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Diffusion Near Buildings as Determined from Atmospheric Tracer Experiments

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DIFFUSION NEAR BUILDINGS AS DETERMINED FROM ATMOSPHERIC TRACER EXPERIMENTS[1]

J. F. Sagendorf, N. R. Ricks,
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ABSTRACT

Data from the innermost arcs and roof top samplers of the Rancho Seco and EOCR field studies were used to examine diffusion close to a building. The minimum length plume paths were determined from each release location to each sampler position at these two test sites. Measured concentrations, normalized by source strength (C/Q), were plotted versus plume path length and an envelope containing 95% of the measured values of C/Q was determined.

The curves from the two sites were similar in shape and implied three zones of diffusion. It is speculated that the three zones represent the rapid diffusion in the building wake; a transition zone where the plume leaves the wake of the building and where the rate of diffusion is reduced; and finally, the region where larger scale atmospheric turbulence again causes more rapid diffusion.

By scaling the plume path length by the minimum cross sectional area of the structure, the curves for Rancho Seco and EOCR showed no significant difference in magnitude for about one scaled distance. Since these studies were conducted at two dissimilar sites, the consistency in measured concentrations suggests that the technique may be useful in predicting maximum expected concentrations near a building.

Comparisons were also made with current NRC methods for predicting maximum expected concentrations close to a building. The NRC model overestimated concentrations in all but one case. The model was generally within an order of magnitude at EOCR, and within two orders of magnitude at Rancho Seco.

I. INTRODUCTION

All facets of wind engineering have been rapidly expanding in the last 15 years. Studies of mean wind and gust loading on structures, diffusion in the building wake, and aerodynamics of bluff body flow continue to be actively investigated. These phenomena are being investigated primarily through the medium of physical modeling in the wind tunnel. Flow characteristics and diffusion in the boundary layer of a building, long recognized to be applicable to recirculation of building exhausts to local intakes, is now receiving increased emphasis. For the nuclear power plant licensing process, there is a need for more realism in the assessment of potential control room and exclusion area radioactivity exposures during postulated design basis accidents and for evaluation of the conservatism of models currently in use. Both wind tunnel modeling and actual field study data are now becoming available for the re-examinations of these near building diffusion questions.

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In December 1977, the Nuclear Regulatory Commission requested that the sets of field measurement data taken during the EOCR and the Rancho Seco diffusion field studies be analyzed with an emphasis on evaluating the licensing formula in use at that time, and to develop a technique to more realistically estimate relative concentrations close to the building. The original field studies to be discussed in this manuscript [Rancho Seco (Start, et al, 1977) and EOCR (Start, et al 1979)] were designed to emphasize the diffusive character of the turbulent wake at many reference lengths downwind (distance divided by some characteristic dimensions of the structure). However, those samplers located on the roof and ground-level at short downwind distances yielded a significant collection of useful data relevant to the near building problem.

II. QUALITATIVE RESULTS

The Rancho Seco field measurements were collected in the fall of 1975 at the Rancho Seco Nuclear Power Station located approximately 25 miles south of Sacremento, California. The EOCR study was conducted in the summers of 1975 and 1976 at the EOCR facility at the Idaho National Engineering Laboratory (INEL) near Idaho Falls, Idaho. The Rancho Seco site consisted of many large structures set in a broad, dry interior valley of central California. Relatively flat valleys and low hills surround the site. The EOCR facility is much smaller, with one main building and a few smaller structures nearby. It lies in the broad, flat upper Snake River Plain of Southeastern Idaho; the terrain in the immediate vicinity of the building is slightly rolling. Figures 1 and 2 show the buildings and sampler layouts for the two sites. At Rancho Seco, tracers were released from the ground surface, the roof of the auxiliary

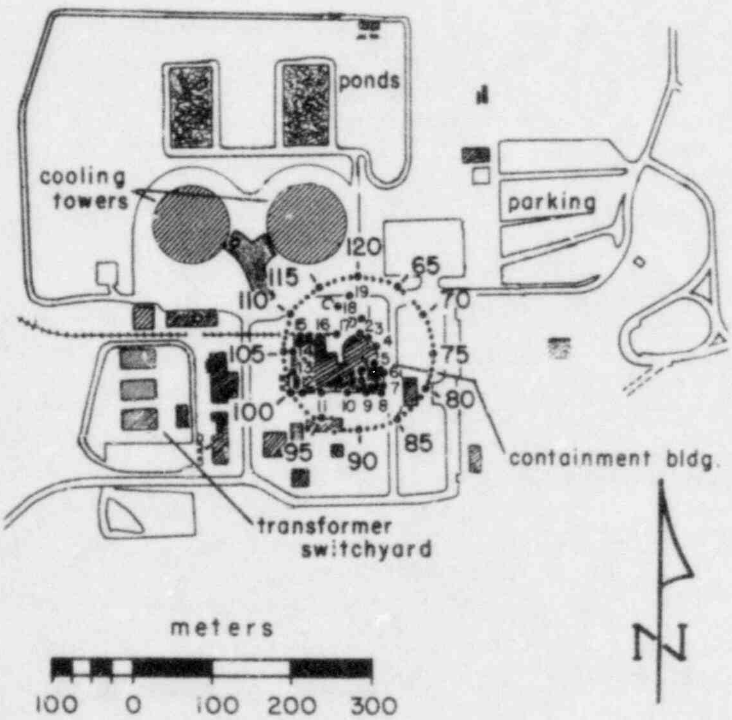

Figure 1. Close-in sampling positions at Rancho Seco.

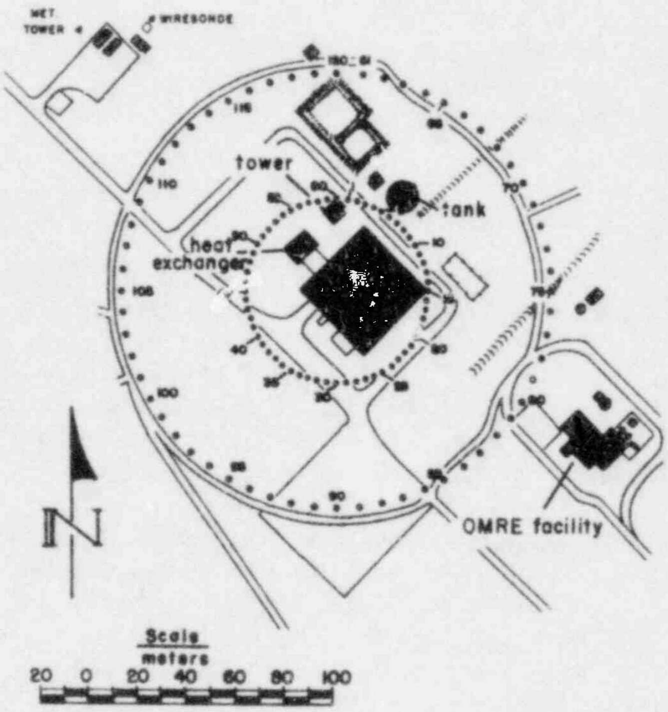

Figure 2. Close-in sampling positions at EOCR.

building, and on top of the containment vessel. Samplers examined for this study include those on the roof of the auxiliary building, the surface samplers adjacent to or near to the auxiliary building and containment vessel, and on the ground-level 100 meter arc. At EOCR, tracers were released from the ground surface, the highest roof of the building and out of the stack. Samplers used in this study were located on the lowest roof and on the ground-level 37.5 m and 87.5 m arcs. The plume travel distance from each release location to each sampler position was determined. If a building was between the release point and the sampler, the shortest possible path length around the building was chosen to be the plume travel distance. Scatter diagrams showing sampled C/Q (concentration normalized by source strength) versus distance for EOCR and Rancho Seco are shown in Figures 3 and 4 respectively. The solid curves on these plots represent the value of C/Q which exceeded 95% of the sampled values at that range of distance. These curves were determined by grouping the points into bands 10 m in width and computing the average distance for the band and the C/Q value at the 95% cumulative frequency level (5% of the values of C/Q exceeded this 95% cumulative frequency). A fourth order curve was fit to the resulting 95% level C/Q values and average distances. The 95% level C/Q values and average distances are contained in Tables 1 and 2 for EOCR and Rancho Seco, respectively.

Figures 5 and 6 are examples of the 10 m bands of C/Q values versus cumulative frequency plotted on log-normal graphs. In these plots a straight line would indicate a normal distribution of C/Q values within the band. In figure 5 it can be seen that the upper part of each curve departs from a normal distribution and turns toward relatively lower values of C/Q. This departure from normality affects a larger fraction of the total values of C/Q within a given band for bands closer to the EOCR structure. For example, the 5-15 meter band is badly distorted from a normal distribution at the higher concentration end of the curve. In figure 6 the same general pattern is seen, although the Rancho Seco bands of C/Q never as closely approached a normal distribution as did the curves for the EOCR data. This greater deviation from normal is likely due to the effects of the much larger complex of buildings at the Rancho Seco facility. It is interesting to note that a normal distribution of C/Q values within each band would give higher extreme values of C/Q than were measured at Rancho Seco or EOCR. Without the presence of buildings it is likely that these distributions would have been more Gaussian. The fourth order equations used to describe the curves seen in figures 3 and 4 are as follows:

$$\mathrm{Log}[C/Q(95\%)] = -1.5482\times10^{-8}X^4 + 3.6677\times10^{-6}X^3 - 1.1213\times10^{-4}X^2 - 2.4971\times10^{-2}X - 2.0440 \quad (1)$$

for EOCR, and

$$\mathrm{Log}[C/Q(95\%)] = -7.3268\times10^{-9}X^4 + 2.6446\times10^{-6}X^3 - 2.3121\times10^{-4}X^2 - 1.1795\times10^{-2}X - 2.1554 \quad (2)$$

for Rancho Seco, where X is distance in meters.

These curves are plotted in figure 7 with a scatter diagram of the points from Tables 1 and 2. The two curves are similar in appearance and appear to document three types of diffusion. It is suggested that the three diffusion types represent a) the zone of rapid diffusion in the near-building wake, b) a transition zone where the plume leaves the near-wake of the building and the turbulence within the wake is small or comparable to plume size, and finally, c) the "far wake" region where atmospheric turbulence now interacts with the wake to cause the plume to revert to the rate of diffusion expected without the presence of the structure(s). The zones, or types of diffusion are displaced further downwind (for absolute instead of normalized distances) at Rancho Seco

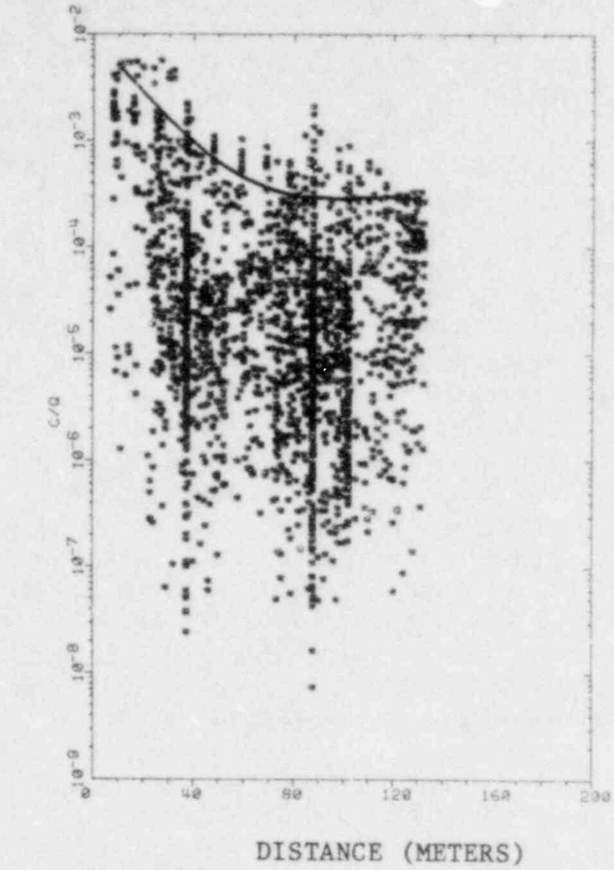

Figure 3. Scatter diagram of normalized concentrations versus distance for EOCR test.

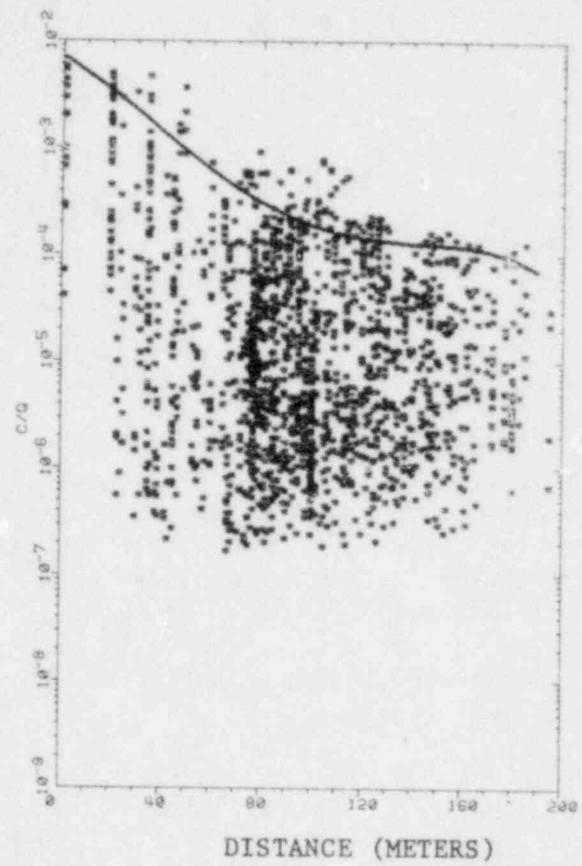

Figure 4. Scatter diagram of normalized concentrations versus distance for Rancho Seco tests.

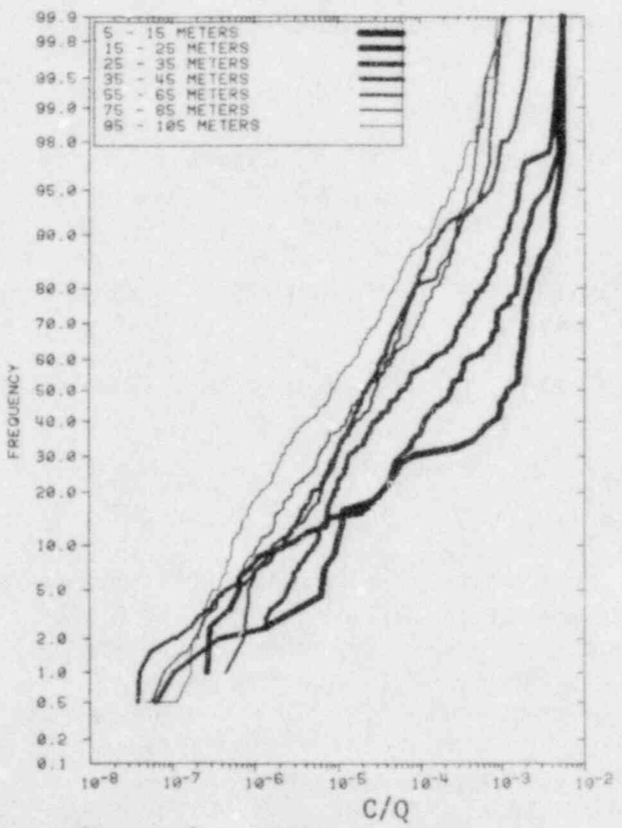

Figure 5. EOCR normalized concentrations versus cumulative frequency.

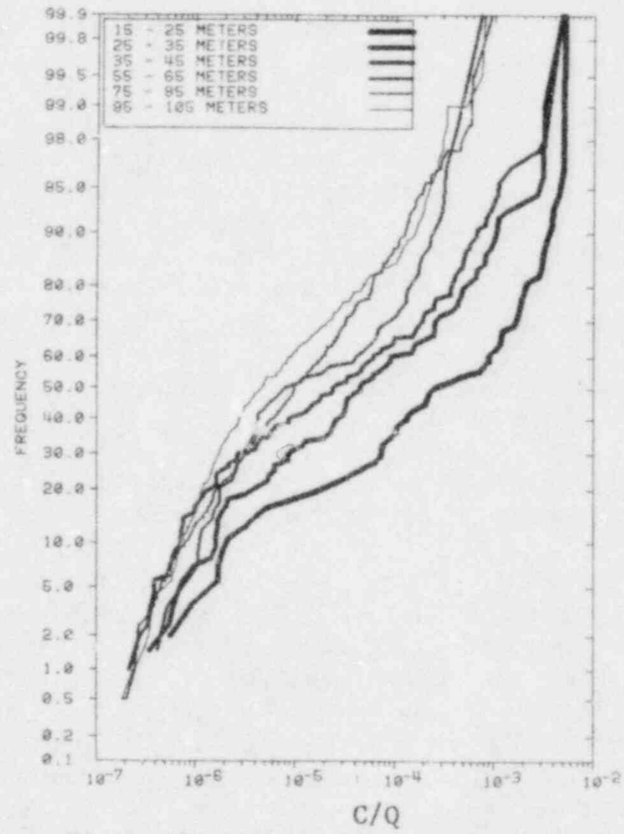

Figure 6. Rancho Seco normalized concentrations versus cumulati'e frequency.

Table 1. EOCR 10 meter bands

Band (meters)	Average distance (meters)	Number of points	C/Q (sec/m^3)
5-15	9.6	44	4.736×10^{-3}
15-25	21.6	84	3.255×10^{-3}
25-35	29.3	170	1.619×10^{-3}
35-45	38.3	454	7.295×10^{-4}
45-55	49.3	156	5.460×10^{-4}
55-65	60.8	99	5.702×10^{-4}
65-75	71.1	160	4.411×10^{-4}
75-85	79.8	229	3.877×10^{-4}
85-95	88.6	666	1.504×10^{-4}
95-105	99.9	270	2.541×10^{-4}
105-115	110.3	90	4.320×10^{-4}
115-125	120.7	119	2.903×10^{-4}
125-135	128.2	106	2.693×10^{-4}

Table 2. Rancho Seco 10 meter bands

Band (meters)	Average distance (meters)	Number of points	C/Q (sec/m^3)
0-10	1.0	16	5.485×10^{-3}
15-25	21.3	56	4.495×10^{-3}
25-35	33.0	73	4.273×10^{-3}
35-45	39.4	114	1.072×10^{-3}
45-55	48.3	82	1.434×10^{-3}
55-65	60.2	58	3.151×10^{-4}
65-75	70.2	119	4.080×10^{-4}
75-85	79.7	302	1.883×10^{-4}
85-95	90.1	226	2.075×10^{-4}
95-105	99.0	244	2.224×10^{-4}
105-115	110.0	134	2.579×10^{-4}
115-125	120.5	124	1.908×10^{-4}
125-135	129.0	120	1.717×10^{-4}
135-145	140.0	97	7.865×10^{-5}
145-155	149.5	109	1.273×10^{-4}
155-165	159.5	66	9.701×10^{-5}
165-175	169.0	38	9.833×10^{-5}
175-185	179.9	45	9.685×10^{-5}
185-195	189.4	9	8.075×10^{-5}

due to the influence of larger structures at that site. As can be seen in figure 7 the EOCR curve just reaches the beginning of zone 3.

Samples were collected out to 800 m at Rancho Seco and to 1600 m at EOCR. In a later study the above techniques will be applied to further examine the zone 3 region and determine if the two curves become parallel.

As a first attempt to scale the distance, in order to make the two curves comparable, the height of the structure (42.9 m for Rancho Seco and 22.9 m for EOCR) was used as a scaling length. In figure 8, this scaling by building height is shown. In a second and apparently better approach, the square root of the minimum cross sectional building area was used to scale downwind distance. These cross-sectional areas were 1090 m^2 for EOCR and 2050 m^2 for Rancho Seco. The results are illustrated in figure 9. Both curves fall rather sharply in zone 1, which extends for about one and one half scaled distances. In zone 2 both curves flatten out for about two more scaled distances. The difference in magnitude between the curves in this zone is probably related to the difference in the cross-sectional areas of the structures; the larger structure yields a greater total volumetric type of initial dilution. The curves differ by about a factor of two in this zone and the ratio of cross-sectional areas of the two facilities is essentially of the same magnitude. Zone 3 begins at about four scaled distances downwind where the curves appear to resume a more negative slope.

For much of zone 1 the two curves in figure 9 are not very different. In fact, at the 95% confidence level the curves show no significant difference out to about one scaled distance. This first zone of agreement

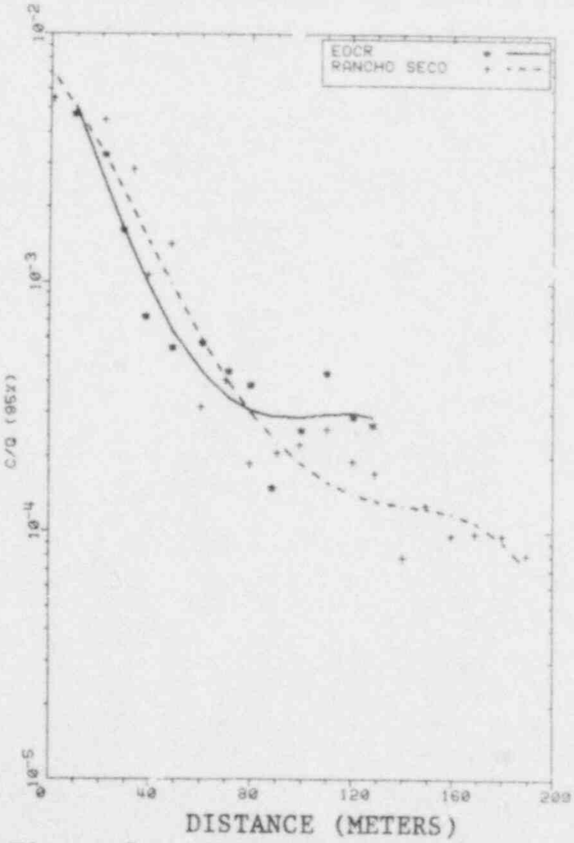

Figure 7. EOCR and Rancho Seco 95% level 4th order curves of normalized concentrations versus distance.

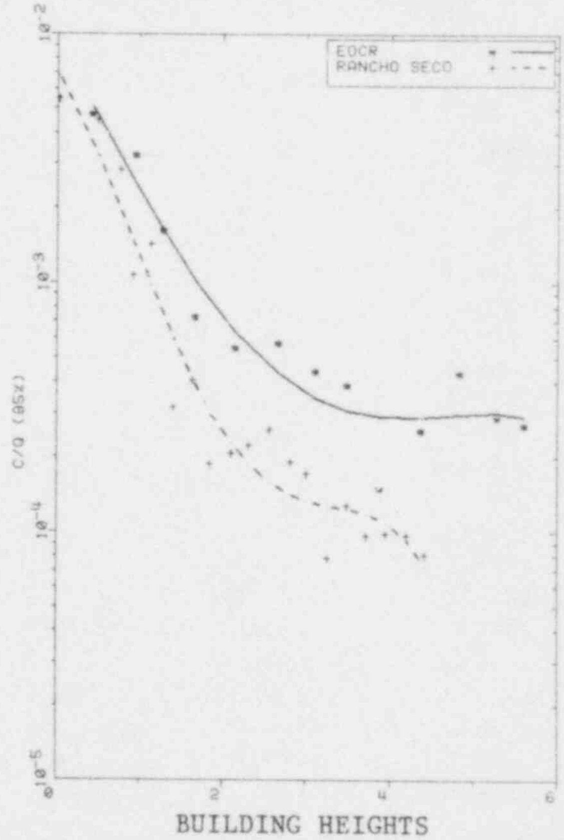

Figure 8. EOCR and Rancho Seco 95% level 4th order curves of normalized concentrations versus building heights.

suggests that close to the building a curve such as those shown in figure 9 would have some general applicability in describing maximum expected concentrations. At the Rancho Seco facility one scaled distance is about 45 m and at EOCR one scaled distance is about 33 m.

III. NRC MODEL COMPARISONS

When activity is assumed to leak from many points on the surface of the containment in conjunction with a single point receptor, NRC (Murphy and Campe, 1974) uses the following equation:

$$C/Q = [U(\sigma_y \sigma_z + a/(k+2))]^{-1} \quad (3)$$

$$k = 3/(s/d)^{1.4}$$

s = distance between containment surface and receptor location

d = diameter of containment

a = projected area of containment building

C/Q = relative concentration at the plume centerline (sec/m^3)

$\sigma_y \sigma_z$ = standard deviations of the gas concentration in the horizontal and vertical crosswind directions, respectively. These are evaluated at the distance from the source to the receptor.

Q = source strength (gm/sec)

U = wind speed (m/sec)

The parameters σ_y, σ_z and U are determined by statistical analysis of site meterological data to determine values that are indicative of the five percentile dispersion at the site. Typically Pasquill "F" conditions with wind speeds of 0.5 to 1.5 m/s are assumed (Murphy and Campe, 1974).

Table 3 includes the stability class for each test [as determined by vertical temperature gradient measurements, (NRC Regulatory Guide 1.23)], the distance from the source to the maximum concentration at the same level (i.e., ground-to-ground or roof-to-roof), the wind speed for the test, the maximum measured relative concentration, the calculated relative concentration [using (3)], and the ratio of calculated to measured concentration [using

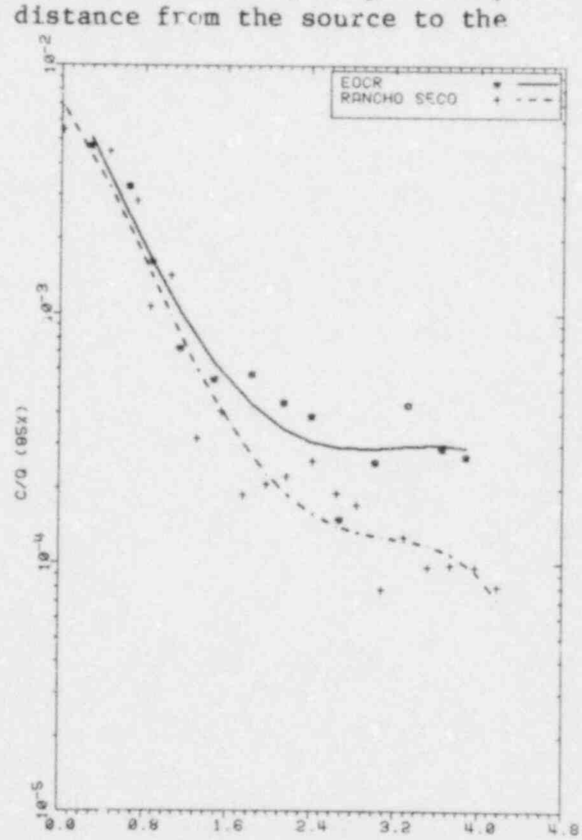

Figure 9. EOCR and Rancho Seco 95% level 4th order curves of normalized frequency versus scaled distance.

Table 3.

Test[1]	Stability	Distance (Meters)	U (m/x)	C/Q(Meas) (Sec/m^3)	C/Q(calc) (Sec/m^3)	Ratio (Calc/Meas)
1-SMUD	A	17	1.0	8.81×10^{-5}	7.85×10^{-3}	89.1
7-SMUD	A	20	4.6	2.07×10^{-3}	3.23×10^{-3}	1.56
5-EOCR	A	38	7.4	9.42×10^{-4}	6.44×10^{-4}	0.684
10-EOCR	A	61	0.8	1.05×10^{-4}	1.65×10^{-3}	15.7
11-EOCR	A	23	1.5	1.53×10^{-4}	8.95×10^{-3}	58.5
13-EOCR	A	20	1.9	7.68×10^{-4}	7.11×10^{-3}	9.26
6-SMUD	D	6	2.8	5.13×10^{-3}	1.52×10^{-2}	2.96
9-SMUD	D	20	1.5	8.74×10^{-4}	5.86×10^{-2}	67.1
15-SMUD	D	20	0.8	5.00×10^{-3}	5.75×10^{-2}	11.5
22-SMUD	D	20	1.9	7.09×10^{-4}	4.68×10^{-2}	66.0
6-EOCR	D	27	1.8	1.77×10^{-3}	3.32×10^{-3}	1.88
15-EOCR	D	25	2.0	1.79×10^{-3}	3.70×10^{-2}	20.7
16-EOCR	D	8	3.1	2.29×10^{-3}	6.55×10^{-3}	2.86
11-SMUD	E	20	3.7	4.93×10^{-3}	1.02×10^{-2}	2.07
12-SMUD	E	20	1.3	4.97×10^{-3}	5.55×10^{-2}	11.2
13-SMUD	E	6	0.8	1.03×10^{-3}	5.37×10^{-2}	52.1
16-SMUD	E	35	1.0	3.08×10^{-3}	6.53×10^{-2}	21.2
19-SMUD	E	30	1.1	3.32×10^{-3}	7.33×10^{-2}	22.1
4-EOCR	E	26	3.1	1.57×10^{-3}	2.03×10^{-3}	1.29
12-EOCR	E	30	2.3	7.13×10^{-4}	2.45×10^{-2}	34.4
14-EOCR	E	32	[illegible]	4.02×10^{-4}	3.33×10^{-3}	8.28
22-EOCR	E	8	[illegible]	9.17×10^{-4}	$8.72\times10^{-}$[illegible]	9.51
23-EOCR	E	16	1.9	2.26×10^{-3}	1.94×10^{-2}	8.58
10-SMUD	F	20	2.9	1.82×10^{-3}	1.71×10^{-2}	9.40
18-SMUD	F	20	0.7	3.15×10^{-3}	2.56×10^{-1}	81.3
23-SMUD	F	24	0.8	2.95×10^{-3}	5.86×10^{-2}	19.9
3-EOCR	F	26	0.5	8.14×10^{-4}	1.29×10^{-2}	15.8
8-EOCR	F	27	0.9	5.72×10^{-3}	4.89×10^{-2}	8.55
18-EOCR	F	8	4.1	1.78×10^{-3}	5.23×10^{-3}	2.94
24-EOCR	F	8	1.8	2.02×10^{-3}	1.16×10^{-2}	5.74
4-SMUD	G	35	1.3	4.68×10^{-4}	1.37×10^{-1}	293.
5-SMUD	G	20	0.9	1.85×10^{-3}	2.77×10^{-1}	150.
8-SMUD	G	35	0.9	4.75×10^{-3}	2.09×10^{-1}	44.0
14-SMUD	G	20	0.9	4.39×10^{-3}	2.63×10^{-1}	59.9
17-SMUD	G	49	2.0	3.62×10^{-3}	6.97×10^{-2}	19.3
20-SMUD	G	20	2.1	3.46×10^{-3}	1.16×10^{-1}	33.5
21-SMUD	G	20	2.3	3.84×10^{-3}	1.04×10^{-1}	27.1
7-EOCR	G	11	0.5	4.88×10^{-3}	4.74×10^{-2}	9.71
9-EOCR	G	100	1.9	3.58×10^{-4}	1.58×10^{-3}	4.41
17-EOCR	G	8	1.1	2.17×10^{-3}	1.75×10^{-2}	8.06
19-EOCR	G	8	1.0	2.91×10^{-3}	2.04×10^{-2}	7.01
20-EOCR	G	8	1.5	1.90×10^{-3}	1.44×10^{-2}	7.58
21-EOCR	G	8	1.3	4.18×10^{-3}	1.57×10^{-2}	3.76

1 SMUD refers to Rancho Seco.

(3)], and the ratio of calculated to measured concentrations. Somewhat higher concentrations than those in the table were occasionally measured at distances less that 5 m from the source. These higher values were not listed in the table because of the close proximity of the sampler from the source.

In calculating σ_y and σ_z the following expressions were used:

$$\sigma_y = ax^{.9031}$$

$$\sigma_z = bx^{c}$$

where a, b and c are functions of stability as indicated in table 4 (Eimutis and Konicek, 1972).

Table 4.

Stability	a	b	c
A	.3658	.192	.936
D	.1471	.079	.881
E	.1046	.063	.871
F	.0722	.053	.814

For stability class G: $\sigma_y(G) = 2/3\sigma_y(F)$ and $\sigma_z(G) = 3/5\sigma_z(F)$

From the values in Table 3 we can see that in only one case did (3) underestimate the measured peak value. This was in test 3 at the EOCR facility under "A" atmospheric stability conditions. The wind speed in this case was 7.4 m/s. Perhaps in this example the use of temperature gradient, by itself, was insufficient to accurately determine the stability class. Eqn. (3) was usually within a factor of 10 at the EOCR facility and within two orders of magnitude at Rancho Seco.

IV. CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

Since the EOCR and Rancho Seco sites and structures are very different, it is significant to note that the maximum measured relative concentrations from numerous samples were just under 6×10^{-3} sec m^{-3} at both sites. It is postulated that there is enough turbulence generated close to the buildings within a surface boundary or skin layer that values of C/Q much larger than 6×10^{-3} sec m^{-3} will not be measured for sixty minute averaging times. For shorter averaging times, somewhat larger values may be expected (Smith, 1978).

In this paper a consistency in measured tracer concentrations at the two sites was found that enables one to determine a more realistic maximum expected C/Q within about one scaled distance units from the building. This "method" is also simple to use since the only information required is the minimum cross sectional area of the building and the distance from source to receptor.

Further progress in our understanding of diffusion in the near-building environment will hinge on well-planned field measurements which are carefully correlated with wind tunnel studies. R. N. Meroney, Colorado State University, has conducted wind tunnel modeling of the EOCR and Rancho Seco sites in order to make comparisons with the field studies.

Several specific problems need to be resolved:

a) By means of field studies, the effect of building wakes needs to be separated from that of wind meander in time-averaged concentration distributions. Licensing requirements might then consider the magnitudes of these effects for a given site.

b) The impact of changes in basic building shapes probably requires additional wind tunnel and field investigations. The effects of surface roughness, relative wind direction, turbulent intensities, Reynolds numbers, and eddy scale need to be documented. In this way, a useful data base for analytical modeling may be built. The state of the art in wind tunnel modeling could be particularly aided if full scale studies evaluated the nature of flow around buildings with projecting surfaces, circular cross-section, and curved roof surfaces (Cermak, 1975).

c) The nature of air flow along the building skin needs to be studied. Such factors as the steadiness of the approach flow, the wind shear (profile) and the turbulent characteristics of the wind all affect locations of flow separation and reattachment, and should be well-documented. Data defining the relationships between mean surface pressure distributions and flow patterns at various distances from the building surface are not well understood. The majority of flow studies have concerned themselves with the wake side of buildings. Attention needs to be given to measurements on each of the other sides, as well. Remote sensing technologies might be exploited as a cost effective means to obtain some of the data.

d) Little is known about the speed of movement of gases within the near-building environment. Sampling techniques suitable for study of transient (or fluctuating) pollutant fields may be utilized for understanding classes of problems related to short period phenomena.

e) The relative magnitudes and effects due to varying building geometry, atmospheric parameters, topography, and source exit speed need definition. These four variables introduce a wide field of research for both the wind tunnel and full-scale investigations. As measurement programs progress from the simple to the complex, close coordination among the three areas of analytic modeling, full scale field studies, and wind tunnel measurements should be maintained. Judicious exploitation of the advantages of each of the separate methods may best help fill the gaps in understanding.

V. ACKNOWLEDGEMENTS

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APPENDIX A

The bibliography which follows represents a compilation of the known research work in close-to-building diffusion. It includes complete listings on known research work dealing directly with diffusion, but lists only a portion of those references which address related topics such as the structure of atmospheric boundary layers and turbulence, or restrictive hardware or theory development. The papers are ordered chronologically by topic. Approximately 3% of the listings were thought to pertain to more than one topic listing. Where this is the case, the reference is enclosed in parenthesis under the secondary topic.

The topic areas used are:

I. Summary Papers

   A. Empirical data summary

II. Theoretical Studies

III. Analytic Development

IV. Wind Tunnel Tests

   A. Area of Flow Separation

   B. Wake Area

   C. Effects of Other Structures

   D. Measured Surface Pressures and their effects on Building Surface Flows

   E. Effects of Meteorological Parameters, Surface Roughness, and Upstream Turbulence

   F. Modeling Problems

   G. Wind Tunnel Hardware Development

   H. Scaling Validation Studies

   I. Studies of Specific Building Complexes

V. Studies for Engineering Diffusion Estimates

VI. Field (Prototype) Studies

VII. Comparison Studies - Model to Prototype

VIII. Related Research Topics

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APPENDIX B

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Data from the innermost arcs and roof top samplers of the Rancho Seco and EOCR field studies were used to examine diffusion close to a building. The minimum length plume paths were determined from each release location to each sampler position at these two test sites. Measured concentrations, normalized by source strength (C/Q), were plotted versus plume path length and an envelope containing 95% of the measured values of C/Q was determined.

The curves from the two sites were similar in shape and implied three zones of diffusion. Comparisons were also made with current NRC methods for predicting maximum expected concentrations close to a building. The NRC model overestimated concentrations in all but one case. The model was generally within an order of magnitude at EOCR, and within two orders of magnitude at Rancho Seco.

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