centerline and the effects due to wake flow, some knowledge of peak-to-mean ratios as a function of displacement is required.

An indication of the effect of displacement from the centerline is shown by a preliminary analysis on peak-to-mean concentration ratios observed. Mr. J. V. Ramsdell has kindly made available data from twenty Geiger–Mueller tubes exposed and read simultaneously during the release of ^{85}Kr from a continuous point source 200 m from the sensors. Four tests with durations varying from 10 to 20 min provided the data used in FIG. 5. The figure indicates peak-to-mean ratios observed as a function of T/t, but with lines indicating the average behavior observed at various displacements from the centerline in units of standard deviation of the test. Note that the line for y/σ_y between 0 and 0.7 is very nearly identical to the data from tests C-3, C-4, and W-7. Furthermore, the line for y/σ_y between 0.7 and 1.4 lies in the region in which the data from test W-6 occur. Thus it seems clear that the most, if indeed not all, of the tendency for the test W-6 toward high peak-to-mean ratios is due to displacement from the local centreline, and not due to a diffusive mechanism peculiar to wake flow.

DISCUSSION AND CONCLUSIONS

The lack of evidence to indicate that wake diffusion is different than point source diffusion (for ground level sources at the upwind edge) is reflected in the behavior of the time-average concentrations, as shown in FIG. 6. Here, the maximum exposure (g sec m^{-3}) normalized to the source strength (g) is plotted against distance from the source. Clearly the only significant difference between the two types of tests is a tendency for the maximum exposures for the wake tests to be higher than those for the control tests near the source. An examination of the isopleths of the tests (FIG. 1) reveals the probable cause of this tendency: because the source was at an upwind edge, the plume was confined against the wall of the building by the streamlines of the displacement zone, thus effectively inhibiting the diffusion of the plume until the downwind edge of the building was reached. Consequently, higher exposures were experienced near the source in the wake tests than in the major mode of the point source tests. HALITSKY *et al.* (1963) found similar patterns and diffusion rates in their wind tunnel tests from ground level releases at the side of a cylindrical building.

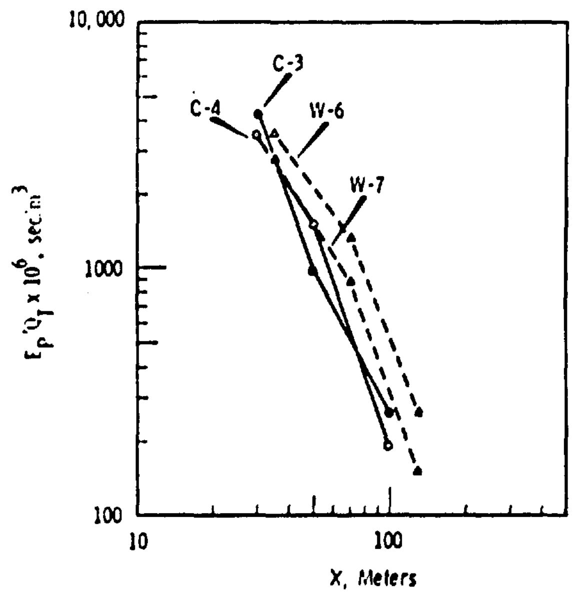

FIG. 6. Exposure (normalized to source strength) as a function of distance for the test series.

The rather close correspondence between point source and wake tests noted in this series has no bearing on results to be expected from tests conducted with the source located at points other than near the upwind stagnation point. Specifically, if the source were near the *downwind* stagnation point, initial diffusion of the wake plume would be rapid indeed. However, field measurement of this type of test is no simple task (as opposed to the design used for tests W-6 and -7, which was simple indeed). Primarily, diffusion from a downwind stagnation source would be enhanced in the vertical direction, due to the upward currents in the upwind portion of the cavity, (see EVANS, 1957) suggesting a three-dimensional sampling grid to define the distribution of tracer in the cavity. This important task has yet to be attempted in the field, where peak-to-mean concentration ratios are meaningful. [ISLITZER (1965) and DICKSON *et al.* (1968) used a downwind location for the source point; however, concentration variability was not measured.] Peak-to-mean ratios to be expected from sources near the downwind stagnation point can only be conjectural at this time.

Another source point location of immediate concern is near and just above the roof of a building—the "short stack" geometry. There is no question that the results from the short stack configuration will be quite different than the results reported here (cf. DAVIES and MOORE, 1964). Principally, the difference is expected because the plume from a short stack may be alternately entrained in and released from the cavity as wind speed fluctuates (thus altering the entrainment criterion defined by Davies and Moore). If this alternate entrainment and release does in fact occur, the time-average concentrations will be altered, and the peak-to-mean ratios observed in the cavity may be strongly affected. It seems probable that intermittency will be increased by the short stack configuration, so that the range of peak-to-mean ratios should be increased relative to a comparable source in unobstructed flow.

At this point, such speculative conclusions are no more than perhaps a reasonable extrapolation of existing data. There is no doubt that well designed field experiments are needed to provide some data for these important problems. The conclusion to be drawn from the tests described here, namely that there is no significant difference between unobstructed point sources and point sources located immediately upwind of a building, is indicative of the importance of future research, since this conclusion is in direct opposition to earlier discussions of these data (HINDS, 1968*b*) and to the hypothesis the tests were designed to confirm or deny. Caution is clearly necessary if one must impute concentration variability in wake conditions from existing data.

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