GASEOUS PLUME DIFFUSION ABOUT ISOLATED STRUCTURES OF SIMPLE GEOMETRY$^{\Delta}$

by

Robert N. Meroney*
Bing-Tsien Yang**

To be presented at

2nd International Air Pollution Conference

of the

International Union of Air Pollution Prevention
Associations

December 6-11, 1970

Δ Research Support by AEC Contract AT(11-1) - 2053 for the Fallout Studies Branch, Division of Biology and Medicine, Atomic Energy Commission.

* Associate Professor, Colorado State University.
** Research Assistant, Colorado University

GASEOUS PLUME DIFFUSION ABOUT ISOLATED STRUCTURES OF SIMPLE GEOMETRY

by R. N. Meroney, Associate Prof., Colorado State University

B. T. Yang, GRA, Colorado State University

ABSTRACT

Wind tunnel measurements of flow and diffusion downwind of a simple cubical structure are reported for various building orientations and flow stratification conditions. Data obtained include model smoke plume trajectories and local concentrations of a radioactive tracer gas. The body of information in this paper is directed to those individuals concerned with site analysis in industrial and nuclear safety investigations.

LIST OF SYMBOLS

A	Cross-sectional area of model normal to flow direction
K	K-factor (non dimensional form for local concentration) = χ UA/Q
ℓ	Length of side of model cube
Q	Source strength - (curries/cc sec)
U	Velocity of flow at model height ℓ
$u*$	"Friction" velocity
$\theta*$	Characteristic "friction" temperature
χ	Local concentration (curries/cc)
x	Downwind distance measured from center of structure

INTRODUCTION

Nuclear power reactors are generally enclosed in an airtight shell which prevents arbitrary release of ratioactive gases or air to the atmosphere. However, in normal operation of some reactor configurations the air around and within a reactor becomes contaminated with radioactive isotopes of such gases as argon, xenon, krypton, and the halogens. It is a general practice to store the contaminated products until such time that meteorological conditions are favorable for dilution and dispersion. In the event of a power excursion or accident, however, it may be necessary to make a release in meteorologically unfavorable conditions. The containment vessel may even conceivably be ruptured or cracked; thus, because of the leakage of the vessel, radioactive gases may escape and cause serious contamination downwind of the reactor complex.

It has been a traditional design technique to release polluted gases through the top of a tall stack located near the reactor, where the stack is at least two and one-half times taller than nearby buildings. Calculation of peak and mean ground concentrations are then based on some semi-empirical model which relates the release rate from an elevated point source to the concentration at some point downwind.

In the future however, it may be desirable due to aesthetics, cost and public relation reasons to utilize a shorter stack or vent connected directly to the reactor building. In these cases plume dispersion is sufficiently modified by the presence of the local building structure or ground topography that the only approach available is one of wind-tunnel model tests. When the stack height is such that the effluent is discharged near the cavity boundary, the momentum of the effluent may or may not be such that the gas is projected beyond the cavity separation streamline.

If the contamination remains within the cavity-wake region the average concentration may be approximately predicted by semi-empirical expressions primarily derived from previous wind-tunnel experiments. In the event the gas does initially penetrate the cavity boundary there is still the possibility that the lower edge of the expanding plume may re-enter the cavity-wake region and provide a secondary source of building and ground contamination.

Only in the period since 1958 have there been published experimental data on concentrations close to buildings suitable for extrapolation to full scale prototype situations. These measurements include only a limited number of geometries and release conditions. Buildings consisting of rounded or curved external surfaces have in particular received limited attention, yet cylindrical containment structures are commonly proposed for a nuclear power reactor. In addition, recent architectural practice tends to favor the introduction of compound curves for building shapes.

This paper reviews the state of gaseous dispersion prediction in the vicinity of buildings and reports some further results on the effects of building orientation, leakage location, and thermal stratification.

REVIEW OF PUBLISHED LITERATURE

The dispersion of gases released from some point removed from significant topographic details or building structures may be predicted on the basis of semi-empirical models which relate the release rate from one elevated source to the concentration at some point downwind. Models have been suggested by Sutton, Hay and Pasquill, Roberts and Cramer.[1] [2] [3] [4] These models require the assumptions of homogeneous atmospheric turbulence and constant lateral and vertical velocities. These assumptions are satisfied for a point release over a flat undisturbed terrain.

In addition, considerable effort has been made to determine the effects of vertical stack velocity and gas buoyancy on the effective stack release height. Recently Carson and Moses[5] have reviewed over 15 available plume-rise formulas to calculate effective stack heights for conditions where there are no effects from local terrain or buildings. They concluded however, that no available plume-rise equation can be expected to accurately predict short-term plume rise.

Unfortunately the analytical prediction of the dispersion of gases in the vicinity of building structures is even less tractable mathematically. Hence, as Halitsky has suggested the only practical approach available is one of wind-tunnel model tests.[6] [7]

A number of wind tunnel studies have considered some of the effects of variations in a single building geometry on plume entrainment and dispersion.[8] [9] [10] [36] [37] [38] [39] These studies have permitted the specification of pertinent scaling criteria for model studies of plume excursions near buildings.

MODEL SCALING CRITERIA

The use of a wind tunnel for model tests of atmospheric gas diffusion is dependent on the expression of concentration results in a non-dimensional coefficient whose value is independent of the variations in scale between model and prototype. The concentration coefficients will only be independent of scale if certain similarity criteria are met by the modeled flows. These criteria are generally understood as a result of analysis or experience, and they are discussed in detail in References 8, 16, and 19. Basically, these model laws may be divided into those expressing geometric, dynamic, and kinematic similarity. In addition, one must specify upstream and ground boundary conditions.

Dynamic similarity is dependent upon equivalence of the inertial to buoyancy force ratio from model to prototype. Normally, this is assumed by equivalence of the atmospheric Froude Number (Richardson number) and the control of stack gas densities; however, near building structures aerodynamic turbulence may be assumed to dominant gas dispersion. Usually radioactive effluents may be assumed at ambient temperature due to dilution before release. Gifford and Bryant, however, have suggested corrections to plume rise for radioactive heating.[32] [33]

Kinematic similarity requires the scaled equivalence of streamline movement of the air over prototype and model. It has been shown by Golden that flow around geometrically similar sharp-edged buildings at ambient temperatures in a neutrally stratified atmosphere should be kinematically similar when the background flow is dynamically similar.[7] This approach depends upon producing flows in which the flow characteristics become constant (independent of Reynolds number) if a lower limit of the Reynolds number is exceeded. For example, the resistance coefficient for flow in a sufficiently rough pipe as shown in Schlichting (20 p 521) is constant for a Reynolds number larger than 2×10^4. This implies that surface or drag forces are directly proportional to the mean flow speed squared. In turn, this condition is the necessary condition for mean turbulence statistics such as root-mean square value and correlation coefficient of the turbulence velocity components to be equal for the model and the prototype flow.[8 19]

Golden, as cited by Halitsky,[7 8] found that for flow about a cube for Reynolds numbers above 11,000, there was no change in concentration measurements. Correlated tests of flow about the Rock of Gibralter, flow over Pt. Arguello, California, and flow over San Nicolas Island, California, may be cited as examples of large Reynolds number flows which have been modeled successfully in a wind tunnel.[21 22 23]

On buildings with rounded surfaces, flow is such that the separation point is dependent upon the Reynolds number.[32] If the boundary flow is laminar then separation will occur approximately 80 to 90° from the stagnation point, while if the flow is turbulent separation will be delayed until 110 to 120° from the stagnation point. Variation in the separation point will introduce changes into the remainder of the flow field. For the turbulent boundary layer case pressures behind the cylinder will be nearly ambient. It is generally expected for large curved surfaces in the atmospheric boundary that turbulent separation occurs, especially when there are other upstream structures to perturb the flow.[8] It was found that a model of a cylindrical containment vessel and complex in the wind tunnel flow exhibited turbulent separation. This probably resulted from the presence of the upstream building complex, the logarithmic upstream velocity profile, and the sharp edged geometry of the top region of the containment structure. A more isolated curved structure may require the use of tripping devices to produce separation at the desired locations.[30]

The dynamic interaction of any emitted effluent with the wind is governed by the ratio of their respective momenta.[7 8 9 13 16] When the prototype and model plumes have the same density this reduces to a ratio of velocities.

Finally, the need for scaling of the atmospheric mean wind profile is demonstrated in Reference 11. Substitutions of a uniform velocity profile for a logarithmic profile results in three fold variation in the dimensionless pressure coefficient downstream of a model building. The length scale used for scaling the velocity profile is the roughness height Z_o.[19]

Since each arrangement of reactor building and auxiliary buildings or terrain may have separate effects on the generation of mechanical turbulence and mean flow movement, any specific pollution problem will require individual tests. Hence, there exist in the literature descriptions of a variety of different model studies on reactor and industrial plants.[7 12 13 14 15 16] These studies are significant in that their results have been essentially confirmed by either direct prototype measurements or the absence of the pollution problems the study was directed to remove. References 12, 13, 15, and 16 incorporate such comparisons within their text. Reference 7 has recently been compared with prototype measurements at the National Reactor Testing Station in Southeast

Idaho.[17] Agreement of the diffusion concentration results were very satisfactory. Martin favorably compared his wind-tunnel study measurements about a model of the Ford Nuclear Reactor at the University of Michigan with prototype measurements.[16] Finally, Munn and Cole have taken diffusion measurements on a power station complex at the National Research Council, Ottawa, Canada, to confirm the general entrainment criteria suggested by the model studies of Davies and Moore.[13] [18]

When interpreting model diffusion measurements it is important to remember that there can be considerable difference between the instantaneous concentration in a plume and the average concentration due to horizontal meandering. The average dilution factors near a building complex will correlate well with wind-tunnel derived dilution factors since the mechanical turbulence of the wake and cavity region dominate the dispersion. In the wind tunnel a plume does not generally meander due to the absence of large scale eddies. Thus it is found that field measurements of peak concentrations, which effectively eliminate horizontal meandering, should correlate with the wind tunnel data.[16] In order to compare downwind measurements of dispersion to predict average field concentrations it is necessary to use data on peak-to-mean concentration ratio as gathered by Singer, _et al_. Their data is correlated in terms of the gustiness categories suggested by Pasquill for a variety of terrain conditions.[27] It is also possible to determine the frequency of different gustiness categories for a specific site.[28] Direct use of wind-tunnel data at points removed from the building cavity region may underestimate the dilution capacity of a site by a factor of four unless these adjustments are considered.[16] Halitsky even suggests this factor may rise as high as ten in his recent review in Meteorology and Atomic Energy-1968.[29]

A number of empirical formula have been suggested to predict the amount of plume dilution which occurs once it is entrained into the building cavity.[29] [31] Basically all formulas reduce to the form $\chi = 1/C\ (Q/L^2U)$, where C may vary from 1/2 to 2. The coefficient C represents a measure of the fraction of the building cavity width over which the gas is dispersed. All of these formula were developed for sharp-edged building geometries. It should be noted, however, that for a cylindrical building there are no sharp corners at which separation occurs; rather separation occurs over a width less than the building diameter; hence the cavity region is not as wide as the equivalent width rectangular building. The equivalent coefficient actually required for prediction of the average entrained gas concentration may thus be less than one. Halitsky studied the dispersion of gases downstream from a hemispherically capped cylindrical building and obtained values of $C \simeq 1$ at distances of $x/D = 3.0$. Recent tests by the author of a model of a proposed nuclear power station which utilizes a flat-topped cylindrical containment vessel produces similar results.[32]

EXPERIMENTAL EQUIPMENT AND PROCEDURES

The experimental data were obtained in the low speed Army Meteorological Wind Tunnel at Colorado State University.[39] This tunnel was specifically designed to study fluid phenomena of the atmosphere. A 25 m long test section provides a well-developed turbulent boundary layer for different degrees of thermal stratification and surface roughness. The pressure gradient along the test section can be controlled by an adjustable height ceiling. A 15 m long portion of the test section consists of an aluminum plate that can be cooled or heated to temperatures between -8°C and 180°C. The air temperature in the free-stream can be maintained values from 5°C to 90°C. The air speed can be regulated to values from -2 to 35m/sec.

A 15 cm x 15 cm plexi-glass model was constructed under the consideration that the degree of blockage of 0.75% presented by the model would not affect the simulating flow due to the contraction of the side walls of the tunnel (the ratio of projected model area to the area of the 2 m x 2 m wind tunnel cross-section should not exceed 1 to 2%). In order to simulate potential release positions, there were three exit ports--top, middle, and bottom--as shown in Figure 1. The exit gas temperatures were monitored by three copper-constantan thermocouples installed at each exit. Fine screens inside the exit holes were provided to eliminate the jet effects and to insure a uniform flow. The screens could be removed for the smoke ($TiCl_4$) used for visualization.

The model was installed 20 meters from the beginning of the test section in a turbulent shear layer approximately 60 cm deep at a velocity of 2 m/sec. Measurements were made simulating both neutral stratifications and inversion stratifications, (Richardson number at the model height was approximately 0.15). The temperature and velocity profiles were logarithmic with u^* and θ^* equal to 0.144 m/sec and $1.69^{\circ}K$ respectively upstream of the building.

The flow field was examined by smoke visualization and velocity profile traverses. Quantitative gaseous concentration measurements were made downwind of the structure from $x/L = 3$ to 30 at ground level and for the vertical centerline. A radioactive tracer gas Krypton-85 was utilized to monitor plume dispersal in the wake flow. The measurement apparatus and procedures have been described in detail by Chaudry and Meroney.[40] In this experiment the source strength utilized was approximately 10 μ-currie/cc. The release rate at the leakage ports was always maintained below $V_{port}/U_{free\ stream} = 1/4$ to avoid excessive jetting from the flush vents.

EXPERIMENTAL RESULTS

Kinematics of Plume Behavior - Velocity profiles and smoke visualization was accomplished for wind approach orrientations to the cubical structure of $\theta = 0^{\circ}$ to 180° at 45° intervals, where θ is the angle between the downwind direction and the side release ports. A sequence of velocity profiles along the tunnel centerline downwind are shown in Figure 2. The typical defect effect upon the boundary layer is present. The profiles have evidently recovered fully by $x/L = 20$. The cavity appears to extend further downwind for the 45° orientation as might be expected from the results of prior investigations.

Smoke visualization provided a qualitative picture of the mechanisms of mixing behind the structure. Figures 3 through 7 display typical effects of orientation, release port, and stratification.

The mechanism of gaseous dispersion is a combination of two flow phenomena, -the general convective motions transport effluent into downwind area, while the turbulent mixing motions cause vertical and transverse diffusion. At the beginning of the wake region, mechanical turbulence generated by the structure plays a dominant role. This was also discussed in section 6.1. Strong turbulent mixing tends to smooth out the effects of different release ports. Smoke pictures (Figure 3 to 6) show that after approximately three scale lengths downwind the smoke patterns for different release ports, structure orientations, and stratification have almost the same type of distribution, i.e., the densest smoke is near the ground surface. This agrees with the quantitative concentration measurements subsequently discussed in the latter sections.

In each vertical density profile higher concentrations are always at ground level. This can be appreciated when one notes that streamlines move downwind after passing the structure. Thus part of effluent follows the main convective motion and is transported into the near ground region. Part of effluent is carried by toroidal motion in the cavity.

At the downwind end of the cavity, the effluent is brought to the surface at a stagnation position where streamlines divide both upwind and downwind. The higher turbulent amplification in this region tends to exhaust much of the effluent from cavity into the wake region.

The downwind space between $x/\ell = 3$ and $x/\ell = 5$ may be visualized as a transition region between the cavity and wake dominated flow region.

When the orientation is $\theta = 135^{\circ}$, that is, the release ports are on the upwind face which is 45° to the flow direction, a significant convection-dominant phenomenon is observed in the smoke pictures (Figure 5). A small change of exit momentum may cause quite different distribution patterns at the beginning of wake region; greater exit momentum may cause a more skew transverse distribution. Apparently for upwind release locations a large fraction of the gas is transported directly past the cavity region without becoming diluted by its strong mechanical turbulence effects.

Farther downwind ($x > 5\ell$), higher concentrations remain at ground level. This is due to the reflection effect at the ground ($\partial\chi/\partial z = 0$). This effect can be visualized by considering an image volume or plane source at the beginning of the wake region in a symmetrical position on the negative side of the ground plane.

Similar patterns for vertical concentration distribution are found in the downwind wake region regardless of release ports or building orientation. Wake structure is apparently independent of building orientations if the difference between projected areas normal to the flow is not very great. Since distributions are observed at the beginning stage of the wake region, similar distributions farther downwind are naturally to be expected.

Intuitively, one would expect that beyond some distance downwind, the wake effects will decrease to such an extent that flow field is no longer dependent on the origin of perturbation introduced by the presence of a building. At such a region, (evidently x is at least greater than 30ℓ), the dispersion rate should asymptotically approach that for a general continuous source release (in a open field). Unfortunately, neither this experiment nor those which preceeded it in the field (in the field test done by Dickson, Start and Markee, Jr. the data were measured to 600 meters, i.e., approximate 23 scale length D) clearly delineates a far wake region behavior.

In the previous discussion, equivalent stratification conditions are assumed throughout. For different thermally stratified flow, dispersion patterns can vary significantly. For instance, in the farther downwind region, the consistantly higher ground level concentrations for the inversion case are due to the suppression of the turbulent mixing. On the other hand, small turbulent intensities cause dispersion rates in both vertical and transverse directions. For $x < 5\ell$, the dispersion effects of different stratification conditions is not significant because of the dominant mechanical turbulence produced by the building.

Concentration Measurements and Diffusion Isopleths - The health physicist is primarily interest in the probable environment of the average citizen; hence the distribution of ground level concentration has been a conventional measure of probable health hazard. In fact, for low velocity releases, near building faces, the ground level concentration will also be the maximum concentration. Figure 7 displays the averaged behavior of the ground level concentrations for different building orientations (i.e., different angles between the release sites and the flow directions) and for neutral and inversion stratification.

The curves are presented in terms of the dimensionless group $K = \chi UA/Q$ where A represents the maximum cross-section of the structure presented to the approach flow field.

The ground level concentrations measured varied with downwind distance to powers of from -0.59 to -0.68 depending on wind orientation of the release force. These measurements compare favorably to the value of -0.6 obtained by Dickson et.al., behind an actual reactor complex.[17]

The magnitudes of concentration for the upwind face release, ($\theta = 180^{o}$), are slightly greater than those for the downwind release, ($\theta = 0^{o}$). Part of the effluent follows the outer cavity streamlines and enters directly into the far downwind wake region. When $\theta = 0^{o}$, all the effluent must pass through the strongly turbulent mixing process in the cavity region before entering the wake region.

When theta = 45^{o}, extremely high concentrations are measured at $x/\ell \sim 3,3$. This is because of the significant extension of the cavity length when the cube is oriented with the diagonal parallel to the flow direction.

Ground level concentrations are slightly greater for inversion stratification than for the equivalent neutral release condition. In the inversion condition, turbulent mixing in vertical direction is impeded. Each air parcel tends to stay in the same temperature (density) layer because the vertical motion must be against the hydrostatic force.

Dispersion patterns at the beginning of the wake region can be considered to be "frozen" and transported downwind along main streamlines. For neutral stratification gases continuously diffuse upward as they move along their downwind trajectory. In the inversion case, however, the gases obtain vertical growth only through the strong mechanical mixing in the vicinity of the structure; subsequently, the gas is transported downwind with only slight height variation. Stable stratification does not tend to inhibit lateral motions; hence, the plume will continue to spread to the sides at only a slightly reduced rate.

In Figures 8 through 11 isopleths (equi-concentration contours) are plotted for various building orientations and stratification conditions. Figure 8 compares for $\theta = 0^{\circ}$ (90°, 180°) the top port release for both neutral and inversion stratification. Isopleths in the inversion case show somewhat concave downward shapes. However, in the neutral case, isopleths tend to be concave upward. Smaller transverse spread for the inversion case are also observed. Figure 9 displays a similar behavior for the middle release vent.

Figure 10 compares isopleth distributions for different exit ports (bottom and middle) at $\theta = 45^{\circ}$ for the inversion stratification. One finds no significant difference between the two sets of isopleth patterns.

Figure 11 compares the isopleths at $\theta = 180^{\circ}$, middle exit ports, for both neutral and inversion stratification conditions. The convective motion dominance is very marked for the inversion case.

CONCLUSIONS

This study has led to the following conclusions.

1. Dispersion patterns differ in regions with and without the presence of a building structure. The ground-level concentration variation with longitudinal distance in the wake region show much flatter slopes (~ -0.6 ~ -0.7) than those in open fields (~ -1.3 ~ -1.7).

2. For a specific building orientation, dispersions are similar for different release ports (from the top, middle, and bottom of the building height). Strong turbulent mixing motions are believed to smooth out any effects from the origin of release.

3. Aerodynamic effects due to building orientations (0^o, 45^o, 90^o, 135^o, 180^o) cause a slightly different concentration distribution in the cavity and near wake region. This difference depends on the portion of effluent which is initially carried downwind by convective motions.

4. Farther downwind the dispersion will be independent of the original building shapes, ($x/\ell \geq 5$).

5. Mechanical turbulence dominates the dispersion behavior in the $x/\ell \leq 5$ region. The stratification becomes more important further downwind.

6. Inversion stratification ($Ri\big|_{z=\ell} = 0.15$) causes about 8% higher ground concentration than obtained for neutral stratification.

7. Strong inversion stratification causes smaller transverse dispersion and "freezes" the plume growth in the vertical direction.

8. The plume growth in the transverse direction is about 3-5 times greater than that in the vertical direction for both neutral and stablized stratified shear flows.

REFERENCES

1. Sutton, O. G., "The Theoretical Distribution of Airborne Pollution from Factory Chimneys," Quart. J. R. Meteor. Soc. 73, p. 426 (1947).

2. Pasquill, F., Atmospheric Diffusion, D. Van Nostrand Co., London (1962).

3. Roberts, O. F. T., "The Theoretical Scaling of Smoke in a Turbulent Atmosphere," Proc. Roy. Soc., A. 104, p. 640.

4. Cramer, H. E., "A Practical Method for Estimating the Dispersal of Atmospheric Contaminants," Proceedings, First Nat'l. Conf. on Appl. Meteor., Amer. Meteor. Soc., C. pp. 33-35. Hartford, Conn., (Oct. 1957).

5. Carson, J. E., and H. Moses, "Validity of Currently Popular Plume Rise Formulas," USAEC Meteorological Information Meeting, (September 11-14, 1967), Chalk River, Canada, AECL-2787, pp. 1-15.

6. Moses, H. G., H. Strom and J. E. Carson, "Effects of Meteorological and Engineering Factors on Stack Plume Rise," Nuclear Safety, Vol. 6, #1, (Fall 1964), pp. 1-19.

7. Halitsky, J., J. Golden, P. Halpern; and P. Wu, "Wind Tunnel Tests of Gas Diffusion from a Leak in the Shell of a Nuclear Power Reactor and from a Nearby Stack," Geophysical Sciences Laboratory Report No. 63-2, New York University (April 1963).

8. Halitsky, J., "Gas Diffusion Near Buildings," Geophysical Science Laboratory Report No. 63-3, New York University, February 1963).

9. Strom, G. H., M. Hackman, and E. J. Kaplin, "Atmospheric Dispersal of Industrial Stack Gases Determined by Concentration Measurements in Scale Model Wind Tunnel Experiments," J. of APCA, Vol. 7, #3, pp. 198-204, (November 1957).

10. Evans, B. H., "Natural Air Flow Around Buildings," Research Report 59, Texas Engineering Experiment Station, (1957).

11. Jensen, M., and N. Frank, "Model-Scale Test in Turbulent Wind, Part I.," The Danish Technical Press, Copenhagen, 1963.

12. Kalinske, A. A., "Wind Tunnel Studies of Gas Diffusion in a Typical Japanese Urban District," National Defense Res. Council OSCRD Informal Report #10.3A-48 and 48a, (1945).

13. Davis, P. O. A. L., and P. J. Moore, "Experiments on the Behavior of Effluent Emitted from Stacks at or near the Roof Level of Tall Reactor Buildings," Int. Jour. Air Water Pollution (1964), Vol. 8, pp. 515-533.

14. Sherlock, R. H., and E. A. Stalker, "The Control of Gases in the Wake of Smokestacks," Mechanical Engineering, Vol. 62, #6, pp. 455-458, (June 1940).

15. Hohenleiten, H. L. von and E. Wolf, "Wind Tunnel Tests to Establish Stack Heights for the Riverside Generating Station," Trans ASME, Vol. 64, pp. 671-683, (Oct. 1942).

16. Martin, J. E., "The Correlation of Wind Tunnel and Field Measurements of Gas Diffusion Using Kr-85 as a Tracer," Ph.D. Thesis, MMPP 272, University of Michigan, (June 1965).

17. Dickson, G. E. Start and E. H. Markee, Jr., "Aerodynamic Effects of the EBR-II Containment Vessel Complex on Effluent Concentrations," USAEC Meteorological Information Meeting, Chalk River, Canada, AECL-2787, (September 11-14, 1967), pp. 87-104.

18. Munn, R. E., and A. F. W. Cole, "Turbulence and Diffusion in the Wake of a Building," Atmospheric Environment, Vol. 1, pp. 33-43, (1967).

19. Meroney, R. W., et al., "Simulation of Atmospheric Motion by Wind-Tunnel Flows," Colorado State University, Report Number CER66-JEC-VAS-EJP-GJB-HC-RNM-SI-17, (May 1966).

20. Schlichting, H., Boundary Layer Theory, McGraw Hill, New York, 1960).

21. Field, J. H., and R. Warden, "A Survey of the Air Currents in the Bay of Gibraltar, 1929-2930," Air Ministry, Geophys., Mem. No. 59, London (1933).

22. Cermak, J. E., and J. Peterka, "Simulation of Wind Fields over Point Arguello, California, by Wind-Tunnel Flow over a Topographical Model," Final Report, U.S. Navy Contract N 126(61756)34361 A(PMR), Colorado State University Report Number CER65JEC-JAP64 (December 1965).

23. Meroney, R. N., and J. E. Cermak, "Wind Tunnel Modeling of Flow and Diffusion over San Nicolas Island, California," U.S. Navy Contract N123(61756)50192A(PMR), Colorado State University Report Number CER66-67RNM-JEC44, (September 1967).

24. Plate, E. J., and J. E. Cermak, "Micro-Meteorological Wind-Tunnel Facility: Description and Characteristics," Fluid Dynamics and Diffusion Laboratory Report Number CER63EJP-9, Colorado State University (1963).

25. Integrated Army Meteorological Wind-Tunnel Research Program, Eleventh Quarterly Progress Report, (1 November 1967-31 January 1968), 22 pages.

26. Singer, I. A., and I. Kazukiko, and G. D. Roman, "Peak to Mean Pollutant Concentration Ratios for Various Terrain and Vegetative Cover," Journal APCA, Vol. 13, #1, p. 40, (1963).

27. Singer, I. A., and M. E. Smith, "The Relation of Gustiness to Other Meteorological Parameters," Jour. Meteor. Vol. 10, #2, (1953).

28. Barry, P. J., "Estimation of Downwind Concentration of Airborne Effluents Discharged in the Neighborhood of Buildings," Atomic Energy of Canada, Limited, Report AECL-2043, (July 1964).

29. Slade, D. H., Editor, Mereorlolgy and Atomic Energy 1968, U. S. Atomic Energy Commission, Division of Technical Information, TID-24190, (July 1968).

30. Culkowski, W. M., "Estimating the Effect of Buildings on Plumes from Short Stacks," Nuclear Safety, Vol. 8, #3, pp. 257-259, (Spring 1967).

31. Meroney, R. N., J. E. Cermak, and F. H. Chaudhry, "Wind Tunnel Model Study of Shoreham Nuclear Power Station, Unit I, Long Island Lighting Company," CSU Fluid Dynamics and Diffusion Laboratory Report CER 68-69-1, (July 1968).

32. Gifford, F. A. Jr. "The Rise of Strongly Radioactive Plumes," U.S.A.E.C. Meteorolotical Information Meeting, September 11-14, 1967, Chalk River Nuclear Laboratories AECL-2787, p. 37.

33. Bryant, P. M. "Effect of Diluting Stack Gases on Downwind Concentration," Nuclear Safety, Vol. 8, #2, pp. 161-164, (Winter 1966-67).

34. Smith, M. E., "Reduction of Ambient Air Concentrations of Pollutants by Dispersion from High Stacks," Nuclear Satety, Vol. 9, #1, pp. 46-53, (January-February 1968).

35. Chien, N., Y. Fang, H. Wang, and T. Si, "Wind Tunnel Studies of Pressure Distribution on Elementry Building Forms," Iowa Institute of Hydraulics Research, State University of Iowa, (1951).

36. "Wind Forces on Structures," ASCE Trans., Vol. II, Paper No.. 3269, pp. 1124-1199, (1961).

37. Purdy, D. M., "Model Studies of Wind Loads on Flat-top Cylinders" Journal of the Structural Division, ASCE. ST2, Paper 5209, pp. 379-395, (April 1967).

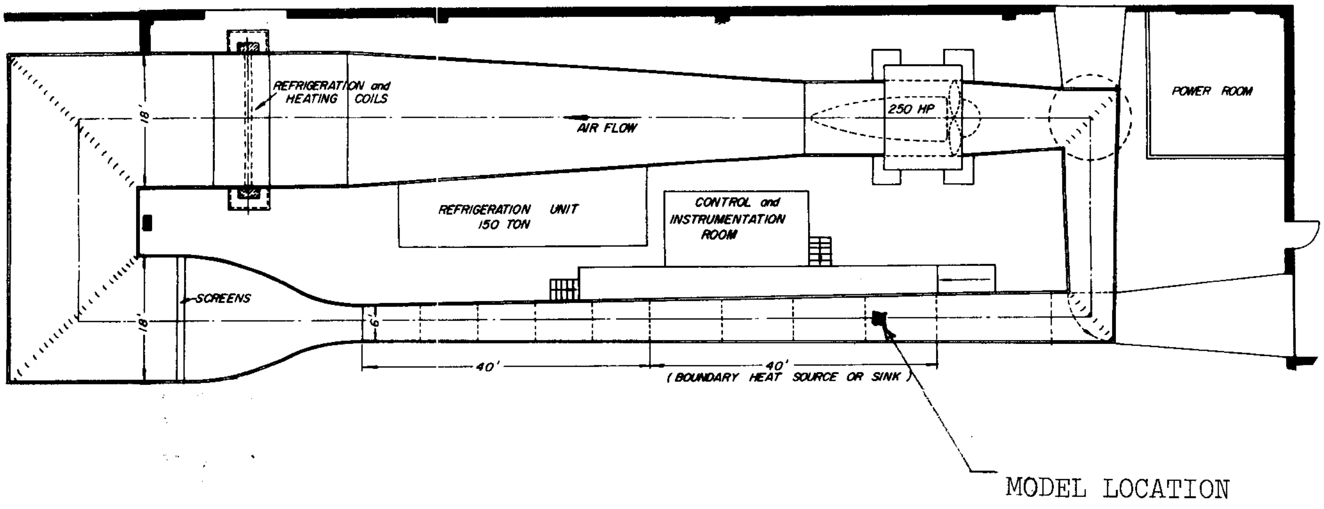
38. "Method of Reducing the Turbulent Zones Around Structures," Mitsubishi Heavy Industries Ltd., 6 pages, Japanese, (1966-67), Vol. 3, #4.

39. Plate, E. J., and J. E. Cermak, "Micrometeorological Wind Tunnel Facility, Description and Characteristics," Fluid Dynamics and Diffusion Laboratory Report. CER63EJP-JEC9, Colorado State University, (1963).

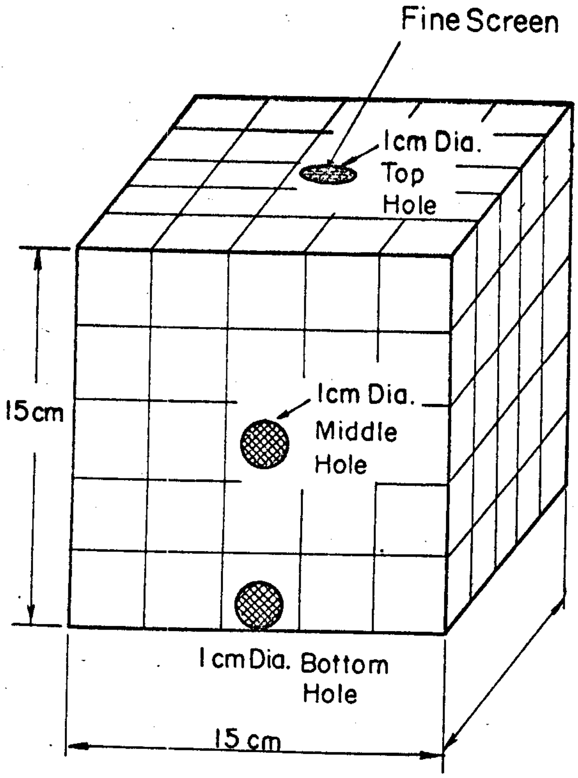
40. Chaudhry, F. H. and R. N. Meroney, "Turbulent Diffusion in a Stably Stratified Shear Layer," Task II B Research Technical Report Desert Test Center, TR ECOM-0423-5, (Fluid Dynamics and Diffusion Laboratory Report, CER69-70FHC-NM12), Colorado State University, (September 1969).

FIGURE CAPTIONS

1. METEOROLOGICAL WIND TUNNEL AND MODEL BUILDING
2. VELOCITY PROFILES IN BUILDING WAKE ($\theta = 0^\circ, 45^\circ$)
3. SMOKE VISUALIZATION $\theta = 0^\circ$, NEUTRAL AND INVERSION STRATIFICATION, TOP EXIT PORT
4. SMOKE VISUALIZATION $\theta = 0^\circ$, NEUTRAL AND INVERSION STRATIFICATION, MIDDLE EXIT PORT
5. SMOKE VISUALIZATION $\theta = 135^\circ$, NEUTRAL AND INVERSION STRATIFICATION, BOTTOM EXIT PORT
6. SMOKE VISUALIZATION $\theta = 180^\circ$, NEUTRAL AND INVERSION STRATIFICATION, MIDDLE EXIT PORT
7. MAXIMUM GROUND CONCENTRATION VARIATION WITH DISTANCE DOWNSTREAM
8. CONCENTRATION ISOPLETHS FOR $\theta = 0^\circ$, TOP EXIT PORT, NEUTRAL AND INVERSION STRATIFICATION
9. CONCENTRATION ISOPLETHS FOR $\theta = 0^\circ$, MIDDLE EXIT PORT, NEUTRAL AND INVERSION STRATIFICATION
10. CONCENTRATION ISOPLETHS FOR $\theta = 45^\circ$, MIDDLE AND BOTTOM EXIT PORT, NEUTRAL AND INVERSION STRATIFICATION
11. CONCENTRATION ISOPLETHS FOR $\theta = 180^\circ$, MIDDLE EXIT PORT, NEUTRAL AND INVERSION STRATIFICATION



METEOROLOGICAL WIND TUNNEL _ Fluid Dynamics and Diffusion Laboratory, Colorado State University



Sketch of the Model

Figure 1. METEOROLOGICAL WIND TUNNEL AND MODEL BUILDING

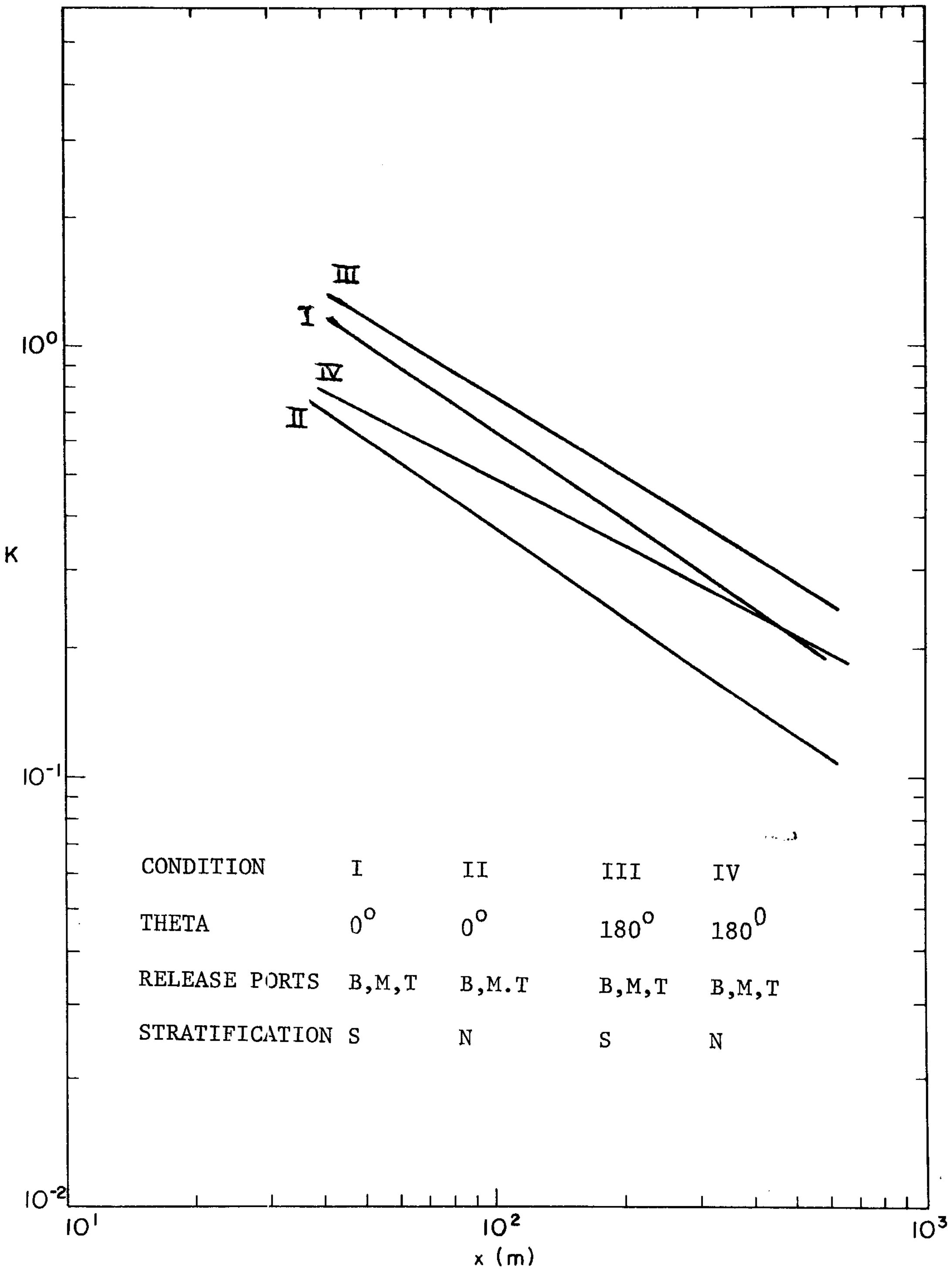
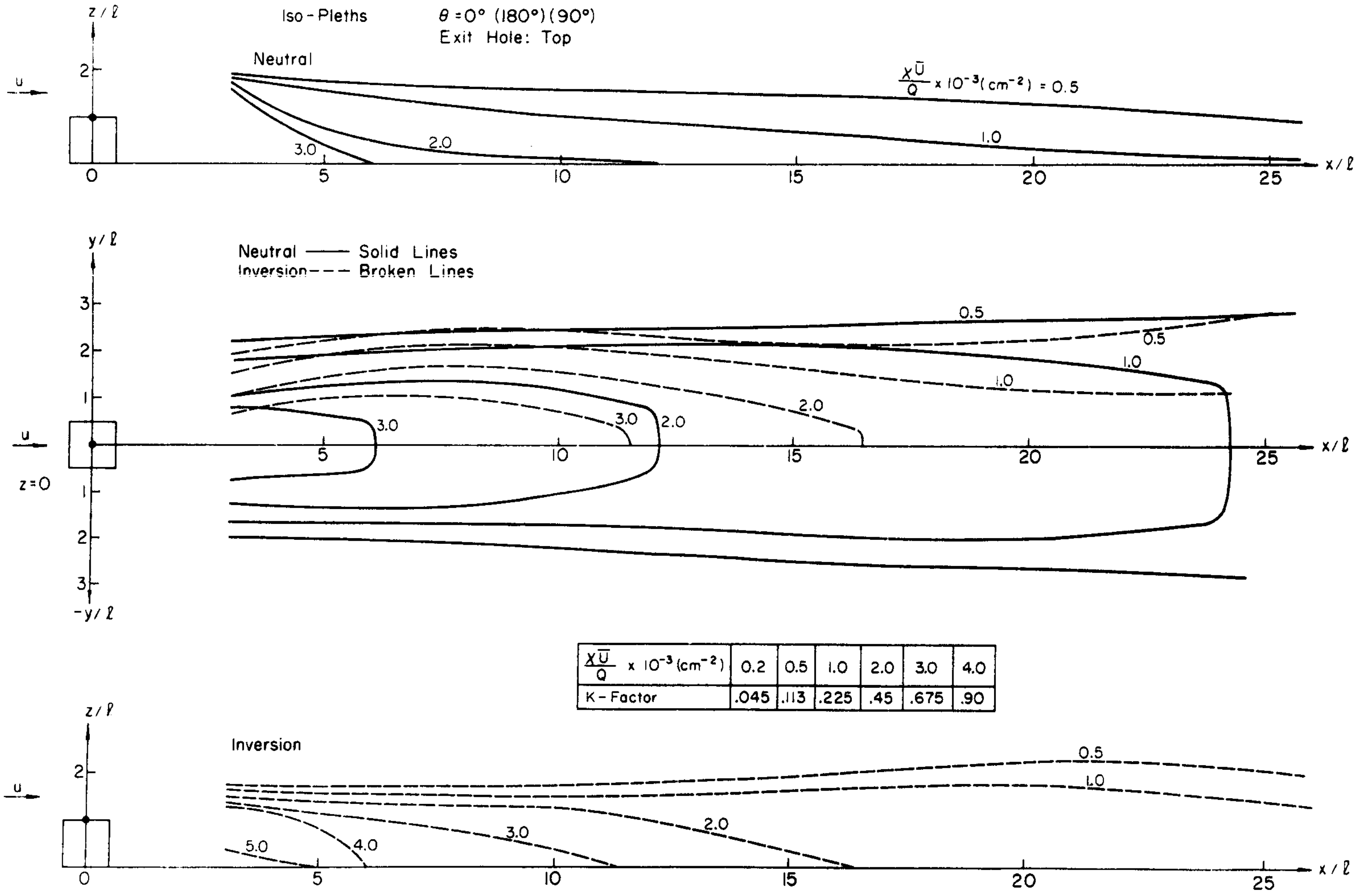
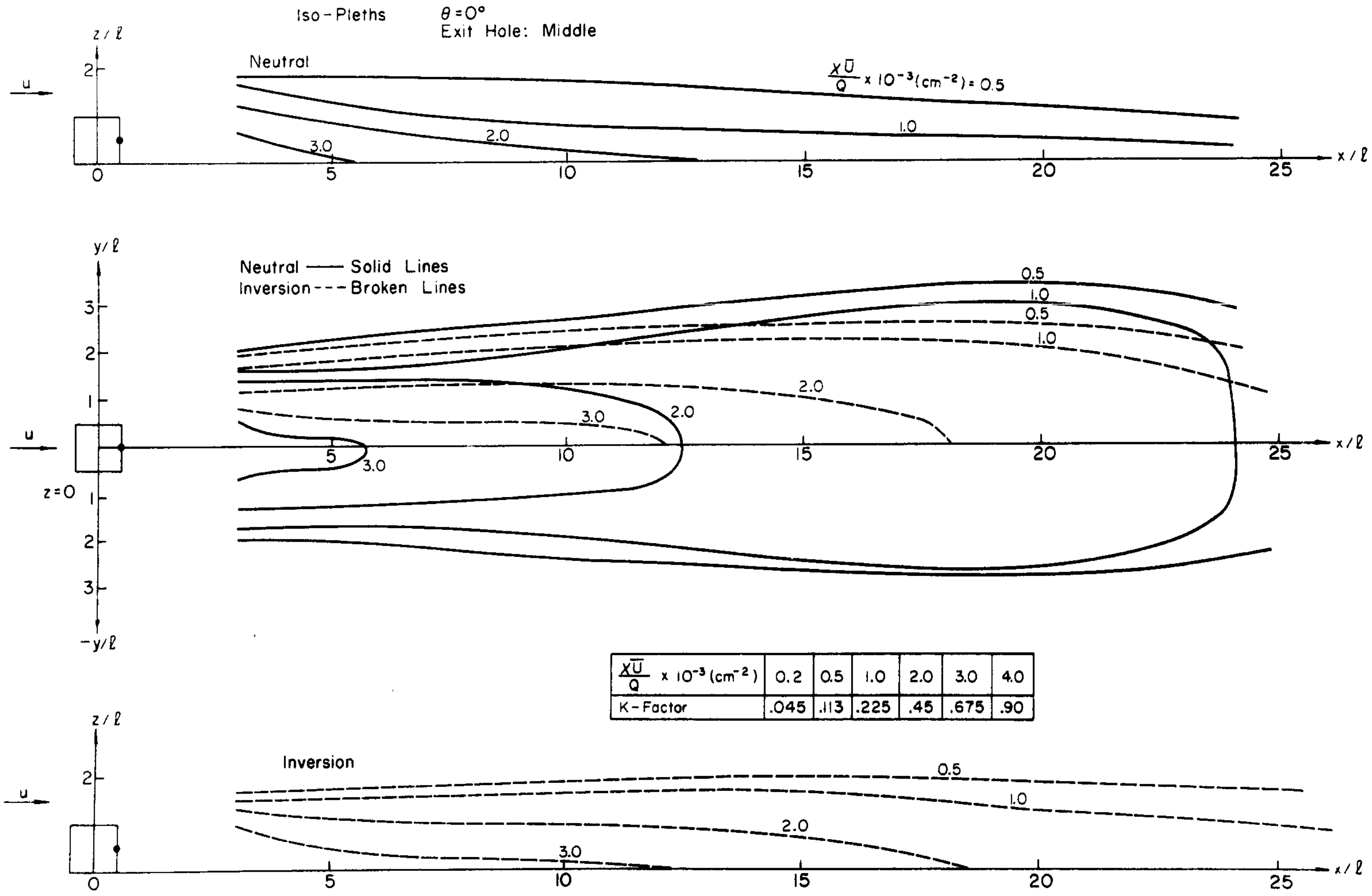


Figure 7. MAXIMUM GROUND CONCENTRATION VARIATION WITH DISTANCE DOWNSTREAM



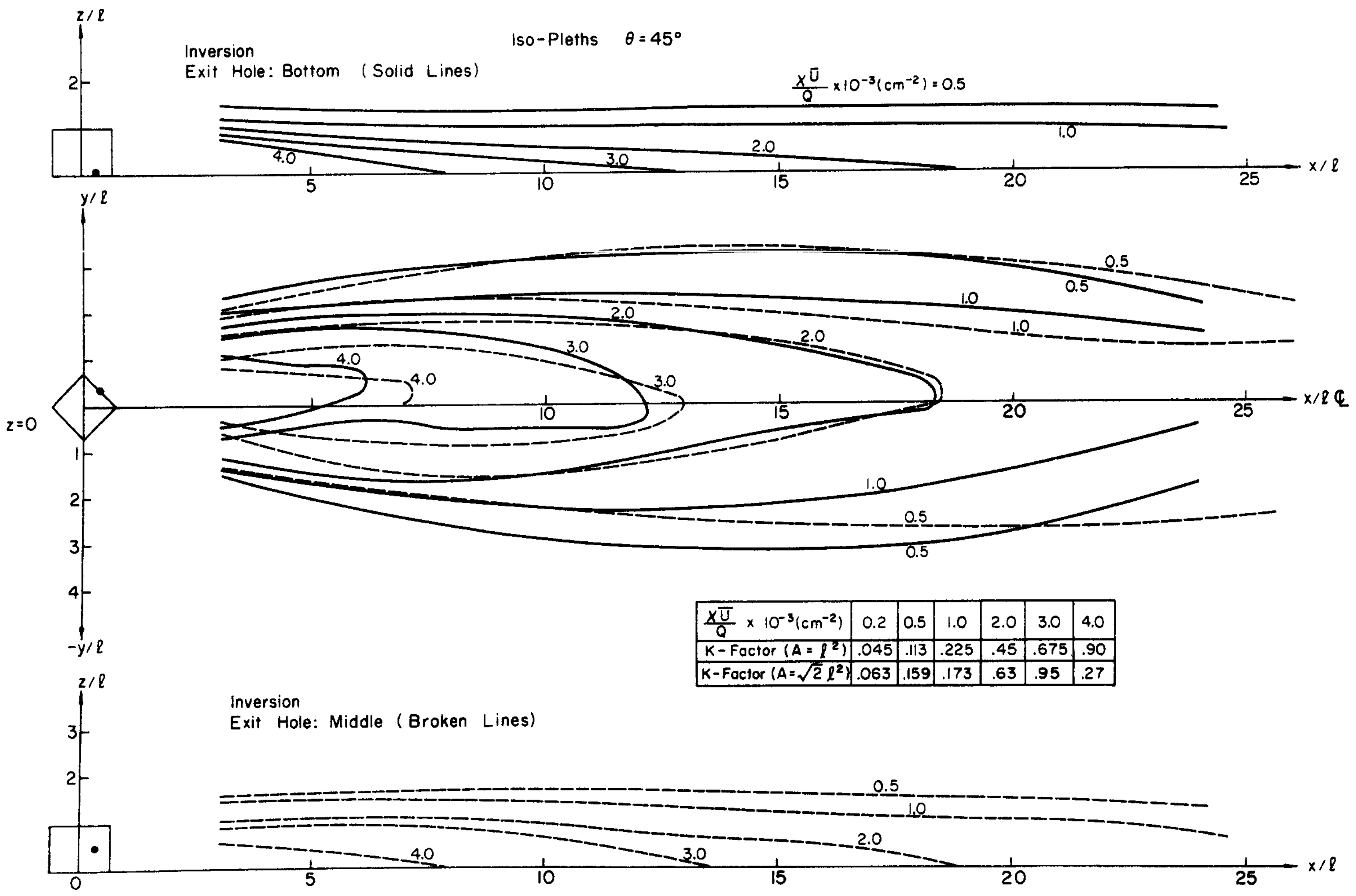
$\frac{\chi\bar{U}}{Q} \times 10^{-3} (cm^{-2})$	0.2	0.5	1.0	2.0	3.0	4.0
K-Factor	.045	.113	.225	.45	.675	.90

Figure 8. CONCENTRATION ISOPLETHS FOR θ = 0°, TOP EXIT PORT, NEUTRAL AND INVERSION STRATIFICATION



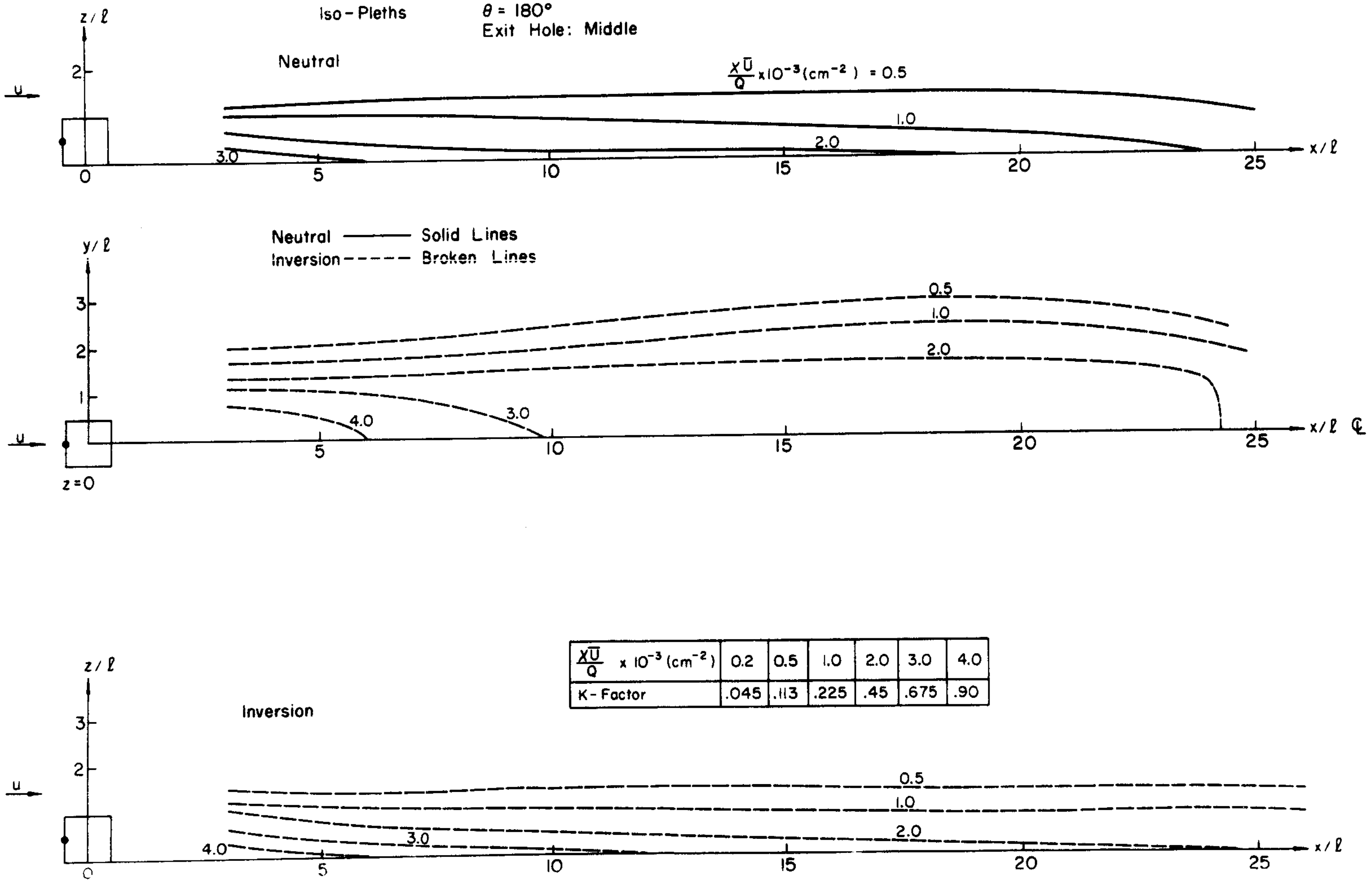
$\frac{\chi \bar{U}}{Q} \times 10^{-3} (cm^{-2})$	0.2	0.5	1.0	2.0	3.0	4.0
K-Factor	.045	.113	.225	.45	.675	.90

Figure 9. CONCENTRATION ISOPLETHS FOR $\theta = 0^{o}$, MIDDLE EXIT PORT, NEUTRAL AND INVERSION STRATIFICATION



$\frac{\chi \bar{U}}{Q} \times 10^{-3} (cm^{-2})$	0.2	0.5	1.0	2.0	3.0	4.0
K-Factor ($A = \ell^2$)	.045	.113	.225	.45	.675	.90
K-Factor ($A = \sqrt{2}\,\ell^2$)	.063	.159	.173	.63	.95	.27

Figure 10. CONCENTRATION ISOPLETHS FOR θ = 45°, MIDDLE AND BOTTOM EXIT PORT, NEUTRAL AND INVERSION STRATIFICATION



$\frac{\chi \bar{U}}{Q} \times 10^{-3}(cm^{-2})$	0.2	0.5	1.0	2.0	3.0	4.0
K-Factor	.045	.113	.225	.45	.675	.90

Figure 11. CONCENTRATION ISOPLETHS FOR $\theta = 180^{\circ}$, MIDDLE EXIT PORT, NEUTRAL AND INVERSION STRATIFICATION