ENTRAINMENT OF STACK CASES BY BUILDINGS OF ROUNDED GEOMETRY*

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INTRODUCTION

Nuclear power reactors are generally enclosed within a containment vessel to prevent the harmful release of solid contaminants or radioactive gases into the atmosphere. In the event of a power failure, the containment vessel may conceivably be ruptured allowing radioactive gases to escape and cause serious contamination downwind of the reactor complex. The unusual shape of some of the modern nuclear reactors prompted the present wind tunnel study of four increasingly tapered cone frustums situated in a shear layer. A cylinder of the same base diameter and altitude was also tested to afford a standard by which the other models could be judged. Radioactive Krypton-85 gas was released from various positions on the models at a rate that would simulate the "leakage" condition of the prototype.

Buildings and building complexes produce nonuniform fields of flow which perturb the regular upstream atmospheric wind profiles. Around each building a boundary layer exists, where the velocity is zero at the surface but increases rapidly to a relatively constant value a short distance from the building wall. Outside of the boundary layer and downstream there exists a region of low velocities and pressures called the cavity. In this region circulations are such that flow may actually reverse with respect to the upstream winds. Surrounding the cavity but extending further downstream is a parabolic region called the wake in which the presence of the building is still evident in terms of deviations of velocity, turbulence, and pressure from conditions found in the upstream atmospheric boundary layer.

The formation of the wake and cavity regions are associated with a phenomenon called boundary layer separation. Under certain conditions the boundary layer actually detaches and enters the flow streaming about the building. This may occur at the corner of a sharp edged building or on a curved surface if the pressure increases due to a decelerating flow field. The separated boundary layer forms a sheet which completely surrounds the cavity region which contains relatively stagnant fluid. The extent of the cavity region for a typical reactor building may be approximated by

$$X_c = 5 \text{ or } 6 \sqrt{A/\pi} = 140 \text{ to } 170 \text{ meters.}$$

On buildings with rounded surfaces, flow is such that the separation point is dependent upon the Reynolds number. 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. It has been 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.(1)

Culkowski suggested that a practical conservative estimate for diffusion downwind of a building would be to assume a ground-level source and to recognize that the resulting ground level concentration distribution is an upper boundary of all other maximum ground concentrations.(2) This method may over-estimate ground concentration by a factor of twelve for releases into the cavity region, and may over-estimate the case above cavity releases by a factor of seventy. Such conservation hardly seems necessary or economical.

Diffusion in the turbulent cavity-wake region of a building has been studied both in the field and wind tunnel with increasing interest during the past ten years. Many formulae for the prediction of downstream concentration distributions have been proposed in the light of these studies and Barry (1964) provides a summary of the more popular ones.(3) Meroney and Yang (1970) have also recently reviewed results for the building entrainment problem.(4) In addition they present data for plume entrainment by simple sharp edged structures in neutral and stratified shear flows. Basically all formulas reduce to the form $\chi/Q = 1/cA\bar{u}$ where the constant c may vary from 1/2 to $\underline{2}$. Gifford combined this equation with the Gaussian Plume formula and suggested $\chi/Q = 1/(\pi\sigma_y\sigma_z + cA)\bar{u}$ as an estimate of the downwind concentration from an extended area source.(5) Crossections of model plumes suggest it is incorrect to assume the plume is dispersed evenly across the cavity for an elevated plume. In addition c is not a good criteria for plumes only partially entrained by the building cavity. The value of c measured for buildings of rounded geometry will vary from those suggested for sharp edged configurations since the flow separation about a cylinder results in a cavity region of less width than an equivalent cross-section rectangular structure.

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EXPERIMENTAL SIMULATION

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 5, 6, and 7. 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.

The experimental work was carried out in the Micro-meteorological Wind Tunnel at the Fluid Dynamics and Diffusion Laboratory, Colorado State University. The test section is 80 ft long and has a cross-section of approximately 6 ft by 6 ft. The first 6 ft length of the test section has been roughened with 1/2" gravel attached to its perimeter in order to thicken the boundary layer and thus reduces the wall effects. Also, a trip fence at the entrance is utilized to further stabilize the flow patterns. The ceiling of the tunnel is adjustable for control of pressure gradient in the direction of flow, which in this study was adjusted to zero. The air speed can be controlled by varying both the RPM of the drive motor and the pitch of the propeller.

Five models with varying degrees of taper were chosen for this study. The basic shape was a 6" altitude cylinder. The remaining 4 models were cone frustums of the same base diameter and altitude as the cylinder. The largest frustum had a top diameter of 4 inches and will be referred to as frustum 4. The remaining frustums were of 3, 2 and 1 inch top diameter and will be referred to accordingly. All tests except the flow visualization and the smooth cylinder study were run with the models covered in 80 D weight open coat cabinet paper. The ratio boundary layer thickeness to model height (δ/h) was 3.58 and tunnel blockage due to the model was less than 1%.

Radioactive Krypton-85 gas was used as a tracer for obtaining the concentration distribution. The measurement apparatus and procedures have been described in detail by Chaudhry and Meroney.(8) The set of five models used had one top leak site and three side holes all normal to the surface. The source was released from the top, side top, and side bottom with orientations to the freestream of $\theta = 0$, 90, and 180 degrees.

RESULTS

K-isopleths, dimensionless parameters describing the local downstream concentration, were computed for each model and release configuration. By plotting the corresponding co-ordinate for a particular K value against downstream distance (X/D) isoconcentration lines were formed for each model and release configuration (See typical Fig (1)). The ground concentration data was also put into K-isopleth form (on log-log paper; see typical results in Fig (2)). As expected the model with the largest projected area (vis., the cylinder) has the largest defect velocity and the largest cavity. This would imply larger downstream ground concentrations which is generally observed in the ground concentration figures. For the different models varying concentrations in the cavity region ($X/D < 2\ 1/2$) are observed but for the near wake ($10 < X/D < 20$) and far wake regions ($X/D > 20$) these concentrations converge to straight lines of almost constant slope for all models and all release configurations. The average value of the slope is -0.95.

It was interesting to note the lower ground concentrations for $X/D < 10$ for the frustums compared to the cylinder for top and side top releases. This is believed due to the effect of frustum taper. The increasing taper of the frustums tends to deflect the released gas higher into the freestream. (The smoke photographs also show this). Thus, for elevated releases lofting of the plume due to frustum taper causes lower ground concentrations (cf. the cylinder) near the models. This effect was not present for side bottom releases where the rate of downstream dilution was almost constant for all models.

In the EBR-II field study by Dickson (1967) the ground concentrations are plotted in the same way as in Figure (2).(5) For $X/D < 15$ Dickson fits straight lines of slope -0.6 to these curves. As just discussed, the effect of frustum taper on ground concentration for top and side top releases makes fitting of a general straight line to these curves unreasonable. It is possible, however, to fit straight lines to the side bottom release curves. The slope of -0.95 is again steeper than that fitted by Dickson.

One anomaly in the overall picture is the side bottom $\theta = 0^o$ release where the projected area effect is almost exactly reversed. The cylinder has the lowest ground concentration and the smaller frustums the highest. In the case of the cylinder the gas is being injected into the upstream part of the horseshoe vortex system developed at the base of the upstream face of the cylinder and is then swept downstream outside the cavity formed by the model. Roper (1965) has a good picture of this effect for the cylinder.(9) Possibly this upstream vortex is lost after a certain amount of frustum taper which explains the increased center line ground concentrations of the more tapered frustums.

Turning now to the vertical and horizontal isoconcentration lines (See Fig (1)) consider first the top release configuration. The isoconcentration lines show that the shape of the model has almost no effect on the final plume height but that plume rise rate did tend to decrease slightly with decrease in model size. As expected the plume width decreased with decrease in model projected area. The release configuration having the most marked effect on plume width was the side bottom $\theta = 0^o$ position. The rate of plume width growth was much greater for the cylinder and frustum 4 than for the other frustums. The explanation for this was tendered in the ground concentration discussion for the same release configuration. Gas is leaked into the upstream horseshoe vortex system that is generated by the two larger models (cylinder and frustum 4). It is entrained in this regime and swept downstream in the "legs" of this vortex system causing the very sudden plume width growth observed. The crowding of the isoconcentration lines for the cylinder and frustum 4 is due to this entrainment. In the change from frustum 4 to frustum 3 it seems that the upstream horseshoe vortex system present for the cylinder and frustum 4 is lost and this loss also deprives the wake of some of its high velocity component around the side of frustum 3.

An estimation of the average K value at the end of the cavity region has been proposed where the average concentration at the end of the cavity is predicted to be approximately the source strength divided by the total volume flow. The wake area at the end of the cavity is assumed to be twice the model projected area and the average velocity across the section to be half the freestream velocity. On this basis the average K value is unity. (For discussion of this see Meroney and Yang).(4) For the cylinder the average K value is 0.61. Barry in his summary of estimation formulae gives the average K value a range of 0.5 to 2 for the various methods he describes.(3)

It is obvious from the isoconcentration curves that model shape effects are predominantly reflected in plume width changes. Both side top and bottom releases for all θ have little effect on the final plume height ($X/D > 30$); however faster plume rise was noted for the side bottom releases and especially the $\theta = 0^{\circ}$ orientation. The highest plumes occurred when the gas was leaked directly into the cavity ($\theta = 180^{\circ}$) from either the side top or side bottom positions. This plume height and corresponding plume width growth decreased with decreasing model projected area (due to decreasing cavity size).

The final major conclusion to be drawn from this section is from the $\theta = 90^{\circ}$ orientations. Here again there was little change in final plume height for side top and side bottom releases for each model and between all models. The plume height tended to decrease with decreasing model projected area. The asymmetry of the horizontal plume was much more pronounced in the side bottom than in the side top release. This is due to the increased velocity near the top of the models tending to wash out this effect.

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 frustum taper caused decreased ground concentrations for the frustums (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 ($\theta = 0^{\circ}$) 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 frustum 3 over frustum 4 and the higher defect parameter values of frustum 3 are also attributed to this effect.
5. 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).

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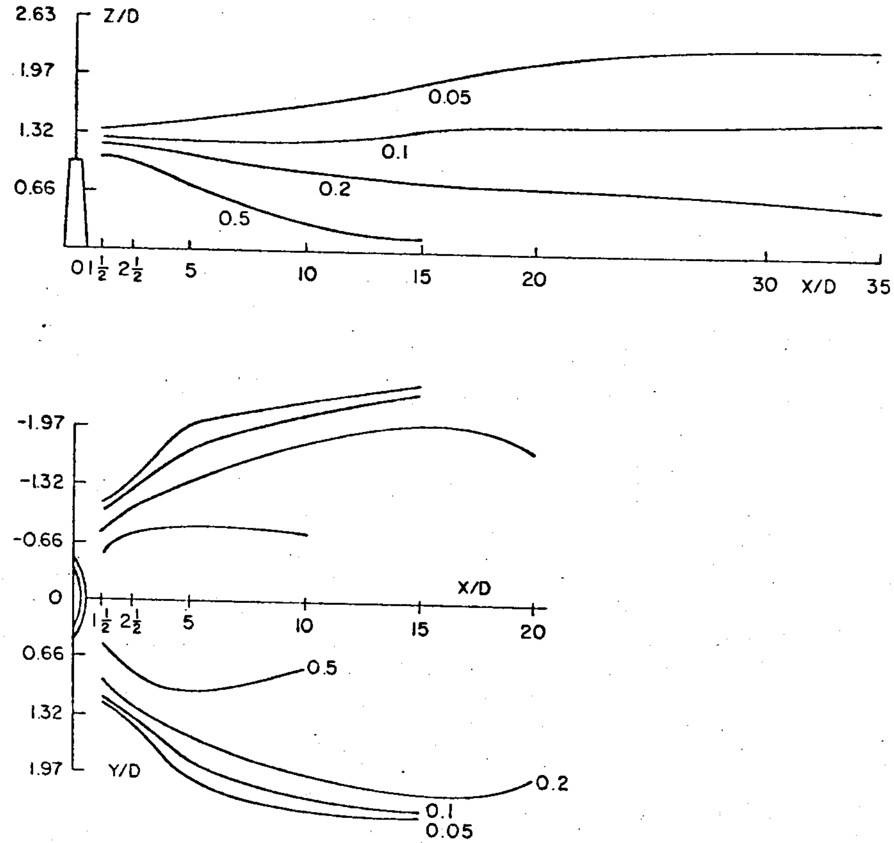

Fig. 1. Frustum 3 side top θ = 180° release.

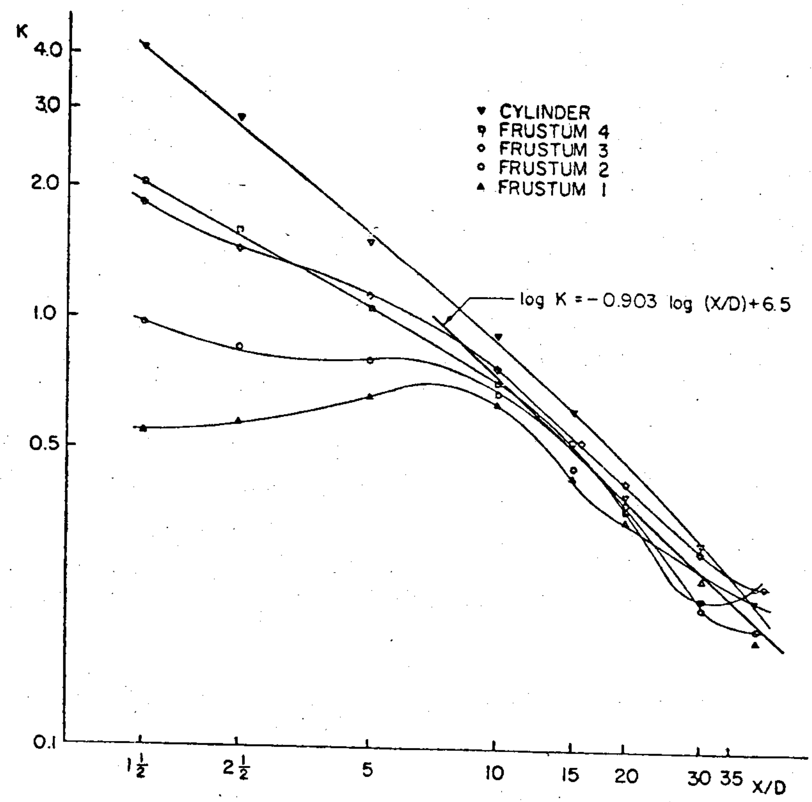

Fig. 2. All models side top θ = 180° release.