Building affected dispersion from elevated releases in neutral and stable boundary layers

by

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Happiness thou lovely name,
Where's thy seat, O tell me where?
Learning, pleasure, wealth and fame,
All cry out, "It is not here."

Not the wisdom of the wise,
Can inform me where it lies;
Not the grandeur of the great
Can the bliss I seek create.

Object of my first desire,
Jesus, crucified for me,
All to happiness aspire,
Only to be found in Thee.

Thee to praise and Thee to Know,
Constitute our bliss below;
Thee to see and Thee to love,
Constitute our bliss above.

Source and Giver of repose,
Singly from Thy smile it flows;
Happiness complete is Thine;
Mine it is, if Thou art mine.
Summary

A wind tunnel study was used to investigate flow and the dispersion of elevated emissions over and in the wake of both generic building groups and a real industrial site. Much research has been previously carried out on low level releases passing through extensive building arrays, but very little has treated elevated releases. The objective of the present research was to investigate the requirements of 'practical' models to predict dispersion from elevated releases above an industrial complex. The experiments were carried out in the EnFlo wind tunnel at the University of Surrey in simulated neutral and stable boundary layers at 1:500 scale.

The behaviour of the mean flow and turbulence in array wakes was compared with predictions from an analytical, three dimensional, eddy viscosity model. The model was successful when arrays were aligned normal to the approach flow but, as it did not treat the secondary flows associated with roof vortex systems, it was not adequate for other wind directions. The measurements showed that when roof vortex systems were prominent they created strong mean streamline deflections downwards over the wake, leading to velocity excess rather than deficit within the central part of the wake.

Diagonal wind directions produced the higher ground level concentrations, or the greater reduction in effective stack height, for all the building groups studied. This correlated well with the measured mean streamline deflections. Dispersion measurements in the stable boundary layer for releases below 1.5 building heights were very similar to those made in the neutral boundary layer, but the building effect appeared larger in the stable boundary layer for the higher releases. This latter feature probably resulted from interactions with the boundary layer edge in the relatively shallow stable layer.

Analysis of extensive measurements in the neutral boundary layer showed that a group of buildings could be adequately represented by a single, effective building of appropriate dimensions as far as the maximum ground level concentrations were concerned. However, the size of the effective building was a function of array orientation relative to the wind.

Vertical plume spread in elevated releases was unaffected by the presence of the buildings. Streamline deflections or downwash, which caused the mean height of a plume to reduce, were the predominant cause of increased ground level concentrations in the array wakes. In situations where the plume was significantly entrained into the wake, the lateral plume spread was enhanced. A modified Gaussian plume model including downwash and enhanced lateral spread represented the resulting concentration field quite well.
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**Notation**

\(a, b\)  
Substitution variable used in integrations

\(A_R\)  
Surface area of recirculation 'bubble'

\((A, B, n)\)  
Constants in fit for the hot wire velocity calibration

\(B, L\)  
Abbreviation for 'boundary layer'

\(b_0\)  
Initial radius of the released plume

\(C\)  
Ratio of the sample to source concentration, \(C_{\text{sample}}/C_{\text{source}}\)

\(C_{\text{sample}}\)  
Concentration at the sample position in parts per million (Vol)

\(C_{\text{source}}\)  
Concentration of the source gas in parts per million (Vol)

\(C_{\text{max}}\)  
Maximum ground level concentration from the \(C_{\text{Non Dim}}\) profiles

\(C_{\text{Non Dim}}\)  
Non dimensional concentration, \(\frac{CU_{\text{ref}}H_b^2}{Q}\)

\(C_R\)  
Mean concentration in the recirculation region

\(E\)  
Hot wire anemometer voltage

\(\text{EffInt}\)  
Effective integral of the coil trace after normalising by the coil factor

\(F\)  
Froude number

\(F_B\)  
Buoyancy flux in plume

\(g\)  
Acceleration due to gravity

\(H, h, g\)  
Self preserving profile shapes in wake model

\(H_b\)  
Building height

\(H_e\)  
Effective height of the stack

\(H_s\)  
True height of the stack

\(i, j\)  
Einstein's summation indicies

\(k\)  
Turbulent kinetic energy

\(k_{\text{Temp}}\)  
Temperature Correction factor from Bearman (1969)

\(k_y, k_z\)  
Lateral and vertical eddy viscosities in the wake model
Notation

\( L \)  Monin-Obukhov length scale
\( L_b \)  Building streamwise length
\( L_p \)  Briggs 'lift off' criterion
\( L_R \)  Recirculation length
\( L_x \)  Longitudinal length scale in the wake
\( L_y \)  Lateral length scale in the wake \( f(x) \)
\( L_z \)  Vertical length scale in the wake \( f(x) \)
\( m \)  Ratio of the vertical to lateral growth rates
\( \hat{m} \)  Constant used in the derivation of the wake model
\( n \)  Power index to fit the boundary layer profile
\( N \)  The buoyancy frequency in a stable flow
\( P \)  Pressure
\( p \)  Exponent of growth of lateral spread with \( x \)
\( \rho \)  Decay of the velocity deficit in the building wake
\( q \)  Growth rate for the vertical spread
\( q' \)  Turbulent heat flux in the stable boundary layer
\( Q \)  Source flow rate
\( Q_{out} \)  Release gas flow rate out of the recirculation region
\( R_e^{*} \)  Roughness Reynolds number
\( S_p \)  Spacing between buildings
\( t \)  Time
\( T_{\text{pulse}} \)  Time that the concentration pulse is integrated over
\( T_R \)  Time constant in recirculation region
\( T \)  Temperature
\( T' \)  Instantaneous temperature fluctuations
\( T_a \)  Ambient air temperature
\( T_s \)  Temperature of the source gas
\( T_{\text{calib}} \)  Flow temperature during the cross wire velocity calibration
\( T_{\text{meas}} \)  Temperature of the flow during cross wire measurement
Notation

\( T \) Friction temperature in the stable boundary layer

\( u', v', w' \) Instantaneous components of velocity

\( \overline{u^2}, \overline{v^2}, \overline{w^2} \) Turbulent normal stresses in \((x, y, z)\) directions

\( \overline{uw} \) and \( \overline{uv} \) Turbulent shear stresses

\( \overline{uw_{cs}} \) Shear stress in the constant stress region of undisturbed BL

\( u, v, w \) Perturbed velocities in the wake

\( \hat{u} \) Constant in the 3D wake model representing the couple acting on the building due to the flow

\( u_0 \) Magnitude of the velocity perturbation

\( u_c \) Flux of concentration

\( U, V, W \) Mean velocities in the undisturbed boundary layer

\( \bar{U}, \bar{V}, \bar{W} \) Mean velocities in the building wake

\( U_e \) Source exit velocity

\( U_{10} \) 10m wind speed in the undisturbed BL at full scale

\( U_h \) Velocity in the undisturbed BL at the building height

\( U_{ref} \) Velocity at the top of the boundary layer

\( U_{advec} \) Mean advection velocity of the plume

\( U_r \) Velocity when probe at angle \( \gamma \) to downstream component

\( u^* \) Friction velocity

\( V_R \) Volume of recirculation region

\( W_b \) Width of the building to the flow

\( (x, y, z) \) Distances in longitudinal, transverse, and vertical directions from the base of the stack

\( \tilde{x}_0x, \tilde{x}_0z \) Virtual source positions upstream of actual release position

\( X_{max} \) Downstream position at which \( C_{max} \) occurs

\( y_p \) Lateral position of the centre of the Gaussian distribution.

\( z_p \) Plume centreline height

\( z_p' \) Modified plume centreline height due to the building effect
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<th>Definition</th>
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<tr>
<td>$\Delta z_p$</td>
<td>Rise in plume centreline height</td>
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<tr>
<td>$z_0$</td>
<td>Roughness length, scaling parameter in the boundary layer</td>
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<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>$\alpha$</td>
<td>Dimensionless factor used in integral model</td>
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<tr>
<td>$\alpha_v$</td>
<td>Velocity gradient in the stable boundary layer</td>
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<tr>
<td>$\alpha_c$</td>
<td>Coefficient in the modified plume model that is a function of $x$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Shape factor for the recirculating flow region</td>
</tr>
<tr>
<td>$\beta_e$</td>
<td>Entrainment constant into plume taken as 0.6</td>
</tr>
<tr>
<td>$\beta_t$</td>
<td>Constant in log/linear temperature profile for the stable BL</td>
</tr>
<tr>
<td>$\beta_v$</td>
<td>Constant in log/linear velocity profile for the stable BL</td>
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<tr>
<td>$\chi_R$</td>
<td>Non dimensional concentration in the recirculating region</td>
</tr>
<tr>
<td>$\delta$</td>
<td>Boundary layer depth</td>
</tr>
<tr>
<td>$\epsilon$</td>
<td>Dissipation rate in turbulent flow</td>
</tr>
<tr>
<td>$\phi_m$</td>
<td>Non dimensional velocity gradient in the boundary layer</td>
</tr>
<tr>
<td>$\phi_H$</td>
<td>Non dimensional temperature gradient in the boundary layer</td>
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<tr>
<td>$\gamma$</td>
<td>Angle of probe to the longitudinal velocity component</td>
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<td>$\eta$</td>
<td>Non dimensional width in the wake, $y/L_y$</td>
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<tr>
<td>$\kappa$</td>
<td>Von karman constant = 0.41</td>
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<tr>
<td>$\lambda$</td>
<td>Ratio of lateral to vertical lengths scales</td>
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<tr>
<td>$\lambda_R$</td>
<td>Non dimensional recirculation length</td>
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<tr>
<td>$\lambda_1$</td>
<td>Ratio of $\frac{\Delta h^2}{\tau_{zz}}$ in the 3D wake model</td>
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<tr>
<td>$\lambda_2$</td>
<td>Ratio of $\frac{\Delta w^2}{\tau_{zz}}$ in the 3D wake model</td>
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<tr>
<td>$\nu$</td>
<td>Kinematic viscosity taken as $1.5 \times 10^{-5}$ m$^2$/s for air</td>
</tr>
<tr>
<td>$\theta$</td>
<td>Overheat ratio</td>
</tr>
<tr>
<td>$\theta'$</td>
<td>Approach flow wind direction in degrees</td>
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<tr>
<td>$\rho_a$</td>
<td>Ambient density of the fluid</td>
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\( \Delta \rho \) Difference in density of two fluids
\( \sigma_x, \sigma_z \) Lateral and vertical plume spread coefficients
\( \sigma_x', \sigma_z' \) Modified plume spread coefficients due to the building effect
\( \tau_n \) non dimensional time constant in the recirculating region
\( \tau_{u} \) Shear stress perturbation
\( T_{u} \) Shear stress in the undisturbed boundary layer
\( \bar{T}_{u} \) Shear stress in the building wake
\( \zeta \) Non dimensional downstream distance in wake, \( x/H_b \)
\( \zeta \) Non dimensional height in the wake, \( z/L_z \)
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This work was funded by British Nuclear Fuels Ltd in conjunction with Westlakes Scientific Consulting Ltd. I am very grateful for the help, encouragement and patience afforded by Dr. Ian Teasdale of Westlakes, throughout this seemingly endless project.

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I would also like to acknowledge God's goodness to me in answering my many prayers concerning this project, and providing those people to help me, realising that everything is at His control and He rules and guides each circumstance. He is worthy to receive praise for all things in this life, but much more so, if he reveals to us that sin is mixed with all we do, and then leads us to see that Jesus came "to seek and to save that which was lost." (Luke 19 v 10)
Chapter 1. Introduction

Assessment of the dispersion of gases released in the locality of building groups is required for industrial sites to obtain construction and operating licences. Tall stacks are built to release the plume higher up in the boundary layer, so that by the time the plume comes into contact with the ground it is sufficiently dispersed. However, it is well established that buildings bring the plume into contact with the ground much sooner than would otherwise be the case. This can increase the maximum ground level concentration by more than an order of magnitude. Much of the research into building affected dispersion has concentrated on releases at or below roof level, where the plume becomes rapidly mixed in the recirculation region at the lee of the building. In this situation the lateral and vertical spread of the plume are the main parameters that need to be enhanced in any dispersion model.

Previous studies have examined in some detail plumes affected by a isolated rectangular building. Castro and Robins (1977) showed that the 45° wind direction, compared to the 0° case, gave rise to significantly higher ground level concentrations for releases at roof level and above. Huber and Snyder (1982), investigated dispersion from short stacks, with the approach flow normal to the upwind building face. In this study the centreline ground level concentration measurements were complemented by vertical and lateral profiles for a range of release heights. Later Huber (1989) investigated the influence on building width and orientation for a number of single buildings having width-to-height ratios ranging from 2 to 22. Some of his dispersion experiments used a release height of 1.5 times the building height whilst the rest were at ground level. The emphasis of his paper is on the behaviour of the cross-stream concentration profiles, so no centreline ground level concentrations or vertical profiles are presented. Higson et al. (1995) carried out a field study in the USA on a 2m cube normal to the flow in stable and unstable conditions. Higson et al. (1996) compared field and wind tunnel studied for dispersion around an isolated building at various orientations. However, all their experiments used an upwind release at half the building height. Dispersion through an array of 2m cubes was studied by Davidson et al. (1995), but once again this was for an upwind release below the obstacle height.

Previous research has been carried out for British Nuclear Fuels Ltd on dispersion from elevated releases over their Sellafield site in Cumbria, Singh (1990). The overall influence of the site was determined by making ground level concentration measurements. One of the aims of our research is to determine the effect of surrounding buildings on dispersion from an elevated release above a single building. For example, if the effect of the single building closest to the stack dominates the dispersion behaviour, can the other surrounding buildings be ignored from a modelling point of view? This question requires studying both simple and complex building groups to determine the effect of adding surrounding buildings. The other major objective is to determine the influence of stratification on dispersion from elevated releases above building groups. No reported research has been done in this area of interest, but it is a scenario which would often occur for releases made on a clear night.

Knowledge obtained on how buildings affect the dispersion of elevated releases, can be fed into dispersion models to improve their ability to predict the concentration field in the vicinity of buildings. For a safety
assessment to be carried out for a routine release, typically 5 independent meteorological variables need to be catered for, such as: wind speed, wind direction, heat flux, boundary layer depth and precipitation. This can mean between 2000 and 4000 dispersion scenarios need to be evaluated. Clearly, to perform such an exercise, the model used needs to run within a few minutes at most, to make the assessment possible within the available time. Computational fluid dynamics can be used to model the flow around a single building, but currently each case takes several hours to run after it has been set up. The implication of this is that for some time to come, relatively simple dispersion models such as the Atmospheric Dispersion Modelling System, CERC (1995), will be required to perform assessment exercises. Therefore, it is important to make these models as realistic as possible by investigating which parameters are most important to adjust when evaluating plume behaviour in regions affected by buildings.

This project investigates a range of building groups at 0 and 45° in a simulated neutral and stable boundary layer at 1:500 scale. All the experiments were carried out in the Environmental flow research centre at the University of Surrey. The wind tunnel used had a working section of 1.5m by 3.5m with a length of 20m. The flow in this tunnel can be stratified by demanding a vertical inlet temperature profile, and the internal surfaces can be heated or cooled, depending on whether a convective or stable boundary layer is to be simulated. In the stable boundary layer it was necessary to isolate the central flow from the influence of the slightly cooler side walls to reduce the cross flows that were present. This was achieved by placing perspex side walls half a meter from the tunnel side. The central metre of the stable boundary, was then approximately two dimensional, with a downstream fetch of 2.5m over which the boundary layer development was not very significant.

The project was funded by Westlakes Scientific Consulting Ltd, acting on behalf of British Nuclear Fuels Ltd (BNFL) in Cumbria. All the building groups studied were based on a building (B204) at the BNFL Sellafield site, which has a stack of twice the building height. Single buildings of 3, 5 and 7 times the plan dimensions of B204 were investigated, and nine B204 buildings were arrayed with three different spacings between the buildings. Centreline ground level concentrations were measured for a range of release heights from 1.2 to 3.2 times the building height. The lower limit ensured that the plume did not become completely entrained into the building wake, while above 3.2 times the building height, the resulting ground level concentrations were so low that they could not accurately be measured. This upper limit was not really restrictive since for most of the building groups their effect was negligible for these tall stacks. The maximum concentration values from the centreline distributions were used to calculate an effective stack height, based on dispersion measurements in the undisturbed boundary layer. For some of the cases vertical and lateral concentration profiles were taken at a number of downstream positions to investigate in more detail how the plume was developing in the perturbed boundary layer flow. These results were then compared with a modified Gaussian model to determine which parameters should be adjusted to best describe the observed concentration profiles. Cross-wire measurements were also made downstream of some of the building groups in the neutral boundary layer with a view to linking the flow and dispersion characteristics in the building wakes.

In the neutral boundary layer many building groups were studied in terms of their effective stack heights to determine which configurations produce similar effects on the plume dispersion. This should enable the infinite
number of possible building layouts to be represented by equivalent building groups, so simplifying the problem. After studying the behaviour of these generic building groups, a model of the Sellafield site was installed into the tunnel to determine the effect of the surrounding buildings and topography on the dispersion of releases from B204. The downstream fetch investigated in the neutral boundary layer was equivalent to 3 km at full scale. Beyond this distance downstream the plume has become sufficiently dispersed that initial building effects make negligible difference to its behaviour. Some of the interesting dispersion experiments in the neutral boundary layer were repeated in the stable one, to investigate the sensitivity of the results to stratification. Practically no previous dispersion measurements have been made for elevated releases above buildings in a stable boundary.

Chapter 2 contains the literature review which details some of the important previous studies, and highlights the very limited number of building affected dispersion experiments that have used releases above roof height. In the stable boundary there have been no previous dispersion experiments carried out for elevated releases above buildings. In Chapter 3 is discussed the apparatus and techniques used to make flow and dispersion experiments in the EnFlo wind tunnel. The results of the flow measurements made in the undisturbed boundary layers, and in the wake of some of the building groups in the neutral boundary layer, are presented in the Chapter 4, together with comparisons with a 3D momentum dominated wake model that has been developed. The dispersion results for elevated releases are presented in Chapter 5, firstly in the absence of any buildings, and then with the range of generic building groups, progressing to the full Sellafield site. Chapter 6 investigates which parameters in the Gaussian plume model need to be adjusted to give good agreement with the observed concentration field. The conclusions from this research project are given in Chapter 7, along with suggestions for further work in this area.
Chapter 2. Literature review

2.1 Introduction

A large body of literature exist for flow and dispersion around isolated buildings and groups in the neutral boundary layer. Predominantly the interest has been for effluents released at or below roof level, where the plume is significantly affected by the immediate flow field around the building. Very few studies have investigated elevated releases around groups of buildings in the neutral boundary layer, and according to the literature this has never been done in non-neutral stability.

First of all this review considers the flow and dispersion behaviour over a single block normal to the wind and then moves on to the diagonal approach flow. Work has been done on buoyant emissions from the sides of cuboids and for elevated releases above a single building. All these dispersion experiments were carried out for a neutral stability. Snyder (1994b) investigated dispersion around a cube in stable stratification for a ground level release showing that the near building wake was unaffected for obstacle Froude numbers to be expected in the atmosphere. Further downstream the wake was influenced by the stability, which indicates that elevated releases are more likely to be effected than releases at or below roof level.

Field and wind tunnel studies have been carried out around a number of Nuclear Reactor sites, but all of these investigated releases just above roof level or below. However, many industrial sites do have elevated stacks, that need to be adequately modelled from a dispersion point of view for the site to obtain a licence to operate. Previous research in this area has been carried out on behalf of British Nuclear Fuels Ltd, to determine the reduction in effective stack height for releases over its Sellafield site in Cumbria. It was the intention of this project to make a more detailed study of the effect of surrounding buildings on dispersion from an elevated release above a cuboid. Also some experiments were carried out in a stable boundary layer to determine how stratification influences the plume dispersion over groups of buildings, and the Sellafield site.

The Gaussian plume model is by far the most common way of simply representing the time averaged concentration field downstream of a release. Many of the dispersion studies reviewed in this chapter describe the effect of buildings on the plume in term of modifications to the Gaussian model parameters. The equation for the Gaussian spreading of the plume is therefore presented at this early stage in the report and can be expressed as:

\[
\frac{CU_{ref} H_b^2}{Q} = \frac{H_b^2 U_{ref}}{2\pi U_{adv} \sigma_x \sigma_z} \left[ \exp\left( \frac{-y^2}{2\sigma_y^2} \right) + \exp\left( \frac{-(z-z_p)^2}{2\sigma_z^2} \right) \right]
\]

where \( C \) is the ratio of the volumetric concentration in the plume to that of the source, \( U_{ref} \) is the velocity at the top of the boundary layer, \( H_b \) is the building height, \( Q \) is the source flow rate in m\(^3\)/s, \( U_{adv} \) is the mean advection velocity of the plume, \( \sigma_x \) and \( \sigma_z \) are the lateral and vertical spreads and \( z_p \) is the plume centreline height. This is often known as the bi-
Gaussian equation since it has a vertical reflection term (the right hand term in the square brackets), which models the effect of the ground and satisfies continuity. The plume dimensions, $\sigma_x$ and $\sigma_z$, increase with downstream distance to represent the effect of the plume spreading, which results in the maximum concentration in the plume being reduced.

2.2 Flow and dispersion around a rectangular building

2.2.1 For approach flow incident to the surface of a cuboid.

If a surface mounted cube were subjected to a uniform flow having only a thin surface boundary layer the positive pressure on the upstream face would be fairly uniform apart from near the edges (Castro and Robins 1977). However in the case of a cube in a deep boundary layer the curvature in the velocity profile produces a pressure gradient on the lower two thirds of the front building face driving the flow downwards. Any pollutant emitted below this level from a vent on the upwind face, will be carried down to ground level and then will travel upwind to meet the separation point. The upstream separation point is about one building height ($H_b$) in front of the upstream face for a cube, but may be up to $2H_b$ in front for wider buildings. Above this standing eddy the oncoming flow strikes the normal face and is directed upwards or sideways depending on its proximity to the roof and sides of the cube. The dimensions of the upwind recirculation region are very dependent on the building width to height ratio and the shape of the wind profile. The standing eddy spanning the building width curls round the sides to form the horse shoe vortex system as shown in Figure 2.1. Turbulence in the approach flow makes the horse shoe vortex system unsteady, but the vortex system itself produces the high turbulence levels experienced near the ground at building corners.

At the sharp edges between the windward face and the roof and sides the flow separates and the free shear layers curve inwards towards the wake axis as they travel downwind. If the ratio of the streamwise length of the building $L_b$ to its height $H_b$ is large enough, the flow will reattach onto the respective faces, forming closed recirculation bubbles on the roof and sides. This is the case shown in Figure 2.1. Reattachment is enhanced by turbulence in the approach flow since it increases the momentum transfer between the shear layer and the recirculation region. However, it should be remembered that reattachment is always unsteady and for a range of building geometries the flow randomly oscillates between being reattached or fully separated. When the reattached flow reaches the leeward edges of the sides and roof, it will again separate to form an 'arch' vortex. The flow over the cube stretches the top of the 'arch' downwind with decreasing height. Downstream the mean flow reattaches onto the ground forming the downwind extent of the cavity region. Where reattachment does not occur on the roof and sides, the near wake cavity extends upwind to the leading edges of the roof and sides of the building. If any pollutant is emitted or entrained into the cavity all the building surfaces apart from the upwind face will then be contaminated.

The cavity region is characterised by low velocity and pressure, but high turbulence intensity. This region is relatively well mixed and is often modelled as having a uniform concentration. However it was shown by Fackrell and Robins (1981), that this assumption was more valid for an entrained plume than for a source within the cavity. The flow in the
recirculation region is very complex and unsteady, thus most descriptions of the flow are only true in a time averaged sense. The dimensions of the cavity are strongly dependent on the building width to height ratio, \( W_b/H_b \), and on whether the flow reattaches to the building's roof and sides. The distance from the lee of the building to reattachment point is the streamwise extent of the cavity region and is denoted by \( L_R \). For a large \( W_b/H_b \) ratio, say greater than 10, the region of recirculating flow will extend to about \( L_R/H_b = 7 \) when roof flow reattaches, compared to \( L_R/H_b = 11 \) when the flow remains separated over the building roof (Hosker 1979). The scatter in the experimental data obtained by many different researchers for the reattached case is much less than for the separated one. Evidently the physics of the wake cavity are much more sensitive to the incident flow conditions in the latter case since this was the only varying parameter between data sets. The approach flow upstream of the cuboid in all the studies, was a deep boundary layer of neutral stability. The maximum cavity height for the separated case is between 1.5 and 2.5 \( H_b \) above the ground and is strongly affected by roof slope. For the reattached case the cavity height and width are approximately the same as that of the building.

The main wake, commencing at the downwind end of the recirculation region, is characterised by a velocity deficit and a turbulence excess when compared to the flow in the absence of the building. The longitudinally oriented vortices from the horse shoe system and from the building sides, are usually dissipated quite rapidly by the turbulence in the approach flow when the building face is normal to the flow. This causes the wake to be dominated by the momentum deficit resulting from the drag on the building. The wake spreads with downstream distance by entraining the external flow. Thus, downwards and lateral flow towards the wake centreline is produced which causes the downwash of plumes. The velocity deficit in the wake decays roughly as \( \left( \frac{x}{H_b} \right)^{-\hat{p}} \) where the value of \( \hat{p} \) is between 1.5 & 1.6, and the turbulence excess decays slightly quicker at about \( \left( \frac{x}{H_b} \right)^{-2} \). After about 10 to 20 \( H_b \) downstream the wake is generally indistinguishable from the background flow. However, it should be remembered that the decay rate is strongly dependent on the background turbulence levels.

There have been many previous dispersion experiments around rectangular buildings, but the majority have used release positions at or below roof level. Experiments by Robins & Castro (1977), used release heights up to 2.5 times that of the isolated cube as well as some below roof level. Huber and Snyder (1982) investigated elevated releases above a rectangular-shaped building which had a length equal to twice its height and width. It was orientated with the long side perpendicular to the approaching neutral boundary. They compared their results with a Gaussian plume model with enhanced vertical spreading, and were able to achieve good agreement with the centreline ground level concentration measurements. Later Huber (1989) investigated ground level and elevated releases for buildings having width-to-height ratios ranging from 2 to 22. The main emphasis of the paper was to determine how the cross-stream concentration profiles varied with building width and orientation.
2.2.2 For approach flow at an angle to the surface of a cuboid.

For a block like building at 45° to the flow direction the most significant change in the flow pattern around the building is the intense roof vortices that are produced by roll-up of shear layers as the flow above the horse shoe vortex system travels diagonally up and along the building sides, see Figure 2.2. Experiments by Robins & Castro (1977), measuring ground level concentrations from a release at the top centre of a cube, found that the 45° case yielded approximately a four fold increase in the concentration levels when compared to the 0° case. As the release height was increased towards 2.5 times that of the cube, this ratio decreased as a consequence of the lessening influence of the cube when the plume is higher up. The enhanced ground level concentrations for the 45° case illustrates the effective vertical transport produced by the roof vortices. Ogawa et al 1983, showed that the downstream extent of the cavity region increased as the angle between the wind direction and the building changed from 0° to 45°.

In the main wake the roof vortices transport higher momentum fluid downwards, increasing the wake velocity, and after $10 H_b$ downwind a velocity ‘overshoot’ is often observed. i.e. the velocity in the wake centreline is greater than it would have been in the absence of the building. However, at locations further from the axis, lower mean velocities will appear. Meandering of the wake axis makes measurement of these vortices difficult further downwind and their presence may have to be inferred from the excess in mean velocity or from the tracer transport and dispersion. For conditions of low background turbulence, these vortices may persist to about $100 H_b$ downwind. If the building is inclined at say 30° to the flow, the vortex created on the more upstream side of the building as the flow separates over the roof will be the dominant one. Roof vortices become significant if the approach flow is more than 15 degrees off normal to the upstream building face.

Recent research has been carried out by Higson et al. (1996), for an isolated building having an upwind source at half the building height. The normal and diagonal wind directions were investigated in both field and wind tunnel studies, paying particular attention to the fluctuating components of the dispersion. It was found that, in general, concentration fluctuation intensities occurring in the field were larger than those measured in the wind tunnel, except in the near-wake region.

Apart from Robins & Castro (1977) and Huber (1989), previous dispersion experiments have predominately considered releases at or below roof level for cuboids diagonal to the approach flow.

2.2.3 Effects of plume buoyancy

Plume buoyancy reduces the ground level concentrations when compared to the passive case, because the mean plume height is increased. Hall and Waters (1986) investigated the effects of buoyancy on emissions at model scale covering a range of heat release rates from 1 to 100 MW over a wind speed range of 1 to 10 m/s for a cuboid. Releases from either the downwind, upwind or roof surfaces of the building were investigated. They found that as the emission buoyancy was increased, the ground level concentrations decreased more rapidly until plume 'lift off' occurred at which point the ground concentration levels were undetectable. This behaviour is illustrated in Figure 2.3. It can be seen that the effect of the source position is small relative to the buoyancy parameter over the range...
that has been investigated. The experiments were carried out in neutral boundary layers having roughness lengths corresponding to 20 and 60 cm at full scale. The results appear insensitive to the roughness length used within the experimental scatter. On the figure is marked the position at which 'lift off' would occur as predicted by Briggs as the value of $L_p$ reaches 29, where $L_p$ is given by

$$L_p = g \frac{\Delta \rho H_b}{\rho_a u^2}$$

(2.2)

The results do show a sharp change in gradient around this position rather than a step change in concentration that was predicted by Briggs.

The shape of the building has a significant affect on the ground level concentrations which varies with emission buoyancy. For low buoyancy emissions, as the building width is increased, the concentrations levels reduce, which is the instinctively expected result since the width of the wake has increased. However, for highly buoyant emissions the ground level concentrations are increased for the wider building case. The cause of this seems to be that the initial dilation produced by wider buildings reduces the relative plume buoyancy. Thus, the plume rise is reduced and the ground level concentrations increase. At an intermediate buoyancy these two opposite effects cancel, and the ground level concentrations become independent of the building width.

Snyder (1994a) considered elevated releases above a single building, and found qualitatively that the additional buoyancy in the effluent is similar to an increase in vertical exit velocity. Both these effects increase the plume height, so that the plume moves further away from the heart of the building wake. This results in the plume being less influenced by the wake. Often elevated buoyant releases are modelled using a release having the same density as the surrounding air, but with an enhanced release height. This method works well because most of the plume rise occurs close to the release position, since as the plume spreads and entrains more surrounding air, the mass of the plume increases and the rate of rise falls.

### 2.2.4 Effects of atmospheric stability

Unstable stratification increases the vertical mixing and background turbulence in the flow, so promoting the dispersion of plumes. The convective boundary layer is made up of rising thermals and cool downdrafts, so pollutant emitted at stack height can be advected down to ground level by a downdraft causing the local ground level concentrations to increase. For dispersion from a ground level source the effect of unstable stratification will reduce any local ground level concentrations since strong vertical mixing must transport pollutant upwards. The effect of the building wake is less persistent in unstable conditions since the high turbulence levels increase momentum transfer and rapidly break up trailing vortex systems generated by the building.

Stable stratification dampens the vertical motions so that the turbulence and the vertical mean motions are attenuated. The dispersion of the plume is reduced both laterally and vertically, so that the pollutant contaminates a smaller volume of air but with obviously higher concentrations. If the plume is entrained into the near wake recirculation region of a building, the ground level concentrations can be increased due to the stability.
However, if the plume is elevated it may remain so for a long time, (small vertical mixing), and consequently the maximum ground level concentrations will be significantly reduced and will occur much further downwind from the source.

Up to a point increasing stability enhances the trailing vortex system since it reduces the background turbulence that breaks up the vortices. For strong stability the vertical motion induced by the vortices will be attenuated directly due to buoyancy forces. For the moderately stable case the wind direction will be important in determining the effect of stratification, since a 45° wind direction produces the strong roof vortices.

Meroney and Yang (1970) reported concentration measurements behind a cube for neutral and stably stratified approach flows. Releases were made from the top, middle and bottom of the cube, but the downwind concentrations were found to be very similar for each source location. They found that in stable flows, at downwind distances of less than five building heights, the mechanical turbulence generated by the building was dominant and the effect of stability was not significant. At distances greater than five building heights the non-dimensional ground level concentrations were about 8% higher in the stable case. However when considering the natural variability of dispersion an 8% increase is not very significant.

Experiments have been carried out by Ogawa and Diosey (1980), for flow over a 2 dimensional fence, where it was found from wind tunnel studies that the extent of the cavity region reduced significantly with increasing stability. This was not observed in the field study, since tests were only carried out under weakly stratified conditions. A more recent wind tunnel study by Steggel and Castro (1998), has demonstrated that the recirculation length behind a 2 dimensional fence increases, rather than decreases, with stability, since the background turbulence in the approach flow is lower. Ogawa et al (1983), made field and wind tunnel measurements for flow round a cube. In this case, the wind tunnel study was carried out in neutral flow conditions, and the field tests only covered a limited range of stabilities, so no information was gained on how the stability affected the cavity dimensions. The results did however demonstrate that an increase in background turbulence reduces the length of the recirculation region.

Snyder (1994) investigated flow over a cube in a stably stratified water tank, for a uniform approach flow. Concentration profiles were measured on the block surfaces and downwind from a source positioned at ground level on the lee side of the building. For Froude numbers greater than 2.5 the concentration field was only affected downwind of the recirculation region, but in the near wake, no significant changes were observed. However, as the Froude number was reduced to 1, dramatic changes occurred in the near wake region.

Equation (2.3) shows an expression for the obstacle Froude number as a function of the building height $H_b$, the surface roughness length $z_0$, the Monin-Obukhov length $L$ and the log-linear profile constants $\beta_u$ and $\beta_T$.

$$
F = \frac{\log \left( \frac{H_b}{z_0} \right) + \beta_u \frac{H_b}{L}}{\frac{H_b}{L} \sqrt{\frac{L}{H_b}}} + \beta_T
$$

(2.3)
The derivation of this equation appears in Appendix 1, and uses the log-linear profiles for the temperature and velocity in the stable boundary layer, along with the equations for the obstacle Froude number and Monin-Obukhov length. The Monin-Obukhov length scale is the height at which the mechanical shear production of kinetic energy matches the dissipation due to buoyancy effects. As the stability increases, $L$ decreases so $\left(\frac{H_b}{L}\right) \gg 1$, and the Froude number tends to:

\[
F = \frac{\log\left(\frac{H_b}{\varepsilon_a}\right) + \beta_u \frac{H_b}{L}}{H_b} \left(\frac{L + \beta_r}{H_b + \beta_r}\right) = \frac{\beta_u H_b}{L \beta_r} \left(\frac{L}{\sqrt{\beta_r}}\right)
\]  

(2.4)

Fitting the measured velocity and temperature profiles in our stable boundary layer with the log-linear relationships gave values of 4 and 4.2 respectively for the constants $\beta_u$ and $\beta_r$, see Section 4.2. Putting these values into the above expression indicates that as the stability increases the obstacle Froude number tends to a value of about 2. So in atmospheric stable boundary layers it is unlikely that the obstacle Froude number will be less than 2, but Snyder has shown that for a value of 2.5, the near wake of the building is unaffected by the stratification. This indicates that the effect of stratification on flow around buildings is going to occur in the main wake region and further downstream but not in the recirculation zone. So elevated releases, that do not get involved in the near wake, are more likely to be affected by stratification than those at or below roof level.

Higson et al. (1995) carried out field experiments of dispersion around a 2m cube in stable and unstable conditions. The source was positioned 20m upwind of the cube and 1m above the ground. The cube was rotated so that the flow was approximately normal to the upwind face during the measurement period. Concentration measurements were made on the surfaces of the cube and on the wake centreline at an elevation of 1m, excluding those sample points on the roof. Particular attention was paid to the fluctuating components of the dispersion enabling measurements to be made of the residence time of concentrations in the recirculation region. It was found that it may take up to five times as long for concentrations to fall to a low level in the stable boundary layer when compared to unstable conditions.

From the limited amount of research that has been carried out on building affected dispersion in the stable boundary layer and from meteorology, it appears that the atmospheric boundary layer is seldom stable enough to significantly affect the immediate flow around the building. So the dispersion from releases at or below roof level is dominated by the mechanical turbulence generated by the building. Only in the far wake, where the concentrations are fairly insensitive to the release position, will the effects of stratification be seen. However, when considering elevated releases of say 1.5 times the building height, the plume does not become involved in the immediate building wake, but is affected by the more external perturbations in the mean streamlines over the wake. These parts of the wake are far more likely to be affected by the stratification than the highly turbulent recirculation region.
2.3. Flow and dispersion around groups of buildings

2.3.1 Field and model scale studies of nuclear reactor sites

There has been a number of field and wind tunnel studies carried out on dispersion around a group of buildings mainly in connection with the nuclear power industry. The first full scale dispersion experiments involved releasing a visible smoke plume and observing its behaviour. Two such tests were carried out in the UK at Berkeley and Bradwell power stations (Davies and Moore, 1964). After this, a succession of large field studies were carried out in the United States.

The EBR-II (Experimental Breeder Reactor) study was carried out to simulate an accidental release using a Uranine dye that was detected on five concentric arcs between 30 and 600m from the release point, during near neutral conditions (Dickson et al., 1969). The reactor complex was made up of a number of buildings varying in height from 4 to 29m. The results showed enhanced dispersion due to the wake of the building complex. The wake dispersion converged to the free atmospheric rate about 500m downwind of the source. The corresponding wind tunnel study was carried out at a 1:90 scale in neutrally stable flow, and simulated near field effects up to 70m downwind. The axial concentrations of the field and wind tunnel trials collapsed very well over the limited range of model scale studied.

Subsequent studies began to take more interest in the elevated plume behaviour to determine threshold wind speed values for a roof level source becoming significantly entrained in the building wake. The Peach Bottom study released smoke though a roof vent to visualise the plume, which remained elevated for wind speeds below 2.1m/s (Dames and Moore, 1974). The Millstone study was conducted to quantify the entrainment of a roof level released plume into the building wake, (Johnson et al., 1975). The results led to some useful relationships between the ratio $U_e/U_h$ and the percentage of tracer remaining elevated, where $U_e$ is the vertical exit velocity of the release.

The Racho Seco study was the first to release two tracer gases simultaneously so that dispersion from two separate sources could be evaluated during one experiment (Start et al., 1978). An oil fog was also released during the runs for photographic documentation of the plumes. The dispersion experiments were carried out during conditions of light wind and the Pasquill stability category was determined by the temperature lapse rate. Four sampling arcs where used to sample ground level concentrations and five 30m towers were instrumented in an attempt to measure vertical concentrations. A very limited number of samples were collected from the towers but the results were never analysed. From the ground level concentrations, values for $\sigma_y$ and $\sigma_z$ were estimated which were significantly enhanced due to the building complex, which was in agreement with the observed smoke behaviour.

The 1:500 model scale study was carried out in the Colorado State University meteorological wind tunnel, having the capability of simulating stratification effects (Allwine et al., 1980). Neutral, slightly unstable and moderately stable boundary layers were set up in the tunnel, characteristic of the atmospheric conditions during the field study.

There are two main problems associated with comparing non-dimensional concentrations between model and full scale for the same release and
sampling positions. Firstly, there may be mismatch in the wind direction and stratification, and secondly, large eddies that exist in the atmosphere causing plume meandering cannot be simulated in the wind tunnel. Interpolation methods between available data points can be used to aid comparisons in the former case, but to compensate for the meandering affects, specific experiments have been carried out on the dispersion of smoke plumes in the atmosphere (Hino, 1968). Hino found that the smoke cloud width increases at a rate proportional to the 1/2 power of the observation time. Using this relationship it was calculated that during the Rancho Seco field studies the wind meandering effects reduced the one hour averaged concentrations by a factor of 2.5. Taking this into account, the wind tunnel results at best still over predicted the field concentrations by a factor of 1.7. Eight wind directions at 45° increments were tested in the tunnel and it was found that the dispersion was significantly enhanced if the two cooling towers situated Northwest of the reactor were either directly upwind or downwind of the release point.

The EOCR field study was very similar to that undertaken at the Rancho Seco site (Start et al., 1980) with the corresponding wind tunnel simulation carried out once again at Colorado State University. The seven sampling arcs had radii ranging from 37 to 1600m, collecting samples released from ground, roof and stack level simultaneously. The stack height was 1.2 times the height of the main building. Measurement of the vertical concentrations profiles using instrumented masts again proved to be unsatisfactory and although some lidar data was taken it was never fully analysed. Visual smoke plume observations proved very useful showing that releases at ground level in the cavity region, were swept up to roof level before streaming off downwind. An elevated Gaussian plume was assumed to model the dispersion and values for \( \sigma_z \) and \( \sigma_z \) were calculated from the ground level concentrations. The vertical dispersion parameter was found by the iterative solution of the equation, derived from Equation (2.1):

\[
\sigma_z \exp \left( \frac{1}{2} \left( \frac{z_p}{\sigma_z} \right)^2 \right) = \frac{\sqrt{2Q}}{\sqrt{\pi U_{10}} \int_{-\infty}^{\infty} Cdy}
\]  

where \( \int_{-\infty}^{\infty} Cdy \) is the ground level cross wind integrated concentration obtained from the field measurements and \( U_{10} \) is the 10m wind speed measured during each field experiment. The derivation of this expression from the bi-Gaussian plume model, is given in Appendix 2. Problems were encountered because there are two solutions to the equation, either the plume is elevated and \( \sigma_z/z_p \) is small or the plume is low and \( \sigma_z/z_p \) is large. It was not always possible to tell which root should be taken without more detailed information on the plume structure.

The wind tunnel experiments (Hatcher et al 1978) enabled a complete range of flow directions to be studied whereas the field studies corresponding to flow directions prevailing at the time. The wind tunnel study used an oil film technique to help determine the nature of the flow field at the surface around the buildings. Tests were carried out for the eight wind directions shown in Figure 2.4, with and without the auxiliary buildings present. The presence of the auxiliary buildings had little or no effect on the separation and reattachment of the flow on the main reactor, but for cases where the tank and silo were to the side of the reactor the width of the wake was
increased by up to 40%. Smoke releases showed that the near wake flows were not significantly affected by stratification except during strongly stable conditions where smoke from a ground level release would lie almost stagnant on the floor.

Generally it was found that in the wake of the complex structure, dispersion from ground level releases is enhanced both horizontally and vertically, but for stack releases the dispersion was only significantly enhanced in the vertical plane. By about eight building heights downwind the dispersion was independent of both release position and building orientation, and after 15 building heights the rate of dispersion was unaffected by the complex. Non dimensional concentration levels increased slightly with stratification. A comprehensive comparison has not been made between full and model scale studies, but in the near field the agreement was within an order of magnitude.

The Duane Arnold Energy Centre study was carried out to improve the understanding of the behaviour of plumes released at roof level (Thuillier and Mancuso 1980). Bag samplers were placed in arcs having radii of 300 and 1000m and the plume was scanned with the lidar to evaluate the three dimensional concentration distribution. The lidar data was rather patchy and was not always in good agreement with the bag sampler profiles. The Pasquill stability category was calculated using five different methods in this study which sometimes produced very different results. The method using temperature lapse rate alone was the least recommended. The results showed that dispersion parameters were very sensitive to both source position and wind direction.

In the last three field studies that have been discussed most of the dispersion experiments were carried out in light wind conditions, with significant fluctuations in the wind direction. This resulted in a few runs falling into each of the stability categories, which, with the large natural variability of the concentrations, could only really give qualitative information. The CEGB decided that it would be more beneficial to investigate dispersion from roof and ground level sources under simpler, near neutral, meteorological conditions. The Oldbury power station site, near Bristol in the UK was chosen because of the flatness of the surrounding terrain, and because the building effects were likely to be dominated by the single, large reactor building (Foster and Robins 1986).

Simultaneous releases of both smoke and SF6 were made so that the elevated plume could be scanned with the lidar, and the ground level concentrations measured using bag samplers. Calibration of the lidar was achieved by comparing the low level scans with the bag sampler concentrations and this comparison also provided a check on the general quality of the data. These calibration profile shapes showed good agreement and the quality of the lidar data was much better than the Duane Arnold study, partly because the standard deviation in wind direction during the Oldbury experiments was much lower. A diagram of the source positions and wind directions for the Oldbury power station is shown in Figure 2.5. The agreement between full and model scale vertical concentration contours was within 25% for source positions 2 & 3 but not quite so close for the ground level source. At full scale the peak in the vertical concentration profile rose slightly as it travelled downwind in the near wake although the plume certainly did not leave the ground. This effect was not observed in the wind tunnel and may have been caused by heat loss from the surface of the reactor. This would tie in with the fact that this plume centre line rise was not observed under the higher wind speed field studies.
For the wind tunnel study the variation of the peak ground level concentration with distance, wind direction and source position are shown in Figure 2.6. It can be clearly seen that the sensitivity of ground level concentrations to the source position decreases with increasing distance downwind. In the far wake the concentrations are affected predominantly by the width of the building wake, thus, the peak values are obtained at 90° which corresponds to the wind direction seeing the minimum reactor frontal area. At $x/H_b = 2$ the ground level concentrations vary by a factor of 20 depending on the source position and wind angle, and it is unrealistic to expect relatively simple dispersion models to predict this behaviour. However after 10 building heights downwind the effects of source position have become much less significant, enabling the model predictions to be more accurate.

The next field study carried out by the CEGB was at the Hinkley Point Power station situated on the south bank of the Bristol Channel, in the UK (Macdonald et al, 1988). This site was more complex than Oldbury since there are three dominant 50m reactor buildings, (two for station 'A' and one wider one for station 'B'), which enabled the effects of building wake interaction to be investigated for some wind directions. However the main difference from the previous study was that many of the releases were buoyant and were emitted from a stack terminating at roof level on the north, generally upwind, building face. Thirteen field trials were carried out in wind speeds ranging from 2.4 to 12.7m/s. Five of the light wind trials were conducted in slightly non-neutral stability, but the complementary wind tunnel study only simulated a neutral boundary layer. Much of the analysis has centred around the effect of wind speed on the non-dimensional ground level concentrations for the buoyant plume compared with passive releases (which are essentially independent of wind speed). The wind tunnel experiments showed clearly that for buoyant plumes there was an increase in ground level concentrations with wind speed until the effect of buoyancy became so insignificant that the plume acted as a passive release. An example of this behaviour is shown in Figure 2.7. The field data showed a similar trend but with more scatter and generally lower concentration levels, which was expected due to wind meandering affects observed during the experiments.

16 wind directions spaced by 22.5° increments were investigated in the wind tunnel study for a passive release from the 'A' station reactor without station 'B' present. The highest ground level concentrations were measured when the wind direction was at 45° to the face of the square reactor building which demonstrates the strength of the roof vortices at this flow angle. A few experiments were carried out with station 'B' 6 building heights downwind of 'A', and it was found that the ground level concentrations were reduced by 20%. This reduction in concentration was caused by the plume being spread as it passed around station 'B'.

Dispersion around a typical Advanced Gas-Cooled Reactor (AGR) site, where the reactor and turbine hall complex dominate the dispersion, was studied by Fackrell and Robins (1981). Two 1:300 scale models were tested, one simple, and the other a more detailed version so that the local effects due to the auxiliary buildings could be assessed. This study measured fluctuations in the concentrations as well as the averaged values and it was found that in the near wake the r.m.s. values are comparable to the mean, indicating the very unsteady nature of the near wake flow.

The time averaged concentrations in the cavity were not found to be very uniform close to the building when the source was within the recirculation
region, but for entrained plumes the concentrations were more evenly distributed. Peak local concentrations were observed when the plume was advected directly from the source to the receptor, or when the source and receptor were both in the upstream recirculation region, or when the receptor was within the cavity region and the plume was entrained or emitted into it.

To investigate the residence time for pollutants trapped in the recirculation region, short releases were made from a ground level source within the cavity whilst measuring instantaneous concentrations with a fast response flame ionisation detector. This experiment was automated so that the concentrations could be ensemble averaged over many identical realisations of the experiment. The time constant for the exponential decay of the concentration levels was found to be between 8 and 10 times the characteristic time scale for the flow given by $\frac{H_b}{U_h}$, where $U_h$ is the velocity at the building height.

All these field and wind tunnel studies around groups of buildings have considered releases just above roof level or below. In this situation the plume becomes involved in the highly turbulent region in the lee of the building which rapidly spreads the plume to similar dimensions to that of the building. This behaviour is not true of more elevated releases which only become entrained into the wake further downstream. Dispersion from elevated releases over the Sellafield site owned by British Nuclear Fuels Ltd, has been studied at full and model scale, in an attempt to assess the long term effect. A wind tunnel study was carried out in the BMT tunnel which considered ground level concentrations for releases from four different stacks under three different wind directions selected to take the plume directly over locations of concern. The ground level concentrations over the site were compared to the R91 model to obtain the effective height of these stacks. This method is not the most reliable way of determining the effective stack height since it assumes that the dispersion characteristics in the undisturbed wind tunnel boundary layer are identical to the R91 model. In the report, no mention was made that this assumption had been verified by dispersion measurements in the absence of the site. Their study found that the effective height of B204 was 50-70% of its physical height, depending on the direction of the approaching neutral boundary layer.

2.3.2 Field and model studies in built up areas.

Bachlin and Plate (1988) carried out some research on dispersion within a typical industrial site in West Germany. Wind tunnel studies showed that the dispersion is affected by the complex flow conditions near the buildings, the angle between the main street and wind direction and the roughness of the industrial area. For the wind parallel to the main street direction, the peak ground level concentrations are increased by a factor of 2.5, when compared to uniform roughness. When the wind is at 45° to the dominant street direction the maximum concentrations were similar to those for uniform roughness, but the plume axis was shifted. The change in plume axis was more pronounced when the source and sampling points were closer to the ground. The subsequent field studies showed very good agreement between non dimensional concentrations, confirming the validity of model scale studies (Bachlin et al 1991). No investigation was made using a non-neutral boundary layer since the diffusion was assumed to be dominated by the mechanical turbulence generated by the complex.
Concentration levels on the faces of building blocks separated by street canyons and avenues running perpendicular to one another, has been studied at model scale by Dabberdt and Hoydysh (1991). A line source was used up the centre of the street under investigation. It was found that for rectangular blocks the maximum concentration was found at the midpoint of the street side surface of the block, but for square blocks the maximum occurred at the ends.

Field experiments were carried out by Davidson et al. (1995) to investigate the dispersion of a neutrally buoyant plume released upwind of an array of 2m cubes. The release was below the height of the obstacles, and a second control plume was released alongside the array, so that the effect of the array on the dispersion could readily be determined. It was found that the form of the cross-sectional profiles, the decay along the centreline and the lateral growth of the plume were unaffected by the presence of the array. However, the mean vertical extent of the plume was increased by 40-50%.

All these previous studies used release heights at or below the obstacle height and one would expect their findings to be quite different if they used an elevated release above the centre of the building array.

2.4. Analytical Models of building affected dispersion.

This section reviews the existing flow and dispersion models currently used to estimate concentrations downstream of a release. They range from simple Gaussian models to those involving modelling of the Navier Stokes equations. The latter are often referred to as computational fluid dynamics models.

2.4.1 Gaussian models with modified dispersion parameters

2.4.1.1 A modified Gaussian model.

The Gaussian model is one of the well known simple dispersion models to predict the concentration in a plume as it is advected downwind. The model assumes that concentrations in both vertical and horizontal directions at a given downstream cross section have a Gaussian distribution about the plume centreline. The increase in the cross sectional size of the plume as it travels downwind is modelled by increasing the standard deviation parameters, \( \sigma_y \) and \( \sigma_z \), whilst decreasing the magnitude of the concentrations to satisfy continuity. Often the ground level centreline concentrations are of most interest when deciding on the pollution hazard associated with a particular release. The Gaussian equation for the centreline ground level concentrations is obtained by setting \( z=0 \) and \( y=0 \) in Equation (2.1), which simplifies to:

\[
C = \frac{Q}{\pi U_{adv} \sigma_y \sigma_z} \exp \left( \frac{z_p^2}{2\sigma_z^2} \right) \tag{2.6}
\]

where \( \sigma_y \) and \( \sigma_z \) are functions of the downstream distance and \( z_p \) is the plume centreline height. To enable the Gaussian plume model to represent
dispersion in the wake of a building the dispersion parameters $\sigma_y$, $\sigma_z$ and $z_p'$ are modified, and it is the way in which this is achieved that differentiates the models. So for the building affected dispersion case the centreline ground level concentration becomes:

$$C = \frac{Q}{\pi U_{adv} \sigma_y' \sigma_z'} \exp \left( -\frac{z_p'^2}{2 \sigma_z'^2} \right)$$

(2.7)

where the modified parameters have been primed.

2.4.1.2 Virtual source model, (e.g.: Barker, 1982)

The Barker model is representative of virtual source models that simulate the enhanced spread of the plume using virtual origins that are upwind of the actual source position for releases below roof level. The upwind location of the virtual source, $x_{oz}$, is matched so that:

$$\sigma_y(x_{oz}) = W_b / 3$$

(2.8)

and $x_{oz}$ is found by satisfying the equation:

$$\sigma_z(x_{oz}) = H_b / 3$$

(2.9)

It is clear that the virtual position for the horizontal and vertical spreads will usually be different. Once these positions have been found the modified dispersion parameters are calculated using the following equations:

$$\sigma_y'(x) = \sigma_y(x + x_{oz})$$

(2.10)

$$\sigma_z'(x) = \sigma_z(x + x_{oz})$$

(2.11)

Because of the intense mixing that goes on in the near wake of the building this model assumes a fixed virtual source height for any emission at or below roof level given by:

$$z_p' = H_b / 3$$

(2.12)

It is important to remember that this approach does not model the complex flow pattern in the near wake, but assumes that the pollutant is being advected downwind by a uniform air stream. Thus, prediction of concentrations immediately behind the building are bound to be suspect.

2.4.1.3 Simple multi-region models, (e.g.: Huber Snyder, 1982)

The Huber-Snyder model splits the wake up into three regions, the near wake, the main wake and the far wake. No prediction is made for the near wake region, $x < H_b$ but for the main wake, $x$ between 3 and 10 $H_b$ it assumes that the building effects are dominant. Thus the equation for the dispersion parameters in this region are independent of the incident flow, and are approximated as:
\begin{align}
\sigma_y' &= \left\{ 2 + 35 \left( \frac{x}{H_b} \right)^{-1.8} \right\}^{0.5} \sigma_y \\
\sigma_z' &= \left\{ 2 + 35 \left( \frac{x}{H_b} \right)^{-1.8} \right\}^{0.5} \sigma_z
\end{align}

(Beyond the main wake $x > 10 \, H_b$ the model reverts to using a virtual source model:

\begin{align}
\sigma_y'(x) &= \sigma_y (x+x_{vo}) \\
\sigma_z'(x) &= \sigma_z (x+x_{vo})
\end{align}

calculating the virtual origins from the following equations:

\begin{align}
\sigma_y(10H_b + x_{vo}) &= 1.6 \sigma_y(10H_b) \\
\sigma_z(10H_b + x_{vo}) &= 1.6 \sigma_z(10H_b)
\end{align}

The model recommends that the actual source height be used for $z_{vo}'$, and for source heights above roof level it suggest that only the vertical dispersion parameter $\sigma_z$ should be enhanced.

\subsection*{2.4.2 Integral model near wake, (e.g. Robins et al, 1996) UK-ADMS}

The integral model divides the flow into a number of zones including, the near wake, located between the lee building face and the downstream extent of the recirculation region, and the main wake beyond this. The near wake is modelled as a region of uniform concentration in a time averaged sense since it is well mixed by the high turbulence intensities and the recirculation motion. A schematic diagram is shown in Figure 2.8. for the situation where the source is located within the cavity region. The pollution that escapes from the cavity due to advection by the mean flow and turbulent transport across the boundary can be expressed as a flux ($u_c \alpha c$) acting over the surface area ($A_R$) of the recirculation region. Thus:

\begin{align}
Q_{out} = u_c \alpha c A_R
\end{align}

The flow around the obstacle is assumed to dominate external conditions, so the flux can be written as:

\begin{align}
 u_c \alpha c = \alpha U C_R
\end{align}

where $\alpha$ is a dimensionless factor which depends on the geometry and approach flow characteristics and can be related to the mean residence time for material in the cavity. Thus the equation for $Q_{out}$ becomes:

\begin{align}
Q_{out} = \alpha U C_R A_R
\end{align}

In steady state conditions:

\begin{align}
Q = Q_{out}
\end{align}
If the source of pollution is suddenly removed, concentration levels in the region will decay according to:

\[
\frac{d(C_R V_R)}{dt} = -\alpha A_R UC_R
\]  \(2.23\)

Which has the solution:

\[
C_R(t) = C_R(0)e^{-t/T_R}
\]  \(2.24\)

where:

\[
T_R = \frac{V_R}{\alpha A_R U}
\]  \(2.25\)

This is an exponential decay having a time constant \(T_R\) that is dependent on the shape and size of the cavity and is inversely proportional to the wind speed. In the steady state the mean concentration in the region is given by:

\[
C_R = \frac{QT_R}{V_R}
\]  \(2.26\)

which can be expressed in non-dimensional form as

\[
\chi = \beta \frac{\tau_R}{\lambda_R}
\]  \(2.27\)

where

\[
\chi = \frac{C_R U H_b W_b}{Q}
\]  \(2.28\)

is the non-dimensional concentration,

\[
\beta = \frac{H_b W_b L_R}{V_R}
\]  \(2.29\)

is a shape factor for the recirculating flow region,

\[
\lambda_R = \frac{L_R}{H_b}
\]  \(2.30\)

is the dimensionless recirculation length and

\[
\tau_R = \frac{U \tau_R}{H_b}
\]  \(2.31\)

is the non-dimensional time constant. Thus, \(\chi\) is directly related to the non-dimensional time constant and recirculation length. This theory applies to situations were the width of the building is less than five times its height. For wider buildings the plume will not fill the whole cavity and so
the concentration within the recirculation region becomes a function of lateral position.

If the source is outside the cavity region additional features are needed to represent the entrainment of the plume into the cavity region, see Figure 2.9. Following Puttock and Hunt (1979), the mean concentration within the region is assumed to be equal to the average concentration at the boundary of the recirculation zone. The concentration field downstream of the recirculation region is modelled as a ground based plume emitted from the cavity zone and an elevated plume at reduced mean height containing the remainder of the stack emission that was not entrained into the near wake.

2.4.3 A 3D small perturbations wake model

The main wake model presented here is a simplified 3D version of the small deficit wake model proposed by Counihan et al (1974). The model is based on a momentum dominated wake, so all the coherent vorticity generated by the building is assumed to be broken down very quickly. This will be much more true of buildings normal to the flow than for the diagonal cases. A full derivation of this simplified wake model is given in Appendix 3.

The main wake is modelled using a constant eddy viscosity defined by the upstream flow conditions. Away from the immediate vicinity of the ground and sufficiently far downstream of the recirculation region the only available length scale is the downstream distance \( x \), and it is postulated that the wake structure will be of a self preserving form. This means that all the flow variables, when suitably non-dimensionalised, are functions only of the similarity variables. The three similarity variables, which are effectively non dimensional forms of the wake co-ordinates, are as follows:

\[
\xi = \frac{x}{H_b} \quad \eta = \frac{y}{L_d} \quad \zeta = \frac{z}{L_c}
\]

where \( L_d \) and \( L_c \) are lateral and vertical length scales in the wake that are function of downstream distance. The second order differential equation that we seek a solution for is:

\[
U \frac{\partial u}{\partial \xi} - k_{\eta} \frac{\partial^2 u}{\partial \eta^2} - k_{\zeta} \frac{\partial^2 u}{\partial \zeta^2} = 0
\]

where \( U \) is the approach flow velocity and \( u \) is the perturbed velocity in the wake that decays to zero far downstream. \( k_{\eta} \) and \( k_{\zeta} \) are the eddy viscosities that are assumed constant throughout the wake. \( k_{\zeta} = \kappa u_d H_b \) and \( k_{\eta} \) is normally taken between 1 and 2 times \( k_{\zeta} \).

The postulated similarity solution for the velocity deficit in the wake has the form:

\[
u = u_0(\xi) H(\eta \zeta)
\]

where \( u_0 \) is the magnitude of the disturbance that decays with downstream distance, and \( H \) is a function of both \( \eta \) and \( \zeta \). It is possible to predict the decay of \( u_0 \) with downstream distance for a boundary layer approach flow, but we only have a simple analytical solution for \( H \) when the approach flow is uniform. Assuming a uniform approach flow is the major simplification
in this 3D wake model. From the analysis shown in the appendix, it was found that:

\[
\begin{align*}
\frac{\text{Decay rate}}{\text{Lateral}} & \quad \frac{\text{Vertical}}{\text{Vertical}} \\
\frac{\text{Lateral}}{\text{Vertical}} & \quad \frac{\text{Vertical}}{\text{Vertical}} \\
\frac{\text{Lateral}}{\text{Vertical}} & \quad \frac{\text{Vertical}}{\text{Vertical}} \\
\frac{\text{Lateral}}{\text{Vertical}} & \quad \frac{\text{Vertical}}{\text{Vertical}} \\
\end{align*}
\]  
(2.35)

where \( \hat{u} \) is a constant which is related to the couple that the flow exerts on the building. The length scales in the wake are given by:

\[
\begin{align*}
L_y &= \sqrt{\frac{2k_2 \xi}{H_b U_h}} \\
L_z &= \sqrt{\frac{2k_2 \xi}{H_b U_h}} \\
\end{align*}
\]  
(2.36)

The eddy viscosity model enables us to obtain the perturbation shear stress in the wake by differentiating \( u \) w.r.t. height. The equation then becomes:

\[
\tau_{xz} = \hat{u} k_z \frac{\xi^{\frac{3}{2}}}{e^{-\nu^2}} \\
\tau_{xz} = \hat{u} k_z \frac{\xi^{\frac{3}{2}}}{e^{-\nu^2}} \\
\tau_{xz} = \hat{u} k_z \frac{\xi^{\frac{3}{2}}}{e^{-\nu^2}} (1 - \nu^2) \\
\]  
(2.37)

The perturbations in \( u^2 \) and \( w^2 \) are assumed to behave in a similar manner to the shear stress so:

\[
\Delta u^2 = \lambda_1 \tau_{xz} \quad \text{and} \quad \Delta w^2 = \lambda_2 \tau_{xz} 
\]  
(2.38)

Typical values of \( \lambda_1 \) and \( \lambda_2 \) are 5 and 1.5 respectively in an atmospheric boundary layer as quoted from Counihan et al (1974).

### 2.4.4 Computational fluid dynamics models

The complexity of fluid flow is such that forecasting the path of each individual eddy in a flow, (Direct numerical simulation), is only possible for very simple geometries. The most common way to simplify the problem is to express the flow statistically rather than in a time dependent way. Thus, the time averaged velocity and turbulence intensity is calculated at each point, just the same as would be obtained by placing a hot wire probe in the flow and averaging for a sufficiently long time. This method attempts to solve the time averaged Reynolds equation, but this leads to the well known turbulence closure problem, because there are more unknowns than equations. To close the system of equations, some of the missing variables need to be parameterized in terms of known quantities. For first order closure the Reynolds stresses are modelled as the product of mean velocity gradient and an appropriate eddy viscosity. A number of alternatives have been postulated for obtaining a reasonable estimate of the local eddy viscosity, one of which is known as the k-\( \varepsilon \) model. This method is sometimes denoted a “one and a half” order closure, since it uses two additional second order equations to calculate the turbulent kinetic energy and the dissipation rate. Modelling the boundary conditions at the edges of the flow and using a suitable grid, computation can be iterated through to obtain a stable solution.

The Large Eddy Simulation (LES) method is based on two fundamental observations, namely that the large scale structures of turbulent flow vary greatly from flow to flow, and in contrast, the smaller scale structures are more universal in character and therefore amenable to general modelling.
If the flow variables in a mesh are allowed to vary with time, the flow field can be computed for a series of time steps so that large structures, bigger than two grid spacings, can be resolved. Any features smaller than two times the grid size must be parameterized using a suitable method such as the Smagorinsky model. LES is somewhere between time averaged k-ε type models and direct numerical simulation. After the boundary conditions have been initialized, the turbulent motions are 'kick' started by imposing a pseudo random temperature or velocity perturbation for just a few time steps. The code is then run until the flow settles down to a regular pattern e.g. if flow past a chimney were being simulated, there would be a series of vortices being shed from alternate sides of the chimney.

Benodekar et al (1984) developed a model for predicting the near-field dispersal of releases from a building in a non-neutral boundary layer. The turbulence was mathematically represented by a k-ε type model whose equations were made to be functions of the flux Richardson number. This enabled the model to account for the buoyancy effects that either enhance or dampen the turbulent energy in the flow. However, the turbulent eddy viscosity was taken to be isotropic, meaning that the eddy viscosity at a given point was independent of direction. This simplification does not completely represent the effect of stratification, because primarily the buoyancy forces act only upon the vertical fluctuations. Since turbulence is three dimensional, fluctuations in the horizontal planes will feel the effect of changes in the vertical component. For the scalar concentrations a distinction was made between the lateral and vertical diffusivities so as to more faithfully represent the real behaviour of plumes in a stable boundary layer.

For some time yet it is completely impractical to use computational fluid dynamics to investigate flow and dispersion around a complex site like that of Sellafield. To investigate these effects, it is necessary to use physical modelling, so that the behaviour of the plume can be determined, and the resulting ground level concentrations predicted.

2.5 The context of this present project.

In Section 2.3.1, we considered a whole series of field and wind tunnel dispersion studies which were carried out around nuclear power plant, in both America and the UK. All of these considered releases just above roof level or below, generally using passive tracers. In this situation the plume becomes involved in the highly turbulent region in the lee of the building, which rapidly spreads the plume to similar dimensions to that of the building. This behaviour is not true of more elevated releases, which only become entrained into the wake further downstream. Previous research carried out for British Nuclear Fuels Ltd, has considered elevated releases over its Sellafield site in Cumbria at model scale in the BMT wind tunnel, where the site caused a significant decrease in the effective heights of their stacks.

In dispersion modelling it is important to appreciate what the effect of the most local building is, compared to that of the whole surrounding site. If, for example, a local building dominates the dispersion behaviour, then neglecting the effect of the surrounding complex site is a valid approximation. One of our project objectives was to gain further understanding into how surrounding buildings, such as those on the Sellafield site, affect the dispersion from an elevated release over a single
building. B204 was chosen as the single building since it is a cuboid, close to the centre of the site, and a release of interest to BNFL. Firstly, ground level concentrations were measured for a range of elevated release heights over a 1:500 scale model of B204 with no surrounding buildings or topography. The effect of being surrounded by eight identical buildings was then considered for various spacings, before moving on to the full Sellafield site. Ground level concentration measurements made over the site were compared to those previously obtained in the BMT tunnel. Our study then went on to consider the effects of stable stratification on elevated releases over generic building groups, and the Sellafield site. The results were analysed in terms of effective stack heights in both the neutral and stable boundary layers, by comparing the maximum ground level concentration with those obtained for releases in the respective undisturbed boundary layers.
Figure 2.1. Mean flow pattern around a cube normal to the incident low.

From Foster and Robins (1986)
Figure 2.2. Mean flow pattern around a cube at 45° to the incident flow.

From Foster and Robins (1986)
Figure 2.3. Maximum ground level concentrations at three different distances downwind of source for different buoyancy levels and source configurations from Hall and Waters (1986).
Figure 2.4. Schematic of EOCR reactor site plan showing approach flows investigated in the wind tunnel study. (Hatcher et al 1978)
Figure 2.5. Oldbury Power station site plan and elevation showing source positions and defining wind direction

From Foster and Robins (1986)
Figure 2.6. Variation of peak non dimensional ground level concentration with downstream distance, wind direction and source position for the Oldbury Power station. The numbers shown in the plots denote the source positions, see Figure 2.5

From Foster and Robins (1986)
Figure 2.7. Variation of non-dimensional ground level concentration with wind speed 600m downstream for wind directions 0, 22.5, and 270° for the Hinkley Point Power station study. The non-buoyant release results are indicated by the arrow.

Wind tunnel data from Macdonald et al. (1988)
Emitted material reaches leading edge if roof flow remains separated

Figure 2.8. Simplified representation of dispersion processes in the recirculation region behind a building where the source is located within the cavity.

Plume height controlled by emission conditions and mean flow downwash in wake

Figure 2.9. Simplified representation of dispersion in the wake of a building for an elevated release
Chapter 3. Apparatus and techniques

3.1 Introduction

This study investigates the effect of groups of buildings on elevated releases, moving on to consider the effect of the entire industrial site at Sellafield. This task is far beyond the limits of computational Fluid Dynamics for some time yet, because of the complexity of the site. Simpler Gaussian plume based models could be used, but it is the purpose of this study to improve their performance, which can never be done by running these models themselves. Clearly, what is needed is accurate experimental data that will shed light on the sensitivity of ground level concentrations to the configuration and size of the building group above which the release is made. This could be achieved by conducting a field study, but the cost would be enormous, and added to that would be the difficulty in obtaining consistent approach flow conditions to compare the dispersion effect of different building groups. The most practical way of answering these pertinent questions, is to use a wind tunnel to investigate the various building groups at model scale.

This chapter describes the EnFlo wind tunnel at the University of Surrey, along with the instrumentation and control systems used to obtain the data presented in this study. Since at the commencement of the project this whole facility had just been moved from its previous home in Leatherhead (owned by the CEGB), there was a considerable amount of development and commissioning work required before serious measurements could be made.

3.2 EnFlo Stratified flow Wind Tunnel

All the measurements of flow and dispersion were carried out in the EnFlo wind tunnel at the University of Surrey, see Figure 3.1. This is an open circuit tunnel with a working section area of 3.5 x 1.5m tall and a length of 20m. This tunnel has the capability of setting up stable and convective flows by controlling the inlet temperature profile and the surface temperatures inside the tunnel. The inlet heaters are partitioned into 15 different levels, each of which has a closed loop controller to maintain the demanded flow temperature at that level. 18 of the 40 floor panels can be cooled by circulating chilled water through them. 20 of the remaining floor panels can be electrically heated with closed loop temperature control. The tunnel is constructed in such a way that all the panels are interchangeable, so that heating or cooling of the flow can be achieved at a given location. After the air has travelled down the tunnel, it passes through a heat exchanger, to cool the flow to ambient temperature, before exhausting it into the laboratory.

Obviously a neutral flow can be achieved by running the tunnel without any heating or cooling. To simulate a typical neutral atmospheric boundary layer, the method developed by Counihan (1969) was used. This system consists of a castellated barrier wall, which created a momentum deficit, and seven quarter-elliptic vorticity generators placed near the beginning of the working section, see Figure 3.2. The roughness elements used in the neutral boundary layer were made out of aluminium sheet that had the edges turned as shown in the Figure. The staggered rows of roughness elements were spaced by 0.18m in the flow direction. Beyond an initial
development fetch, this produced a 1m deep boundary layer, which at the model scale of 1:500 used in this project, corresponds to 500m. This is quite typical of what one would observe in the atmosphere for neutral stability. Detailed measurements of the boundary layer characteristics are given in Section 4.2.

To simulate the stable boundary layer which has been characterised in Section 4.2, a uniform temperature flow of 60°C was passed over a cooled floor which began 9m downstream of the inlet heaters. The free stream speed was set to 1.35m/s for all the stable runs. To achieve a uniform temperature profile at the start of the cooling panels, the temperature of the lowest three inlet heaters had to be increased to compensate for heat loss to the floor upstream of the cooling panels. 6m downstream of the start of the cooling panels, a stable boundary layer, having a depth of around 200mm, was developed. To ensure that the flow remained aerodynamically rough in the stable boundary layer, the height of the roughness elements was increased from 10mm, used in the neutral boundary layer, to 20 mm. The new pattern of the roughness was elements of 80mm wide spaced on 240mm centres with the staggered rows 240mm apart in the streamwise direction. Dispersion experiments were carried out in the stable boundary layer to investigate the presence of unwanted cross flows. It proved necessary to install side walls into the tunnel, 0.5m from the real sides, reducing the effective width of the tunnel to 2.5m. These 0.6m tall side walls isolated the boundary layer from the secondary flows created by the unheated sides of the tunnel.

3.3 Developments made to the EnFlo facilities.

The following sections in this chapter give detailed information about the instrumentation used during this study. This section indicates the developments that were made to the facilities over the period that this project ran, which coincided with the first three years of EnFlo’s existence.

When this project commenced, the traverse system in the wind tunnel had a vertical movement of 580mm and a spanwise travel of 600mm. It was mounted on a simple frame which could be positioned manually at the desired downstream location. To map out the two dimensionality of the boundary layers set up in the tunnel, an increased spanwise travel is beneficial, and having travel in the downstream axis is a great asset when studying building wake behaviours. For non-neutral boundary layers, where the tunnel is running heated, having remote control of instrument locations is clearly a great advantage. It was with these thoughts in mind that it was decided to increase the spanwise travel to 1800mm and attach this axis to a carriage which ran on an overhead rail system to facilitate the longitudinal travel. An isometric view of the upgraded traverse system is shown in Figure 3.3.

For the EnFlo laboratory to function effectively, software with the corresponding hardware was required to perform the following tasks:

1. Calibration and measurement of standard analogue instruments such as: hot wires, propeller anemometers, pressure transducers and thermocouples,
2. Measurements with cross-wires which involves two analogue channels that need to be processed together, and requires angle and velocity calibration routines,

3. Calibration and measurement of pulsed-wire probes, which require digital communications for the time of flight,

4. Measurements using the Laser Doppler Anemometry system alone, and also when synchronised with a cold wire to measure heat flux,

5. Moving the traverse to the desired position and checking if it has achieved this,

6. Controlling the gas sampling desk and monitoring the output of the Flame Ionisation Detector (FID), to make mean concentration measurements,

7. Setting the temperature of the inlet heater in non neutral flows, and

8. Monitoring and recording the inlet flow and surface temperatures inside the tunnel.

Many of these tasks needed to be controlled from one computer for a given experiment, so it was decided that all these routines should be written in the same language, namely LabVIEW, which has been developed by National instruments for this type of application. At EnFlo's commencement (which coincided with the start of this project), individual LabVIEW programs existed for making measurements with a single wire, a cross-wire and a pulsed wire, but these were specifically written for a given instrumentation set-up and processing requirement and were not at all general. Also the information recorded in the results file for a given measurement position tended to be the bare minimum.

A general purpose measurement program has been written, which was capable of acquiring and processing up to eight analogue channels of data from instruments such as: hot wires, cross-wires, pitot tubes, propeller anemometers, thermocouples etc. The user can configure the program to take measurements with the desired instruments and compute the statistics for each individual channel and for correlated pairs. Spectra and autocorrelation measurement can also be selected for any of the channels with the capability of automatically saving any of the plots. An analogue calibration program has also been written to calibration this same range of instruments, the user being able to select the desired reference instrument or value.

Software was written in LabVIEW to replace Dantec's program for controlling the one component Laser Doppler Anemometry system. The new software enabled the data to be processed on line, and was able to operate in conjunction with the traverse to automate data collection. Another version of this program was developed to synchronise a cold wire with the laser system so that when a velocity measurement was made, an instantaneous temperature reading was also recorded. This facilitated the measurement of heat flux in the stable boundary layer. More details of how this measuring system operated can be found in section 3.4.2.

Most of these developments took place near the beginning of the project, but modifications to the software did prove to be an on-going task as new requirements became apparent.
3.4 Flow measurement instrumentation

A cross-wire was used to characterise the flow in the undisturbed boundary layer and downstream of the buildings for neutral stability, thus enabling immediate determination of the Reynolds shear stresses. However, in the stable boundary layer the one component Laser Doppler Anemometer was used since its calibration is not affected by the ambient temperature of the flow. The Reynolds shear stresses were obtained using four probe angles at each measurement position.

3.4.1 Cross-wire

3.4.1.1 Summary of how the flow measurements were taken.

Flow measurements in this study were made using two Schiltknecht propeller anemometers, a Dantec cross-wire and a thermocouple. One of the propeller anemometers was used to measure the reference tunnel speed at the top of the simulated boundary layer. The cross-wire, a propeller and the thermocouple were all mounted on the 3 dimensional traverse. The positioning of the probes on the traverse boom is shown in Figure 3.4. The traverse was controlled by the computer used for the data acquisition. Software has been written in the graphical programming language, LabVIEW, enabling a series of profiles to be measured automatically.

The cross-wire angle calibration was carried out in a small ‘calibration’ tunnel and was assumed constant over the life of the probe. The velocity calibration was repeated before each measurement run and was performed in the main wind tunnel, half way up the boundary layer using the onboard propeller as the velocity reference. Since the tunnel speed can be controlled by the computer the velocity calibration routine was automated. The calibration procedures are discussed in more detail in Section 3.4.1.2.

Temperature corrections were applied to the cross-wire results using the temperature reading given by the thermocouple located on the traverse boom (see Section 3.4.1.3 for details). The cross-wire readings were also corrected for rectification and related errors that occur when making measurements in high turbulence flows (see Section 3.4.1.4 for details).

The time scale in the flow, calculated using the velocity at the top of the boundary layer and its depth \( (S/U_{ref}) \), is about 0.4s. The sampling interval used throughout all the flow measurements was 0.05s, so not all of the samples were statistically independent. Between 4000 and 4800 samples were taken in two blocks at each measurement position. Profiles were generally smooth, indicating that a sufficient averaging time had been used.

The alignment of the cross-wire probe is very important when attempting to measure the spanwise and vertical velocity components. The set up of the probe on the traverse was aided by the use of a laser pointer that could be attached to the probe holder. By throwing the laser beam a long way forward, any angular misalignment of the cross-wire probe could be clearly seen and corrected.

Drift in the cross-wire calibration over run periods of 20 hours or so was not generally significant and for most cases the agreement of the mean velocity was within ±1% of the propeller over the whole period. However,
on two runs the agreement was slightly worse, but was still within ±2%. The majority of the results were measured using the same cross-wire probe whose calibration proved to be very stable. Only two of the runs used a different probe whose calibration drifted by about 5% over the measurement period.

It is very difficult to use hot wire anemometry in a heated flow since the wire responds to both temperature and velocity fluctuations. It is possible to use a cold wire to measure the temperature fluctuations and then correct for them but this requires the hot wire velocity calibrations to be done at a range of different temperatures, a time consuming procedure. All the flow measurements made in the stable boundary layer used a one component Laser Doppler system, synchronised with a cold wire to obtain measurement of the heat flux, as well as the mean velocity and Reynolds stresses.

3.4.1.2 Cross-wire calibration

A hot wire consists of a very fine wire, heated to about 200°C, that is cooled by the flow it is measuring. The wire is electrically heated by a wheatstone bridge circuit that is set up to maintain a constant wire temperature. Before measurements can be made, the probe needs to be calibrated to determine the effective angle of the wires to the flow and also a velocity calibration is required. The effective wire angle takes into account the tangential cooling of the wire as well as its physical orientation to the flow. The angle calibration was carried out in a small, low turbulence tunnel, with the probe held in specially designed jig allowing a rotation of ±15° to the flow in 5° steps. The speed of the tunnel was set to around 1.5m/s during the angle calibration, roughly the average velocity that it would see in the EnFlo tunnel. This is important, since the effective wire angles are weak functions of the flow velocity. Unless the probe is damaged, the effective angles should not change during the life of the wire.

The velocity calibration was carried out every time measurements were made. All the velocity calibrations for the cross-wire were carried out half way up the boundary layer where the background turbulence is around 10%. This was the highest position the traverse could achieve without manually repositioning any of the instruments. The onboard propeller was used as the reference speed during the cross-wire calibration. This method proved very successful, and the agreement between the two anemometers was mostly within ±1%.

3.4.1.3 Cross-wire temperature correction

The hot wire velocity calibration is described by the generalised King’s Law equation:

\[ E^2 = A + BU^n \]  \hspace{1cm} (3.1)

where \( E \) is the output from the anemometer, \( U \) is the velocity and \( A, B \) and \( n \) are constants. These constants are optimised to give the best fit with the calibration data.
The temperature correction method of Bearman (1969) was implemented, where the correction factor $k_{\text{temp}}$ is given by:

$$k_{\text{temp}} = 1 - \left( \frac{T_{\text{calib}} - T_{\text{meas}}}{2T_{\text{calib}} \theta} \right)$$

(3.2)

$T_{\text{calib}}$ is the ambient flow temperature that the cross-wire was calibrated at, $T_{\text{meas}}$ is the temperature of the flow being measured and $\theta$ is the overheat ratio. The correction factor is applied to the anemometer voltage before calculating the velocity as:

$$U = \left( \frac{(k_{\text{temp}} E)^2 - A}{B} \right)^{\frac{1}{n}}$$

(3.3)

During a run the ambient temperature change in the laboratory was generally less than one degree. For a one degree difference in temperature the correction factor would change the measured velocity by about 2.5%.

### 3.4.1.4 Cross-wire rectification and third component correction

The output of the hot wire anemometer is proportional to the voltage across the wire, so, as the flow velocity increases, the voltage across the wire also increases to keep the wire temperature constant. The cooling effect on the wire is greatest when the flow is normal to the wire axis but is almost negligible when the flow is parallel. The output of the anemometer is effectively proportional to the component of the flow normal to the wire but it is insensitive to the direction of this component.

Figure (3.5a) shows a single wire probe in a flow which passes from left to right. If the instantaneous flow direction changes by more than 90° the component normal to the wire axis passes from right to left over the wire. However, since the wire cannot differentiate the flow direction, this measurement will still be recorded as if the flow were from left to right, causing a rectification error in the results.

The cross-wire probe shown in Figure (3.5b) has its wires set at approximately 45° to the mean flow, enabling both the velocity components in the plane of the paper to be measured. Considering the wire with the positive gradient, if the instantaneous flow direction changes by more than 45° anti-clockwise, then the component of the flow normal to this wire will change sign. However, this change of sign in the velocity component cannot be registered by the anemometer and so the signal becomes rectified. For the single wire, rectification errors occur if the instantaneous flow directions lie outside a range of ±90° to the mean flow, whereas for the cross-wire this range is reduced to ±45°. Therefore, rectification errors are far more likely to occur for the cross-wire probe than for the single wire probe.

Rectification errors cause the mean flow velocity to be overestimated, as all the negative values are reflected into the positive domain. However, the fluctuations are underestimated, since the range of instantaneous velocities are confined within a smaller sector.
When making measurements with a cross-wire the mean and fluctuating parts of the third velocity component are assumed to have negligible effect. Tutu and Chevray (1975) have presented a mathematical analysis for the response of the cross-wire probe which takes into account the effect of the third component of velocity and the effective rectification caused by the hot wire. The analysis considers how the joint probability distribution of the velocity components is skewed by these effects, and evaluates a correction factor assuming that the true velocity distributions are Gaussian. The analysis has been modified somewhat since the tangential cooling of the wire is already taken into account by the angle calibration which is performed before making any measurements.

The errors in the measurements depend on the magnitude of the turbulence intensities in all three directions, the correlation coefficient for the two components measured, and the effective angles of the cross-wire probe. The analysis assumes that the mean flow of the second component of velocity is zero, which is the case if the probe is aligned with the mean flow. Due to the complexity of calculating the joint probability density functions, it takes a considerable time to compute the relevant correction factors for a given set of inputs. To make it feasible to calculate a correction factor for each individual cross-wire measurement, a specific lookup table was generated for the cross-wire probe used to make the measurements. Given that the effective wire angles of the probe are known, the four remaining variables to be tabulated are $u'/U$, $v'/U$, $w'/U$ and $uw/u'w'$ assuming the wire is in the $X-Z$ plane.

Typically, five values spanning each of the four input ranges were calculated, amounting to $5^4$ or 625 input conditions, which took a Power Macintosh 7100 nearly 16 hours to compute. Once this lookup table (specific for the effective wire angles) had been generated, an Excel macro, written in Visual Basic, was run to determine the correction factors for each individual cross-wire measurement. This macro, which was used to correct a whole profile, had the following structure:

1. Read the cross-wire data for a certain measurement. The value of the third component $v'/U$ or $w'/U$ has to be estimated.

2. Apply a ‘first estimate’ of the correction factor to the data to estimate the ‘true’ turbulence statistics at that point.

3. Carry out a four dimensional interpolation using the lookup table created for that probe, to obtain the corresponding correction factors.

4. Compare these correction factors with the ‘first estimate’ factors applied at stage 2. If the correction factors differ by more than 0.5% then replace the ‘first estimate’ ones with the new correction values and go back to stage 2.

5. The percentage correction factors to be applied to the measured values of $U$, $u^2$, $w^2$ and $uw$ have now been found. These corrections will be used as the ‘first estimate’ for the next measurement position in the traverse profile.

This macro only takes about 1 second to find the optimum correction factors for a particular cross-wire measurement.
The magnitude of the correction factors increased with the turbulence intensity in the flow. For example, for cross-wire measurements made in the bottom of the boundary layer where the turbulence intensity is around 20%, the mean velocity is overestimated by 3%. The Reynolds stresses $u'^2$, $v'^2$ and $u'v'$ are all underestimated, by about 2.9, 7.5 and 9% respectively. All these errors would double if the turbulence intensity was increased to 30%, as was the case for some of the building wake measurements.

### 3.4.2 Laser Doppler Anemometry

Laser Doppler anemometry (LDA) was used to make all the flow measurements in the stable boundary layer because the cross-wire cannot easily be used in a flow having such severe temperature fluctuations. A schematic diagram of the probe for a one component system is shown in Figure 3.6. The two laser beams that enter the probe through the fibre optic cables are split from a single beam of red light. The beams pass through a lens that focuses them together at the measuring position. Where the beams converge, light and dark fringes are created due to constructive and destructive interference of the two beams. When a small particle in the flow passes through these fringes it reflects or scatters pulses of light back towards the probe. The frequency of these light pulses is directly proportional to the component of the particle's velocity perpendicular to the fringe lines. In the Dantec system used in this project, the back-scattered light is focused by the lens into the receiving fibre which transmits the light to the photo multiplier tube situated next to the laser. The photo multiplier tube is effectively a transducer which converts the back-scattered light into an electrical signal. By carrying out Fourier analysis on this signal its frequency can be determined and therefore a measurement can be made of the particle's velocity perpendicular to the fringes.

To determine the direction of the particle, the frequency of one of the beams is shifted by 40MHz so that the fringes scroll through the measurement volume. The instantaneous flow direction is now readily apparent, since, for particles travelling in the direction of the moving fringes the frequency will be lower than 40MHz, and conversely for a particle travelling in the opposite direction the frequency would be greater than 40MHz. When making measurements in the undisturbed stable boundary layer the flow upstream of the measurement position was seeded using a TSI six jet atomiser with sugar water which is specified to produce particles of 1-2 microns in size. This is necessary as the LDA can only measure the velocity of particles, which should be small enough so that they can faithfully follow all the fluctuations in the flow.

A cooling jacket, supplied with ambient temperature air, surrounded the LDA probe to keep it below its maximum working temperature of 45°C. This increased the overall size of the probe from a diameter of 14 mm to 26 mm. Measurements were made around the cooling jacket with a cross-wire at the position were the laser beams intersect, to investigate if the flow was affected by the jacket. The Reynolds stresses remained unchanged but the mean velocity increased by about 2.5%.

For the vertical profiles measured in the stable boundary layer, each position was measured with the probe angle $\gamma$, at 0°, 30°, 45° and 90°. The 0° and 90° orientations directly measure the mean and fluctuating component in the streamwise and vertical directions, shown in the diagram below as $U$.
and \( W \). A third probe orientation enables the shear stress \( \bar{uw} \) to be calculated. Below is a simple derivation of how the shear stress can be determined by the three measurement orientations, \( U, W \) and \( U_r \).

![Diagram of velocity components](image)

The mean velocity \( U_r \) is given by:

\[
U_r = U \cos \gamma + W \sin \gamma
\]

(3.4)

and for the instantaneous velocities:

\[
u' = u' \cos \gamma + w' \sin \gamma
\]

(3.5)

Squaring both sides of the equation gives:

\[
u'^2 = \bar{u}^2 \cos^2 \gamma + 2u'w' \cos \gamma \sin \gamma + w^2 \sin^2 \gamma
\]

(3.6)

which can be rearranged to obtain the shear stress from the three measured normal stresses:

\[
u'w' = \frac{\bar{u}^2 - \bar{u}^2 \cos^2 \gamma - \bar{w}^2 \sin^2 \gamma}{2 \cos \gamma \sin \gamma}
\]

(3.7)

By making a fourth measurement at another probe angle, it is possible to determine the consistency in the measurements. This would clearly show if the conditions in the tunnel had been kept steady during the four angle measurements. From the profiles taken in the stable boundary layer good agreement was found between calculating the shear stress using the 30° and the 45° orientations.

To measure heat flux in the stable boundary layer a cold wire measuring instantaneous temperature was used in conjunction with the LDA system. A schematic diagram of the instrumentation is given at the top of Figure 3.6. Whenever the LDA analysis unit detects a signal that potentially could be a valid one, it immediately tells the cold wire to take a temperature reading. If, after analysing the backscattered light signal, it is found to be outside of the defined limits for acceptance, that data point is marked. After the experiment, all the marked velocity points and the corresponding temperature values are removed from their respective arrays. The heat flux measurement can then be found by correlating the velocity and temperature arrays containing the synchronised measurement points.

**LDA specification**

- Probe diameter with cooling jacket: 26 mm
- Probe length with cooling jacket: 200 mm
- Focal Length: 50 mm
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Measurement volume | 0.15 x 0.15 x 1.87 mm
Wave length of light | 632.8 nm
Number of fringes | 37
Fringe spacing | 3.97 μm
Frequency shift | 40 MHz

3.5 Gas sampling system

This section described the gas sampling system in the EnFlo laboratory that enables 16 mean concentration measurements to be made during one run. The samples are collected in parallel and analysed in series after the experiment, using a Flame ionisation detector that responds to the hydrocarbons released from the source.

3.5.1 General description of the gas sampling system

The gas sampling system enables 16 samples of gas to be taken from various positions in the tunnel, and their concentrations to be analysed in series after the experiment. Since the gas samples are not analysed on line, the system only measures mean concentration values.

To measure the downwind concentration of a plume emitted from a chimney as shown in Figure 3.7, gas having a known composition, (e.g. 3% Ethylene in Nitrogen) is released from the source into the desired boundary layer flow. Gas is sucked through the 16 sampling tubes into storage coils for about 15 minutes, allowing time to purge thoroughly all the previous gas from the coils and tubes (see Figure 3.8). The pump generating the suction pressure is then switched off, and after a short delay, to allow the coil pressures to equalise, the valves at either end of each coil are closed.

The samples stored in the coils are then passed serially through the Flame Ionisation Detector (FID) to analyse the hydrocarbon content in each gas sample. The computer that controls all the solenoid valves in the gas sampling desk records the signal from the FID and calculates the integral of the 'pulse' corresponding to the sample in each coil. Figure 3.9 shows a typical trace of the FID output during analysis of a sample, and indicates the background level that is subtracted to obtain the sample integral.

To calibrate the FID (which gives an output voltage proportional to concentration), one coil is filled with gas of known composition during the experiment. This coil is analysed first to determine the current calibration factor between the area under the pulse and the sample concentration this represents. The concentration of the calibration gas would ideally be close to that of the samples being measured. However, for cases where the concentrations do differ by orders of magnitude, the only significant error arises due to the resolution of the 12 bit A/D converter. The response of the FID itself to hydrocarbons is linear over many decades of concentration.

The FID has a range of gains, spaced by factors of 10, that can be applied to its output signal. So, when measuring concentrations that differ significantly from the calibration gas strength, the FID gain can be changed between analysing the calibration gas and the sample gas.

To take into account the background level of hydrocarbons in the approach flow, an extra sampling tube is placed upstream of the source which fills a separate coil in the gas sampling desk during the experiment. This background coil is analysed after the calibration coil, making a total of 18
coils to be analysed in order to obtain the desired 16 concentration measurements. The background concentration, usually around 1-2 parts per million (ppm), is subtracted from all the other samples. These 18 coils have the same nominal length (and consequently similar volumes), but before making dispersion measurements they were all filled with the same gas, and then analysed to obtain calibration coefficients for the relative volume of each of the coils. This is important, since the coil volume affects the width of the sample pulse which obviously changes the value of the integral. The concentration at the sample position is then calculated using equation (3.8):

\[
C_{\text{sample}} = \frac{\text{Sample EffInt} - \text{Bkgd EffInt}}{\text{Calib EffInt}} \times \text{Calib Concentration} \quad (3.8)
\]

where EffInt is the effective concentration integral obtained from the FID trace after the coil correction factor has been applied. Having obtained the sample concentration in units of ppm, it is convenient to present the results in a non-dimensional way, so that they become independent of the exact experimental set up used. This enables concentrations taken at different tunnel speeds and using various release rates to be directly comparable. All the concentration results presented in this report have been non-dimensionalised in the following way:

\[
C_{\text{Non Dim}} = \frac{C_{\text{sample}} (\text{ppm})}{C_{\text{source}} (\text{ppm})} \times \frac{U_{\text{ref}} (\text{m/s}) \times H_b^2 (\text{m}^2)}{Q (\text{m}^3/\text{s})} \quad (3.9)
\]

where \(U_{\text{ref}}\) is the flow velocity at the top of the boundary layer, \(H_b\) is the building height of the B204 building which in the 1:500 scale model is 0.125m and \(Q\) is the source flow rate.

All the neutral flow experiments were carried out with a free stream speed of 2.5m/s, but when the tunnel was running stratified the speed was reduced to 1.35m/s to obtain the desired ratio between the inertial and buoyancy forces in the stable boundary layer. The source gas hydrocarbon concentration was 2.97% (29700ppm) and was released at flow rates between 2 and 15l/min.

### 3.5.2 Detailed description of the gas sampling desk and its operation.

**Gas sampling specification**

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage coil volume</td>
<td>300-330ml</td>
</tr>
<tr>
<td>Sampling tube length</td>
<td>approx. 17m</td>
</tr>
<tr>
<td>Sample tube volume</td>
<td>7.5ml/m</td>
</tr>
<tr>
<td>Total sample tube volume</td>
<td>128ml</td>
</tr>
<tr>
<td>Max. coil flowrate</td>
<td>150ml/min</td>
</tr>
<tr>
<td>Typical suction rate</td>
<td>100ml/min @ Tunnel speed 2.5m/s</td>
</tr>
<tr>
<td>FID output Scan speed</td>
<td>50Hz</td>
</tr>
<tr>
<td>FID output Scan period</td>
<td>70-85s</td>
</tr>
</tbody>
</table>

A schematic diagram of the gas sampling system is shown in Figure 3.8. The gas desk has two basic modes of operation. During the sampling stage the coils are all filled simultaneously with the sample gas, but during the
analysis stage, the contents of the individual coils are passed one by one through the FID.

When carrying out dispersion experiments the 'sample manual' valves are left open but the 'common manual' valves are shut. This enables each coil to be filled with the gas travelling through its own plastic sampling tube. To fill the coils with sample gas, all the control valves labelled A and B are opened, and the suction pump is switched on. Gas from the plastic sampling tubes is then drawn through the open 'manual sample' valve, through control valve A, filling the sampling coil, then passes out through control valve B, through the needle valve and flowmeter unit, through the flow regulator and into the suction pump. The needle valves allow the flowrate through each individual coil to be balanced, but to change the flowrate through all the coils the flow regulator Hi-tec 5 is adjusted. The length of sampling time is set so that the coils are adequately purged from the previous sample, but the air flow must also be sampled for long enough to obtain an accurate mean value for the concentration at that position in the tunnel. The sampling time to satisfy this second requirement is dependent on the time scales in the flow. After the sampling time has elapsed, the suction pump is switched off, and after a short delay, to allow the coil pressures to equalise, all the A and B sample control valves are closed, thus trapping the sample in the coil until it is analysed.

At the heart of the FID is a flame which is used to ionise the hydrocarbons in the sample to create the electrical signal. To keep the FID alight, it is necessary to maintain a flowrate of gas into its sample inlet. Purified air is used to purge the sample gas out of each individual coil and pass it through the FID to be analysed. When none of the coils are being analysed, i.e. the 'neutral' condition, the stream of purified air passes through the open bypass valve to maintain the flowrate through the FID.

To analyse the contents of a coil, first valve C for that coil is opened allowing the pressure in the coil to equalise to that of the purified air. Then valve D is opened and the bypass valve shut so that the purified air now flows through the coil being analysed, pushing the sample in the coil into the FID. A typical output from the FID during this stage of the analysis is shown in Figure 3.9. The background level is the output when purified air is passing through the FID. The exponential decay can be seen at the tail of the trace as the clean air progressively purges all the remaining hydrocarbons out of the coil. After the coil is sufficiently purged, valves C and D are shut and the bypass valve is opened again. The system has now returned to its 'neutral' condition and is ready to analyse the next coil.

3.5.3 Coil Calibration of the sampling system

The coil calibration factor accounts for differences in the coil volumes, and will help compensate for any slight consistent leakage in the system, whether from a solenoid valve or the pipe work. If a calibration factor differed by more than 5% from unity, the valves and pipe work for that channel were investigated to determine where the undesirable leakage was occurring. When the sample integral has been calculated, as shown in Figure 3.9, it is divided by the coil correction factor to produce the effective integral, $EffInt$, of the coil.

The most realistic way of determining the true coil correction factor, is to fill all the sample tubes with calibration gas contained in a gas bag at ambient pressure. The calibration gas is sucked into the gas sampling coils.
from the gas bag via the plastic tubes in exactly the same way as when real samples are taken in the tunnel. The only difference is that the hydrocarbon concentration of the samples is now known, and so the coil calibration factor for each individual coil can be determined. Figure 3.10a shows the coil factors that were obtained using this method. Figure 3.10b shows that the repeatability is within ± 2% when analysing the same gas sample, which for dispersion work is quite acceptable.

3.5.4 Causes of ‘random’ errors in analysing the gas samples

The coil calibration described in the previous section checked that all the channels were behaving in a similar manner, and determined the coil correction factors which were within ± 2% of each other. However, it is important to appreciate that there are random type errors which can affect the analysis of the coils. The following is a list of these random errors, and how they influence the measured concentrations:

a. The average of the first 10-15 seconds of the FID trace and the last 5 seconds is used to calculate the coil background. Errors caused by noisy signals not being averaged for long enough, or an inflated background level due to contamination from the previous coil will result in the wrong value being subtracted from the FID trace. This error only becomes significant if the sample concentration is very small and could have a typical value of ± 0.4 ppm.

b. If the quality of seal produced by the solenoid valves is not consistent, then the variation in leakage past the valve when it is shut will lead to scatter in the measured concentrations.

c. Experiments have shown that the gas concentration measured in each coil is contaminated by around 0.5% of the previous concentration stored in that coil. For example, if the concentration in the coil were 400 ppm, and on the next run the true concentration was around 5 ppm, the coil would be analysed as having a concentration of around 7 ppm (40 % error). This error only becomes significant if the previous concentration in the coil is greater than the present one by more than an order of magnitude. When this is the case, the low concentration experiment can be repeated to flush out the original sample. However, if it is appreciated before performing the low concentration experiment that the previous run had significantly higher concentrations, the coils could be flushed by sampling the background lab air for about 20 minutes before measuring the low concentrations.

d. With our particular system the voltage output from the FID corresponding to the concentration of the sample was digitised by an A/D converter remote from the computer. The data was then transmitted via a GPIB link to the computer. This method had a drawback that if the computer was interrupted by another task whilst recording the trace, it would miss data points. This had the effect of reducing the integral under the pulse, resulting in the sample concentration being underestimated. It was important therefore in our system to ensure that the computer did not run other tasks during the analysis of the coils.
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Apparatus and techniques

3.6 Flow visualisation equipment

Flow visualisation is another technique for investigating the dispersion behaviour of a smoke plume. A schematic diagram of a typical set up is shown in Figure 3.11. The requirement of the smoke generator is to produce non toxic smoke that disappears after about 30 seconds so that the laboratory does not become filled with smoke. A laser light sheet was used to illuminate the smoke so that the behaviour of the plume at a particular cross section could be investigated. A CCD camera was used to record the flow characteristics onto video tape during the run, which would typically take a couple of minutes. The intensity of light scattered by the smoke is assumed to be proportional to the density of the smoke at a given position. This is true provided the light sheet itself does not become too attenuated by the smoke. Clearly the intensity of the light sheet does fall with downstream distance as the sheet expands, but this can be compensated for during the post processing stage.

After the experiment, the video tape was analysed using the PC image analysis package DigImage that allowed mean and fluctuating concentrations to be calculated in the plane of the light sheet. For the set up shown in the Figure 3.11, the mean plume height and the vertical spread can be determined for any downstream position within the field of view. To gather a reasonable mapping of this area using the gas sampling equipment could take several hours of tunnel time. However, to obtain quantitative information of the concentration field using flow visualisation is not very straightforward.

To non-dimensionalise the concentrations in a dispersion experiment it is necessary to measure all the concentrations relative to the source strength. The problem is that, even within the first 500mm of plume travel, the peak concentration has reduced by a factor of about 150. The frame grabber used to convert the analogue video signal into an 8 bit digital one, has only 256 levels. Clearly with this dynamic range it is not possible to faithfully measure the smoke concentrations at the source and further downstream. Another option is to change the aperture of the camera lens by a known amount between measuring the source and downstream concentrations, but this relies on the smoke flow rate remaining constant for a period of time, which proved difficult to achieve. With our system if quantitative mappings are required, the concentrations need to be calibrated against a few FID measurements in the area of interest. In this study though, only qualitative data has been taken with the visualisation equipment to create time averaged concentrations of the plumes.

3.7 Generic building groups studied and the experimental design

Figure 3.12 shows the generic building groups that were studied based on the B204 building situated on the Sellafield site which is owned by British Nuclear Fuels Ltd (BNFL). The B204 has a chimney stack that is twice the height of the building. One of the objectives of this study was to determine the effect that this building and the surrounding site was having on dispersion from the stack in both neutral and stable boundary layers. Before investigating the building effect over the full Sellafield site model, simpler generic building groups were studied.
In dispersion modelling it is important to recognise which sets of building groups will influence the elevated plume in a similar manner. Questions such as, can an array of buildings be adequately represented by a single cuboid of appropriate dimensions, need to be answered. With this in mind, cases A, B, E, F and G shown in Figure 3.12, consider different spacings of nine buildings, where in case A, the buildings have infinite separation, and in case B, the spacing is zero. Cases A, B, C and D are a range of single buildings that could possibly be representative. A range of release heights was studied from 140 to 400mm, which as a ratio of the 125mm building height, is 1.12 to 3.2. At the lower end the release is significantly entrained into the recirculation region of the building, like a roof level release, and at the upper end the plume is almost entirely unaffected by the presence of the building group in most cases.

Preliminary experiments for approach flow angles of 0°, 30°, 45°, 60° and 90° showed that the maximum and minimum effects occurred at approach flow angles of 45° and 0° respectively (see Figure 3.12 for the angle datum). The results for the 30° and 60° angles however, were much more similar to the 45° results than those obtained for the 0° case. Thereafter only the 45° and 0° wind directions were studied since they represent the range of effects due to a given building group.

For all the building cases in the neutral boundary layer, ground level concentration profiles were measured for a range of release heights and for two wind directions. Cases A, B and F have been studied in the most detail with extensive cross-wire measurements being made in the building wakes. Elevated vertical and lateral concentration profiles were also measured for some of these cases to complement the centreline ground level distributions. Linking the flow and dispersion behaviour in the building wakes should lead to a better understanding as to what are the important parameters to adjust in a dispersion model.

In the stable boundary layer, only building cases A, B and F were studied to investigate the influence of stratification on the effective stack heights. No flow measurements were made in the building wakes with the stable boundary layer.

### 3.8 Sellafield site model

The 1:500 scale model of the Sellafield site was provided by British Nuclear Fuels Ltd, and had been used in previous wind tunnel studies. Figure 3.13 shows a map of the site with the building identification numbers. Emissions from the B204 stack (found at approximately the centre of the circle), were studied over the model for the 270° and 150° wind directions in both the neutral and stable boundary layers. Although to the East of the site after about 10km the land rises to form the Lake district, the site itself is reasonable flat and is approximately 20m above sea level. It can be seen from the Figure that the buildings are mainly rectangular and are predominantly orientated so that the upwind sides are normal to a 270° wind. The 150° direction was chosen to investigate the dispersion effect when the approach flow is diagonal to the buildings on the site.

Figure 3.14 shows a plan view of the part of the model that was installed in the EnFlo tunnel to study the 270° wind direction. For this wind direction the release from B204 passes directly over Calder Farm, a scenario which has been investigated in previous research carried out for BNFL. The model
was constructed of hard foam built up in 10mm layers and attached to a plywood base board. These contour levels represent 5m steps at full scale. A ramp was added at the upwind edge to minimise disturbances caused by the transition from the wind tunnel floor to the model surface level. Figures 3.15 and 3.16 show some photographs taken of the model when it was installed in the EnFlo wind tunnel to investigate the 270° wind direction. Figure 3.15 gives an idea of the extent of landscape that was modelled around the main site buildings. The expanse of model upstream of the site buildings represents about 800m at full scale. From Figure 3.16 we can see that the buildings surrounding B204 are around half its height, and that it lies close to the centre of the industrial site. Some of the buildings located in the vicinity of B204 were remade because their edges had become damaged during transportation between the various wind tunnel studies in which this model has been used. Because of the range of wind directions which have previously been studied using this model, it had become very fragmented as pieces were cut to facilitate its installation into the respective tunnels. The first task that needed to be done before assembling the model, was to label and photograph every piece, so that a map could be produced showing how the huge jigsaw fitted together. This proved very useful, particularly when deciding on where the existing cut lines were. Figure 3.17 shows the model pieces that were installed when investigating the 150° wind direction.

Having described the experimental facilities, and the building groups to be investigated, we are now in a position to look at some of the measurements that have been made of flow and dispersion with and without the buildings present.
Figure 3.1. Isometric view of the stratified flow wind tunnel in the EnFlo laboratory.
Figure 3.2. Diagram of the boundary layer simulation system used in the tunnel
Figure 3.3. Isometric view of the traverse system
Figure 3.4. Showing the probe positions on the traverse
A. Single wire probe

B. Cross-wire probe

Figure 3.5. Diagram of the single and cross-wire probes
Figure 3.6. Schematic diagram of the LDA synchronised with a cold wire.
Figure 3.7. Schematic diagram of the gas sampling system used to obtain mean concentration measurements.
Figure 3.8. Schematic diagram of the gas sampling desk
Figure 3.9. Showing how a typical FID trace is analysed to obtain the sample integral.
a. Coil correction factors to compensate for any variation in coil volume. The Calibration coil was taken as having a coil factor of 1.

b. Coil factor variations for the seven calibration tests.

Figure 3.10. Coil calibration results for the gas sampling equipment, obtained from 7 successive calibration runs.
Figure 3.11. Schematic diagram of a flow visualisation experiment

Laser Light sheet

Flow

Laser sheet probe

Video camera

Fibre optic link

Smoke generator

Post processing of images

Laser

Video recorder
Figure 3.12. Generic building groups studied based on the B204 building at Sellafield. All releases were made above the group centre.
Figure 3.13. Map showing the wind directions studied over the Sellafield site for the B204 release.
Figure 3.14. Plan view of the Sellafield site model as used in the EnFlo tunnel for the 270 degree wind direction
Figure 3.15. 270° wind direction over the Sellafield site model in the EnFlo tunnel at Surrey University. (looking downwind)

Figure 3.16. Close up of the buildings surrounding B204
Figure 3.17. Plan view of the Sellafield site model as used in the EnFlo tunnel for the 150 degree wind direction.
4.1. Introduction

To determine the effect that buildings have on elevated dispersion, it is important to characterise the behaviour of the approaching flow. For example, it is well known that higher turbulence intensities in the upstream flow, lead to a reduction in the length of the separated flow regions created on the building roof and sides. Clearly, if the complex flow patterns around the building are sensitive to upstream flow conditions, the height at which a release becomes significantly influenced by the perturbed building flow will also be affected. Flow measurements have been made in the undisturbed neutral and stable boundary layers to determine these characteristics, and to establish the spanwise distance over which the boundary layers were approximately two dimensional. All the measurements in the neutral boundary layer were made using a cross-wire, but in the stable boundary layer, where velocity and temperature variations are both significant, a one component Laser Doppler Anemometer (LDA) was used in conjunction with a cold wire. At each position in the stable boundary layer, measurements were made at four different probe angles to determine $U$, $u^2$, $w^2$, and $uw$. The synchronised cold wire, about 4mm downstream of the LDA measurement volume, enabled the temperature fluctuations and fluxes $\overline{T^2}$, $\overline{uT}$ and $\overline{wT}$ to be determined.

The emphasis of this project was to investigate the dispersion effect caused by various building groups for elevated releases. However, since the resulting dispersion of a plume is very much a product of the behaviour of the flow, understanding more about the wake perturbations was clearly beneficial. Cross-wire measurements have been made in the wakes of building groups A, B and F (See Figure 3.12), for both the $0^\circ$ and $45^\circ$ wind directions, in the neutral boundary layer. Measurements have not been made in recirculation regions or where the turbulence intensities are very high since a cross-wire is not suitable for these flows. For the purposes of our study this was not considered restrictive, since elevated plumes remain above the near wake region and only become significantly entrained further downwind. The wake measurements have been compared to a simplified 3D version of the small deficit wake model proposed by Counihan et al (1974) to investigate its suitability. By mapping out the flow fields for some of the building groups I intended to identify what type of flow perturbation gave rise to the resulting enhancement of the ground level concentrations for an elevated release.

Some cross-wire measurements have been made over the Sellafield site to compare the wake of the isolated B204 building with that over the site, thus enabling us to determine the net effect that this large industrial site is having on the boundary layer characteristics.

4.2. Flow characteristics in the undisturbed boundary layers

Vertical profiles of the mean velocity and turbulence in the neutral and stable boundary layers are presented in Figure 4.1. These measurements were made on the tunnel centreline at $x=13.5m$ and $x=16m$ respectively in the neutral and stable boundary layers. These positions are both 1m
downstream of the source location used during the respective dispersion studies. Profiles at other locations were also made to determine the development of the boundary layers with downstream distance and the cross stream width over which the flow was two dimensional. The velocity profiles in the top plot in Figure 4.1 show clearly the different boundary layer depths for the neutral and stable flows. Working with a model scale of 1:500 these boundary layer depths correspond to 500m for the neutral case and 125m for the stable case at full scale. Both these values are quite typical of the depths one would expect to observe in the atmosphere for their respective stabilities.

In the middle plot, these profiles have been fitted by the log-linear boundary layer equation given by:

$$U = \frac{u_*}{k} \left\{ \log \left( \frac{z}{z_0} \right) + \frac{\beta_u}{L} \frac{z}{L} \right\}$$  \hspace{1cm} (4.1)

where $k$ is the von Karman constant taken as 0.41, $u_*$ is the friction velocity, $z_0$ is the roughness length, $\beta_u$ is a constant, and $L$ is the Monin Obukhov length scale. In the neutral boundary layer, $L$ tends to infinity, so the second term in the curly brackets goes to zero, leaving just the log part of the equation. An estimate for the friction velocity in the neutral boundary layer can be found from the slope of the velocity profile when plotted in this way. Since by definition the friction velocity is given by:

$$u_* = \sqrt{-\frac{\tau_w}{\rho}}$$  \hspace{1cm} (4.2)

it can be determined more directly from the shear stress measurements in the constant stress region $\tau_w$. Both methods of obtaining the friction velocity were within 5% of each other, but the value recorded on the plot was calculated from the shear stress. The roughness length was found by extrapolating Equation (4.1) back to the point at which it crosses the Y axis, i.e. the height at which the velocity is zero. This height is not directly measurable since it is a lumped parameter describing the surface aerodynamic roughness. Local three dimensionality, induced by the individual roughness elements, dominates the flow behaviour at these low elevations. $z_0$ is significantly less than the height of the roughness elements, as would be expected, and should be independent of the tunnel speed provided the surface is aerodynamically 'rough'. Castro and Snyder (1997), showed that for bluff obstacles the roughness Reynolds number, $R_{e*}$, should be greater than 1 for this criteria to be satisfied. The roughness Reynolds number is written as:

$$R_{e*} = \frac{u_* z_0}{\nu}$$  \hspace{1cm} (4.3)

where $\nu$ is the kinematic viscosity which for air is taken as $1.5 \times 10^{-5}$. For the neutral boundary layer where $U_{ref}$ was 2.5m/s, $R_{e*}$ equals 7.6, indicating that the surface was indeed aerodynamically rough.

Flow and dispersion experiments were carried out in the neutral boundary layer long before the tunnel was commissioned to simulate a stable flow. To simulate non-neutral conditions, the buoyancy forces in the flow needed to become significant compared to the inertial ones. Because of this it was desirable to run the tunnel slowly, to keep the inertial forces low, and use a large vertical temperature gradient, to enhance the influence of buoyancy.
However, the flow over the roughness elements had to be kept aerodynamically rough otherwise Reynolds number effects became important. By increasing the height of the roughness elements in the stable boundary these criteria could be achieved at a tunnel speed of 1.35 m/s, giving a roughness Reynolds number of 3.6. This resulted in the neutral and stable boundary layers not using the same roughness elements, so the increased roughness length measured in the stable case was predominantly due to the fact that the roughness elements were 20 mm tall instead of the 10 mm ones used in the neutral case. Flow measurements made under neutral conditions using the taller roughness elements gave very similar values for $z_0$, as were recorded in the corresponding stable case. However, since all the flow and dispersion experiments around buildings under neutral conditions used the 10 mm roughness, this is the boundary layer for which the flow characteristics have been presented.

Figure 4.1 shows the Reynolds stresses in the two boundary layers, with the height normalised by the boundary layer depth. We can see that the stresses in the stable boundary layer are suppressed by the stability, that has the primary effect of damping the vertical fluctuations. The effect of the stability may have appeared greater if the 20 mm roughness elements had been used in both boundary layers. The ‘kink’ in the longitudinal normal stress profile, half way up the neutral boundary layer, suggests that the barrier wall was somewhat too high for the roughness elements. However, the boundary layers were judged to be perfectly adequate for the requirements of this study.

Spanwise velocity profiles, measured in the neutral boundary layer, showed that in the central 1.5 m of the tunnel the velocity is within ±5% of the average value for that height. All the dispersion experiments, except some over the Sellafield site, were carried out with the source on the tunnel centreline. Even 4 m downstream the plume would be almost wholly contained within the central 1.5 m, where the flow is approximately two dimensional.

To characterise the velocity profile in the stable boundary layer the variables that need to be determined are $u_\ast$, $z_0$, $\beta_u$ and $L$. These were determined along with the parameters for the log-linear temperature profiles whose equation is given by:

$$\Delta T = \frac{T_\ast}{\kappa} \left\{ \log \left( \frac{z}{z_0} \right) + \beta_T \frac{z}{L} \right\}$$

(4.4)

where $T_\ast$ is the friction temperature in the stable boundary layer and $\beta$, is a profile constant. So we now have to optimise six variables to obtain representative fits to the velocity and temperature profiles in the stable boundary layer. The curve fitting was subject to the following constraints:

1. the roughness length, $z_0$, to lie within ±20% of its value in the neutral boundary layer for the 20 mm roughness elements,
2. the friction velocity, $u_\ast$, to vary within the limits of experimental scatter when calculated from the shear stress measurements in the constant stress region,
3. the friction temperature, $T_\ast$, to vary within the limits imposed by matching the normalised temperature fluctuations, $T'/T_\ast$, to full scale, and
4. the profile constant, $\beta_u$, to lie between 4.0 and 5.5.
The curve fits to the velocity and temperature in the stable boundary layer, along with the values obtained for all the parameters appear on the left of Figure 4.2. The height \( z \) is normalised by the Monin Obukhov length scale that represents the height at which the shear production of turbulent kinetic energy balances the damping due to the buoyancy. These plots indicate that the log-linear regime in our stable boundary layer is bounded at about \( z = L \).

The non dimensional velocity and temperature gradients in the stable boundary layer are given by:

\[
\frac{\kappa z}{u_*} \frac{dU}{dz} \quad \text{and} \quad \frac{\kappa z}{T_*} \frac{dT}{dz}
\]  

(4.5)

The plots on the right of Figure 4.2 show these gradients in our stable boundary layer compared to a compilation of field results made by Hogstrom (1988). Our results fall quite centrally within the range of field observations, giving us confidence that the stable boundary layer set up in our wind tunnel is typical of atmospheric nocturnal boundary layers. Figure 4.3 shows measurements of the turbulent heat flux and the temperature fluctuations in our stable boundary layer. These measurements were made using the Laser Doppler Anemometry system synchronised with a cold wire. The maxima in the longitudinal and vertical turbulent heat flux profiles compare with values of 3 and -1 respectively from measurements made in the atmospheric stable boundary layer by Caughey et al (1979).

In the stable boundary layer vertical profiles of the flow characteristics were made at the centreline, then at \( y = -313 \text{mm} \) and \( y = -625 \text{mm} \) for one of the downstream positions, to determine over what width the layer was two dimensional. The measurements at \( y = -313 \text{mm} \) were very similar to the centreline ones, but in the further position, the characteristics had changed somewhat. All the dispersion experiments carried out in the stable flow used a source at the tunnel centreline, so over the limited downwind distance investigated, the plumes were completely contained within the region of two dimensionality, taken as the central 600mm of the flow.

Figure 4.4 shows spectra and autocorrelation measurements made in the neutral boundary layer, with the corresponding time scales calculated from the results. The top plot presents the spectra at \( z = 25, 100 \) and \( 450 \text{mm} \), with the values shifted by an order of magnitude with increasing height. The solid lines each have a slope of \(-5/3\) associated with the energy cascade from the larger scales to the smaller ones. Higher up in the boundary layer the spectra have a slope of \(-5/3\) for about 2 decades, but closer to the ground the scale of the energy containing eddies decreases. The middle plot in Figure 4.4 shows the autocorrelation of the streamwise velocity component normalised by \( \overline{u^2} \) at each position. The integral time scales were calculated by integrating beneath the plots up to the point at which they first cross the \( x \) axis, to remove contributions from the small positive or negative values at large times.

The lower plot shows the calculated length scales for both the vertical and longitudinal velocity components for a range of heights in the neutral boundary layer. These were calculated by multiplying the integral time scales by the local advection velocity. The length scales increase with height, and for the vertical component they are approximately equal to \( z \) closer to the ground. These length scales are just a little above those
measured in other simulated boundary layer, Robins (1979), and to measurements made in the atmospheric boundary layer.

4.3. Flow measurements in the building wakes compared with 3D model.

4.3.1 Introduction

The perturbed flow characteristics in the building wakes were investigated by measuring vertical and lateral profiles using a cross-wire, see Section 3.4.1 for details. By making such measurements at a number of downstream positions the spread and decay rates in the wakes could be analysed and compared to the 3D wake model, summarised in Section 2.4.3 and fully documented in Appendix 3. A catalogue of all the measurements made downstream of building cases A, B and F, is presented in Appendix 4. The automated traversing routine, used to map out the wake characteristics with the cross-wire, was run once in the absence of any buildings. This data set was taken as the undisturbed flow values when calculating the flow perturbations in the building wakes.

4.3.2 Velocity deficit in the wakes

Lateral profiles of the velocity deficit for the three building cases are shown in Figures 4.5 to 4.7. These measurement were made at half the building height for all the downstream stations. The solid lines drawn on the upper plots are the results of the 3D wake model, the only free parameter being \( \bar{u} \), which has been optimised to give the best fit to the measured velocity deficits for the three building cases. The equation for the velocity deficit appeared as Equation 2.35 in Chapter 2, but is repeated here for reference:

\[
\begin{align*}
\text{Decay rate} & : u = \bar{u} e^{-\xi^{2}/2} \\
\text{Lateral} & : e^{-\eta^{2}/2} \\
\text{Vertical} & : \xi e^{-\xi^{2}/2}
\end{align*}
\]  

(4.6)

The vertical eddy viscosity \( k_z \) was defined by the upstream flow conditions so \( k_z = k_u \cdot H_b \) and \( k_z \) was set at 1.5 times \( k_u \). A Gaussian shape seems fairly representative of the lateral profiles for the normal wind direction, but particularly for building case B, the smaller side peaks may indicate the presence of the trailing horse shoe vortex system, which is assumed by the model to have decayed into insignificance. However, when the buildings are placed diagonally to the approach flow the Gaussian profile predicted by the model is clearly not applicable. For building cases B and F diagonal to the flow, beyond ten building heights downstream there is an excess instead of a deficit of velocity on the wake centreline. These wakes are not acting as a momentum dominated ones, but coherent vorticity is sweeping elevated, higher velocity fluid down into the centre of the wakes. This is leading to a velocity overshoot at the wake centreline of around 10% for building case F, at 25 building heights downstream. This strong vortex system, generated at the swept back leading edges of the building roof, is renowned for producing significant wake downwash. Hereafter, results from the 3D wake model will not be compared to wake measurements when the buildings are at 45 degrees to the approach flow, since the modelling assumptions for this situation are invalid.
Vertical centreline profiles of $u$, $\overline{u^2}$, $\overline{w^2}$, and $\overline{uw}$ are shown in Figures 4.8 to 4.13 for the three building cases normal to the approach flow. The solid lines once again indicate the predictions of the 3D wake model. $\hat{u}$ is the only empirical input to the model that has been changed between the different building cases, and its value has been optimised to give the best fit to the vertical profiles for velocity deficit. The magnitude of the maximum velocity deficits are within 10%, apart from far downstream where the measured perturbations become of similar magnitude to the experimental errors. The vertical height, $L_z$, at which the maximum velocity deficit occurs, is well predicted by the model for building cases A and B. The peak in the measurements occur a little lower when compared to the model in the wake of building case F. Substituting our definition of $k_z$ into the equation for $L_z$ we obtain:

$$L_z = H_b \sqrt{2k_b \left( \frac{\hat{u}_t}{U_{ref}} \right)}$$

(4.7)

So, for a specified number of building heights downstream, $L_z$ is directly proportional to the building height, and to the square root of the friction velocity. Therefore, changing $\hat{u}$ has no effect on $L_z$, thus all three building cases are assumed to have the same vertical length scale in their wakes. However, it seems reasonable to expect that the position of the maximum velocity deficit ($z=L_z$), should be a function of the porosity of the array of buildings.

The constant $\hat{u}$ in the model is related to the couple that the flow exerts on the building and nearby surfaces via the pressure distribution and the shear stresses. It is this couple that is conserved in the building wake since interaction between the wake and the surface downwind of the obstacle can only produce a drag without affecting the couple. We would expect that the value of $\hat{u}$ should therefore be related to the flow obstruction caused by the building group. A value of 1.25 for $\hat{u}/U_{ref}$ gave good agreement with the measured velocity perturbations for case A. A value of 3.75 worked well for building case B, which has three times the frontal area of case A. It is somewhat surprising to note that for case F, which consists of nine case A buildings spaced by one building width, we observe that $\hat{u}/U_{ref}$ has a value of around $9 \times 1.25 = 11.25$. So it appears that, for the spaced building array, each building is acting similarly to how it would if it were in isolation. Clearly, more building groups would need to be investigated before any general rules could be established, but none-the-less, this is an interesting observation.

4.3.3 Reynolds stress perturbations in wakes

The 3D model was derived originally to obtain the velocity deficit in the building wake, but using the eddy viscosity relationship, we can calculate the perturbed shear stress. This leads to the equation:

$$\tau_{zz} = \hat{u}k_z \frac{e^{-\frac{z}{L_z}}}{L_z} \frac{2}{\epsilon} \left( 1 - \frac{z^2}{L_z^2} \right)$$

which appeared as Equation 2.37 in Chapter 2. The maximum perturbation in the vertical profile now occurs at $z=L_z \sqrt{3}$ rather than at $L_z$ as for the velocity deficit. Vertical profiles of the perturbed stresses for building
Chapter 4

Flow Results

cases A, B and F are presented in Figures 4.8 to 4.13. The positions of the peaks in the perturbed shear stress profiles are again very similar between the model and the measurements for building cases A and B. Case F, consistent with its performance on the velocity perturbations, has measured peaks occurring below the modelled ones. The assumption that the shear stresses can be modelled by the mean velocity gradient certainly seems to work well in the main wake region, when at a sufficient distance from the ground. Below \( z=L_z \) the shear stress perturbation in the wake becomes a deficit rather than an excess. Closer to the ground this leads to an unrealistic result, because the constant eddy viscosity approximation is no longer valid; \( k_z \) needs to be reduced to zero at the surface. This is coped with by Counihan et al (1974) in their 2D wake model by introducing a separate flow region close to the ground. When comparing our 3D wake model to the perturbed Reynolds stresses we will only consider the part of the profile that is above \( z=L_z \) (the position at which the curved line crosses the vertical axis).

Beyond 7 building heights downwind, the maximum excess shear stress predictions for cases A and B are within the scatter of the experimental data, but closer in the values are significantly overestimated by the model. For building case F, the predictions for the excess shear stress are poor at all the stations. The overestimation for all the building groups close in could be caused by the violation of one of the modelling assumptions, namely that the velocity deficit is 'small' relative to the approach flow. The definition of 'small' is often taken as less than 30%. For both building cases B and F, the maximum velocity deficit is in excess of 30% for the two most upstream stations, so at these positions the application of the model may well be suspect. However, no assumption has been made in the model about the size of the perturbed stresses relative to the approaching flow. So, although in some cases we see the stresses enhanced in excess of 100%, this in itself does not render the model's application invalid.

The 3D model assumes that the other perturbed stresses \( \bar{u}^2 \) and \( \bar{w}^2 \) are directly proportional to the shear stress so that:

\[
\Delta \bar{u}^2 = \lambda_1 \tau_{xc} \quad \text{and} \quad \Delta \bar{w}^2 = \lambda_2 \tau_{xc}
\]

Typical values in the atmosphere are \( \lambda_1=5 \) and \( \lambda_2=1.5 \), but in the wake model we have found that when \( \lambda_1=2.5 \), much better agreement is achieved with the perturbed \( \bar{u}^2 \) profiles for all the wakes. The position of the maximum excess in \( \bar{u}^2 \) is quite well predicted by the model for cases A and B, but once again the peak in the measured profiles occurs at a lower elevation for case F. After changing the value of \( \lambda_1 \) to 2.5 instead of 5 the magnitude of the perturbation given by the model is much more reasonable. The behaviour of the \( \bar{w}^2 \) perturbation in the wake is somewhat different from the other two stresses, since the measurements never go negative in the lower part of any of the profiles. This indicates that in no part of the wake do the vertical fluctuations fall below the undisturbed boundary layer value. Also the measured peaks occur approximately at \( z=L_z \) rather than \( z=L_z \sqrt{3} \) as predicted by the model.
4.3.4 Decay of the perturbations in the wakes

The decay of the perturbations in the wake were analysed by considering the maximum measured deficit or excess at a given cross section. For the diagonal cases, the positions of the maximum velocity deficit and turbulence excess move upwards and outwards from the wake centreline with downstream distance. Placing the probe in the right position to measure these maximum values was not straightforward, and required some preliminary measurements to determine approximately where they occur. Since the vertical gradients in the flow are much sharper than those in the spanwise direction, it was more important to have the probe at the correct elevation than at the exact spanwise location. Therefore, most of the values for the maximum perturbations are taken from the vertical profiles, which were measured at approximately the ‘best’ spanwise position for that particular cross section. Tracking the maximum perturbation for the ‘normal’ cases was much more straightforward, since the peak in the spanwise profiles always occurred on wake centreline.

Figure 4.14 shows the maximum measured perturbations for the three building cases at 0° and 45° to the approaching flow. The lines drawn on the plots indicate the decay of the maximum perturbation with downstream distance as given by the 3D model with the same inputs as described in the previous sections. The decay rate of the velocity deficit is \((x/H_b)^{1.5}\), but for the decay of the enhanced Reynolds stresses \((x/H_b)^{-2}\) is predicted. As we noticed from the vertical profiles, the model well represents the decay in velocity deficit for all the building cases normal to the wind. Comparing the measurements for the normal wind direction to those in the diagonal, we see that the maximum perturbations are always greater for the corresponding diagonal case. The results tend to be more scattered for the diagonal approach flow, probably because of the ambiguity of knowing where to place the probe. Any errors in probe positioning would lead to lower maximum perturbation values being recorded. In general it seems that the decay rate for all the perturbed Reynolds stresses for the diagonal approach flow is less than \((x/H_b)^{-2}\), whereas for the normal approach flow, this value is in good agreement with our experimental observations, particularly for building cases A and B. Building Case F normal to the flow, which is not a single cuboid but an array, has slower decay rates for all its perturbed Reynolds stresses, and is more similar to the diagonal case in terms of wake decay.

4.3.5 Performance and suitability of the model

Figure 4.15 shows the measured angle that the mean streamlines make with the horizontal, in the \(xz\) plane at the wake centreline. The angle was calculated using the longitudinal and vertical velocity components from the cross-wire, when the probe was located at the building height. A negative angle denotes downwash in the wake which is most significant for the diagonal cases. From our dispersion results presented in Chapter 5 we will notice that the downwash in the building wake has a significant effect on the ground level concentrations for elevated releases. The descending streamlines above the wake cause elevated flow to become part of the spreading building wake, bringing the plume in contact with the ground much sooner. Currently our wake model makes no prediction of this downwash velocity, so if this model is to be used for elevated releases it will need to be extended. Continuity tells us that:
but more assumptions would need to be made about the wake behaviour before we can obtain an equation of the downwash, \( \langle \nu \rangle \) in the wake.

Measurements have shown that the 3D wake model can predict the velocity deficit and the excess in the Reynolds stresses reasonably well for a momentum dominated wake. The roof vortices, whose presence is significant when the building is diagonal to the approach flow, entrain elevated higher velocity fluid down into the building wake. Beyond ten building heights downwind, this leads to an excess instead of a deficit in velocity at the wake centreline. So there are two separate processes that are going on in such a wake, a momentum deficit as for the normal wind direction, but with the superimposed action of coherent vorticity. The 3D momentum dominated wake model that has been developed could therefore still be used in the diagonal building wakes along with another model, yet to be developed, which could suitably describe the behaviour of the roof vortices. The difficulties in producing a model of the roof vortices are, how to determine both their initial strength and decay rate in the highly turbulent flow downstream of the building. The roof vortices are rarely if ever balanced, so one side will be stronger than the other causing the wake to be unsymmetrical. The model would also need to represent the effect of the ground on the vorticity.

The flow measurement results for these 6 building wakes have formed a comprehensive data base against which future models can be tested, and has increased our understanding of the dominant flow regimes that occur.

**4.4 Flow measurements over the Sellafield site model**

Cross-wire measurements were made in the neutral boundary layer as it passed over the Sellafield site model for the 270° wind direction. Vertical profiles were measured 500m, (full scale units) upstream of the main buildings, to characterise the approach flow. The site model extended another 500m upstream of this position, where a fairing was constructed to smooth the flow over the transition. Figure 4.16 shows the profiles with and without the site model present, compared with earlier measurements made in the BMT wind tunnel for the same Sellafield site model (Singh (1990)) but in a different approach flow.

The lines drawn on the velocity profiles indicate that the roughness length \( z_0 \) has decreased from a value of 0.175m (0.35 mm at model scale) for the approaching boundary layer, to 0.01m over the site for both wind tunnel studies. This effect may be caused by the acceleration that takes place in the lower part of the boundary layer, as it passes up the smoother fairing and model, upstream of this measuring station. This would cause the roughness length to decrease as the flow velocity close to the ground has been increased. A greater upwind fetch of model terrain would have helped these transient effects to settle out. Additional roughness was not placed over the model, so for the rural, undeveloped areas of the site, the roughness length truly would have been lower than that upstream of the model. The contour steps formed when modelling the topography help to increase the surface roughness, but the Sellafield site is relatively flat,
resulting in sparsely spaced contour steps. So it seems reasonable to expect the roughness length of the boundary layer over the Sellafield topography alone (no industrial buildings), to be lower than that of the approach flow boundary layer.

The longitudinal fluctuations and shear stresses over the site compare fairly closely with those measured during BMT's previous study. These quantities are both a little below the values obtained in the absence of the site. This again could have been influenced by the acceleration of the flow over the site model which would tend to suppress turbulent fluctuations.

Figures 4.17 and 4.18 show the perturbations in the wake of B204 when it was placed in its position on the site, compared to measurements made when it stood in isolation (building case A). Figure 3.16 shows a photograph of the Sellafield site model looking downwind for the 270° wind direction. The buildings immediately downstream of B204, which are approximately half its height, prevented the vertical profiles in this region being continued to the lower elevations. Clearly, the velocity deficit in the site wake is very much enhanced, and the peaks in the perturbed Reynolds stress profiles always occur higher up. These differences seem predominately caused by the site buildings downstream of B204, which are sufficiently closely spaced to form a zero plane displacement at their roof level. If we shift the site results for the Reynolds stresses downwards by half the height of B204, they would be quite similar to those obtain when B204 was studied in the absence of the site and surrounding topography.

To obtain a feel for the overall effect of the Sellafield site Cross-wire measurements were made at four spanwise positions, and at 10 downstream stations for the 270° wind direction. The longitudinal positions were in the range of 500m upwind of B204 (upstream of all the buildings), to 2000m downwind of B204 which is about 1250m downwind of the cooling towers, see Figure 3.14. The spanwise positions were as follows:
1. directly in line with B204,
2. 125m to the right of B204 looking downwind,
3. 125m to the left of B204 looking downwind, and
4. directly in line with cooling tower F8 which is to the right of B204 looking downwind.

Obviously the spanwise positions showed large variations for the same downstream location depending on the proximity to any of the major site buildings, but at the furthest downstream station all the profiles were similar, showing a sort of bulk effect that the industrial site has had on the boundary layer. Figure 4.19 shows the boundary layer characteristics for the furthest upstream and downstream stations for all four spanwise positions. The flow speed close to the ground has certainly been reduced by the site buildings, but higher up in the boundary layer the velocities have increased a little to compensate for the blockage effect of the Sellafield site. At around 100m elevation, the rate of change of velocity with height is far greater for the downstream station. This corresponds to the height at which the maximum Reynolds stresses occur. The measurements in the wake of the cooling tower, (one of the largest structures on the Sellafield site) shows the largest perturbations, since this individual wake has not yet decayed back to the bulk perturbation due to the site.

1250 m downwind of the main site, apart from the cooling tower wake, all the effect of the individual buildings have merged together to form an almost 2 dimensional change in the boundary layer. The site has acted like a large change in surface roughness, but which was not extensive enough
in the longitudinal direction for characteristic boundary layer profiles to fully develop. Downwind of the main site, the surface roughness has reverted to that of the rural site, so the lower part of the boundary layer is no longer so restricted by the surface and the velocity there starts to increase. What we are seeing at this station, is a developing boundary layer that is in the process of responding to a sudden decrease in surface roughness.

4.5. Conclusions from the flow measurements

We have characterised both the neutral and stable boundary layers and have shown that they are representative of typical atmospheric flows. Cross-wire measurements in the building wakes have shown that for the diagonal wind direction, the wake is significantly affected by the roof vortices generated at the swept back leading edges. Beyond ten building heights downstream, this caused the longitudinal velocity at the wake centreline to be above that of the undisturbed flow. The hypothesis that the building wake is momentum dominated, is clearly an invalid modelling assumption for diagonal approach flow. However for the normal wind direction, comparisons of the wake perturbations with our 3D model have yielded reasonable agreement.

Cross-wire measurements made over the Sellafield site have shown that the flow downstream of B204 is significantly affected by the site buildings in this region when compared to those results obtained for the isolated B204 building, (building case A). Measurements made at four spanwise positions 1.25 km downstream of the main industrial site, indicated that the effect of the individual building wakes had almost completely merged, to form a two dimension change in the boundary layer characteristics. The effect of the industrial site at this position downstream would be best modelled as the rural approach flow, having passed over an area of large roughness for about 1.5 km. Even though the local surface roughness downwind of the site has now returned to its upwind value, the effect of the 'rough' area can still clearly be seen by the enhanced Reynolds stresses higher up in the boundary layer.
Figure 4.1. Flow measurements in the undisturbed neutral and stable boundary layers at the tunnel centreline, 1m downstream of the release position.
Figure 4.2. Mean velocity and temperature profiles in the stable boundary layer at x=16m, showing coefficients of log-linear fits. Plots on the right compare the non-dimensional velocity and temperature gradients with field data.
Figure 4.3. Heat flux and temperature fluctuation measurements made in the stable boundary simulated in the EnFlo wind tunnel at $x = 16$ m
Longitudinal spectra at different heights in the neutral boundary layer.

Autocorrelation of the longitudinal turbulence at various heights in the neutral boundary layer.

Integral length scales

Figure 4.4. Spectra, autocorrelations and length scales obtained using a cross-wire in the undisturbed neutral boundary layer at $x=13m$
Figure 4.5. Lateral profiles of the mean velocity deficit for building case A at $z=H_b/2$. 

Building normal to the flow

Building at 45 degrees to the flow

3D wake model parameters

$\frac{\bar{u}}{U_0} = 1.25$

$K_x = 1.5 \text{ Kz}$

$K_z = k_{ref} \times 0.00235$

× Cross-wire measurements
— 3D wake model predictions
Figure 4.6. Lateral profiles of the mean velocity deficit for building case B at $z=H_b/2$. 

3D wake model parameters

$$\frac{\bar{u}}{U_{ref}} = 3.75$$

$\text{Kx} = 1.5 \text{ Kz}$

$Kz = k_x\frac{Uref}{Hb}$

$= 0.00235$
Figure 4.7. Lateral profiles of the mean velocity deficit for building case F at $z=H_b/2$. 
Figure 4.8. Centreline wake perturbations of $U$ and $u^2$ in building case A normal to the approach flow.
Figure 4.9. Centreline wake perturbations of $w^2$ and $uw$ in building case A normal to the approach flow
Figure 4.10. Centreline wake perturbations of $U$ and $u^2$ in building case B normal to the approach flow.
Figure 4.11. Centreline wake perturbations of $w^2$ and $uw$ in building case B normal to the approach flow.
3D wake model parameter
\[ \frac{\bar{u}}{U\infty} = 11.5 \]

Velocity deficit / \( U_h \)

- Cross-wire measurements
- 3D wake model predictions

\( u^2 \) excess / \( u^2 \) at the building height in the undisturbed flow

Figure 4.12. Centreline wake perturbations \( U \) and \( u^2 \) in building case F normal to the approach flow
Figure 4.13. Centreline wake perturbations of $w^2$ and $uw$ in building case F normal to the approach flow.
Figure 4.14. Longitudinal decay of the maximum perturbations in the building wakes compared to the 3D wake model. All the values are normalised by the undisturbed flow at the building height.
Figure 4.15 Centreline variation of flow angle in xz plane with downstream distance at z=H_b for the six building wakes studied.
Figure 4.16. Comparison of the boundary layer characteristics in the EnFlo and BMT wind tunnels in full scale units.
Figure 4.17. Centreline flow perturbations of $U$ and $u^2$ in the wake of the isolated B204, compared to these measured over the Sellafield site for the normal wind direction
Figure 4.18. Centreline flow perturbations of $w^2$ and $uw$ in the wake of the isolated B204, compared to those measured over the Sellafield site for the normal wind direction.
600m upwind of B204
500m downwind of ramp

2km downwind of B204,
and 1.25km downwind of F8

Figure 4.19. Centreline profiles of mean velocity and Reynolds stresses, up
and downstream of the main Sellafield site for the 270° wind direction.
Chapter 5. Dispersion Results

5.1 Introduction

This chapter presents results from dispersion experiments carried out at 1:500 scale in the stratified flow wind tunnel at the University of Surrey. Firstly, dispersion was considered in the undisturbed neutral and stable boundary layers that were developed in our wind tunnel. Once satisfactory dispersion behaviour in the undisturbed boundary layers was obtained, I then investigated elevated releases above generic building groups for a range of release heights and two wind directions. Finally, releases over the large industrial site at Sellafield were investigated, to ascertain how it would be best to simplify this complex situation for the purposes of dispersion modelling. This chapter plays a central part in the investigation of how elevated releases are influenced by buildings, using the percentage reduction in effective stack height to quantify this effect. An effective stack height was calculated from the maximum ground level concentration, \( C_{\text{max}} \), in each building wake, using the relationship between release height and \( C_{\text{max}} \) obtained in the appropriate undisturbed flow. In this way the true perturbation due to the presence of the building was found, rather than comparing the building wake concentrations with some arbitrary dispersion model which may or may not represent the undisturbed boundary layer dispersion characteristics.

5.2 Dispersion characteristics in the undisturbed boundary layers

5.2.1 Growth of vertical and lateral plume dimensions.

Before investigating the effect that the presence of a building has on dispersion from an elevated release, it is important to characterise the behaviour in the undisturbed boundary layer. This was done by measuring vertical and lateral concentration profiles at a number of positions downstream of the source. These profiles were compared with the bi-Gaussian plume equation that appeared as Equation 2.1 at the beginning of the literature review. For the reader's convenience it is repeated here:

\[
\frac{C U_{\text{ref}} H_b^2}{Q} = \frac{H_b^2 U_{\text{ref}}}{2 \pi U_{\text{advec}} \sigma_y \sigma_z} \exp\left(\frac{-y^2}{2 \sigma_y^2}\right) \left[ \exp\left(\frac{-(z-z_p)^2}{2 \sigma_z^2}\right) + \exp\left(\frac{-(z+z_p)^2}{2 \sigma_z^2}\right) \right] \quad (5.1)
\]

where \( H_b \) is the building height (which was 0.125m for all the wind tunnel results), and \( U_{\text{advec}} \) is the mean advection velocity of the plume which is often taken as the velocity at the release position. \( \sigma_y \) and \( \sigma_z \) are the lateral and vertical plume spread coefficients, and \( z_p \) is the plume centreline height. A least squares fit was used to determine the optimum values of the coefficients for each of the measured profiles. All the concentration measurements presented in this report are in non-dimensional units, so that experiments using different release rates etc. can readily be compared. \( Q \) is the source flow rate in \( \text{m}^3/\text{s} \), and \( U_{\text{ref}} \) is the wind speed at the top of the boundary layer.
In the neutral boundary layer, concentration mappings were made for release heights of 15, 100, 175, 250 and 400mm, to determine how the dispersion of the plume was influenced by the release height. A set of vertical profiles for a source height of 100mm is shown in Figure 5.1. The solid lines drawn on the plots indicate a bi-Gaussian vertical profile with optimised values of $\sigma_z$, $z_p$ and the maximum non-dimensional concentration, to give the least squares error with the measured data. The Gaussian parameters, $\sigma_z$ and $z_p$, are recorded at the top right of each individual plot. As the plume is advected downwind its size increases, but its maximum concentration obviously decreases to satisfy continuity. For many of the downstream positions, the Gaussian profile gives a good fit to the concentration distribution. However, considering the profiles at $x=1000$, 1250 and 1600mm, it can be seen that the value of $\sigma_z$ determined from the fitting routine is too small for the dispersion above the release height, but too large for the dispersion below.

The observed difference in spread above and below the mean plume height was most pronounced for the release height of 100mm. The Gaussian model assumes that the plume is spreading in a uniform flow, which of course is particularly invalid in the lower part of the boundary layer, where gradients in the mean velocity and Reynolds stresses are quite significant. For plumes released higher up in the boundary layer ($H_s = 175$mm and above), the Gaussian profile gave a good fit at all the downstream locations, since the majority of the plume is in a region where gradients in the flow are relatively weak. At the 100mm release height, the flow characteristics above and below this plume centreline are substantially different, which causes the Gaussian dispersion model to break down a little for some of the downstream positions.

Looking at the position $x=2500$mm in Figure 5.1, it can be seen that the vertical spread in the neutral boundary layer is nearly twice that of the stable one. The positive temperature gradient with height in the stable boundary layer has suppressed the vertical turbulent fluctuations that are primarily responsible for the growth in $\sigma_z$.

Figure 5.2 shows lateral concentration distributions in the neutral boundary layer, with a similar case in the stable boundary layer. As for the vertical profiles, we see that the stability has significantly reduced the spread of the plume. In the neutral case, the plume centreline remains at the same lateral position as it travels down the tunnel, but in the stable boundary layer, the plume that was released at the centreline has drifted by about 100mm during its 2.5m travel downwind. This cross flow in the stable boundary layer, was originally much more severe and unsteady before perspex side walls were installed in the tunnel to isolate the main flow from the secondary flows generated by the unheated sides of the tunnel. With the side walls installed, the stable boundary layer set up in the tunnel was steady and dispersion results showed good repeatability. This stable boundary layer was judged to be adequate for the requirements of this study, provided centreline ground level concentration profiles were measured along the plume axis, rather than the tunnel centreline.

Figure 5.3 shows the lateral and vertical growth of the plume dimensions in our neutral and stable boundary layers, overlaid onto the Pasquill category C, D and E values used by the R91 model, Clarke (1979). The neutral $\sigma_y$ values shown in the upper plot, were measured at an elevation of 125m, (the boundary layer depth being 500m), for an upwind release at this same height. These lateral plume spreads compare very closely with Gifford's category D values for turbulent diffusion in the atmosphere when applying
Chapter 5

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a scale factor of 1:500 to the wind tunnel data. These are the appropriate curves to compare to the wind tunnel data, since they represent short averaging periods, during which the wind direction remains constant. For both the lateral and vertical plume spreads in the stable boundary layer, the data points at x=250, 500 and 750m, used a release height of 25m, (the boundary layer depth being approximately 100m). The last two downstream positions, used a release height of 50m. The lateral plume spreads in the stable boundary layer are similar to Gifford's category E, but the growth rate, with downwind fetch, is significantly less.

The lower plot in Figure 5.3 compares the vertical plume spreads in both boundary layers to the Hosker fit to Smith's data for a roughness length of 0.4m. The neutral data presented here is for a release height of 50m. These \( \sigma_z \) values are quite typical of the average 'best' fit for the other release heights of 87.5, 125 and 200m which have been studied in the neutral boundary layer. The vertical spreads measured in the neutral boundary layer are quite similar to the category D curve, though further downwind, our values are a little higher. These differences are well within the scatter of the original full scale studies used to determine these atmospheric dispersion curves. The vertical spreads in our stable boundary layer lie between categories D and E, but as was the case for the lateral dispersion results, the growth rate with downwind fetch is significantly less than those observed in the atmosphere. It is not clear why, closer to the source, both the lateral and vertical spreads in the stable boundary layer are nearly identical to those obtained under neutral conditions.

Stability only directly suppresses the vertical fluctuations, but since turbulence is three dimensional, if energy is subtracted in one dimension, it will have a secondary effect in the other directions. Therefore, in the stable boundary layer, we would expect \( \sigma_z \) to be affected more than \( \sigma_y \). The dotted lines on the figure, are power law fits to the data, with the exponent for each case being indicated. We can compare lateral and vertical growth rates of the plume, by taking the ratio of the exponents which for the neutral boundary layer is \( \frac{0.84}{0.88} = 0.95 \). In the stable boundary layer, this ratio is \( \frac{0.65}{0.5} = 1.3 \), so although both the spread rates have been reduced, the vertical component has felt the effect of the stratification more than the lateral component.

5.2.2 Centreline ground level concentrations.

Often, when considering the pollution dosage from a particular elevated release, it is the ground level concentrations that are of the most interest. By placing sample tubes along the centreline of the plume axes, the position and value of the maximum ground level concentration can be found from just one dispersion experiment. Figure 5.4 shows the ground level concentration distributions for a range of release heights in the undisturbed neutral boundary layer. As the release height increases, the maximum concentration, \( C_{\text{max}} \), decreases, and the position at which it occurs, \( X_{\text{max}} \), moves further downstream from the source. The solid lines drawn through the profiles have the equation:

\[
C_{\text{NonDim}} = C_{\text{max}} \left[ \left( \frac{x}{X_{\text{max}}} \right)^{(1+m)p} \exp \left( \frac{1 + m}{2} \left( 1 - \left( \frac{x}{X_{\text{max}}} \right)^{-2q} \right) \right) \right] (5.2)
\]
that was derived assuming Gaussian dispersion with the lateral and vertical plume spreads being represented by simple power law relationships, \( \sigma_y \propto x^p \) and \( \sigma_z \propto x^q \). The ratio between the lateral and vertical growth rates is given by \( m = \frac{p}{q} \). I have used this equation, but treated \( C_{\text{max}} \), \( X_{\text{max}} \), \( m \) and \( q \) as free (which are not free if the dispersion is Gaussian), so that a good representation of the measured concentration distributions could be achieved. Values of 1 and 0.73, were used respectively for \( m \) and \( q \) in Figure 5.4, and were chosen to give the best fit to the concentration distributions for all the release heights in the undisturbed neutral boundary layer. A least squares fit was carried out on each ground level concentration profile to optimise \( C_{\text{max}} \) and \( X_{\text{max}} \). The curves represent the measured data very well, which will enable us to use just these fits rather than all the data points in some of our later comparisons with ground level concentrations measured in building wakes.

Figure 5.5 shows the stable boundary layer results, compared with the corresponding neutral ones. The ground level concentrations, for the releases much above 125mm, were unmeasurable over the measurement range of 2.5m. The curves drawn through the neutral results are the same as those in Figure 5.4, but to facilitate good fits to the stable data, the values of \( m \) and \( q \) were adjusted by the fitting routine for each release height. Taking a first glance at these results, it appears that the change in the dispersion characteristics in the stable boundary layer, compared with the neutral, has led to a significant reduction in \( C_{\text{max}} \), particularly for the taller release heights. Whilst this is true to a certain extent, looking at the vertical concentration profiles measured in the undisturbed stable boundary layer for release heights of 50 and 100mm, it was clear that a modest plume rise of about 15mm per metre was occurring.

To investigate the plume trajectory in the stable boundary layer, a Gaussian plume model was used with a specified plume rise \( (z_p = H_s + 0.015x) \), and compared to one without plume rise \( (z_p = H_s) \), for the 50 and 100mm release heights. The results are shown in Figures 5.6 and 5.7. The modelled lateral and vertical plume spreads were taken from data presented in Figure 5.3 for the stable boundary layer. The solid curve is calculated using the plume rise, and an average advection velocity across the plume depth, to maintain a constant source flux at each downwind cross section, (Section 6.1 goes into more detail about how this was calculated). The dotted line is calculated in exactly the same way, except it uses a constant value of \( z_p \), determined by that of the release height. The solid line is a reasonably good fit to both the vertical and ground level concentration profiles. However, when the plume is modelled using a constant \( z_p \), the fits are poor all round, and the ground level concentrations become significantly larger than the measured values. This suggest that plume rise was occurring in our dispersion experiments in the stable boundary layer. Possible reasons for this are discussed later on in this section, but it appears that the most likely cause was mismatch between the release temperature and that of the surrounding flow.

The results for the 'no plume rise Gaussian model', have been plotted back onto Figure 5.5 for the respective release heights, and appear as the thick dotted lines. Comparing these curves with the neutral results we see that \( C_{\text{max}} \) has not been significantly affected, but \( X_{\text{max}} \) has increased. One would expect the position of the maximum concentration to move further downwind in the stable boundary, since the vertical and lateral plume spreads are both significantly reduced. This was another reason why the
measured ground level concentration in the stable boundary appeared odd, as their \( X_{\text{max}} \) values are very similar to those observed in the neutral boundary layer. This behaviour is explained by the plume rise that was taking place in the stable boundary layer releases.

The upper plot in Figure 5.8 shows the values of the maximum non-dimensional ground level concentrations for the profiles presented in Figures 5.4 and 5.5. The purpose of plotting the results in this way is to obtain empirical relationships between the release height and the corresponding value of \( C_{\text{max}} \), for both the neutral and stable boundary layers. The curves drawn through the data have the equations shown on the plots and will be used to determine an effective stack height for releases made in the vicinity of buildings. One way of determining the dispersion influence that near by buildings have on an elevated release, is to compare \( C_{\text{max}} \) measured with the buildings present, with these data obtained in the undisturbed boundary layer. Using the appropriate equation, we can determine what release height in the undisturbed boundary layer would have produced the same \( C_{\text{max}} \) value. The release height that has just been found is know as the effective stack height.

The lower plot in Figure 5.8, indicates how the position of the maximum ground level concentration increases with release height in the neutral boundary layer. The curve through the data, having the equation shown on the plot, will be used later on, when trying to reproduce representative ground level concentration profiles for any release height in the undisturbed neutral boundary layer.

The reason for the plume rise in the stable boundary layer has not yet been discussed. The possibilities are, either that there was a small vertical velocity in the boundary layer, or that buoyancy effects have been responsible for the plume rise. It is not really practical to measure accurately a mean vertical component that is only 1.5% of the mean flow with the LDA system, since the probe alignment would need to be within 0.1 of a degree (0.85° corresponding to the 1.5% of the mean flow). To investigate whether buoyancy could be responsible for this amount of plume rise, we will consider what temperature difference would be required to produce the observed amount of rise. Briggs (1975), has developed simple plume rise theories for releases having no initial upwards momentum in a stable boundary layer, e.g.:

\[
\Delta z_p = \frac{3}{\beta_e^2} \frac{F_B}{\pi N^2 U} \left( 1 - \cos \left( \frac{N}{U} \right) \right) - b_0 \frac{b_0}{\beta_e}
\]

where \( F_B \) is the buoyancy flux given by:

\[
F_B = Q g \left( \frac{T_s - T_a}{T_s} \right)
\]

where \( T_s \) is the source temperature and \( T_a \) is the temperature of the flow at the release height. \( Q \) is the release flowrate in m³/s, \( \beta_e \) is the entrainment constant, taken as 0.6, and \( b_0 \) is the initial radius of the released plume. The buoyancy frequency given by:

\[
N^2 = \frac{g}{T} \frac{dT}{dz}
\]
is the natural frequency at which a fluid particle will oscillate if it is vertically displaced in a stably stratified flow. The top plot in Figure 5.9, shows the temperature profile in the stable boundary layer at the release position, and the middle plot shows the calculated local buoyancy. At \( z=100\)mm the buoyancy frequency is about 1.75rad/s and the ambient temperature around 52°C. The lowest plot shows how the plume rise, 1.5m downstream of the source, varies with source temperature as calculated by this model. Only a 4 or 5 degree temperature difference is needed to give a plume rise similar to that observed in the stable boundary layer. The tube supplying gas to the source was supported by cable ties, close to the tunnel roof, over a distance of about 4m, where the ambient temperature was around 60°C. The tube then passed vertically downwards to connect to the metal passive stack. The gas entered the tunnel through the pipe at about 24°C, but it is quite possible that, by the time the gas was released at the source, its temperature was close to 60°C. When the experiment was carried out, the importance of the buoyancy effects had not been appreciated, so no measurement was made of the release temperature.

5.3 Ground level concentrations for elevated releases above buildings

5.3.1 The isolated B204 building (Case A).

Having established in the previous section how the ground level concentration profiles vary with release height in both the undisturbed neutral and stable boundary layers, we are now in a position to investigate the effect that any group of buildings is having on the dispersion from an elevated source. Figure 5.10 shows the ground level concentration profiles for building case A in neutral and stable flow for the two wind directions studied. The curves fitted to the data were used to obtain a good estimate of the maximum ground level concentration for each case. The dotted line indicates the undisturbed neutral boundary layer results for the respective release heights, which were obtained from Figure 5.4. The ground level concentration results in the undisturbed stable boundary layer have not been plotted, since, for these release heights, they were immeasurably small.

It is clear from the results, particularly for the lower release heights, that the building has significantly enhanced the ground level concentrations, and has moved the position of the peak closer to the source. For both the neutral and stable data, the 45° wind direction yielded much higher concentrations than the equivalent 0° case. This is due to the strong roof vortices that are created when the approach flow is diagonal to the building, which are very efficient at bring the elevated plume down into the building wake. For a release of 1.4 times the building height, the 45° wind direction increased the ground level concentrations by a factor of 3, compared to the 0° case in the neutral boundary layer. However, in the stable boundary layer, the diagonal wind direction increased the maximum ground level concentration by a factor of 5 for this release height. If we look at the results for the 1.68 building heights release in the stable boundary layer, we find that the factor between \( C_{\text{max}} \) values for the 0° and 45° wind directions has increased yet further, and is tending to infinity as the 0° ground level concentrations become immeasurably small. In the neutral boundary layer, at the higher release heights, the difference between the two building orientations reduces as the influence of the building dies away. The differences in behaviour of the neutral and stable
boundary layers to building orientation sensitivity, are discussed in Section 5.3.4.

One method of assessing the effect that a building is having on the dispersion from an elevated release, is to calculate an effective stack height in the undisturbed flow, which would produce the same maximum ground level concentration as is experienced with the building present. Take, for example, the result of the isolated B204 building in neutral flow for the 45° wind direction and \( H_s = 175 \text{mm} \). The maximum non-dimensional ground level concentration for this profile is about 0.8. Using the upper plot in Figure 5.8, this corresponds to an undisturbed release height of \( H_r = 70 \text{mm} \). In this example, the presence of the building has reduced the effective stack height by 105mm, which is 60% of the actual stack height. To automate the process of obtaining an effective stack height from \( C_{max} \) in both the neutral and stable boundary layers, the appropriate equation shown in Figure 5.8 was used. The tabulated values of effective stack height above each plot shown in Figure 5.10, were calculated in this way using the \( C_{max} \) value determined by the curve fitting routine.

Another way of presenting the building effect, is to determine the increase in \( C_{max} \) compared to the undisturbed flow value for the same release height. For the isolated B204 building in neutral flow for the 45° wind direction, and a release height of \( H_r = 175 \text{mm} \), which was the example used in the previous paragraph, \( C_{max} \) was 0.8. In the undisturbed neutral boundary layer, \( C_{max} \) for a release height of 175mm is 0.1 (see Figure 5.4), so, the ground level concentration has been increased by a factor of 8.

Figure 5.11 plots the analysis of the ground level concentration distributions from Figure 5.10, showing the percentage reduction in effective stack height, and the increase factor in \( C_{max} \) for the range of release heights. If releases are made above the top of the boundary layer, the dispersion of the plume will be very slow indeed, since the turbulence intensities are below 5%. Ground level concentrations for these conditions will be negligible until a long way downwind. The depth of our stable boundary layer was around 200mm, so release heights much in excess of 1.6 \( H_b \) were emitted above the top of the boundary layer, provided the boundary layer depth was unaffected by the presence of the building. This height is indicated on the plot by the vertical dotted line. In the stable boundary layer, ground level concentrations were measured for both building orientations for a release height of 1.68 times that of the building. This suggests therefore, that the building downwash has been responsible for bringing the plume back down into the boundary layer.

Effective stacks heights in the neutral boundary layer have been reduced by up to 50% for the normal wind direction, and by up to 70% for diagonal approach flow. As the release height is increased, the reduction in effective stack height decreases, or in other words, the building effect is reduced. For the 0° case, release heights above twice the building height are practically unaffected by the building, but in the diagonal case, the building effects are still significant at 2.5 \( H_b \). The percentage reduction in effective stack heights obtained in the stable boundary layer are within 10% of those obtained in the neutral boundary layer, and tend to lie above the neutral results.

Error bars have been shown on the neutral results for the normal wind direction, and have been calculated assuming a 0.4 part per million uncertainty on the ground level concentration measurements, as suggested in Section 3.5.4. For the lower release heights, the ground level
concentrations are quite large, and so this error becomes insignificant. However, as the release height increases, this error becomes more like ±5% on the reduction in effective stack height. In other words, the measurement of the maximum ground level concentration becomes progressively more difficult as the release height is increased. Errors for the other series on the plot will behave very similarly, and so have been omitted for clarity.

The factor increase in $C_{\text{max}}$ for the stable boundary layer could not be plotted, since, for the corresponding heights in the undisturbed flow, the ground level concentration were so small as to unmeasurable. From the neutral results, it is clear that the effect of the building is very significant for the lower release heights, and can increase the ground level concentrations by up to a factor of 20.

Using an effective stack height is a simple way of adjusting a model to compensate for the enhanced ground level concentrations in the wake of a building. In this analysis, we are taking the effective stack height distributions straight from the undisturbed flow results presented in Section 5.2.2 and Figure 5.8. To see how well this simple model performs, the neutral measurements presented in Figure 5.10 have been replotted in Figure 5.12, with curves representing the ground level concentration distribution for each effective stack height. In Figure 5.4, we demonstrated that a good fit could be obtained to the ground level concentration data in the undisturbed neutral boundary layer, using Equation 5.2, with $m=1$, $q=0.73$ and appropriate values of $C_{\text{max}}$ and $X_{\text{max}}$. Figure 5.8 plotted the variation of $C_{\text{max}}$ and $X_{\text{max}}$ with release height, and also gave the empirical relationships which have been rearranged to give:

$$C_{\text{max}} = \exp(9.5229 - 2.2861 \ln H) \text{ and } X_{\text{max}} = \exp(1.32 \ln H + 1.15) \quad (5.6)$$

This is how the ground level concentration distributions, corresponding to the desired effective stack height, have been plotted in Figure 5.12. The values used for each curve are tabulated above the plot.

Apart from the 45° building orientation for the lowest two release heights, all these ground level concentration profiles are represented very well using an effective stack height. Certainly, as far as these centreline ground level concentrations are concerned, modelling the building influence on dispersion as just a downwash, which reduces the mean plume height, seems a plausible option. For the lower releases, where the building effect is very significant, the effective stack height simplification does not work as well.

5.3.2 Generic building groups in neutral flow.

In the previous section the ground level concentrations were analysed for a range of stack heights and two wind directions in the neutral and stable boundary layers for building case A. Table 5.1 gives a summary of all the ground level concentrations that have been measured for release heights in the range of 150mm to 400mm or 1.2 to 3.2 as a ratio of the building height. Refer to Figure 3.12 to determine the meaning of the building case names.
Building group | Boundary layers | Wind directions
--- | --- | ---
Case A, Single W=64 | Neutral, Stable | 0,45
Case B, Single W=192 | Neutral, Stable | 0,45
Case C, Single W=320 | Neutral | 0,45
Case D, Single W=448 | Neutral | 0,45
Case E, Nine Sp=32 | Neutral | 0
Case F, Nine Sp=64 | Neutral, Stable | 0,45
Case G, Nine Sp=128 | Neutral | 0,45

Table 5.1. Summary of ground level concentrations measurements made downstream of the generic building cases

The non-dimensional centreline ground level concentration profiles, in both the neutral and stable boundary layers for all the building cases studied, are presented in Appendix 5. The curves fitted to the data are given by Equation 5.2 using values for $C_{max}$, $X_{max}$, $q$ and $m$ as tabulated above each plot. The appropriate effective stack height for each profile has been calculated from $C_{max}$ using the empirical relationships shown in Figure 5.8. The empty plots indicate that no measurements were made for that release height for the building case concerned.

The incentive for studying this range of building cases was to determine the sensitivity of the maximum ground level concentrations for elevated releases to the building group's size and spacing. Figure 5.13 shows the reduction in effective stack height for the seven building cases investigated in the neutral boundary layer. All the lines have in general a negative gradient, showing that as the release height is increased, the building effect reduces, which satisfies our intuitive notions. Comparing the results for the two wind directions, we see that the patterns are significantly different. For the $45^\circ$ wind direction, all the building cases, apart from case A, behaved in a similar manner, whereas for the $0^\circ$ approach flow, the range of effects was much greater. Case E was not studied for the $45^\circ$ wind direction, because it falls between cases B and F in terms of building spacing, and these cases yielded very similar results for this orientation. For the diagonal wind direction for release heights of twice the building height and beyond, the ground level concentrations are insensitive to the spacing between nine similar buildings, when it is changed from zero to twice the building width (case B to case G).

The complex effect of the spacing between the surrounding buildings, has been shown in the upper plots of Figures 5.14 and 5.15 for the $0^\circ$ and $45^\circ$ wind directions. As the spacing is increased from zero to infinity, there is a minima corresponding to a spacing of one building width for the normal wind direction, and two building widths for the diagonally orientated buildings. It is thought that this minima corresponds to the spacing at which the individual building wakes interact the strongest, generating the highest turbulence intensities in the combined wake. This would enhance the lateral dispersion in the wake, reducing the maximum ground level concentrations as a consequence. We know from cross wire measurements made downstream of building case A, that the wake at $45^\circ$ is significantly wider than for the normal wind direction. It seems reasonable therefore, if the individual wakes are wider, that the separation producing maximum interaction should also increase for the $45^\circ$ building orientations.
One of the commonest ways of representing a group of buildings in dispersion models is by forming a single cuboid of appropriate dimensions. The Atmospheric Dispersion Modelling System (ADMS) CERC (1995), represents surrounding buildings in this way. After specifying the main building, if any of the surrounding buildings are above half the height of the main building, and are spaced by less than half the main building's width, then an enclosing building is formed around the group. If the flow is diagonal to the group, the orthogonal width of each building is used. The upper plot in Figure 5.14 shows that as the spacing between the eight surrounding buildings is increased from zero, the dispersion effect caused by the group decreases, reaching a minima when $Sp/(W_b \text{ for case A}) = 1$. However, if this group were modelled using an enclosing building, from the lower plot we see that the building effect would increase with the size of the cuboid. As the spacing becomes more than half that of the main building width, ADMS would ignore the surrounding buildings, and treat the main building as isolated. For the higher release heights, this is a good approximation, but it is conservative for releases below 1.5 times the building height.

The effect of the building array spacing on dispersion for the diagonal approach flow is shown in Figure 5.15. If we ignore the results for building case A, sensitivity of the effective stack height to increasing the spacing, or increasing the total size of the cuboid, is weak particularly, for the higher release heights. So, for the 45° wind directions, the exact size of the cuboid chosen to represent the building array, is not very important, as long as $W_b/(W_b \text{ for Case A})$ is greater than about 3. However, when the surrounding buildings are spaced by more than half their orthogonal width to the flow, $Sp/W_b = 3$, ADMS will consider the central building to be isolated from the group. For the higher releases this will lead to the ground level concentrations being underestimated.

A number of methods of estimating the effect of a group of buildings on the dispersion of an elevated release above the array centre have been compared in Figure 5.16. The cross symbols indicate the measured results for the array of nine building for the range of spacings investigated in the neutral boundary layer (cases B, E, F and G) having spacings: $Sp/(W_b \text{ for case A})=0$, 0.5, 1 and 2 respectively. The solid diamonds show the effect of putting an enclosure around the whole array, to form a single cuboid having the same external dimensions as the group, (cases C and D). From these plots, it is clear that the building effect has been enhanced by enclosing the array to form one large building, causing estimates of ground level concentration in some cases to be very conservative. This is particularly true for the normal wind direction, since as the spacing is increased, the building effect decreases, but if the enclosed array is considered, the building effect is amplified.

Another way of representing an array of buildings is to collapse them together to form a single building having a volume equal to the sum of all the individual ones. In our study, this is true of case B, and is indicated on the plots as one of the horizontal lines. For the diagonal wind direction, this simplification is quite good over the range of array spacings and release heights investigated. However, for the normal wind direction, as the spacing increases, this approximation becomes progressively conservative.

As the spacing between the nine buildings is increased, it seems logical to expect that the dispersion behaviour will become more like that of the isolated central building over which the plume is released. The results for the isolated building (case A), are indicated as another horizontal line on
the plots. For the normal wind direction, provided the buildings are spaced by more than half their width, the effect of the eight surrounding buildings is almost negligible, as far as the maximum ground level concentrations are concerned. However, for the diagonal wind direction, the surrounding buildings do significantly enhance the measured ground level concentrations.

So, for the normal wind direction, provided the buildings are spaced by more than half their width, the building effect can be approximated to that of the isolated central building (case A). But for the diagonal approach flow, representing the array as an equivalent single building having a volume equal to the sum of the individual buildings, appears to be the best simplification. The horizontal lines on the plots, indicating the Sellafield site results, will be discussed in Section 5.3.3.

Predictions from the ADMS dispersion model CERC (1995), were also compared with data in terms of the reduction in effective stack heights for the building groups. The boundary layer was modelled using a 10m wind speed of 5m/s, a depth of 500m, and a surface roughness of 0.175m. The standard deviation of wind speed was set to zero, to match the wind tunnel conditions as closely as possible. The model was first run with the building module inactivated, to determine the relationship between release height $H_s$ and the maximum ground level concentrations in the modelled undisturbed boundary layer. $C_{max}$ values were then obtained for the various release heights over the building groups for the range of spacings. Effective stack heights were calculated using the relationship between $H_s$ and $C_{max}$ obtained for the modelled, undisturbed boundary layer. This method helps to eliminate differences between the undisturbed dispersion characteristics in ADMS, compared to our neutral boundary layer in the wind tunnel.

The step changes in the output from ADMS, over the range of building array spacings, is caused by the way in which the enclosing cuboid is determined. As mentioned earlier, if the surrounding buildings are separated by more than half the width of the main building, then they are not included when determining the enclosing cuboid. The reason for the two steps, which appear for the normal wind direction, is because the longitudinal and lateral separations, are not equal in our building array configurations. So, as the spacing is increased from zero, ADMS firstly enclosed all nine buildings, then only the closest three, and finally just the dimensions of the central building are used. For the diagonal wind directions, because ADMS considers the dimensions orthogonal to the flow, the effective width of the central building is increased, and so, over the range of spacing we considered, the main building was never represented as isolated. The only step change occurred when the enclosing building changed from including all nine buildings to just the 3 closest ones.

For the diagonal wind direction, the results from ADMS agree reasonably well with those obtained over the spaced arrays of buildings. Measurements made over the enclosed groups also gave similar reductions in the effective height of the release. Provided the buildings produce sufficient downwash to bring the plume into contact with the ground just downstream of the recirculation region, $C_{max}$ seems insensitive to the size of the building, or the porosity of the array. However, this is not true of the normal wind direction, since increasing the array spacing decreases ground level concentrations, but increasing the size of the enclosing building leads to enhanced ground level concentrations.
As the spacing between the buildings is increased for the normal approach flow, ADMS overestimates the effect of the group quite substantially for some situations. Looking more carefully at the results, we see that the discrepancy is not coming from the way in which the array has been represented, but is due to the dispersion effect that ADMS attributes to the isolated building. The effective stack height reduction predicted by ADMS for building case A with $H_b/H_s = 2$, is a significant 32%, but for releases above 2.5 times the building height, the presence of the building is ignored completely. For the lower releases, when the spacing is zero (case B) ADMS, seems to underestimate the building effect.

It would appear from these results that the main weakness with the current ADMS model lies in the fact that it predicts too large an effect for a single cuboid at 0° to the wind. The way in which complex building groups are simplified by ADMS, seems quite reasonable as far as predicting the maximum ground level concentrations are concerned. For the diagonal approach flow ADMS predictions are much more realistic, maybe because the sensitivity of the ground level concentrations to the building size, and porosity, is fairly weak.

### 5.3.3 B204 on the Sellafield site model.

We have considered in the previous sections the effect that a range of generic buildings have on the dispersion from an elevated release. Building case A is a 1:500 scale model of the B204 building at the Sellafield site. So we have already considered the effect on dispersion of the isolated B204 building, and then with it surrounded by other buildings of the same size. Now we will investigate how the real surrounding buildings and topography at Sellafield alter the plume dispersion behaviour of elevated releases above B204. Figure 5.17 shows the ground level concentrations over a 1:500 scale model of the site in neutral and stable flows for a range of release heights. The buildings on the Sellafield site are mainly cuboids, which are aligned in the same orientation as B204; see Figure 3.16. The data marked as 0° in the legend, was actually the 270° wind direction over the site, and the diagonal wind direction, marked as 45°, was actually 150°. The data has been marked in this way to aid comparison with the generic building groups results. The solid lines on the plots are curves fitted to the data to obtain a best estimate of $C_{max}$, from which the effective stack heights have been calculated that are tabulated above each plot. The dotted curves represents the ground level concentrations that would be observed in the neutral boundary layer for the same release height, without the site being present. Ground level concentrations for these release heights in the stable boundary layer, were immeasurable.

The actual stack height for B204 is twice the height of the building, so we can see that, in the neutral boundary layer for the normal (270°) wind direction, the effect of the site is negligible. For a diagonal approach flow, the site reduces the effective stack height of B204 by around 26%. For the lower release heights, the presence of the site has significantly enhanced the ground level concentrations in both boundary layers, but what we need to determine is how much of this effect is caused by the closest building to the release, namely B204. Put another way, is the dispersion behaviour dominated by one local building, or is the surrounding site and topography, also playing an important role?

The reduction in effective stack heights for releases over the site, have been compared with the isolated B204 building results (case A) in the lower
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plot of Figure 5.18. Surprisingly, we note that the corresponding experiments with and without the site present, yield similar effective stack heights, and in the neutral boundary layer, the influence on dispersion of the entire site appears less than B204 on its own. Elevated concentration profiles, measured over the site, indicated that the increased turbulence generated by the surrounding buildings has slightly enhanced the lateral spread of the plume, whilst leaving the vertical spread and plume centreline height unchanged. This has caused the maximum ground level concentration to be reduced, since the same volume of stack gas is now distributed over a greater cross stream area.

For the higher release heights in the stable boundary layer, the ground level concentrations measured with the site present were greater than for the isolated B204. This behaviour may indicate that the surrounding site is having an important effect on these higher release heights in the stable boundary layer. Alternatively, this effect may have been caused by the site model allowing no heat transfer from the flow, as it was constructed of foam plastic. With no heat flux through the floor, the stability in the boundary layer decreases, allowing primarily the vertical fluctuations to grow. This would enhance the vertical spreading rate of the elevated plume, causing the ground level concentrations to be increased.

Experiments were carried out around the isolated B204 building for the lowest release height in the stable flow, with and without the cooling panels operating downstream of the release position. The centreline ground level concentrations measured in these two scenarios were nearly identical. It was not appreciated at the time, that for the higher releases, where the building affect is less dominant, changes in the background flow could be more important. Therefore, no similar test was carried out with higher releases, so we cannot be sure how much effect the insulating properties of the site model had in perturbing the dispersion behaviour in these cases.

In Section 5.3.2, we were considering the effect of the spacing between an array of nine B204 buildings on the dispersion of elevated releases above the array centre in the neutral boundary layer. Comparisons are made of different methods of representing the array in Figure 5.16; the neutral results obtained over the Sellafield site have also been plotted. Considering firstly the normal wind direction, we find that the cross on the far right of each plot (building case G representing the largest spacing), is closest to the Sellafield results over the range of release heights. This generic case is similar to the actual constructions around B204 at the Sellafield site, except that, most of the actual surrounding buildings are more like half the height of B204. However, the simplification of assuming B204 in isolation is not a bad estimate, particularly for the higher release heights.

For the diagonal approach flow, building case G, yields significantly larger ground level concentrations for the higher release heights than does the Sellafield site. Taking the B204 in isolation for the diagonal case, is the closest of all the generic building groups studied to the dispersion behaviour over the Sellafield site.

5.3.4 Effect of the stable boundary layer on dispersion.

The top three plots in Figure 5.18 compare the reduction in effective stack heights caused by building cases A, B and F, in the neutral and stable boundary layers for the two wind directions. The plot for case A, has already appeared in Figure 5.11, but has been shown again for ease of
comparison with the other cases. The vertical dotted lines on the plots, indicate the height beyond which releases would be above the top of the undisturbed stable boundary layer. The building height to boundary layer height ratio, is about 0.625 in the stable boundary layer, compared to 0.125 in the neutral boundary layer. Some of the trends in the stable boundary layer results are similar to those observed under neutral conditions; for example, the diagonal building orientation in both flows had the larger effect on dispersion. It appears that for the higher release heights in the stable boundary layer, the reduction in effective stack height caused by the building is greater than in the corresponding neutral case. It was noted, when discussing Figure 5.10 in Section 5.3.1, that the sensitivity of the maximum ground level concentration, $C_{\text{max}}$, to the building orientation, increased with release height in the stable boundary layer, whereas the opposite was true for the neutral boundary layer. Similar behaviour can be observed from the concentration measurements made over the Sellafield site, which were presented in Figure 5.17.

The difference between our stable and neutral boundary layers is not just the stratification; the neutral boundary layer is roughly five times the depth of the stable boundary layer. Whilst, in a statistical sense, these depths are quite typical of atmospheric boundary layers in their respective stability classes, from a dispersion point of view we have changed two parameters at once. Plume dispersion is highly related to the turbulence intensity in the flow, which, in a boundary layer, is a strong function of height. Since the stable boundary layer is relatively shallow with respect to the neutral boundary layer, the vertical gradients in the Reynolds stresses are much steeper. If an elevated plume underwent the same downwash, due to a building in both boundary layers, the change in the local dispersion characteristics of the flow would be much more significant in the stable boundary layer due to the sharper vertical gradients. This effect would be accentuated if the plume was initially above the top of the boundary layer, with the downwash causing the plume to move into the boundary layer.

The obstacle Froude number can be calculated for the building in the stable boundary layer and given by:

$$F = \frac{U_b}{N H_b}$$

where $U_b$ is the velocity at the building height. From Figure 4.1, we can see that $\frac{U_b}{U_{\text{ref}}}$ is about 0.84 for $H_b=125$ mm, and $U_{\text{ref}}$ in the stable boundary layer is 1.35m/s. The buoyancy frequency $N$, was plotted in Figure 5.9, and has a value of about 1.5 rad/s at the height of the building. So, for all the generic buildings studied in the stable boundary layer, the obstacle Froude number is around 6. Snyder (1994) found that for Froude numbers greater than 2.5, the behaviour of the immediate flow around the building was dominated by the mechanical turbulence generated by the building. This was deduced by the concentration field, for a ground level release at the lee of the building, remaining unchanged in the near wake when compared to the neutral case. However, further downwind, the stratification in the background flow becomes important, thus affecting the concentration field. So for a Froude number of 6, we would expect the size and shape of the recirculation region to be similar to that obtained in the neutral boundary layer. This means that the initial downwash caused by the building on an elevated release is probably also similar. However, further downstream the dispersion behaviour becomes dominated by the undisturbed flow characteristics, which differ significantly between our neutral and stable boundary layers.
This may be why the behaviour of the lower release heights in the stable boundary layer is so similar to those in the neutral, since they are dominated by the immediate flow around the building.

Earlier on in this section, mention was made of the sensitivity of the ground level concentrations to building orientation for the higher releases in the stable boundary layer; see Figures 5.10 and 5.17. For releases of 1.68 and 2 times the building height, the plumes would remain above the top of the stable boundary layer, if the building downwash was not present. So, this increased sensitivity is caused by the importance of whether the downwash is large enough to bring the plume down into the boundary layer or not. If the plume remains above the boundary layer, the ground level concentrations will be zero, but once the plume is within the boundary layer, the vertical spread will enable ground level concentrations to be observed.

It is difficult to determine which stability would give rise to the highest ground level concentrations with the buildings present at full scale. Just looking at Figures 5.10 and 5.17, it appears that the neutral boundary layer will be the worst case, but there are a number of other factors that could change this conclusion. Stable boundary layer flows are generally associated with light winds, whereas in a strong wind the vertical temperature gradient would have to be very steep for buoyancy effects to be important. All the concentrations have been normalised by the flow speed at the top of the boundary layer. Typical values of wind speed in the atmosphere would be 2m/s, for a stable boundary layer, but more like 6m/s in the neutral case. This would effectively triple all the concentrations in the stable flow relative to those in the neutral boundary layer. Another factor to consider is that the standard deviation of the wind direction increases significantly as the wind speed falls. Increasing the variation in wind direction leads to a significant increase in the lateral spread of the plume, which would result in the maximum ground level concentrations being reduced.

Returning to Figure 5.18, we have seen that the effective stack heights in both the boundary layers are similar for the lower releases, (below 1.5 building heights), but as the release height increases, the building influence in the stable boundary becomes greater than for the corresponding neutral flow set up. This behaviour for the higher releases may be a result of the stratification, or an effect caused by the proximity of the plume to the top of the stable boundary layer. Further work is necessary to determine this in a stable boundary layer, having a smaller building height to boundary layer depth ratio. More care also needs to be taken in future to match the release temperature to that of the local flow, so that a truly passive release is achieved. For the higher releases, vertical concentration profiles, with and without the buildings present, would help in determining the effect that the building is having on the plume. This is because the high releases lead to very low ground level concentrations that cannot be measured very accurately.

5.3.5 Dispersion over the Sellafield site compared with the BMT study.

The centreline ground level concentrations over the Sellafield site model, have been compared to earlier measurements made by Singh (1990), in the British Maritime Technology (BMT) tunnel, for releases above B204. This previous research project was undertaken for BNFL, to investigate amongst
other things, the influence of topography and buildings on dispersion from tall stacks in neutral stability. Our research project has built up to this complex situation by firstly considering the B204 as an isolated building, then with it surrounded by similar buildings, before studying the full Sellafield site model. We then took the problem one stage further, to consider the building influence when a stable boundary layer approaches the site.

The comparison of the flow characteristics in the neutral boundary layers, immediately upwind of the main site buildings for both wind tunnels, was presented in Figure 4.16, and discussed at the end of chapter 4. The main conclusions were that the simulated boundary layers were quite similar, but in the BMT tunnel, the turbulence intensities were slightly higher. Turning to the dispersion characteristics of the undisturbed boundary layers, the only data we have from BMT’s study are ground level concentrations for the isolated B230 stack, having a full scale height of 76m, with a exit velocity ratio of 5.3. The B230, is a stack that is not connected to any building, but protrudes straight out of the ground. The top plot of Figure 5.19, compares the results with a corresponding set up in the EnFlo tunnel, using a conventional stack, with a vertical exit velocity of 5.3 times that of the local wind speed. Beyond 2km downstream, the concentrations are very similar, but closer to the source BMT’s values do not seem to fall off as one would expect. In the BMT tunnel, the concentration measurements were made using on-line flame ionisation detectors, sampling for 50 seconds at each measurement position. Since their free stream tunnel speed was about 10m/s, compared to ours, which was 2.5m/s, this averaging period would correspond to 200 seconds in the EnFlo tunnel. We sampled for about 18 minutes, but the majority of this time is spent in purging the sampling tubes and coils. However, it is clear from the results, that the increased sampling time has significantly smoothed the profile. Without information on the elevated plume behaviour in BMT’s undisturbed boundary layer, it is not possible to know why such high ground level concentrations were present so close to the elevated release. When determining the effect of a building on any dispersion problem, it is imperative to have a reliable reference set of data that adequately describes the dispersion behaviour in the undisturbed flow.

The lower plot in Figure 5.19 shows the ground level concentration profiles from the B204 stack for two wind directions in each tunnel. The central part of the Sellafield site model is constructed to form a 4.5m diameter circle, which was positioned on a turn table in the BMT tunnel, so that the desired wind directions could be studied. However, the EnFlo tunnel is only 3.5m wide, so only part of the circle could be installed. This made certain wind directions more favoured than others, depending on the existing cut lines in the model. This is why the exact wind directions were not repeated in our investigation, but the 264° and 270° direction are very similar, and represent the 0° cases; and the 68° and 150° directions are both representative of diagonal approach flows. From the generic results, it was found that the exact angle of the building to the flow did not significantly influence the ground level concentrations, provided the flow was basically diagonal, but this was not explicitly demonstrated over the site model.

The ground level concentrations for both wind directions in the BMT tunnel are higher than our corresponding values by about 33%. Since the ground level concentrations further downstream for the isolated stack are similar in both tunnels, it is not clear why the effect of the site appears to be more significant in the BMT study. The release above B204, in the BMT tunnel, had a vertical exit velocity of around twice the local wind speed, but
in the EnFlo tunnel, a passive release was used, having no initial vertical momentum. Figure 5.20 compares ground level concentrations for the passive release, with those obtained using a conventional stack above B204 for the 270° wind direction. As the exit velocity ratio is increased, the ground level concentrations fall off, since the effective plume height is being increased. However, it can be seen that, for a velocity ratio of 2, the results for the conventional and passive releases are virtually identical. Differences between the EnFlo and BMT ground level concentrations cannot therefore be attributed to the release conditions. In the EnFlo tunnel, elevated concentration profiles were taken to complement those made at ground level, to increase our understanding of the influence of the site on dispersion. With no such information from the BMT tunnel, it is not possible to check if their results are self consistent.

BMT obtained effective stack heights from the ground level concentration distributions by comparing them with the R91 Gaussian model for dispersion in the undisturbed neutral boundary layer. This method assumes that the dispersion characteristics in BMT’s undisturbed boundary layer are well represented by R91, but this was not demonstrated. All our effective stack heights are calculated by comparing the maximum ground level concentration in the building wake with values of $C_{max}$ obtained for a range of release heights in the undisturbed boundary layer. Our method does not make any assumptions about what the undisturbed boundary layer dispersion characteristics are, but makes a straight comparison between the ground level concentrations with and without the building present. The BMT study claimed that the influence of the Sellafield site on the B204 release, caused its effective height to be between 50 and 70% of its physical height. Our study suggests that these values are rather conservative, and that the actual effective height of B204 lies more between 74 and 97% of its physical height, depending on the direction of the approach flow. If we recalculated our effective stack heights, assuming that our ground level concentration distributions over the site for the 150° and 270° wind directions should both be enhanced by 33%, the effective height of the B204 release would still be between 65 and 86% of its physical height. It seems clear, therefore, that the discrepancy in effective stack height predictions between the two studies does not arise purely from the differing ground level concentrations but is also strongly influenced by the method used to determine these effective stack heights from the ground level concentrations.
5.5 Conclusions drawn from the dispersion results

Comparisons of the dispersion characteristics for our neutral boundary layer have shown that the plume spreads are very similar to those observed in the atmosphere for a category D Pasquill stability. The dispersion in the stable boundary layer falls between categories D and E, but with lower growth rates for both the vertical and lateral plume spreads. For all the building groups studied, the diagonal wind direction produced the higher ground level concentrations, or the greater reduction in effective stack height. The results for the reduction in effective stack height that were obtained in the stable boundary layer tend to lie above the corresponding neutral results, particularly as the release height increases. The higher release heights were above the top of the undisturbed stable boundary layer, but for the diagonal building orientations downwash brought the plume back down into the boundary layer, causing ground level concentrations to be measurable. For these higher release heights, the proximity of the plume to the top of the boundary layer is certainly influencing the effective stack height predicted in the stable boundary layer. So, not all the differences in dispersion behaviour between the two boundary layers can be attributed directly to the stratification.

It was found that for elevated releases above the nine spaced building groups in the neutral boundary layer (Cases E, F and G) the following simplifications could be used. For the normal wind direction, provided the spacing between the buildings is more than half their width (Sp>Wb/2), the building effect can be approximated to that of the isolated central building (case A). For the diagonal approach flow, representing the array as an equivalent single building having a volume equal to the sum of the individual buildings, yields the most similar behaviour in terms of the maximum ground level concentrations. This result implies that, an array of nine spaced buildings can be adequately represented by a single cuboid, of appropriate dimensions, for a wide range of elevated release heights.

We have found that the ground level concentrations, for releases above B204 over the Sellafield site, are not significantly different to those obtained when B204 is an isolated building (case A). This is a surprising result, considering the complexity and extent of the industrial site. Our results indicate that the effective height of B204 is between 74 and 97% of its physical height, rather than 50 to 70% as indicated by the BMT study. Although the ground level concentrations measured by BMT over the site are 33% higher than our corresponding values, it is believed that the major difference is being introduced by the method used to obtaining an effective stack height from the ground level concentration distribution.
Figure 5.1 Vertical concentration profiles in the undisturbed neutral boundary layer for a range of downstream positions, (including one stable profile at x=2500mm). Also shown are Gaussian fits and their parameters.
Figure 5.2 Lateral concentration profiles for passive releases in the undisturbed neutral boundary layer for a range of downstream positions, (including one stable profile at x=2500mm). Also shown are Gaussian fits and their parameters.
The horizontal standard deviation, \( \sigma_y \), of plumes released in the undisturbed neutral and stable boundary layers, compared to Gifford values of horizontal turbulent diffusion for stability categories C, D and E.

The vertical standard deviation, \( \sigma_z \), of plumes released in the undisturbed neutral and stable boundary layers, compared to the Hosker fit to Smith's data for Pasquill stability categories C, D and E with \( z_0 = 0.4 \text{m} \)

Figure 5.3. Growth in plume dimensions with downstream distance in EnFlo's undisturbed neutral and stable boundary layers, compared to plume dispersion observed in the atmosphere for three Pasquill stability categories. Wind tunnel scale is 1:500.
Figure 5.4. Centreline ground level concentration profiles in the undisturbed neutral boundary layer for a range of release heights. Curves fitted to the data to obtain a best estimate of $C_{\text{max}}$ and $X_{\text{max}}$ for each profile.
Figure 5.5. Centreline ground level concentration profiles in the undisturbed neutral and stable boundary layers for a range of release heights. Curves fitted to the data to obtain a best estimate of $C_{\text{max}}$ and $X_{\text{max}}$ for each profile.
Figure 5.6. Concentration measurements in the undisturbed stable boundary layer for $H_s=50$, compared to two Gaussian models, one with, and one without $z_p$ remaining constant.
Figure 5.7. Concentration measurements in the undisturbed stable boundary layer for $H_s=100$, compared to two Gaussian models, one with, and one without $z_p$ remaining constant.
Figure 5.8. Variation of the maximum non-dimensional ground level concentration, and its downstream location with increasing release height in the undisturbed neutral and stable boundary layers.
Temperature profile in the stable boundary layer at the release position, X=15m

Buoyancy frequency in the stable boundary layer

Plume rise 1.5m downstream of the release for a release height of 100mm

Figure 5.9. Temperature and Buoyancy frequency profiles used to predict plume rise associated with a buoyant release at $H_s = 100$ mm in the stable boundary layer.
Figure 5.10. Centreline ground level concentration distributions for building case A in neutral and stable flow for a range of release heights. The curves fitted to the data were used to obtain the maximum non dimensional concentration, \( C_{\text{max}} \), from which the effective stack height has been calculated.

\[
C_{\text{H} \alpha \text{max}} = C_{\text{max}} \left[ \frac{x}{X_{\text{max}}} \right]^{(\text{H} - H_{\alpha})/H_{\alpha}} \exp \left( \frac{1 + m}{2} \left( 1 - \frac{x}{X_{\text{max}}} \right)^2 \right)
\]
Figure 5.11. Reduction in effective stack height, and the enhancement of the maximum ground level concentrations, with increasing release height above building case A in both the neutral and stable boundary layers.
Figure 5.12. Centreline ground level concentration distributions for building case A in the neutral flow for a range of release heights. The solid lines indicate the concentration distributions for the appropriate effective stack height in the undisturbed boundary layer.
Figure 5.13. Reduction in effective stack height caused by the building groups at 0 and 45 degrees to the approach flow in the neutral boundary layer.
Figure 5.14. Effect of the spacing between surrounding buildings on the reduction in effective stack height for the normal wind direction in the neutral boundary layer.
Figure 5.15. Effect of the spacing between surrounding buildings on the reduction in effective stack height for the diagonal wind direction in the neutral boundary layer.
Figure 5.16. Results for how the spacing between nine identical buildings influences the effective height of the release are shown by the crosses. The other series show the performance of various simplifications or models that represent the array as a single cuboid.
Figure 5.17. Centreline ground level concentration distributions for a range of release heights over B204 on the Sellafield site in neutral and stable flow. The curves fitted to the data were used to obtain the maximum non-dimensional concentration, $C_{\text{max}}$, from which the effective stack height has been calculated.
Figure 5.18. Variation of the reduction in effective stack height, with increasing release height, for the building cases studied in both the neutral and stable boundary layers.
B230 isolated stack $H_s=76m$ with a vertical velocity ratio of 5.3. The same release conditions were used in both tunnels.

Release above B204 with the Sellafield site model installed $H_s=122m$. BMT releases made using a vertical stack having a velocity ratio of 2. EnFlo releases were made using a passive stack (No vertical velocity).

Figure 5.19. Comparison of EnFlo’s centreline ground level concentrations with the BMT results for the isolated B230 stack (upper), and for releases above B204 (lower).
Figure 5.20. Centreline ground level concentration measurements made in the EnFlo tunnel for releases above B204 with the Sellafield site model installed for the 270 degree wind direction. The release conditions were varied over a range of velocity ratios from 0 (passive) to 8, with the release height remaining constant at 122m.
Chapter 6. Development of a Gaussian plume model

6.1. A simple Gaussian model

Vertical, lateral and ground level concentration profiles have been measured for plumes dispersing in the wakes of various building groups. These profiles have been compared to Gaussian distributions to quantify the dispersion behaviour in terms of the lateral and vertical spreads, \( \sigma_y \) and \( \sigma_z \), and the position of the plume centreline height. In many of the cases studied, Gaussian shaped distributions have fitted the measured data very well. For these profiles, the maximum concentration was optimised to obtain the best fit to the data, but to test the applicability of the Gaussian model to predict the dispersion behaviour, it is necessary to calculate the concentration magnitude, using the chosen values of \( \sigma_y \) and \( \sigma_z \). The equation for the bi-Gaussian plume model appeared previously as Equation 2.1, but is repeated here for the reader's convenience:

\[
\frac{CU_{ref}H_b^2}{Q} = \frac{H_b^2U_{ref}}{2\pi U_{adv} \sigma_y \sigma_z} \exp\left(\frac{-y^2}{2\sigma_y^2}\right) \left[ \exp\left(\frac{-\left(z-z_p\right)^2}{2\sigma_z^2}\right) + \exp\left(\frac{-\left(z+z_p\right)^2}{2\sigma_z^2}\right) \right] \tag{6.1}
\]

The parameters on the right hand side that need to be determined are \( U_{adv} \), which is the mean advection speed of the plume, the plume spreads: \( \sigma_y \) and \( \sigma_z \) and the centreline height of the plume \( z_p \). In the simplest Gaussian model, \( \sigma_y \) and \( \sigma_z \) are functions only of downstream distance \( x \), and the advection speed is taken as the local velocity at the release position. The plume height is assumed to remain constant with downstream distance, i.e. no plume rise or downwash is occurring. The growth of \( \sigma_y \) and \( \sigma_z \) with downstream distance in our undisturbed neutral boundary layer can be found from the lateral and vertical concentration profiles that were presented in Figures 5.1 and 5.2. The plume spreads \( \sigma_y \) and \( \sigma_z \) are plotted in the left hand plot of Figure 6.1, along with representative curves that will be used by the Gaussian model. This formulation of the dispersion allows the plume to grow initially as \( x \), but further downstream it tends to \( x^{0.5} \).

To conserve the volume flux of concentration in the boundary layer the mean advection speed needs to be determined. Knowing the velocity profile in the boundary layer, the mean advection velocity across the plume depth can be calculated in the following way:

\[
U_{adv} = \frac{\int_0^{750} C(z)U(z)dz}{\int_0^{750} C(z)dz} \tag{6.2}
\]

where the concentration, \( C(z) \), is calculated from the vertical spread part of Equation 6.1, and \( U \) from the velocity profile power law fit shown in Figure 6.1. In the Gaussian model that has been written in Excel 5.0, the advection velocity was calculated numerically by summing over 75 steps of 10mm. This was implemented by writing a function that ran in Visual Basic which is available within Excel 5.0.
From fitting bi-Gaussian profiles to the measured vertical concentration distributions for a release height of 250mm in the neutral boundary layer, it was found that the least square error with the data was achieved if the plume height, \( z_p \), slightly increased with downstream distance. The bottom right plot in Figure 6.1, shows the variation of the fitted \( z_p \) values with downstream distance, which can be modelled as a straight line having a gradient \( \frac{dz_p}{dx} = 0.0012 \).

Using the relationships shown in Figure 6.1 to describe the behaviour of \( \sigma_y \), \( \sigma_z \) and \( z_p \) with downstream distance, and calculating \( U_{adv} \) from equation 6.2, we can compare the Gaussian model results to the vertical and ground level concentration measurements along the plume centreline. This comparison is shown in Figure 6.2 for a release height of 250mm in the undisturbed neutral boundary layer. The values of \( \sigma_y \), \( \sigma_z \), \( U_{adv} \) and \( z_p \) were evaluated every 250mm in the \( x \) direction to form the ground level concentration distribution and at the positions of the vertical profiles. The lowest data point from each vertical profile has been plotted along with the ground level concentrations to give a feel for the experimental scatter when measuring these small concentrations, relative to the background hydrocarbon concentration in the approach flow. The Gaussian model describes the elevated dispersion behaviour very well, with the peak concentrations being predicted within 10%, for most of the downstream positions. The position of the peak in the ground level concentration distribution, \( X_{max} \) is underestimated but the maximum concentration value is well predicted. \( X_{max} \) is very sensitive to \( \sigma_z \), so when a single value is used above and below the plume centreline, it results in the modelled plume contacting the ground too quickly.

The variation of calculated plume advection velocity with downstream distance, (using Equation 6.2), has also been plotted in Figure 6.2. As an elevated plume spreads vertically with downstream distance in a boundary layer, the average advection velocity initially slightly falls due to the sharper velocity gradient below the plume centreline (closer to the ground), than above it. Further downwind, when the ground reflection term in the bi-Gaussian model becomes significant, the net result of the vertical dispersion increases the average height of the plume causing the advection velocity to rise. However, the variation of the advection velocity with downstream distance only changes the concentration predictions by just over 1% in this example, so if a constant value for \( U_{adv} \) was used, determined by the release height, the difference in model performance would have been negligible.

Figure 6.2. has demonstrated that when optimised values of \( \sigma_y \), \( \sigma_z \) and \( z_p \) are used in a Gaussian model, the elevated concentrations are predicted very well, but close to the ground, where there are sharp gradients in the boundary layer dispersion characteristics, the model over predicts the concentrations for smaller values of \( x \). With the majority of the plume being faithfully represented by a Gaussian model, we can now start to investigate what parameters need to be adjusted to describe the plume behaviour when it is affected by buildings.

Vertical profiles at downstream positions of \( x=500, 1250, 2500 \) and 4000mm have been measured along the centreline of the plume for building groups A, B and F for the normal and diagonal wind directions. The plume was released at twice the building height from a ‘passive stack’ having no initial vertical momentum and of ambient density in the neutral boundary layer. The measured profiles were all well represented by the bi-Gaussian shape enabling values for \( \sigma_z \) and \( z_p \) to be obtained from the fits. Figure 6.3
shows the effect the building groups have on these parameters compared to the undisturbed boundary layer results. Looking firstly at $\sigma_z$ we notice that for all the building cases the values are very similar and within experimental scatter they are the same as for the undisturbed boundary layer. However, the $z_p$ values clearly are significantly affected by some of the building groups. The six cases studied seem to divide up into three groups of two in terms of the effect they have on an elevated release. Building groups B and F at $45^\circ$ produced the largest downwash in the plume which resulted in the most enhanced ground level concentration profiles. The increase in ground level concentrations caused by the building groups is due to vertical advection of the plume as a whole (downwash), rather than the plume being spread downwards more rapidly by the excess turbulence in the wake. Building groups A and F normal to the flow, only slightly reduced the plume rise from the undisturbed case and produced only marginally higher ground level concentrations.

The downwash of elevated releases due to the presence of the buildings was also observed in the flow visualisation experiments which were carried out. Figure 6.4 shows time averaged video images for releases at 1.4 and 2 times the building height over building case F, at $0^\circ$ and $45^\circ$ to the flow. Downwash of the plume in the building wake is clearly taking place for the diagonal approach flow, particularly at the lower release height. Over the downstream distance visualised, which was about 10 building heights, downwash for the normal wind direction was not apparent.

Having established from the elevated plume behaviour that the most important parameter to modify is the mean plume height, $z_p$, we will adjust this in the Gaussian model and compare the results to the measured vertical and ground level concentration profiles in the building wakes. Figures 6.5 to 6.10 show the comparisons. The dotted lines indicate a Gaussian model using parameters that give the best fit to the dispersion in our undisturbed boundary layer, and was compared to measured data in Figure 6.2. The solid line on the plots represents an identical Gaussian model, but with the inclusion of downwash. Building groups A and F normal to the flow, shown in Figures 6.5 and 6.7, have a negligible effect on the elevated plume so, since the Gaussian model gives a reasonable description of the undisturbed dispersion, it is no surprise that it also fits these data sets quite well.

Case A at $45^\circ$ and case B at $0^\circ$, both had a similar influence on the plume behaviour and caused downwash of around 14mm per metre. Their comparison with the Gaussian models is presented in Figures 6.6 and 6.8. The ground level concentrations, which are increased by a factor of two relative to the undisturbed dispersion results, are well represented by the Gaussian model that adjusts the plume centreline height. The agreement between the predicted elevated plume concentrations and the data has improved dramatically by including downwash.

Building cases B and F at $45^\circ$ which are shown in Figures 6.9 and 6.10, produced the highest ground level concentrations and caused a plume downwash of around 65mm per metre. However, when this downwash was included in the Gaussian model, it overpredicted the maximum ground level concentration by about 50%. For these cases where the plume become significantly involved in the combined wakes of the buildings, the assumption that the lateral spread of the plume is the same as in the undisturbed boundary layer is probably invalid. It seemed reasonable to expect that $\sigma_y$ could be a function of height, when only part of the plume is in the building wake. A modified Gaussian model will be investigated in the
next section that includes the enhanced lateral spread of the plume as it becomes entrained into the main building wake.

6.2. A modified Gaussian model

6.2.1. Modelling elevated releases of twice the building height

In Section 6.1 it was found that when a building causes significant downwash, such as for building case B at 45° to the flow, if the same downwash is implemented in a simple Gaussian model, the ground level concentrations are over estimated. It was suggested that this may be caused by the enhanced lateral spread of the plume as it is entrained into the main, highly turbulent, building wake. This was investigated by taking lateral profiles at 6 different heights at cross sections of interest to determine the variation of \( \sigma_y \) through the plume depth. The highest lateral profile was generally too close to the top of the plume for the concentration measurements to be reliable so this point has been omitted in the analysis.

Measurements were made at positions of 10, 12.8, 20, 26 and 32 building heights downstream, for the building case B at 45° to the flow, and a release height of twice the building height. Gaussian profiles were fitted to the lateral distributions by optimising the maximum concentration, \( y_p \) and \( \sigma_y \), at each elevation through the plume. The variation of lateral spread through the plume depth, for the downstream locations investigated, is shown in the upper part of Figure 6.11. The dotted vertical lines indicate the lateral plume spreads observed in the undisturbed boundary layer at each downstream position. The solid line is a polynomial curve describing the way the lateral spread is enhanced as the plume becomes entrained into the building wake. Beyond 26 building heights downstream, the vertical mixing in the plume causes the variation of \( \sigma_y \) with height to become less important, but the lateral spread is significantly larger than it was in the undisturbed dispersion case.

The lower plots in Figure 6.11, show how the position of the maximum in the lateral concentration profiles, varies across the plume. We can see that the cross flow in the building wake has moved the plume centreline in the negative y direction. This asymmetry in the wake is due to the building shape not being square, so at 45°, one building side is longer to the flow than the other. This means that the ground level concentration profiles were measured a little off the centreline of the plume, but this would only account for about 6% of the 50% difference between the Gaussian model and the experimental results as shown in Figure 6.9.

The growth of \( \sigma_y \) with \( x \) at ground level with the building present is shown in Figure 6.12, compared with similar measurements made for a release height of 1.4 times that of building case B. The lateral spread of plumes in the undisturbed boundary layer have also been included for comparison purposes. Clearly, the building wake has increased the lateral plume spread, and this enhancement is also a function of the release height. The lower plumes become entrained into the building wake at an earlier stage, and thus are much more affected by its enhanced mixing properties. The next step was to try to incorporate this additional information of the variation of \( \sigma_y \) with height and downstream position into a dispersion model.
to see if better agreement could be achieved with the measured concentrations downstream of the building for elevated releases.

Appendix 6. Shows that a plume model can be described where the lateral spread is not only a function of downstream distance, but is also a function of height. It has been shown that for any well behaved function of $\sigma_y(z)$, the expression for the concentration given by the Gaussian model, Equation 6.1, is still valid.

Having obtained a modified Gaussian model in which $\sigma_y$ can be a function of height, we will compare this model to the measured concentrations in the wake of building case B at 45° to the flow and with a release at twice the building height in the neutral boundary layer. Figure 6.13 shows the comparison between the concentration measurements, a Gaussian model with plume downwash and the modified Gaussian model that has downwash, but also enhances the lateral plume spread in the wake. The former model has already been compared to the concentration measurements in Figure 6.9, where it was noted that the ground level concentrations were significantly overestimated. The variation of $\sigma_y$ with height in the modified Gaussian model was taken from the polynomial curve fit to the measured data that was presented in Figure 6.11. The variation of $\sigma_y$ with downstream distance at ground level was modelled using the expression in Figure 6.12, for a release of twice the building height.

The modified Gaussian model certainly fits the vertical and ground level concentrations distributions much more closely than when the lateral spread is assumed to remain unchanged. The slight overestimation of the maximum ground level concentration may partly be caused by the lateral shift of the plume centreline in the wake, as was shown by the $y_p$ plots in Figure 6.11. The measured “centreline” ground level concentration profile was therefore not along the plume’s centreline. If the measured data were along the plume’s centreline this would increase the concentrations by about 6%. The dotted line is not shown on the first few vertical profiles because the plume has not yet been long enough in the wake to feel the effects of the enhanced lateral spread.

To summarise what has been learned so far about dispersion of plumes that are released at twice the building height is:

a) $\sigma_z$ is not really affected by the building wake, so using the undisturbed flow values is a valid approximation,

b) Plume downwash (caused by either the external flow being entrained into the wake or the strong roof vortices that are generated for the diagonal wind directions) is responsible for enhancing the ground level concentration, not the increased vertical spreading rate,

c) As the plume becomes entrained into the main building wake, the increased turbulence enhances the lateral spread of the plume, which has the effect of reducing the centreline concentrations. Initially this makes $\sigma_y$ a function of height, but further downstream this increased lateral spread affects the whole depth of the plume, and $\sigma_y$ becomes more or less independent of height,

d) For the asymmetric buildings at 45° the plume moves off the tunnel centreline a little,
Chapter 6  Development of a Gaussian plume model

e) All the concentration distribution shapes remain Gaussian throughout the plume, so a modified Gaussian model can be developed which adequately describes the concentration field.

6.2.2. Modelling elevated releases of 1.4 times the building height

The behaviour of the plume released at twice the building height has been investigated in the previous section, but as the release height is reduced we know from the ground level concentration that the building effect becomes progressively more significant. For a roof level emission, where the flow remains fully separated over the building, a major part of the release would become entrained into the recirculating flow region where both the vertical and lateral spread of the plume would be significantly enhanced. With this thought in mind, it was decided to make a detailed mapping of the concentration field for a release height of 1.4 times the building height for case B at 45° to the flow, to determine when the observations made at the end of the last section start to break down. The experimental procedure and analysis of the results was exactly the same as in the previous section, but now with a release height of 175mm instead of 250mm. \( \sigma_y \) and \( y_p \) derived from optimised Gaussian fits to the lateral profiles are presented in Figure 6.14. The first thing that is noticeably different in these results, as compared to the ones presented in Figure 6.11 for the higher release, is that the offset of the plume centreline \( y_p \) is much more significant. The values of \( \sigma_y \) are also far more enhanced, so the building wake effects on the plume have been increased by lowering the release height, as would be expected.

The magnitude of the centreline offset of the plume was not envisaged prior to taking the lateral profiles, so the plume centreline was well to one side of the dispersion rake. This meant that the tail of the distribution on one side was not measured very well, but from available profiles, it appears that the plume was becoming skewed. This perhaps could be modelled using two values of \( \sigma_y \) to describe one lateral profile, one for the left hand side of the plume centreline and other for the right hand side. This modelling has not been tried, since the measured lateral distributions were not completely captured due to the imperfect positioning of the rake. An averaged value for the lateral plume spread at ground level in the wake over the range of downstream positions investigated, is plotted in Figure 6.12.

A modified Gaussian plume model has been compared to the plume centreline vertical and ground level concentration profiles in the same way as for the higher release height, see Figure 6.15. The vertical concentration profiles were measured after the lateral ones, and were positioned at the average plume centreline given by the \( y_p \) values at each downstream location. The two profiles that have been plotted at \( x/H_b = 4 \) show that the concentration distribution is very much a function of spanwise position. Clearly at this downstream location, a simple Gaussian model that assumes \( z_p \) and \( \sigma_z \) are independent of \( y \), cannot predict the concentrations in this part of the plume. However, at \( x/H_b = 10 \), vertical profiles showed that the value of \( \sigma_z \) and \( z_p \) had become independent of the spanwise position. This was the first downstream location at which \( \sigma_z \) measurements were made, and the modified Gaussian model fits the measured concentrations quite well. Further downstream the modified model tends to under-predict the concentrations, because the \( \sigma_y \) values either side of \( y_p \) are not really the same, and the larger of the two has been used by this model. Considering the whole centreline profile, in general
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the ground level concentrations were predicted better by the modified Gaussian model where \( \sigma_x \) is enhanced by the building, than when the undisturbed values were used.

So, comparing the conclusions for a release height of 1.4 times the building height to those made for twice the building height, we find that:

a) Beyond 10 building heights downstream the value of \( \sigma_z \) is not greater than in the undisturbed dispersion case, but nearer the building it becomes a function of lateral position as well as downstream location and for some of the \( y \) locations in this region the vertical spread of the plume is enhanced by the wake,

b) plume downwash is still the major reason why the ground level concentrations are enhanced by the presence of the building,

c) the increase in plume width is more pronounced for this lower release height,

d) the plume centreline offset is also more significant for the lower release case,

e) the lateral profiles measured beyond 10 building heights downstream become progressively more skewed and could be better represented using two values of \( \sigma_y \) either side of \( y_p \).

6.3 Discussion of modified Gaussian model performance

Huber and Snyder (1982) investigated the effects of a rectangular building on dispersion of effluents from short stacks in a simulated neutral boundary layer. They measured centreline ground level concentrations in the wake of the building for a range of release heights, and near the point of maximum concentration vertical profiles were measured. They developed a Gaussian plume model to represent the plume behaviour by adjusting the vertical spread. Looking at the fits that their modified Gaussian model gave to the measured vertical profiles, the agreement was only good over the lower part of the profile. The plume height in their model was held constant and the lateral spread of the plume was kept the same as in the undisturbed boundary layer. To model the increased concentration close to the ground, observed in the measurements, the vertical spread was increased. However this meant that the concentrations higher up were significantly overestimated. Since their objective was to predict the ground level concentration profiles, this was not of immediate concern. However, the Gaussian model conserves concentration flux, so if one part is overestimated, this must mean that another part in the cross section is under-predicted to compensate. They state in their discussion of results that the measured ground level lateral spread was far greater than their model predicted, which assumed no enhancement of \( \sigma_y \). Elevated lateral profiles at 1.5 times the building height showed good agreement with their model spread. Their data confirms what was observed in our measurements, that within the main building wake \( \sigma_y \) is a function of height.

The centreline ground level concentration profiles in their model were well predicted by using a \( \sigma_z \) that was too large, and a \( \sigma_y \) that was too small. The effect of these modelling approximations balanced out to achieve good
agreement in the centreline ground level concentration distributions. If either one of these parameters had been modelled more accurately, the resulting centreline ground level concentration predictions would have become worse. However, they only looked at the situation where the building is normal to the flow and we shall see later that if this model were applied to the diagonal wind direction, where the downwash in the wake is much stronger, it is impossible to get a good fit to even just the centreline ground level concentrations by adjusting $\sigma_z$ alone. The significance of plume downwash for elevated releases above buildings was clearly demonstrated in a more recent paper by Snyder (1994a), where it was shown to be the most important plume perturbation, as far as the ground level concentrations are concerned.

In the modified Gaussian model, whose results were presented in Figure 6.13, the whole concentration field was represented very well. This was achieved by using the undisturbed dispersion values for $\sigma_x$, but letting $z_p$ be a function of $x$, and $\sigma_y$ be a function of both $x$ and $z$. If only ground level concentrations are required, the model would only need to know how $\sigma_y$ varies with $x$, but not how it varied with height. So, to represent accurately the ground level distributions for an elevated release above a building, the variations of $z_p$ and $\sigma_y$ with $x$ need to be determined, but all the other parameters are kept the same as in the undisturbed case.

If a building effect model is required which only adjusts one parameter, it would be best to allow the plume centreline height to vary with $x$. We have already considered such a model in Figure 6.9, and came to the conclusion that $\sigma_y$ had to be enhanced, otherwise the ground level concentrations were over estimated. However, if the modelled plume downwash were reduced somewhat, the maximum ground level concentration would be reduced without needing to increase the lateral spread. This simple model has been compared to the measured concentrations for a release of twice the building height for case B, 45° to the flow, and is shown by the solid line in Figure 6.16. This model is identical to the one presented in Figure 6.9, except the plume is not brought down to ground level until 50 building heights downstream instead of 30. From the vertical profiles in Figure 6.16, we can see that this model has underestimated the plume downwash, but this has led to an improvement in the centreline ground level concentration predictions. Further downwind, in the far wake, the ground level concentration tend to be slightly overestimated, since the lateral spread has not been enhanced.

The dotted lines in Figure 6.16 are results from a Gaussian model that represents the building affect by just enhancing the vertical plume spread, whilst leaving the plume width and its centreline height unchanged. The enhancement of $\sigma_z$ has been optimised to give the best fit to the centreline ground level concentration profile. Beyond 15 building heights downstream, increasing $\sigma_z$ further, results in lower ground level concentrations, since it puts more of the plume higher up in the boundary layer. Looking at both the vertical and ground level distributions, it is clear that when the building is at 45° to the flow, the model which adjusts the plume centreline height is much more representative of the true dispersion behaviour.

Our results have shown that the dispersion of elevated releases of twice the building height and above can be well represented by a modified Gaussian model that includes downwash and enhanced lateral spread of the plume as it becomes entrained into the building wake. If only centreline ground level concentrations are required, this distribution can be adequately
modelled by just including an 'effective' plume downwash, which is less than the observed downwash, to compensate for the fact that $\sigma_z$ is not being enhanced. Certainly, when predicting concentration for both diagonal and normal wind directions, this method yields much better agreement with the measured concentrations than models that enhance the vertical plume spread to compensate for the building effect.

### 6.4 Important flow parameters for dispersion modelling.

Having flow and dispersion measurements around building groups A, B and F for the normal and diagonal wind directions, we are now in a position to determine what perturbations in the wakes correlate with the maximum building effect for an elevated release. Looking at Figure 4.14, we see that in the wake of building case F, normal to the flow, the perturbations are relatively large compared to the other cases studied. However, if we turn to the bottom plot in Figure 6.17, this building group yields the lowest building effect over the range of release heights studied. So the velocity deficit and the enhancement of the Reynolds stresses in the wake are not the major parameters that control how significant the building influence is on an elevated release. The upper plot in Figure 6.17 shows the flow angle to the horizontal in the $xz$ plane along the wake centreline at the building height. This plot appeared earlier as Figure 4.15, but has been repeated here for comparison purposes. The lower plot shows reduction in effective stack height results for these building groups. The negative flow angle is associated with downwash in the wake, which is greatest for groups B and F diagonal to the flow. As can be seen from the plot below, these two cases caused the maximum building effect. This correlation between the flow downwash and the building effect is also followed fairly closely by all the other building groups. This behaviour is in agreement with what we have suggested earlier in this chapter, namely that the most important parameter to adjust in the Gaussian dispersion model is the mean plume height $z_p$, when attempting to simulate the building influence on an elevated release.

For a model that is designed to calculate only dispersion for releases of 1.5 times the building height and above, it is not necessary to calculate the velocity deficit or the Reynolds stresses perturbations in the wake. The most important flow property to model is the vertical velocity (or downwash) in the wake that advects the elevated plume closer to the ground. This would be linked in the Gaussian model to how the mean plume height changes with downstream distance. The second flow property that would be useful to calculate is the width of the building wake. If the plume becomes significantly entrained into the main wake this width can be used to increase the lateral plume spread, thus preventing the centreline ground level concentrations becoming overestimated. Any such flow model must take into account the orientation of the building, since this has a major effect on the wake downwash.
Figure 6.1. Gaussian model inputs to represent the dispersion characteristics of the undisturbed neutral boundary layer for a release height of 250mm.
Figure 6.2. Comparison of a Gaussian model with centreline concentration measurements for a release height of 250mm in the undisturbed neutral boundary layer.
Figure 6.3. Analysis of the effect of the building groups on the dispersion from an elevated release of twice the building height.
Figure 6.4. Flow visualisation over building case F for elevated releases of 1.4 and 2 times the building height in the neutral boundary layer.
Figure 6.5. Concentration measurements in the wake of building case A at 0°, for an elevated release of twice the building height, compared to Gaussian models with and without downwash.
Figure 6.6. Concentration measurements in the wake of building case B at 0°, for an elevated release of twice the building height, compared to Gaussian models with and without downwash.
Figure 6.7. Concentration measurements in the wake of building case F at 0°, for an elevated release of twice the building height, compared to Gaussian models with and without downwash.
Figure 6.8. Concentration measurements in the wake of building case A at 45°, for an elevated release of twice the building height, compared to Gaussian models with and without downwash.
Figure 6.9. Concentration measurements in the wake of building case B at 45°, for an elevated release of twice the building height, compared to Gaussian models with and without downwash.
Figure 6.10. Concentration measurements in the wake of building case F at 45°, for an elevated release of twice the building height, compared to Gaussian models with and without downwash.
Figure 6.11. Analysis of the lateral concentration profiles in the wake of building case B orientated at 45°, for a release at twice the building height, showing the variation of the plume characteristics with height as well as with downstream distance. (Neutral Boundary layer)
Figure 6.12. The effect of the wake of building case B, on the lateral spread of the plume at ground level, for releases at 1.4 and 2 times the building height. Neutral boundary layer; building at 45° to the approach flow.
Figure 6.13. Concentration measurements in the wake of building case B at 45°, for an elevated release of twice the building height, compared to a Gaussian model with downwash, and a modified Gaussian model allowing the lateral plume spread to be a function of height as well as including downwash. (Neutral Boundary layer)
Figure 6.14. Analysis of the lateral concentration profiles in the wake of building case B orientated at 45°, for a release at 1.4 times the building height, showing the variation of the plume characteristics with height as well as with downstream distance. (Neutral boundary layer)
Figure 6.15. Concentration measurements in the wake of building case B at 45°, for an elevated release of 1.4 times the building height, compared to a Gaussian model with downwash, and a modified Gaussian model allowing the lateral plume spread to be a function of height as well as including downwash. (Neutral Boundary layer)
Figure 6.16. Concentration measurements in the wake of building case B at 45°, for an elevated release of twice the building height, compared to two Gaussian models, one having downwash, and the other enhanced vertical plume spread. (Neutral Boundary layer)
Figure 6.17. Variation of flow angle with downstream distance (upper), and the reduction in effective stack height for a range of release heights (lower), for the building cases A, B and F, in the neutral boundary layer.
Chapter 7. Conclusions

7.1 Conclusions of the experimental results and analysis

The wind tunnel instrumentation and control systems have been substantially developed and improved during this project. The traverse system has been upgraded to enable movement along the longitudinal axis, and all three axis can now be controlled from the data acquisition computer, enabling automated data collection. A cold wire has been synchronised with the Laser Doppler Anemometry system, so that heat flux measurements can be made in the stable boundary layer.

Flow measurements made in the simulated neutral and stable boundary layers showed that their depths correspond to 500 and 125m respectively at full scale. For the stable boundary layer, the non-dimensional velocity and temperature gradients fall centrally within the range of field observations compiled by Hogstrom (1988). The characteristics of both boundary layers show that they are typical of what one might expect in the atmosphere for their respective stability classes.

Measurements of vertical and lateral plume spreads in the undisturbed neutral boundary layer, taken at a number of downwind positions, indicated that the dispersion behaviour is similar to that given by the Pasquill scheme for neutral stability using a 1:500 scale factor. The lower turbulence levels in the stable boundary layer caused the plume spreading rates to be approximately halved when compared with the dispersion behaviour in the neutral boundary layer. The vertical spread of the plume is suppressed slightly more than laterally, which is usual for a stable boundary layer.

Comparison of a simplified, integral 3D momentum dominated wake model with cross-wire measurements made for building cases A (isolated B204), B (A single building having plan dimensions three times that of case A) and F (9 buildings spaced by one building width), showed good agreement for the normal wind direction. However, for the diagonal approach flow, the roof vortices generated at the swept back leading edges played an important role in the main wake, causing velocity excesses to occur on the wake centreline beyond 10 building heights downwind. For this situation the assumption that the wake is momentum dominated is clearly invalid.

For the normal wind direction, it was found that the value of the constant $\tilde{u}/U_{ref}$ related to the couple on the building, could be scaled directly on the frontal area of the building faces seen by the flow for the three building wakes studied. So, to give good agreement between the measurements and the model, $\tilde{u}/U_{ref}$ was 1.25 for building case A, 3.75 for case B and 11.25 for case F. This was the only parameter that was changed in the model to fit these three different building cases. The applicability of the model to the normal wind direction has shown that the momentum part of the wake dynamics can be predicted reasonably well. Further work is needed to model the behaviour of the strong, predominantly imbalanced roof vortices that significantly affect the wake behaviour for diagonal approach flows.

Concentration measurements have shown that the building orientations of $30^\circ$, $45^\circ$ and $60^\circ$ all enhanced the ground level concentrations by similar amounts. So it appears that the $0^\circ$ wind direction is more of a special case, with the majority of approach flows acting as diagonal.
The flow and dispersion results for building groups were compared to investigate which perturbations in the wake led to the largest enhancement of the ground level concentrations for elevated releases. Although building case F, normal to the flow, produced relatively large perturbations in all the measured Reynolds stresses, it caused the smallest rise in the ground level concentrations. The vertical extent of the wake was very similar to the other building cases, so this minimal building influence was not because the wake was physically smaller. However, when the mean vertical velocity (downwash) in the wake was compared to the resulting ground level concentrations, they were clearly correlated. So this has demonstrated that when predicting dispersion from elevated releases above buildings, the most important wake perturbation to model is the downwash, particularly so when the approach flow is diagonal to the upwind building face.

For the generic building groups, it was found that for the normal wind direction, provided the spacing of the surrounding buildings was more than half the building width, their influence on the maximum ground level concentration was negligible. However, for diagonal approach flow, the surrounding buildings are best represented by forming a single cuboid of equal volume to the sum of the individual buildings as far as the maximum ground level concentrations are concerned. For this simplification the cuboid should still be considered at 45° to the approaching flow. Dispersion measurements over the Sellafield site for releases above B204 showed that the ground level concentrations were just a little lower than those obtained when B204 was isolated. Elevated concentration profiles demonstrated that the lateral spread was slightly enhanced over the site. The buildings immediately surrounding B204 are about half its height, and appear not to have had a significant effect on the ground level concentrations.

Previous studies conducted for British Nuclear Fuels Ltd, indicated that the influence of the Sellafield site on the B204 release caused its effective height to be between 50 and 70% of its physical height. Our study suggests that these values are rather conservative, and that the actual effective height of B204 lies more between 70 and 95% of its physical height. An important factor contributing to this discrepancy is the way in which the effective stack height is determined from the ground level concentrations. In our study the maximum ground level concentration was compared to corresponding values obtain in the undisturbed boundary layer for a range of release heights. Earlier studies compared the ground level concentrations with the R91 model, which may or may not have been a good description of the dispersion characteristics the undisturbed boundary layer.

This project has demonstrated that the effect of the surrounding buildings and topography at the Sellafield site have caused a negligible change in the maximum ground level concentrations measured downstream of B204. An extension to this project considered the effect of ‘moving’ the B204 building and its elevated release around the site to see how general this conclusion was. Only when B204 was positioned directly upstream or downstream of B570, a large building with an extensive flat roof, were the ground level concentrations enhanced. Even at this position, the resulting effective stack height of B204 was still 65% of its physical height.

Detailed measurements of the elevated plume at a number of downstream stations were made for some of the generic building groups to determine which parameters in a Gaussian model need to be adjusted to represent the building affected dispersion results. It was found for elevated releases that
the vertical spread of the plume was unaffected by the presence of the buildings, but that the downwash, causing the mean height of the plume to decrease, was the predominant reason why the ground level concentrations are enhanced. For release heights of around 1.5 times the building height, the plume becomes significantly entrained into the main building wake, and the lateral plume spread is enhanced, causing a decrease in the maximum ground level concentration. It has been shown that, when these modifications were applied to the Gaussian plume model, it represented the resulting concentration field downwind of the building groups quite well.

The dispersion results in the stable boundary layer for elevated releases above three of the building groups indicated that the reductions in the effective stack heights were similar to those obtained in the neutral boundary layer, for the lower releases of 1.2 and 1.4 times the building height. For the higher releases of 1.68 and 2 times the building height, these elevations are greater than the undisturbed stable boundary layer depth. For the cases where ground level concentrations were still measured, the building downwash must have been responsible for bringing the plume back into the boundary layer. The fact that the building influence for these higher releases heights was more significant than in the neutral boundary layer may well be an affect of the stable boundary layer being only a fifth of the depth of the neutral one. To investigate whether the stratification or the shallowness of the stable boundary layer is giving rise to the enhanced building effect for the higher release heights, either a deeper stable boundary layer would need to be developed, or the scale of the building models changed. However, the differences in the neutral and stable boundary layer depths are quite typical of what one might expect for their respective stability classes.

7.2 Suggestions for further work in this area.

In the neutral boundary layer, more work needs to be done in determining how the downwash and lateral plume spread vary with release height for a range of building groups. Flow visualisation may be useful here, since information is required about the physical shape of the plumes rather than absolute concentration measurements. Our research has shown that provided both the downwash and the enhanced lateral spread due to the building is known, a Gaussian plume model can accurately predict the resulting concentration field. After creating this data base, it will be possible to see if there are any general patterns in the results for which types of building groups similarly affect the downwash, and which ones cause a similar enhancement to $\sigma_Y$. It may be possible to link the increase in lateral plume spread in some way with the building group's size, orientation and spacing. If the downwash and increased lateral plume spread can be adequately modelled, it should be possible to make good estimates of the resulting concentration field for elevated releases above building groups.

The 3D momentum dominated wake model that has been developed needs to be extended so that it can also yield estimates of the downwash or vertical velocity in the wake. Downwash affects the mean height of the plume, which leads to the significant enhancement of the ground level concentrations which have been observed in this study. For the diagonal wind directions, when the roof vortices generated at the swept back leading edges play a significant role in the wake dynamics, an analytical model of
their behaviour is required so that the strong downwash that is observed can be predicted.

In the stable boundary layer, the buildings effect for releases of 1.6 times the building height and above needs to be investigated to determine the influence of stratification compared to the proximity of the release to the top of the boundary layer. A careful study is needed to determine what this effect is, taking care to ensure that the release is not above the top of the boundary layer, and that the temperature of the release is matched to that of the surrounding flow.
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Appendix 1: Obstacle Froude numbers in a stable boundary layer

Appendix 1 Derives an expression for how the obstacle Froude number varies with increasing stratification in the stable boundary layer.

In the stable boundary layer we have the log linear velocity profile given by

\[ U = \frac{U^*}{\kappa} \left( \log \left( \frac{z}{z_0} \right) + \beta_u \frac{z}{L} \right) \]  
\[ \text{(1)} \]

and the temperature profile given by

\[ \Delta T = \frac{T^*}{\kappa} \left( \log \left( \frac{z}{z_0} \right) + \beta_T \frac{z}{L} \right) \]  
\[ \text{(2)} \]

The obstacle Froude number is given by:

\[ F = \frac{U}{N N_b} \]  
\[ \text{(3)} \]

where \( N \) is the buoyancy frequency expressed as

\[ N^2 = \frac{g}{T} \frac{dT}{dz} \]  
\[ \text{(4)} \]

Differentiating equation (2) we obtain

\[ \frac{dT}{dz} = \frac{T^*}{\kappa} \left( \frac{1 + \beta_T}{z/L} \right) \]  
\[ \text{(5)} \]

Substituting this into the equation (4) we obtain

\[ N^2 = \frac{g}{T} \frac{T^*}{\kappa} \left( \frac{1 + \beta_T}{z/L} \right) \]  
\[ \text{(6)} \]

The Monin-Obukhov length scale can be expressed as

\[ L = \frac{T^*}{\kappa g} \frac{u^2}{\bar{w}T} \]  
\[ \text{(7)} \]

but in the surface layer \( \bar{w}T = T_u u^* \). Substituting this into equation (7) and rearranging to obtain the temperature scale we have:

\[ L = \frac{T^*}{\kappa g} \frac{u^2}{T_u} \Rightarrow T_u = \frac{T^*}{\kappa g} \frac{u^2}{L} \]  
\[ \text{(8)} \]

Substituting this result into equation (6) we obtain:

\[ N^2 = \frac{g}{T^*} \frac{T^*}{\kappa g} \left( \frac{1 + \beta_T}{z/L} \right) \frac{u^2}{\kappa g} \left( \frac{1 + \beta_T}{z/L} \right) \]  
\[ \text{(9)} \]

This can now be substituted into equation (3) to give:
Appendix 1

Obstacle Froude numbers in stable BL

\[ F^2 = \frac{U^2}{u_*^2 \left( \frac{u_*^2}{\kappa^2 L} \left( \frac{1}{H_b^2} + \frac{\beta_T}{L} \right) \right)^2} \Rightarrow \frac{(\kappa U)^2}{(u_*)^2} \]  

(10)

where the equation has been evaluated at the building height. The Froude number then becomes:

\[ F = \frac{\kappa U}{u_*} \frac{H_b}{L} \left( \frac{L}{H_b} + \beta_T \right) \]  

(11)

If we rearrange equation (1) and evaluating for the building height we obtain

\[ \frac{\kappa U}{u_*} = \left\{ \log \left( \frac{H_b}{z_o} \right) + \beta_u \frac{H_b}{L} \right\} \]  

(12)

Substituting this into equation (11) we have

\[ F = \frac{\log \left( \frac{H_b}{z_o} \right) + \beta_u \frac{H_b}{L}}{\frac{H_b}{L} \left( \frac{L}{H_b} + \beta_T \right)} \]  

(13)

For strong stratification \( \left( \frac{H_b}{L} \right) \to 1 \) so the Froude number tends to

\[ F = \frac{\log \left( \frac{H_b}{z_o} \right) + \beta_u \frac{H_b}{L}}{\frac{H_b}{L} \left( \frac{L}{H_b} + \beta_T \right)} \Rightarrow \frac{\beta_u \frac{H_b}{L}}{\beta_T \sqrt{\beta_T}} \]  

(14)

Thus as the stability is increased the Froude number limit is \( \frac{\beta_u}{\sqrt{\beta_T}} \)
Appendix 2: The relationship between $\sigma_z$, $z_p$, and the cross-wind integrated ground level concentrations.

Appendix 2 derives an expression which can iteratively be solved to find $\sigma_z$ and $z_p$ from the cross-wind integrated ground level concentrations from the bi-Gaussian plume equation.

The bi-Gaussian equation can be expressed as:

$$\frac{C U_{ref} H_b^2}{Q} = \frac{H_b^2 U_{ref}}{2 \pi U_{adv} \sigma_y \sigma_z} \exp \left( \frac{-y^2}{2 \sigma_y^2} \right) \exp \left( \frac{-z}{2 \sigma_z^2} \right) + \exp \left( \frac{-(z + z_p)^2}{2 \sigma_z^2} \right)$$

(1)

Where $U_{adv}$ is a constant taken as the 10 m wind speed $U_{10}$.

For ground level concentrations this equation reduces to

$$C = \frac{Q}{\pi U_{10} \sigma_y \sigma_z} \exp \left( \frac{-y^2}{2 \sigma_y^2} \right) \exp \left( \frac{-z_p^2}{2 \sigma_z^2} \right)$$

(2)

Integrating w.r.t $y$ gives:

$$\int C dy = \frac{Q}{\pi U_{10} \sigma_y \sigma_z} \int \exp \left( \frac{-1}{2} \left( \frac{z_p}{\sigma_z} \right)^2 \right) \int \exp \left( \frac{-y^2}{2 \sigma_y^2} \right) dy$$

(3)

and since

$$\int e^{-a^2} dy = \sqrt{\frac{\pi}{a}}$$

(4)

Let $a = \frac{1}{2\sigma_y^2}$

$$\int \exp \left( \frac{-1}{2} \left( \frac{z_p}{\sigma_z} \right)^2 \right) dy = \sqrt{\frac{\pi}{a}} = \sqrt{2 \pi \sigma_y^2} = \sigma_y \sqrt{2 \pi}$$

(5)

Substituting this results into equation (3) we obtain

$$\int C dy = \frac{Q \sigma_y \sqrt{2 \pi}}{\pi U_{10} \sigma_y \sigma_z} \exp \left( \frac{-1}{2} \left( \frac{z_p}{\sigma_z} \right)^2 \right)$$

(6)

which can be rearranged to give

$$\sigma_z \exp \left( \frac{1}{2} \left( \frac{z_p}{\sigma_z} \right)^2 \right) = \frac{\sqrt{2} Q}{\sqrt{\pi U_{10}} \int C dy}$$

(7)

there are two solutions to the equation, either the plume is elevated and $\sigma_z/z_p$ is small or the plume is low and $\sigma_z/z_p$ is large.
Appendix 3: 3D Wake model derivation

The main wake model presented here is a simplified 3D version of the small deficit wake model proposed by Counihan et al (1974). The model is based on a momentum dominated wake, so all the coherent vorticity generated by the building is assumed to be broken down very quickly. This will be much more true of buildings normal to the flow than for the diagonal cases. The main wake is modelled using a constant eddy viscosity defined by the upstream flow conditions.

Diagrams show the notation used in the analysis of the wake model
Flow equations in the undisturbed boundary layer

The Navier Stokes momentum equations can be expressed as:

\[ \frac{\partial U_i}{\partial x_j} + \frac{1}{\rho} \frac{\partial P}{\partial x_i} + \frac{1}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} = 0 \]  

(1)

Writing this equation out in full for the mean flow direction in the undisturbed boundary layer we have:

\[ \frac{U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} + \frac{1}{\rho} \frac{\partial T_{xx}}{\partial x} + \frac{1}{\rho} \frac{\partial T_{xy}}{\partial y} + \frac{1}{\rho} \frac{\partial T_{xz}}{\partial z} = \frac{1}{\rho} \frac{\partial P}{\partial x} \]  

(2)

But the undisturbed boundary layer flow is two dimensional and fully developed so

\[ \frac{\partial U}{\partial y} = \frac{\partial U}{\partial x} = \frac{\partial T_{xx}}{\partial x} = V = W = T_{xy} = 0 \]  

(3)

where \( T \) is the shear stress in the undisturbed boundary layer.

Substituting this into Equation (2) we get:

\[ \frac{1}{\rho} \frac{\partial T_{xx}}{\partial x} = \frac{1}{\rho} \frac{\partial P}{\partial x} \]  

(4)

which is the momentum equation in the undisturbed boundary layer approaching the building. Since the viscous effects are very small, relative to the Reynolds stresses, they have been neglected.

Flow equations in the wake of the building

Counihan et al (1974) found that the pressure perturbation in the wake was not significant, so it has been neglected in this 3D analysis. Let the flow in the building wake (symbols with the hat) be expressed in terms of the undisturbed boundary layer (upper case without the hat), and a perturbation (lower case):

\[ \hat{U} = U + u \]
\[ \hat{V} = V + v \]
\[ \hat{W} = W + w \]
\[ \hat{T}_{xy} = T_{xy} + \tau_{xy} \]
\[ \hat{T}_{xz} = T_{xz} + \tau_{xz} \]

Substituting values for the approach flow shown in equation (3) we get:

\[ \hat{U} = U + u \]
\[ \hat{V} = v \]
\[ \hat{W} = w \]
\[ \hat{T}_{xy} = \tau_{xy} \]
\[ \hat{T}_{xz} = T_{xz} + \tau_{xz} \]  

(5)
Writing equation (1) out in full for the wake in the mean flow direction we have:

\[
\frac{\partial \bar{U}}{\partial x} + \frac{\partial \bar{U}}{\partial y} + \frac{\partial \bar{U}}{\partial z} + \frac{1}{\rho} \frac{\partial T_{xx}}{\partial x} + \frac{1}{\rho} \frac{\partial T_{xy}}{\partial y} = -\frac{1}{\rho} \frac{\partial P}{\partial x} \tag{6}
\]

Substituting for the actual quantities using the relationships in equation 5 this becomes:

\[
(U + u) \frac{\partial (U + u)}{\partial x} + v \frac{\partial (U + u)}{\partial y} + w \frac{\partial (U + u)}{\partial z} + \frac{1}{\rho} \frac{\partial (T_{xx} + \tau_{xx})}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_{xy}}{\partial y} = -\frac{1}{\rho} \frac{\partial P}{\partial x} \tag{7}
\]

but \( \frac{\partial U}{\partial y}, \frac{\partial U}{\partial x} \) are zero since the approach flow is fully developed and two dimensional and \( u \frac{\partial u}{\partial x}, v \frac{\partial u}{\partial y}, w \frac{\partial u}{\partial z} \) are second order terms and so can be neglected. This is where the small perturbation assumption for \( u \) is made in the model formulation. Equation (7) then becomes:

\[
U \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} + \frac{1}{\rho} \frac{\partial (T_{xx} + \tau_{xx})}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_{xy}}{\partial y} = -\frac{1}{\rho} \frac{\partial P}{\partial x} \tag{8}
\]

To obtain the perturbed quantities in the wake we need to subtract the undisturbed flow result (Equation (4)) from this giving:

\[
U \frac{\partial u}{\partial x} + w \frac{\partial u}{\partial z} + \frac{1}{\rho} \frac{\partial (T_{xx} + \tau_{xx})}{\partial x} + \frac{1}{\rho} \frac{\partial \tau_{xy}}{\partial y} = 0
\]

The order of magnitude of the first term in this expression is:

\[
U \frac{du}{dx} \Rightarrow U \frac{u}{L_x}
\]

where \( L_x \) is a longitudinal length scale in the wake. Assuming the three terms in the continuity equation:

\[
\frac{du}{dx} + \frac{dv}{dy} + \frac{dw}{dz} = 0
\]

are of the same order of magnitude it follows that:

\[
\frac{du}{dx} = \frac{dw}{dz} \Rightarrow \frac{u}{L_x} = \frac{w}{L_z} \Rightarrow w = uL_z \quad L_x
\]

so:

\[
w \frac{dU}{dz} \Rightarrow uL_z \frac{U}{L_x} \Rightarrow \frac{U}{L_z} \frac{du}{dx} = \frac{L_z}{L_x} \frac{dU}{dz}
\]

where \( \delta \) is the boundary layer depth. Since the ration of \( L_z \) to \( \delta \) is of the order of 0.1 \( w \frac{dU}{dz} \) can be neglected in equation (8). However at a latter stage we assume a uniform approach flow thus \( \frac{\partial U}{\partial z} = 0 \).
The equation of motion for the perturbation in the wake is now given by:

$$\frac{\partial u}{\partial x} = -\frac{1}{\rho} \frac{\partial \tau_{xy}}{\partial y} - \frac{1}{\rho} \frac{\partial \tau_{xz}}{\partial z}$$

(9)

Modelling the Reynolds shear stresses using the eddy viscosity assumption, the equation becomes:

$$\frac{\partial u}{\partial x} = \frac{\partial}{\partial y} \left( k_y \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_z \frac{\partial u}{\partial z} \right)$$

(10)

where $k_y$ and $k_z$ are assumed to be constant.

Momentum flux cannot be used as the conserved quantity in the wake since transfer takes place at the surface. However, if the moment of momentum from the surface is used, this is conserved since the surface stress does not contribute. Multiplying Equation (9) by $z$ and integrating over $y$ and $z$ the right hand side of the equation becomes zero. The left hand side then gives the conservation condition:

$$\frac{d}{dx} \int_{-\infty}^{\infty} (zUu) dy dz = 0$$

(11)

The co-ordinates $x, y$ and $z$ are non dimensionalised by suitable length scales in the flow so:

$$\xi = \frac{x}{H_b}, \quad \eta = \frac{y}{L_y}, \quad \zeta = \frac{z}{L_z}$$

where $H_b$ is the building height and $L_y$ and $L_z$ are lateral and vertical length scales are functions of the downstream distance.

The similarity solution for the velocity deficit in the wake has the form:

$$u = u_0(\xi) H(\eta \xi)$$

(12)

where $u_0$ is the magnitude of the disturbance that decays with downstream distance, and $H$ is a function of both $\eta$ and $\xi$. The objective of the analysis is to determine what these functions are.

The shape of the velocity profile for the undisturbed boundary layer is described by:

$$U = U_b \left( \frac{z}{H_b} \right)^n$$

where $U_b$ is the velocity at the building height in the undisturbed flow, and $n$ is a constant that is optimised to give the best fit to the velocity profile. $n$ is typically about 0.17.

Substituting the non dimensional form of $z$ into the equation it becomes:
Appendix 3
Wake model derivation

\[ U = U_h \left( \frac{L_z}{H_b} \right)^n \xi^n \]  \hspace{1cm} (13)

**Calculating \( \frac{\partial u}{\partial x} \)**

by the product rule:

\[ \frac{\partial u}{\partial x} = \frac{du_0}{dx} H + u_0 \frac{\partial H}{\partial x} \]  \hspace{1cm} (14)

For partial differentiation:

\[ \frac{\partial H}{\partial x} = \frac{\partial H}{\partial \eta} \frac{\partial \eta}{\partial x} + \frac{\partial H}{\partial \xi} \frac{\partial \xi}{\partial x} \]  \hspace{1cm} (15)

This results can be substituted into equation (15) together with the analogous result for \( \zeta \) so this becomes:

\[ \frac{\partial H}{\partial x} = - \frac{1}{H_b} \frac{1}{L_y} \frac{\partial L_y}{\partial \xi} \frac{\partial H}{\partial \eta} - \frac{1}{H_b} \frac{1}{L_z} \frac{\partial L_z}{\partial \xi} \frac{\partial H}{\partial \zeta} \]

Substituting these result back into equation (14) gives

\[ \frac{\partial u}{\partial x} = \frac{1}{H_b} \frac{du_0}{dx} H - \frac{u_0}{H_b} \frac{1}{L_y} \frac{\partial L_y}{\partial \xi} \frac{\partial H}{\partial \eta} - \frac{u_0}{H_b} \frac{1}{L_z} \frac{\partial L_z}{\partial \xi} \frac{\partial H}{\partial \zeta} \]  \hspace{1cm} (16)

**Calculating \( \frac{\partial^2 u}{\partial y^2} \)**

\[ \frac{\partial u}{\partial y} = \frac{\partial (u_0H)}{\partial y} = u_0 \frac{\partial H}{\partial \eta} \frac{\partial \eta}{\partial y} = u_0 \left( \frac{1}{L_z} \frac{\partial \eta}{\partial y} \right) \]

so:

\[ \frac{\partial^2 u}{\partial y^2} = u_0 \left( \frac{1}{L_z} \frac{\partial^2 H}{\partial \eta^2} \right) \]  \hspace{1cm} (17)

Rearranging Equation (10) gives:

\[ U \frac{\partial u}{\partial x} - k_y \frac{\partial^2 u}{\partial y^2} - k_z \frac{\partial^2 u}{\partial z^2} = 0 \]

substituting equations 13, 16 and 17 into this equation:


\[
\begin{align*}
\frac{U_h}{H_b} \left( \frac{L_z}{H_b} \right)^n \frac{du_0}{d\xi} + \frac{u_0}{L_y} \left( \frac{L_z}{H_b} \right)^n \frac{\partial L_y}{\partial \xi} \xi^n \frac{\partial H}{\partial \eta} & - \frac{U_h}{H_b} \left( \frac{L_z}{H_b} \right)^n u_0 \frac{\partial L_y}{\partial \xi} \xi^n \eta \frac{\partial H}{\partial \eta} \\
= - \frac{U_h}{H_b} \left( \frac{L_z}{H_b} \right)^n u_0 \frac{\partial L_y}{\partial \xi} \xi^{n+1} \frac{\partial H}{\partial \xi} - u_0 \frac{k_y}{L_z} \frac{\partial^2 H}{\partial \eta^2} - u_0 \frac{k_y}{L_z} \frac{\partial^2 H}{\partial \xi^2} = 0
\end{align*}
\]

Multiplying by \( \frac{L_z^2}{u_0 k_z} \)

\[
\left[ \frac{H_b U_h}{k_z} \left( \frac{L_z}{H_b} \right)^{2+n} \frac{1}{u_0} \frac{du_0}{d\xi} \right] \xi^n H - \left[ \frac{H_b U_h}{k_z} \left( \frac{L_z}{H_b} \right)^{2+n} \frac{1}{L_y} \frac{dL_y}{d\xi} \right] \xi^n \eta \frac{\partial H}{\partial \eta} \\
- \left[ \frac{H_b U_h}{k_z} \left( \frac{L_z}{H_b} \right)^{2+n} \frac{1}{L_z} \frac{dL_z}{d\xi} \right] \xi^{n+1} \frac{\partial H}{\partial \xi} - \left[ \frac{k_y}{k_z} \left( \frac{L_z}{H_b} \right)^{2+n} \frac{1}{L_y} \frac{dL_y}{d\xi} \right] \xi^n \frac{\partial H}{\partial \eta} = 0
\]

Let this be (18)

It is valid to set one term equal to unity because \( L_z \) has not yet been defined. This second order differential equation must have a solution for \( H \) that is independent of \( \xi \). For this similarity assumption to be true the expressions shown in bracket must be constants.

\[
\frac{H_b U_h}{k_z} \left( \frac{L_z}{H_b} \right)^{2+n} \frac{1}{L_z} \frac{dL_z}{d\xi} = 1
\]

let

\[
(19)
\]

This can be rearranged so:

\[
\frac{H_b U_h}{k_z} \left( \frac{L_z}{H_b} \right)^{2+n} \frac{d}{d\xi} \left( \frac{L_z}{H_b} \right) = 1
\]

which can be integrated to give:

\[
\left( \frac{L_z}{H_b} \right)^{2+n} = (2+n) \frac{k_z}{H_b U_h} \xi
\]

(20)

Also \( L_y^2 = L_z^2 \left( \frac{k_y}{k_z} \right) \)

so we have:

\[
\frac{L_z}{H_b} = \left( 2+n \right) \frac{k_z}{H_b U_h} \xi^{\frac{1}{2+n}}
\]

(21)

\[
\frac{L_y}{H_b} = \left( 2+n \right) \frac{k_y}{H_b U_h} \left( \frac{k_y}{k_z} \right)^{\frac{1}{2+n}} \xi
\]

(22)
Appendix 3

Wake model derivation

both \( L_y \) and \( L_z \) grow at a rate of \( \xi^{2+n} \) in the building wake.

From Equations (19) and (20) it follows that:

\[
\frac{H_b U_h}{k_z} \left( \frac{L_z}{H_b} \right)^{2+n} \frac{1}{L_z} \frac{dL_z}{d\xi} = (2+n) \frac{\xi}{L_z} \frac{dL_z}{d\xi} = 1
\]

Also by analogy the first coefficient in Equation (18) treated in the same way gives:

\[
\frac{H_b U_h}{k_z} \left( \frac{L_z}{H_b} \right)^{2+n} \frac{1}{u_0} \frac{du_0}{d\xi} = (2+n) \frac{\xi}{u_0} \frac{du_0}{d\xi} = \hat{m} \text{ say}
\]

\[
(2+n) \int \frac{1}{u_0} du_0 = \hat{m} \int \frac{1}{\xi} d\xi
\]

so:

\[
u_0 = \hat{\xi} \xi^{\hat{m}_{2+n}}
\]

where \( \hat{\xi} \) is made up of the constants of integration from the two integrals.

To find the value of \( \hat{m} \) we need to use the conservation condition given in Equation (11). Substituting into this expression the known equations it becomes:

\[
\frac{d}{dx} \int_0^\infty \left( \zeta L_z U_h \left( \frac{L_z}{H_b} \right)^{n} u_0 H \right) dydz = 0
\]

and changing the variables gives:

\[
U_h \frac{d}{d\xi} \int_0^\infty \left( u_0 \left( \frac{L_z}{H_b} \right)^{n+1} \xi^{n+1} L_y L_z H \right) d\eta d\zeta = 0
\]

At a given cross section downstream, \( L_y, L_z \) and \( u_0 \) are not functions of \( \eta \) and \( \zeta \) so they can be taken out of the integral. The equation then becomes:

\[
U_h \frac{d}{d\xi} \left[ u_0 \left( \frac{L_z}{H_b} \right)^{n+1} \int_0^\infty \int_0^\infty (\xi^{n+1}) d\eta d\zeta \right] = 0
\]

The result of the integral will be a constant. Therefore, for the derivative to equal zero the expression in the square brackets must also be a constant. Summing up powers of \( \xi \) for this expression yields:

\[
\frac{\hat{m}}{2+n} + \frac{n+1}{2+n} + \frac{1}{2+n} + \frac{1}{2+n} = 0
\]

so \( \hat{m} = -(3+n) \) and \( u_0 \) can be written as:

\[
u_0 = \hat{\xi} \xi^{-(3+n_{2+n})}
\]
Appendix 3

Wake model derivation

We have now found out how the magnitude of the velocity deficit decays in the wake. The constant, \( \hat{u} \), comes from the evaluating the integral in the conservation equation.

Determination of the function \( H(\eta, \zeta) \)

It can be shown that:

\[
\frac{1}{L_y} \frac{dL_y}{d\xi} = \frac{1}{L_z} \frac{dL_z}{d\xi} = 1
\]

Substituting this, and the result for \( \hat{m} \) into equation (18) gives:

\[
(3+n)\zeta^n H + \zeta^n \eta \frac{\partial H}{\partial \eta} + \zeta^{n+1} \frac{\partial H}{\partial \xi} \frac{\partial^2 H}{\partial \eta^2} + \frac{\partial^2 H}{\partial \xi^2} = 0
\] (26)

We only have a simple analytical solution in the limit \( n=0 \), so \( U(z) = U_h \) i.e. a uniform approach flow.

Writing \( H = h(\zeta) g(\eta) \) this equation becomes:

\[
3hg + \eta hg' + \zeta h' g + hg'' + h''g = 0
\]

Writing this expression as two separate equations for the lateral and vertical profiles

**Lateral profile**

\[
hg + \eta hg' + hg'' = 0
\] (27)

dividing through by \( h \) and simplifying using the product rule this becomes

\[
g'' + (\eta g)' = 0
\]

\[
g' = -\eta g
\]

\[
g = e^{-\eta^2/2}
\] (28)

**Vertical profile**

\[2hg + \zeta h'g + h''g = 0\] (29)

\[2\zeta h + \zeta^2 h' + \zeta h'' = 0\]

\[(\zeta^2 h')' + \zeta h'' = 0\]

\[\zeta^2 h + \zeta h' - h = 0\]

\[\zeta h' - (1 - \zeta^2) h = 0\]
Appendix 3

Wake model derivation

\[
\frac{h'}{h} = \frac{1}{\zeta} (1 - \zeta^2)
\]

\[
\int \frac{1}{h} \, dh = \int \frac{1}{\zeta} (1 - \zeta^2) \, d\zeta
\]

\[
h = \zeta \, e^{-\zeta^2/2}
\]

The similarity solution now becomes:

\[
u = \hat{u} \quad \frac{e^{-3\eta/2+n}}{\zeta} \quad \frac{e^{-\eta/2}}{\zeta} \quad \frac{e^{-\zeta^2/2}}{\zeta}
\]

(31)

**Behaviour of the Reynolds stresses in the wake**

The eddy viscosity model approximates the Reynolds stresses as:

\[
\tau_{xz} = k_\zeta \frac{\partial u}{\partial \zeta}
\]

substituting for \( u \)

\[
\tau_{xz} = \hat{u} k_\zeta \frac{e^{-3\eta/2+n}}{\zeta} \frac{e^{-\eta/2}}{\zeta} \frac{\partial (\zeta e^{-\zeta^2/2})}{\partial \zeta}
\]

\[
= \hat{u} k_\zeta \frac{e^{-3\eta/2+n}}{L_\zeta} \frac{e^{-\eta/2}}{\zeta} \frac{1}{L_\zeta} \frac{\partial (\zeta e^{-\zeta^2/2})}{\partial \zeta}
\]

(32)

The decay rate of the shear stress in the wake is given by:

\[
\frac{\zeta (3\eta/2+n)}{L_\zeta} = \frac{\zeta (3\eta/2+n)}{\zeta^{1/2+n}} = \zeta^{-(4+n/2+n)}
\]

(33)

The perturbed flow characteristics in the building wakes were investigated by measuring vertical and lateral profiles using a cross-wire. By making such measurements at a number of downstream positions the spread and decay rates in the wakes could be analysed and compared to the 3D wake model. The cross-wire angle calibration was carried out in a small 'calibration' tunnel and was assumed constant over the life of the probe. The velocity calibration was repeated before each measurement run and was performed in the main wind tunnel, half way up the boundary layer using a propeller anemometer as the velocity reference. Drift in the cross-wire calibration over run periods of 20 hours or so was not generally significant and for most cases the agreement of the mean velocity was within ±1% of the propeller over the whole period.
<table>
<thead>
<tr>
<th>Building</th>
<th>Building Orientation (deg)</th>
<th>Profile</th>
<th>X-Wire Probe orientation</th>
<th>Downstream locations measured in the wake (x/Hb)</th>
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<tr>
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<td>uw, uw</td>
<td>Data</td>
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Appendix 4. Summary of flow measurements in the building wakes
Appendix 5. Ground level concentration measurements in the building wakes.

The centreline concentrations in the building wakes are non-dimensionalised by the height of the buildings which were all 125mm. The curves fitted to the data are given by Equation 5.2 using values for $C_{\text{max}}$, $X_{\text{max}}$, $q$ and $m$ as tabulated above each plot. The appropriate effective stack height for each profile has been calculated from $C_{\text{max}}$, using the empirical relationships shown in Figure 5.8. The values for $X_{\text{max}}$ and $H_e$ are both given in mm. The empty plots indicate that no measurements were made for that release height for the building case concerned.
Ground level concentration distributions for the case A in neutral and stable flow.
Ground level concentration distributions for the case B in neutral and stable flow.
Ground level concentration distributions for building case C in neutral flow
Ground level concentration data

Appendix 5

Ground level concentration distributions for building case D in neutral flow
Appendix 5
Ground level concentration data

Ground level concentration distributions for building case E in neutral flow
Ground level concentration distributions for building case F in neutral and stable flow
Ground level concentration data for building case G in neutral flow.

<table>
<thead>
<tr>
<th>Ha/Hb</th>
<th>Ha (mm)</th>
<th>C_{max}</th>
<th>X_{max}</th>
<th>q</th>
<th>m</th>
<th>H_a</th>
<th>H_a/H_a H_a</th>
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<td>1.2</td>
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<td>1331</td>
<td>0.53</td>
<td>2.56</td>
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<td>128</td>
<td>0.27</td>
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</tr>
<tr>
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<td>805</td>
<td>0.79</td>
<td>0.72</td>
<td>87</td>
<td>0.51</td>
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</tbody>
</table>

Downwind distance in mm
Appendix 6: A modified Gaussian plume model.

Appendix 6 gives a mathematical proof to show that $\sigma_y$ can be any well behaved function of $z$ in the plume model without violating continuity.

Assume that the concentration is given by:

$$C = \alpha_c \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left[ \exp\left(-\frac{(z-z_p)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+z_p)^2}{2\sigma_z^2}\right) \right] (1 + f(z))$$  \hspace{1cm} (1)

where $\alpha_c$ is a coefficient that is only a function of $x$, to be determined, the lateral spread of the plume is given by $\sigma_y(x,z)$:

$$\sigma_y = \sigma_{yo}(x,1+f(z))$$  \hspace{1cm} (2)

$\sigma_{yo}(x)$ is the lateral spread at a reference height, and $\sigma_z$ is the vertical spread that are functions only of $x$. $f(z)$ must always be greater than -1 and less than infinity.

Conservation of emitted material satisfies:

$$Q = \int_0^\infty \int_{-\infty}^{\infty} U_{\text{adv}} C \, dy \, dz$$  \hspace{1cm} (3)

where $U_{\text{adv}}$ is the mean advection velocity of the plume.

Substituting (1) into (3) we obtain:

$$Q = \int_0^\infty \int_{-\infty}^{\infty} \alpha_c U_{\text{adv}} \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \left[ \exp\left(-\frac{(z-z_p)^2}{2\sigma_z^2}\right) + \exp\left(-\frac{(z+z_p)^2}{2\sigma_z^2}\right) \right] (1 + f(z)) \, dy \, dz$$  \hspace{1cm} (4)

Integrating (4) with respect to $y$ first, taking into account:

$$\int_{-\infty}^{\infty} e^{-\frac{y^2}{2\sigma_y^2}} \, dy = \sqrt{\frac{\pi}{a}}$$  \hspace{1cm} (5)

it follows that:

$$\int \left[ \exp\left(-\frac{y^2}{2\sigma_y^2}\right) \right] dy = \sqrt{\frac{\pi}{a}} = \sqrt{2\pi\sigma_y^2} = \sigma_y \sqrt{2\pi}$$  \hspace{1cm} (6)

with $a = \frac{1}{2\sigma_y^2}$

Substituting this results into equation (4) we obtain:
Appendix 6

A modified Gaussian plume model

\[ Q = \alpha_c U_{\text{advec}} \int_0^\infty \sigma_y \sqrt{2\pi} \left[ \exp \left( \frac{-(z-z_p)^2}{2\sigma_z^2} \right) + \exp \left( \frac{-(z+z_p)^2}{2\sigma_z^2} \right) \right] \left( 1 + f(z) \right) \, dz \]  

(7)

and substituting \( \sigma_y \) from equation (2) gives:

\[ Q = \alpha_c U_{\text{advec}} \sqrt{2\pi} \int_0^\infty \sigma_y \left( 1 + f(z) \right) \left[ \exp \left( \frac{-(z-z_p)^2}{2\sigma_z^2} \right) + \exp \left( \frac{-(z+z_p)^2}{2\sigma_z^2} \right) \right] \, dz \]  

(8)

which can be rearranged to give:

\[ Q = \alpha_c U_{\text{advec}} \sqrt{2\pi} \sigma_y \int_0^\infty \left[ \exp \left( \frac{-(z-z_p)^2}{2\sigma_z^2} \right) + \exp \left( \frac{-(z+z_p)^2}{2\sigma_z^2} \right) \right] \, dz \]  

(9)

One of the terms in the vertical integration is:

\[ \int_0^\infty \exp \left( \frac{-(z-z_p)^2}{2\sigma_z^2} \right) \, dz \]  

(10)

Let \( b = z - z_p \Rightarrow \frac{db}{dz} = 1 \)

Then equation (10) is written as:

\[ \int_0^\infty \exp \left( \frac{-(b)^2}{2\sigma_z^2} \right) \, db = \frac{1}{2\sqrt{2\pi\sigma_z^2}} \]  

(11)

Similarly:

\[ \int_0^\infty \exp \left( \frac{-(z+z_p)^2}{2\sigma_z^2} \right) \, dz = \frac{1}{2\sqrt{2\pi\sigma_z^2}} \]  

(12)

It follows therefore that:

\[ \int_0^\infty \left[ \exp \left( \frac{-(z-z_p)^2}{2\sigma_z^2} \right) + \exp \left( \frac{-(z+z_p)^2}{2\sigma_z^2} \right) \right] \, dz = \sigma_z \sqrt{2\pi} \]  

(13)

Substituting this into equation (9) gives:

\[ Q = \alpha_c U_{\text{advec}} 2\pi \sigma_y \sigma_z \Rightarrow \alpha_c = \frac{Q}{2\pi U_{\text{advec}} \sigma_y \sigma_z} \]  

(14)

Now we have found \( \alpha_c \) we can re-write the concentration expression given in (1) as:
A modified Gaussian plume model

\[ C = \frac{Q}{2\pi u_{adv}} \sigma_x \sigma_z \exp \left(\frac{-y^2}{2\sigma_y^2} \right) \left[ \exp \left(\frac{-(z+z_p)^2}{2\sigma_y^2} \right) + \exp \left(\frac{-(z+z_p)^2}{2\sigma_z^2} \right) \right] (1+f(z)) \]  

(15)

which can be simplified using equation (2) to give:

\[ C = \frac{Q}{2\pi u_{adv}} \sigma_x \sigma_z \exp \left(\frac{-y^2}{2\sigma_y^2} \right) \left[ \exp \left(\frac{-(z+z_p)^2}{2\sigma_y^2} \right) + \exp \left(\frac{-(z+z_p)^2}{2\sigma_z^2} \right) \right] \]  

(16)

This result shows that the lateral plume spread can be any function of height provided \( \sigma_y \) is always greater than zero.