

Models For Building Affected Dispersion

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1 SUMMARY

Advanced models for predicting dispersion near buildings, ADMS-BUILD (Robins *et al*, 1997) and AERMOD-PRIME (Schulman *et al*, 2000), have been developed from extensive experimental and, to a lesser degree, theoretical research mainly concerning the behaviour of passive emissions from point sources in neutral boundary layer flows around cuboids. This research identified the main flow features in building wakes, their interactions and the role they played in the dispersion of pollutants released near buildings. The complexities of the processes were obvious and this led to operational dispersion models being developed that comprised a number of sub-models, each designed to treat dispersion in particular regions of the whole flow field. A unified modelling approach is only possible through CFD and wind tunnel simulations, which are both time consuming and expensive.

2 BACKGROUND TO MODELLING

Advanced models for predicting dispersion near buildings, ADMS-BUILD (Robins *et al*, 1997) and AERMOD-PRIME (Schulman *et al*, 2000), have been developed from extensive experimental and, to a lesser degree, theoretical research mainly concerning the behaviour of passive emissions from point sources in neutral boundary layer flows around cuboids. This research identified the main flow features in building wakes, their interactions and the role they played in the dispersion of pollutants released near buildings. The complexities of the processes were obvious and this led to operational dispersion models being developed that comprised a number of sub-models, each designed to treat dispersion in particular regions of the whole flow field. A unified modelling approach is only possible through CFD and wind tunnel simulations, which are both time consuming and expensive.

- a The components of the sub-models seek to represent a number of important features identified by the research, including: entrainment into the near-wake,

- b rapid mixing within the near-wake,
- c streamline and plume deflection over the near and main wakes,
- d the effect of building shape and orientation,
- e the variation in near-wake concentrations with stack height and location,
- f enhanced dispersion rates in the main wake, and
- g the variation of the maximum ground level concentrations with stack height and location.

To central sub-models used to achieve this in ADMS-BUILD (and likewise in AERMOD-PRIME) treat the upstream flow, the near and main wakes and the external flow. Sub-models are expressed at different levels of sophistication, according to the complexity of the local flow and dispersion processes and their amenability to modelling. This leads to the use of empirical correlations, integral modelling and analytical theory.

In ADMS-BUILD a box model is adopted for the near-wake, with parameters defined through empirical data correlations for the residence time and the recirculation region dimensions. This predicts the spatial mean concentration within the whole of the near-wake, not the local point value. There is local variability about the predicted value from the detailed structure of the concentration field, as well as from the limitations of the box model to capture the intricacies of the response of the spatial average to changes in building shape, orientation, approach flow, and so on. The deflection of mean streamlines above the near-wake is modelled empirically as a function of building shape, orientation and source height. The approach used in ADMS-BUILD assumes zero deflection for winds normal to the walls of a block-shaped building and maximum deflection for winds aligned diagonally with the roof. The intent is to represent the downwash generated by roof vortices, even though these may persist into the main wake. The entrainment of material from a plume above the recirculation region is calculated from the distribution of concentration on the region boundary and downwind a two component plume structure is assumed, one component being ground based from the near-wake and the other the remaining fraction of the elevated plume.

Main wake dispersion theory must account for the excess turbulence levels, the mean velocity deficit and streamline convergence to be self-consistent. in ADMS-BUILD the 'momentum deficit' main wake is treated explicitly by constant eddy-viscosity theory that describes the velocity deficit and turbulence excess within the wake. Streamline deflection towards the wake occurs naturally by the decay of the momentum deficit. Additional deflection due to trailing vortex systems cannot be treated explicitly as no theoretical model exist, which explains the approximation of confining all such effects to the near-wake. The modified flow and turbulence fields within the main wake are used to calculate enhanced plume spreading rates that naturally tend to those of the underlying dispersion model as the wake decays. A multi-region Gaussian model is then formed using enhanced plume spreads in the wake in conjunction with the underlying spread behaviour in the external flow.

- a AERMOD-PRIME adopts a similar approach to ADMS-BUILD - the key differences are summarise below (Robins *et al*, 2001): the near-wake is well mixed vertically but with Gaussian lateral concentration profiles (with enhanced spreading rates),
- b entrainment into the recirculation region is calculated from the fraction of any external plume, treated as a Gaussian plume, lying below the region boundary,
- c there is no streamline deflection due to roof vortex systems,
- d free-wake theory is adopted to describe the main wake, and
- e fewer regions are used in the main wake Gaussian plume model

3 DEVELOPMENT AND EVALUATION

Broadly speaking, the modelling achieved its objectives, as comparisons with observations demonstrated. ADMS-BUILD and AERMOD-PRIME have between them used 17 comprehensive experimental studies, comprising 6 field and 13 wind tunnel experiments, in the evaluation of their performance. This has shown that the mean bias within an ensemble of calculations is typically within a factor of three, but with significant case-to-case variations likely within the ensemble (Robins *et al*, 1997, Robins *et al*, 1999). Wind tunnel studies of the dispersion of passive emissions near cuboids dominate the test cases, though some buoyant emissions and power station studies are included. Assessment of the sub-model specifications clearly shows that the reliability of their predictions must vary across them. However, that this is so is but weakly demonstrated by the evaluation studies carried out so far.

As already noted, model development rested on a limited set of experimental and theoretical studies and model applicability must sometimes be compromised by these origins. Nevertheless, BUILD and PRIME have been applied to the full range of practical interests, often perhaps with unjustified expectations of performance; these applications have included

- a. stable and unstable flows,
- b. buoyant emissions,
- c. arbitrary geometry, and
- d. building groups and industrial sites

Success or otherwise in these applications frequently depends on the ingenuity of the user as well as on the strengths and weaknesses of the modelling. However, continued research efforts have provided better grounds for assessing the accuracy of model predictions and, together with practical experience, have highlighted circumstances where improvements are required. The route to satisfying these demands either involves modifications to the models or, where this is not practical, the establishment of best practice and the associated level of accuracy that can be expected.

ADMS-BUILD was adapted to treat dispersion from stacks above tall, thin buildings by refinement of the streamline deflection algorithm. This is still being perfected as more experimental evidence becomes available. Other modifications were undertaken to improve the patching between sub-models and between the building effects module and the underlying dispersion model. In most other circumstances the complexities of real applications have had to be handled by developing best practice methodologies. Examples include the treatment of storage tanks, groups or buildings, industrial sites, and porous obstacles. Here, progress has been hampered by the need to undertake relevant experimental work, as this is often lacking

4 COMPLEX APPLICATIONS

4.1 Tall, thin buildings (Robins *et al*, 2001)

Figure 1 shows vertical profiles of concentration measured in a wind tunnel at a number of positions downwind of a building of square cross-section, side W , and height, $H=3W$. A source of passive material was positioned at a height $h=1.07H$. The building is inclined at 45° to the oncoming flow, so that this is the situation leading to maximum streamline deflection due to any roof vortices that might be present. The first profile, measured at $x=W$ from the building centre, shows a narrow plume aloft with significant entrainment from its lower edge that mixes the emission to the ground. The subsequent profiles at $x/W=2, 3, 5$ show the development of significant plume deflection. Further downwind, at around $x=15W$ in this case, the maximum ground level concentration is observed and this is about four times larger than it would have been without the building. Significant enhancements in maximum ground level concentrations were observed for source heights up to $h/H=1.5$ (the maximum investigated). Figure 2 shows plume centre paths for a passive emission at $h=1.07H$ with the building inclined at 0 and 45° to the approach flow. As expected there is relatively little deflection over the near wake region for the 0° case. The figure also shows the paths calculated from ADMS-BUILD3. This slightly over-predicts deflections in the main wake for the 45° orientation, though further refinement of the algorithm awaits detailed velocity field data becoming available.

4.2 Storage tanks (Hort *et al*, 2001)

Tanks used in the petrol-chemical and other industries typically have diameter to height ratios in the range $D/H=1$ to 4. How these might be represented in operational dispersion models was not clear and this, together with other considerations, prompted a series of experimental studies. Dispersion of passive emissions above tanks was compared with behaviour above cuboids. Figure 3 summarises results from the $D/H=1$ case by comparing maximum ground level concentrations as a function of source height with data for a cube. This shows

that a reasonable and conservatively biased assumption would be to treat a tank as a cube at 45° to the approach flow; that is always at 45° to the flow, regardless of the wind direction. Another set of experiments concerned tanks with bund walls around them, designed so that their volume was slightly greater than the tank volume. Changes brought about by these bund walls were dramatic, as Figure 4 proves. Mean velocity vectors in the centre x-z plane are shown for an isolated and banded tank and on each the path followed by the centre of a plume released above the roof has been added. Clearly the bund wall greatly reduces streamline deflections in the building wake and also changes the structure and dimensions of the near-wake. As a result, ground level concentrations from emissions at and above roof level are significantly reduced. Whether similar changes arise when tanks are located in more complex environments typical of industrial installations remains to be discovered

4.3 Industrial sites (Robins *et al*, 2000)

Extensive wind tunnel studies of the dispersion of stack emissions from the BNFL Sellafield site have been carried out. Results have frequently been interpreted in terms of reductions in effective stack heights for the emissions studied by comparing maximum ground level concentrations over the site model with data for isolated stacks. This has been complemented by studies using small regular arrays of obstacles. Results shown in Figures 5 and 6 refer to stack emissions from the B204 building. Figure 5 refers to arrays of nine buildings with S denoting the spacing between array members in terms of the building side; when $S=0$ they are touching. The source is above the centre building and the results are compared with data for the isolated building. This shows that the array greatly increases the reduction in effective stack height for stack heights greater than about $1.5H$; e.g. for $h/H=2$ the reduction increases from about 10 to 30% for the 0° orientation and from 30 to 50% for the 45° orientation. Similar results from the full Sellafield model provide a different picture. This is clear from Figure 6, where results are shown not only for the B204 building but also for a similar building placed a number of selected locations on the site where significant interactions with surrounding building was anticipated. Now the results show that behaviour is little different than that for the isolated building. Clearly, experiments with regular arrays cannot necessarily be reliably extrapolated to real sites as the positive interactions within regular arrays do not arise at complex sites such as Sellafield.

4.4 Porous structures (Robins *et al*, 1999a)

Porous structures are a common feature of many industrial sites, such as chemical process plant. Wind tunnel studies with generic, three dimensional porous obstacles were undertaken to discover how such structures should be treated in operational dispersion models. The range of flow regimes in the wake of porous structures is illustrated in Figure 7, contrasted with the well-known

recirculating flow that develops immediately downwind from a solid obstacle. Some flow passes through porous structures and the balance between the flow through and that deflected around the structure reflects the degree of porosity. There can be no recirculation immediately downwind of a porous structure because of the flow passing through it. Recovery in the wake and entrainment into the shear layers bounding the near-wake may lead to recirculation developing downwind. This may be a permanent feature of the flow or, if the structure is sufficiently porous, an intermittent feature. In both cases, vigorous mixing over the wake depth arises because of the recirculation and this is the typical situation for process plant. Even more porous structures create a region of reduced wind speed and turbulence in their wakes – this is the wind break regime. The effect of a detached recirculation region on plume behaviour is very marked, as Figure 8 demonstrates. The figure shows ground level concentrations downwind of a passive source at height $h/H=0.85$ behind a solid plate, two porous structures (designated M30,4 and M50,2) and in the undisturbed flow. M30,4 is the least porous of the two and recirculation quickly develops downwind, mixing the emission to ground at around $x=H$. Intermittent recirculation occurs in the other case and mixing to ground level is delayed to around $x=5H$ as a consequence. Representing both by the solid plate case in an operational dispersion model would be a reasonable approximation for $x>7.5H$, but nearer the structure no such approach is reliable. Clearly models could be developed but our understanding of the flows involved would need to be considerably enlarged for this were to become feasible

5 FINAL COMMENTS

Operational models that treat building effects use concepts and understanding that are biased towards neutral flow and cuboid shapes. Comparisons with data from such situations has shown that the mean bias within an ensemble of calculations is typically within a factor of three, but with significant case-to-case variations likely within the ensemble. Occasionally, model developments have been able to cope with the complexities found in some real applications though, in general, these have had to be handled by developing best practice methodologies. This process is clearly case specific and frequently hampered by a lack of suitable empirical information.

ADMS-BUILD and AERMOD-PRIME are very similar models (Robins *et al*, 2001) but their performance has not been assessed against the same data. This is unfortunate and suggests that a collection of data sets should be established that are judged to be of good quality and whose use in model evaluation is 'required' by potential model users. The number of data sets should be large and cover a wide range of applications, as well as generic cases, as only by evaluation against such a collection can model performance be reliably determined.

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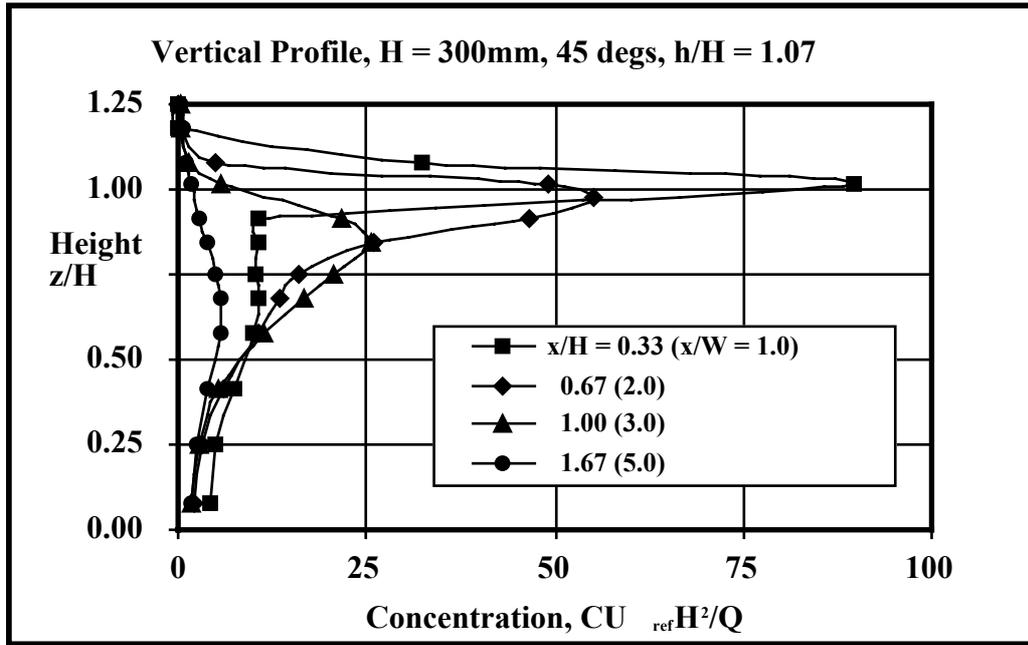


Figure 1. Measured profiles of mean concentration in the wake of a tall building at 45° to the approach flow; $H/W = 3$, $h/H = 1.07$

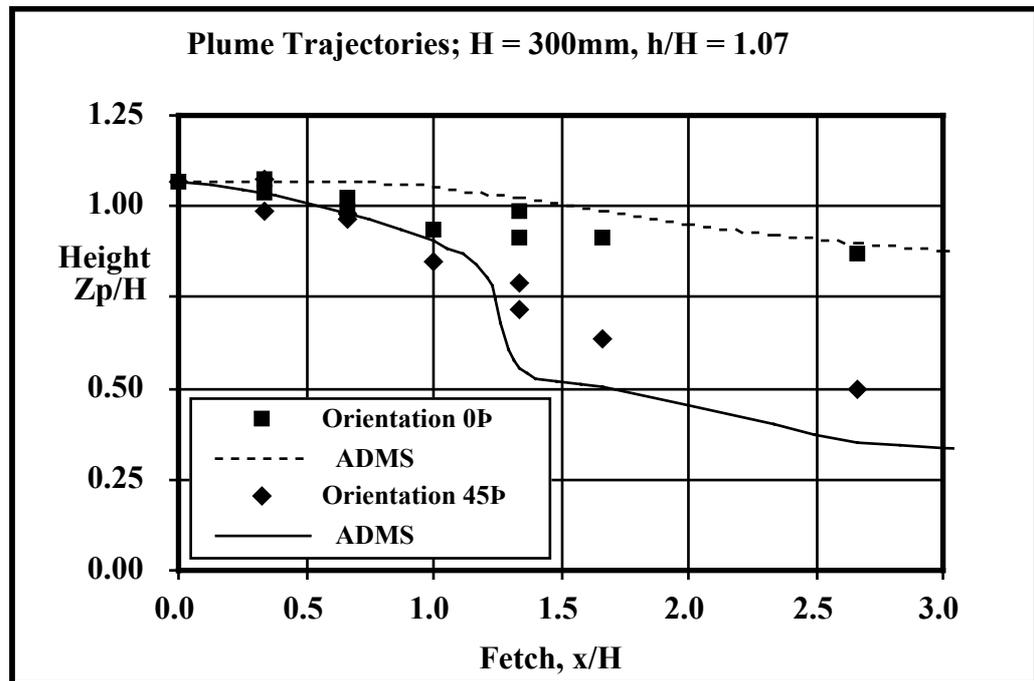


Figure 2. Measured and predicted plume heights, Z_p/H , downstream of a tall building; $H/W = 3$, $h/H = 1.07$

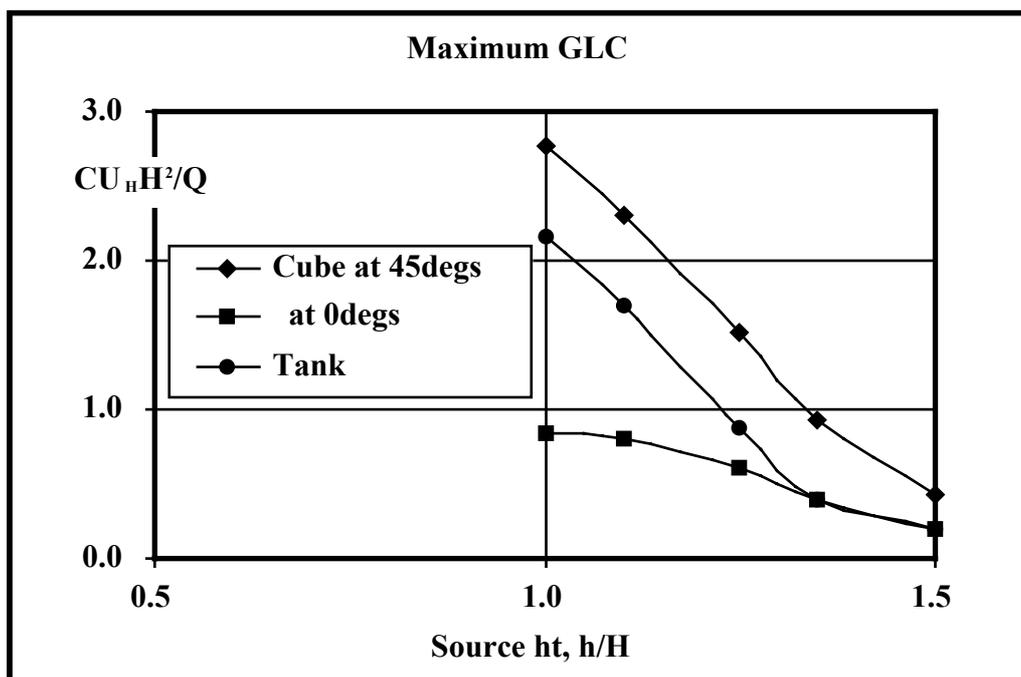


Figure 3. Measured variation of maximum ground level concentration with source height for releases above a cube at 0 and 45° orientation and a storage tank, $D = H$.

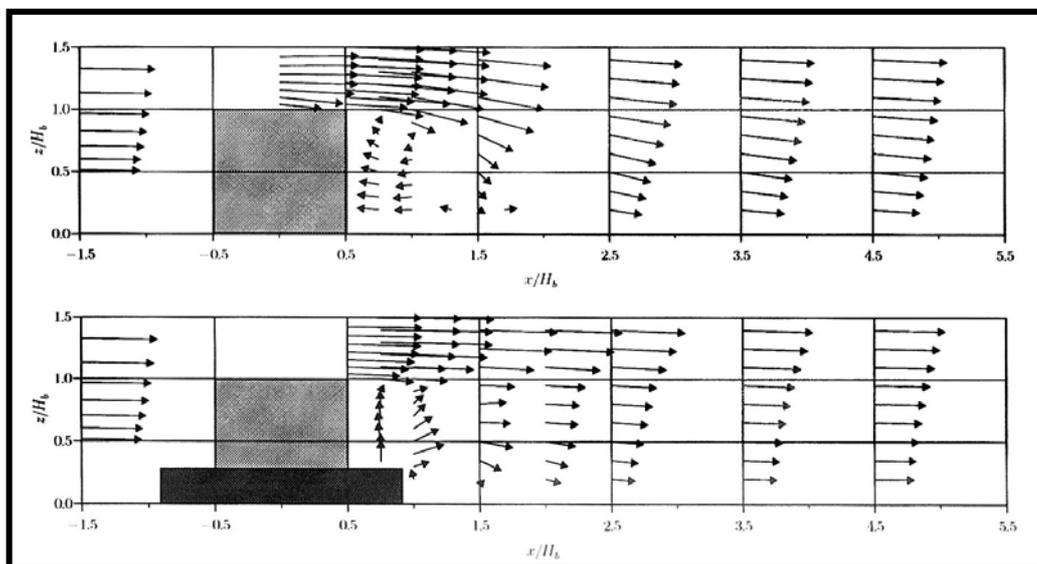


Figure 4. Velocity vectors measured behind a storage tank, $D = h$, in isolation and surrounded by a bund wall. The solid lines illustrate the paths followed by the centre of a plume released above the roof centre.

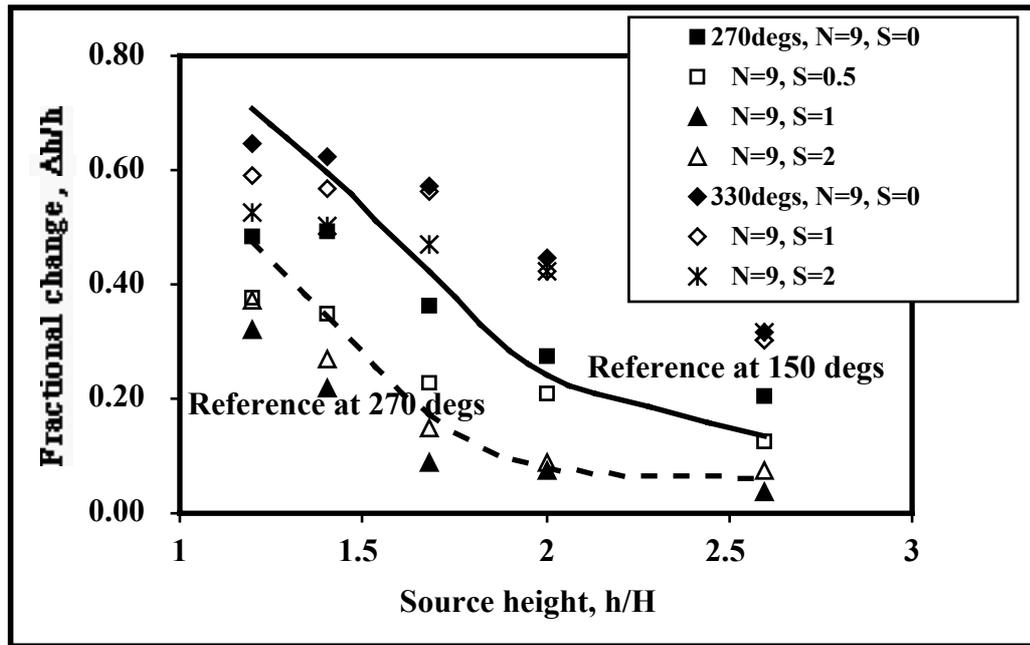


Figure 5. The measured reduction in effective source height from releases above the Sellafield B204 building positioned in the centre of a regular array of nine such buildings compared with a reference case of the isolated building.

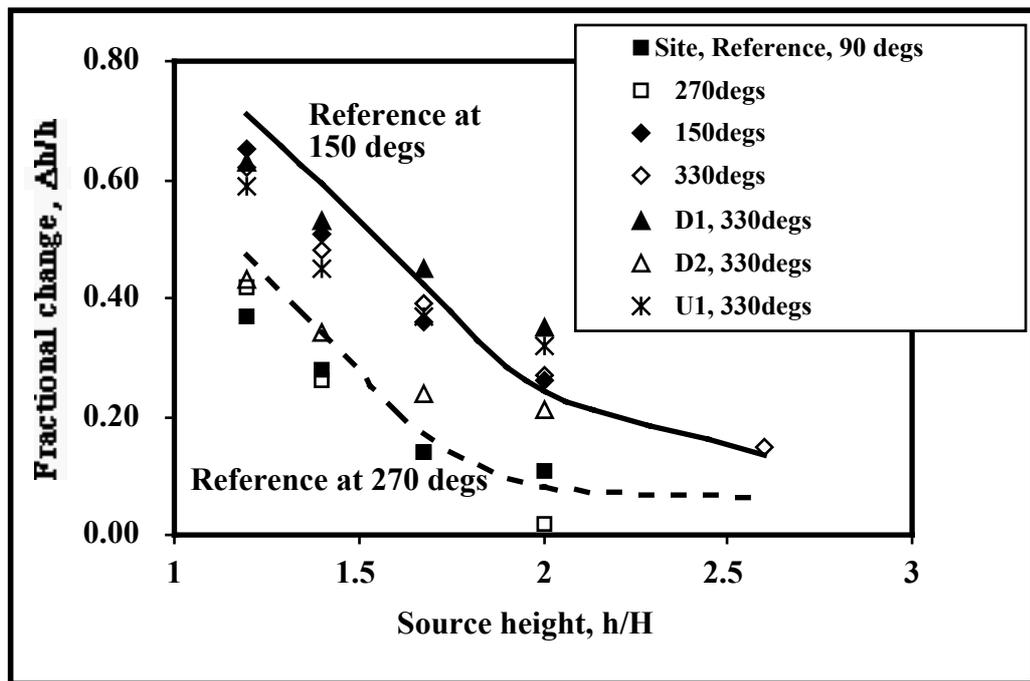


Figure 6. The measured reduction in effective source height from releases above the Sellafield B204 building positioned on the full site model compared with a reference case of the isolated building.

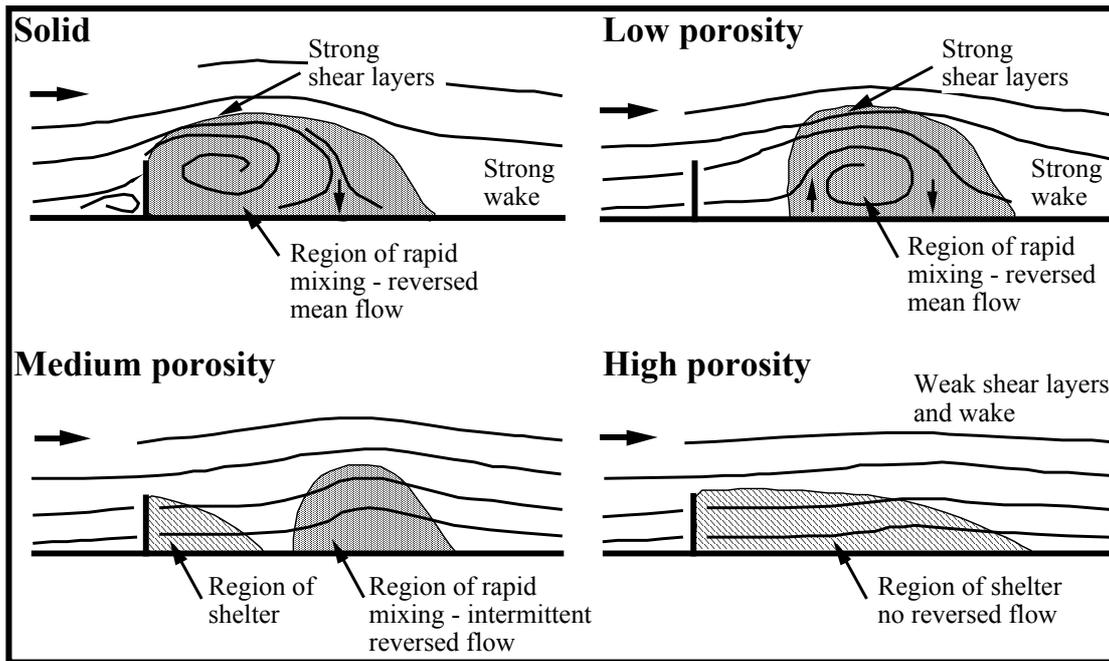


Figure 7. Regimes of flow downstream of a porous structure

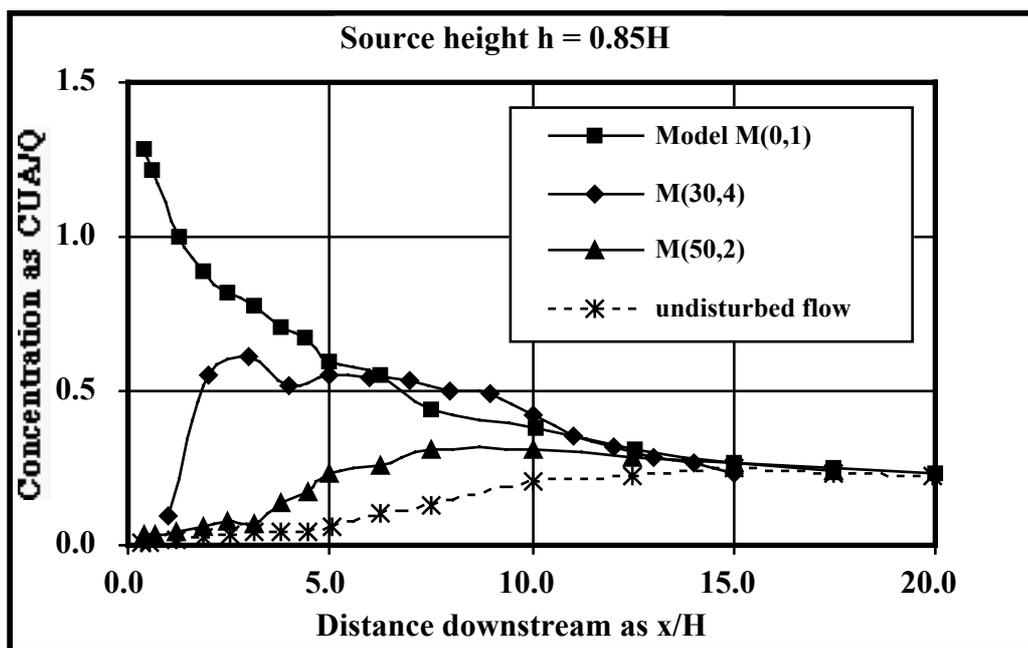


Figure 8. Ground level concentrations from a source, $h/H = 0.85$, just downstream from a porous structure compared with cases of a solid structure and the undisturbed flow.