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GASEOUS PLUME DIFFUSION ABOUT ISOLATED STRUCTURES OF SIMPLE GEOMETRY

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GASEOUS PLUME ENTRAINMENT BY OBSTACLES OF SIMPLE GEOMETRY

Abstract

Interest in the mechanisms of gaseous plume dispersal has increased rapidly over the past forty years. Most efforts have been directed toward understanding diffusion in idealized situations. During the last ten years many authors have stressed the importance of understanding the dispersal processes of gas plume in situations of practical importance. In spite of the high quality and extent of these initial tests the lack of a complete understanding of pollutant behavior in the vicinity of building structures is evident. Many important situations have not been correctly described and the majority of measurements made are not easily correlatable or comparable.

This report presents the results of a systematic experimental study of the entrainment problem in the vicinity of rounded building geometries; the effect of thermal stratification on dispersion near building structures, and the effect of short-stack release height and exhaust velocities. The approach attempts to isolate the peculiarities of such configurations in an effort to make appropriate field predictions possible.

The ultimate objective of this study on gaseous effluent behavior was to help develop a technology which will result in faster, safer and more economical dispersal of gaseous reactor wastes.

GASEOUS PLUME DIFFUSION ABOUT ISOLATED STRUCTURES OF SIMPLE GEOMETRY

FINAL REPORT

I. INTRODUCTION

Nuclear power reactors are generally enclosed in an airtight shell which prevents arbitrary release of radioactive 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.

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.

It is generally accepted that atmospheric stratification should be of only a secondary significance in effect on dispersion in cavity and wake fields of building structures. Nevertheless, public safety suggests that any estimate concerning increased dilution in the wake of structures be considered with caution. It has been suggested that stable conditions might decrease mixing or entrainment in the cavity and increase ground-level concentrations.

Finally, recent practice in reactor construction includes the release of off-gases or minor effluents through short stacks or ventilation shafts. Can the hazard analysis safely give credit for this increased height and subsequent potential increased dilution in estimation of ground level concentrations?

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.

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 dominate 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, such as the proposed Shoreham Nuclear Power Station reactor containment vessel, the flow is such that the separation point is dependent upon the Reynolds number.[31] If the boundary flow is laminar then separation will occur approximately 80 to 90^{o} from the stagnation point, while if the flow is turbulent separation will be delayed until 110 to 120^{o} 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 the modeled reactor vessel for the Shoreham Nuclear Power Station 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.

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 catagories 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. 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 $C = 1$ at distances of $x/D = 3.0$. Recent tests by the author of a model of the Shoreham Nuclear Power Station which utilizes a flat-topped cylindrical containment vessel produces similar results.[31]

II. OBJECTIVES

The research summarized herein was designed to speak to those questions raised above. The specific objectives chosen were:

1. Evaluation of the effect of stratification on dispersion near building structures. (The Meteorological Wind Tunnel Facility at Colorado State University is uniquely capable of simulating atmospheric stability categories.)

2. Evaluation of the effect of rounded building shapes on the dispersion in their wakes and the resultant average concentration in the wake at the end of the cavity.

3. Measurement of the streamline and turbulence behavior behind truncated cylinders in shear layers to determine the character of the wake in the region $0 \leq \frac{X}{D} \leq 30$ as compared with that of sharp-edged cubical geometries.

4. Measurement of pressure distributions and the drag of truncated cylinders mounted on a force balance to determine whether tripping devices permit satisfactory simulation of atmospheric flow over rounded structures.

5. Measurement of the character of dispersion from short stacks operated at various $V_{stack}/V_{free\ stream}$ ratios with possibility for descent of the plume into the wake-cavity region.

6. Measurement of the character of dispersion of instantaneous puffs released in the vicinity of buildings.

7. Development of the proper analytical formulations to generalize the conclusions of Parts 1 through 6.

It was recognized that the results of wind tunnel tests over scaled models are often considered with some reserve by practicing health officers until their veracity has been checked by a prototype comparison. Hence it is suggested this series of tests be culminated with a comparison to a full scale situation by means of a joint wind tunnel - field study program. It was essential that such a program be performed in joint consultation in order that appropriate field and laboratory parameters be recognized and recorded.

Consultation with C. R. Dickson, and E. Markee, at the National Reactor Test Station, Idaho Falls, Idaho, indicated the possibility of a co-operative wind tunnel - field study arrangement which would optimize the value of the proposed experimental program. Although it is conceivable that the entire range of measurements suggested be duplicated in the atmosphere, it was concluded that restriction of prototype measurements to a number of basic configurations would provide an adequately decisive basis of comparison for modeling arguments. Hence, a field program would involve diffusion near isolated structures of simple geometrical shapes such as cubes in various atmospheric stratification conditions.

The wind-tunnel experiment was designed to develop geometrically and dynamically simular conditions to those found in the projected field situation. A test grid was chosen to duplicate measuring stations found on the Idaho-NRTS Diffusion Grid at a scale of 1:50 (see Meroney, AEC Report COO-2053-1, 1970). Due to various delays the planned measurement program at NRTS has not been completed; hence, conclusions on model-field result compatibility must be incorporated in their documentation.

III. RESEACH RESULTS AND REPORT ABSTRACTS

GASEOUS DISPERSION INTO STRATIFIED BUILDING WAKES: (AEC Rept. No. COO-2053-3, AUGUST 1970).

Abstract:

The dispersion of gases in the atmospheric boundary layer released from an elevated source may be predicted by numerous semi-empirical formulas; however, very little information is available to describe the dispersion within the cavity-wake region downwind of a leaking structure. This study reports the results of the first wind tunnel phase of a joint field and wind tunnel program to evaluate the wind tunnel as a site analysis tool for nuclear safety investigations. A series of diffusion measurements are tabulated for a simple cublical structure placed at different orientations in a stratified shear layer.

Conclusions:

Gaseous dispersion from leaks in a cubical structure is a practical engineering problem. From an experimental approach, this study has led to the following conclusions:

1. Dispersion patterns differ in regions with and without the presence of a 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 farther downwind.

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

7. Inversion stratification causes smaller transverse spreads and "freezes" the plume growth in the vertical direction.

8. The plume growth in the transverse direction is much greater than (about 3 ~ 5 times) that in the vertical direction for both neutral and stabilized stratified shear flows.

9. Because of the dispersion characteristics in the wake flow linear superposition is not applicable to predict the real dispersion behavior.

Published in Literature as:

Meroney, R. N. and B. T. Yang, "Gaseous Plume Diffusion About Isolated Structures of Simple Geometry," Proceedings of 2nd International Clean Air Congress, December 6-11, 1970, Washington, D.C. (AEC Rept. No. COO-2053-2) (CSU Paper CEP70-71RNM-BTY-3).

CONE FRUSTRUMS IN A SHEAR LAYER: (AEC REPT. NO. COO-2053-4, AUGUST 1970).

Abstract:

Experimental results are presented for wind tunnel tests on a series of increasingly tapered cone frustrums placed in a shear flow. A cylinder of the same base diameter and altitude was also tested and used as a

standard by which to compare the other models. Extensive pressure, drag and wake measurements are tabulated as well as diffusion characteristics derived from the release of radioactive gas from the models.

Conclusions:

1. Model shape has very little effect on final plume height (i.e., plume height in the far wake) but causes marked changes in plume width growth. Final plume height was about twice the model height and total plume width was greater than five diameters by the time the near wake region was reached. Plume width growth decreased with decreasing model projected area.

2. Ground concentration decreases linearly with downstream distance (on log-log plot) at an almost constant slope in the near wake and far wake regions. The average slope was -0.95 for all models and all release configurations. For top and side top releases lofting of the plume due to frustrum taper caused decreased ground concentrations for the frustrums (cf. cylinder) for $X/D < 10$.

3. Releases from the side top and side bottom had little effect on the final plume height. Bottom releases caused the plumes to rise 1 1/2 to 2 times faster than top releases in the cavity and near wake regions. Releases directly into the cavity ($\theta = 180^{\circ}$) had the fastest plume rise rate.

4. Loss of the upstream part of the horseshoe vortex system due to increasing model taper was believed responsible for the changes in the diffusion character for the side bottom $\theta = 0^{\circ}$ release. The 1% increase in drag coefficient of frustrum 3 over frustrum 4 and the higher defect parameter values of frustrum 3 are also attributed to this effect.

5. At the test Reynolds number the flow was separating in a laminar manner right down the side of all models.

6. The secondary flows generated by the velocity gradient appear to have a compensating effect with the result that there is little change (about a 7% decrease) in the drag coefficient of a unit aspect ratio cylinder in a shear flow compared to that for a similar cylinder in a uniform flow.

7. For decreasing model size the Reynolds number to cause turbulent separation must increase.

8. The turbulent field caused by the model presence decays very quickly in the transverse direction (the background level is reached within one diameter) whereas there is much slower decay in the downstream direction (virtually no decay until after one diameter downstream).

Published in Literature as:

Meroney, R. N. and C. R. Symes, "Entrainment of Stack Gases by Buildings of Rounded Geometry," Proceedings of Conference on Air Pollution Meteorology, April 5-8, 1971, Raleigh, North Carolina. (AEC-COO-2053-5) (CSU Paper CEP70-71RNM-CRS49.)

WIND-TUNNEL STUDY ON GASEOUS MIXING DUE TO VARIOUS STACK HEIGHTS AND INVECTION RATES ABOVE AN ISOLATED STRUCTURE: (AEC REPT. NO. COO-2053-6).

Abstract:

This report is a part of a systematic study on gaseous dispersion about an isolated building structure. In order to estimate the maximum ground concentration distribution, the conventional formulae are compared with the wind tunnel results. Different stack heights are monitored both by smoke visualization and quantitative concentration measurements. The related parameters such as building orientation, stack height, and exit momentum are discussed. The experiment was conducted in a thick, neutral boundary layer, and a radioactive gas, Kr-85, was used as a tracer for concentration measurements.

Conclusions:

This research was undertaken to ascertain the influence of a simple cubical structure on pollutants released from short stacks at varying exhaust velocities.

On the basis of the experimental measurements reported herein, the following comments can be made:

1. Moderate increases in stack height or exhaust velocity may improve dilution before ground interception by tenfold over the levels expected for complete entrainment.

2. For $h_s/h_b \leq 1.5$; high exhaust velocities cannot prevent some immediate downwash; however, concentrations are still markedly reduced.

3. As the stack height increases, the effect of building entrainment decreases. Exhaust velocities, for stack height ratios greater than $h_s/h_b = 2.0$, apparently need only be high enough to avoid downwash behind the stack itself.

4. Building orientation apparently aggravates entrainment even for a simple cubical structure; however, the effect is not a major consideration here. (For more complicated building complexes the influences may be more significant.)

5. The Gaussian plume growth formulae such as the Pasquill-Gifford relations may over predict concentrations in the building vicinity and underpredict levels at distances further downstream

($x/L \geq 20$). (This delayed dispersion may be a characteristic of only isolated structures in shear layers.)

An exploratory effort was made to develop techniques to measure the character of dispersion of instantaneous puffs released in a turbulent shear layer. It was originally expected that dosages from instantaneous gas puffs might be determined utilizing a set of semiconductor detectors of very fast response time in a probe placed in the gas stream. This concept may still be possible, but it was eventually rejected because of the high concentrations of radioactive gas required for significant counting statistics and the expense of necessary digital data processing equipment.

An alternative approach has been successful, however. Light from a 5 mw Laser is scattered from an aerosol puff produced from a spray of dioctyl phthalate. The aerosol formed has a size range of 1-3 microns, negligible fall velocity, uniform sizing, and good light scattering characteristics. By measuring the intensity of forward-scattered light a signal proportional to instantaneous aerosol concentration is obtained. It is planned to use this apparatus to explore objective number 6.

IV. FINAL RECOMMENDATIONS

It is expected of course, that the new information developed by this research will be incorporated into design and health-safety practices. Additional problems which warrent consideration in this area remain. They are:

1. Measurement of the character of dispersion of instantaneous puffs released in the vicinity of building shapes of rounded geometry.

2. Measurement of the effect of scaled turbulence on diffusion over building structures in order to rationalize the use of gustiness ratios in regions at intermediate distances downstream of gas release.

3. Measurement of the effect of rounded buildings in close proximity to one another on cavity size, pressure distributions, and gas dispersion.

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