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AN ANALYSIS OF THE TURBULENCE RECORDS FROM THE THORNEY ISLAND CONTINUOUS RELEASE TRIALS

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Summary

The paper describes an analysis of the fluctuating velocity and concentration records from the three continuous release trials carried out at Thorney Island in 1984.

For each of the Trials 045, 046 and 047 it is shown both qualitatively and quantitatively that the turbulence intensities (defined via a 3-min block average) in all three directions are greatly reduced in the presence of gas. A tentative result is that the quantitative behaviour of the turbulent intensities is surprisingly independent of the value of the local Richardson number. This indicates that a better determination of the local Richardson number needs to be made. It is also found that the turbulence intensities at heights where little or no gas was detected also show a marked reduction over the period when gas was present at lower heights.

Results have also been obtained on velocity covariances, though further work is required on this.

1. Introduction

One of the objectives of the Thorney Island trials was to provide data to further the understanding of the physical processes involved in heavy gas dispersion and to enable hypotheses made in modelling these processes to be tested. Numerical models of dispersion differ in the way they parameterise the turbulent mass and momentum fluxes that appear in the Reynolds averaged equations. The conditions in the Thorney Island continuous release trials were particularly suited to providing the kind of data needed to test these sub-models. The first step towards this end is to examine the effect of the density gradient on the turbulent structure. This paper describes such an examination of the fluctuating velocity and concentration records from the three continuous release trials, i.e. Trials 045, 046 and 047. The description of the trials is given in Ref. [1].

2. Background to the analysis of turbulence data

Statistical rigour dictates that the turbulence quantities should be obtained via suitably defined ensemble averages, i.e. by means of replicated experiments. In most field studies of turbulent flows, because of the impracticably large number of replications that would be required to produce stable averages, time averages are used instead and an ergodic hypothesis invoked to equate time to ensemble averages. Strict application of the ergodic hypothesis requires the flow to be statistically stationary in time and homogeneous in space. It is common practice, in studies of atmospheric turbulence and diffusion, to average over a time that is long compared with the time scales of the turbulence but short compared with the longer time scales associated with the synoptic-scale motions (see, for example, [2,3]). Time averages of the order of tens of minutes are generally indicated.

In the Thorney Island continuous release trials, the gas was released at a steady rate for about 7 min. Some sonic anemometers were within the plume for times between about 10 and 20 min. The effect of the presence of gas was clearly shown on the hard copy records of the w-component of the wind velocity as a marked reduction in the magnitude of the fluctuations. Since the w-component results are immediately available from the sonic anemometer records, these are first reviewed qualitatively to illustrate the effects and to pinpoint those anemometers whose records require quantitative analysis. These quantitative results are then presented in later sections of the paper.

3. Vertical turbulence records at locations at which gas was present: qualitative results

3.1 Sensors within the plume

(a) Trial 45

The sonic anemometers at the height of 1 m on the M2 mast at (400, 275) and on the M3 mast at (450, 275) were in the plume for about $12\frac{1}{2}$ min. The records of the gas concentration and the w-component of the fluctuating velocity at these locations are shown in Figs. 1 and 2. (The concentration records used in this paper are those from the fast-response sensors (see McQuaid and Roebuck [4] unless stated otherwise). It is clear that the magnitude of the fluctuations in the w-component was substantially reduced during the period when gas was detected. This is even true in the record in Fig. 2 for which, apart from the 30-s duration ‘spike’, the concentration was barely above 0.50% for most of the time. More will be said on this observation in Section 4.

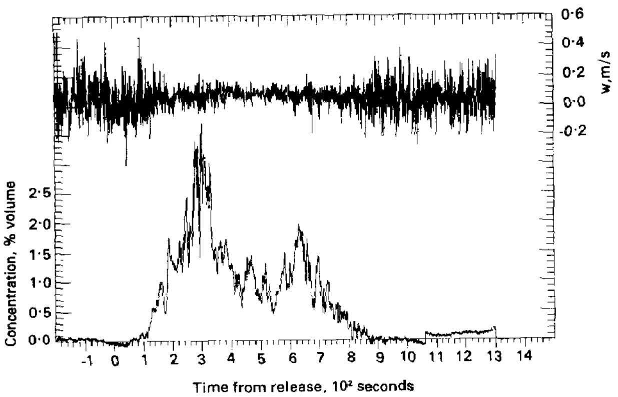


Fig. 1. Trial 45. w-velocity component and gas concentration at 1 m on M2 mast at (400, 275).

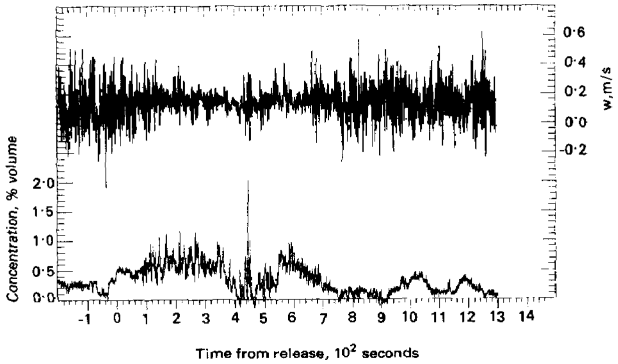


Fig. 2. Trial 45. w-velocity component and gas concentration at 1 m on M3 mast at (450, 275).

(b) Trial 46

For this trial, only one sonic anemometer was in the plume and then near its edge, due to an adverse wind direction. Unfortunately, the w-component channel of the sonic anemometer was faulty. (The A and B channels functioned satisfactorily and the data from them is included in the later analysis.)

(c) Trial 47

The sonic anemometers at the height of 1 m on the M2 mast at (400, 275), on the M3 mast at (450, 275) and on the M3 mast at (500, 275) were in the plume for about 20, 15 and 15 min, respectively. However, the latter location is the same as that at which the faulty w-component channel was noted for Trial 46 above and so is not available for this examination. The records of the gas concentration and the w-component of the fluctuating velocity at the first two locations are shown in Figs. 3 and 4.

It is again clear that the magnitude of the fluctuations in the w-component was substantially reduced during the periods when gas was detected.

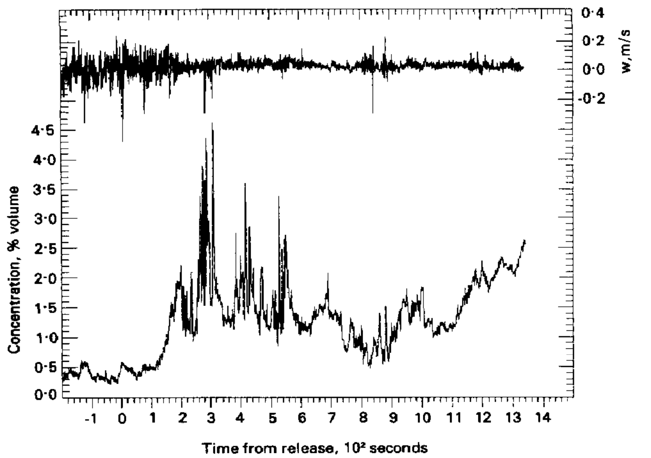


Fig. 3. Trial 47. w-velocity component and gas concentration at 1 m on M2 mast at (400, 275).

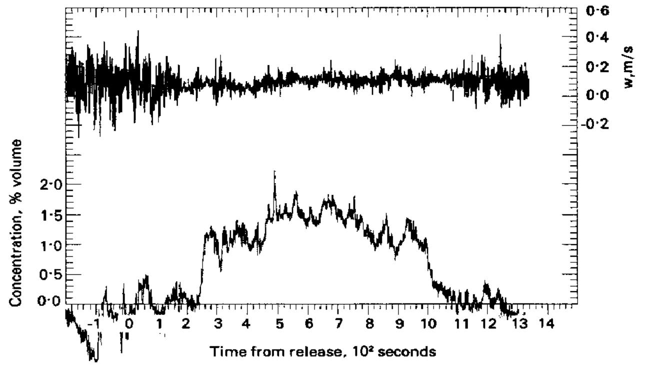


Fig. 4. Trial 47. w-velocity component and gas concentration at 1 m on M3 mast at (450, 275).

3.2 Sensors above the plume

A particularly interesting record from Trial 47 is that from the w-component at a height of 2.4 m on the M3 mast at (450, 275), shown in Fig. 5, together with the corresponding concentration record. The magnitude of the fluctuations in the w-component is seen to be reduced for about the same duration as that for the instrument at 1 m at the same location, shown in Fig. 4. It should be noted that the gas concentration record in Fig. 5 has been extracted from the original data set. It was excluded from the validated records of the trials as the sensor was judged not to have 'seen' gas. However, Fig. 5 shows that gas concentrations of at most 0.2% may have been detected by this instrument, although it is a matter of some judgement. The standard gas sensor at this location was deemed to have seen gas concentrations of up to 0.3% and its record is included in the validated data set. Thus, either a very small concentration affected the w-component or the presence of gas has an effect on the

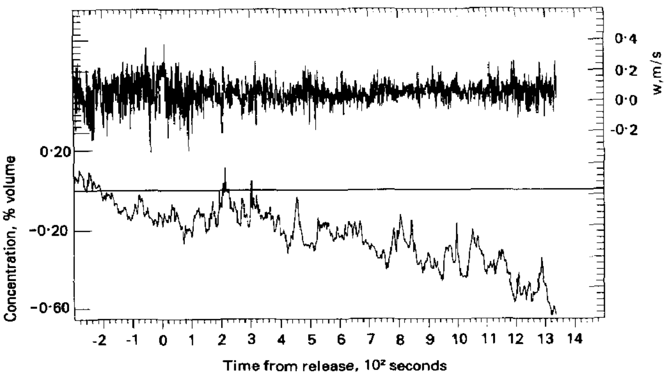


Fig. 5. Trial 47. w-velocity component and gas concentration at 2.4 m on M3 mast at (450, 275).

turbulence in the ambient air above it. That this could be the case has been pointed out by McQuaid [5].

A similar effect, though not so marked, is seen in the records from the corresponding sensor in Trial 45, shown in Fig. 6.

4. Turbulence intensities at locations at which gas was present: quantitative results

The determination of the turbulence intensities σ_u/U, for example, requires a choice to be made on the appropriate averaging time to use and on how the mean velocity should be defined. In general, the sonic anemometers were in the plume for between 10 and 20 min. That these durations are sufficient to give meaningful averages for the vertical velocity fluctuations can be argued as follows.

A turbulence time scale τ can be defined as l/u_*, where l is a length scale in

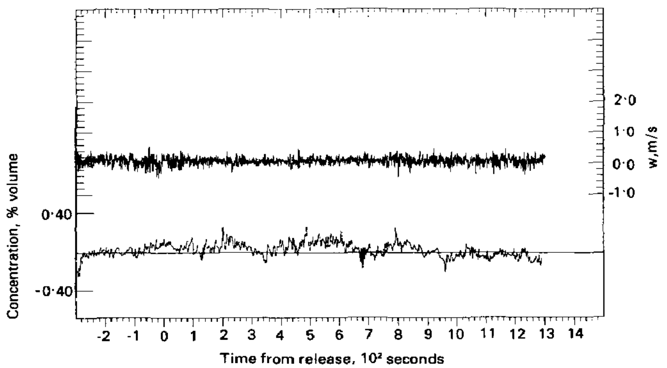


Fig. 6. Trial 45. w-velocity component and gas concentration at 2.4 m on M3 mast at (450, 275).

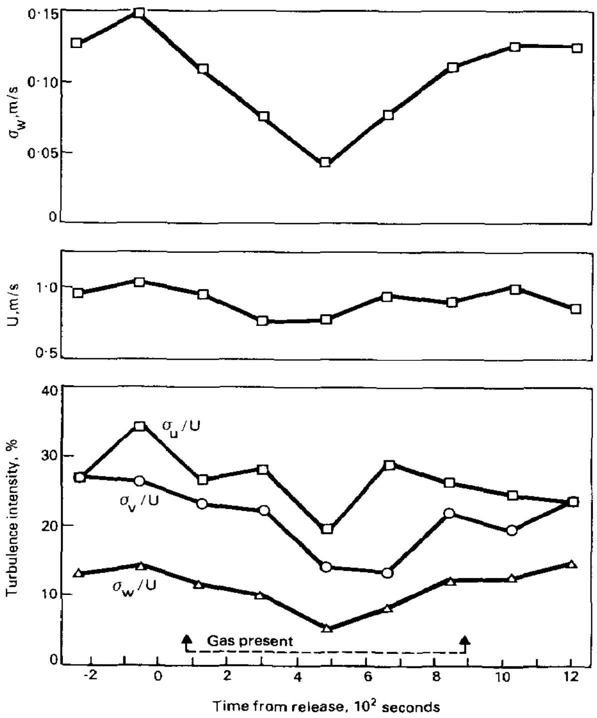


Fig. 7. Trial 45. Turbulence intensities at 1 m on M2 mast at (400, 275).

the vertical direction. The depth of the plume in the three trials was on the order of 2 m [1,6], so that $l \sim 2$ m. The friction velocity, $u_* \sim 0.2$ m s^{-1} (see the Appendix), so that $\tau \sim 10$ s. Stable averages should be obtained by averaging over $\sim 50\tau$ or $\sim 100\tau$, i.e. say 10 or 20 min. The length scale of eddies in the horizontal plane will of course be larger than in the vertical. It will be seen, however, that this appears to have little effect on the suitability of these averaging times.

While these averaging times may be suitable for defining stable turbulence velocity variances, one would like to be able to show how the turbulence intensities changed as the gas swept past a sensor, i.e. provide information on the intensities as a function of a local Richardson number. In order to be able to do this, averaging times of 10 or 20 min are far too long as the 'structure' of the concentration record is lost. (In the continuous release trials, the actual release time was limited to about 6 or 7 min. Near the source, effectively steady-state conditions were realised for times approaching 6 min. At the location of the M-masts, however, the concentration records indicate completely transient conditions.) It will be seen below that an averaging time of 3 min gives reasonably stable values of the turbulence velocity variances but that much of the 'structure' of the concentration record is still lost. An averaging time of 60 s appears to be about right for determining $C(t)$. There is then, however, a lot of variability in the values of the turbulence velocity variances. This poses problems for the determination of the turbulence transport terms like $\overline{c'w'}$. The other consideration is the choice of a velocity scale with which to normalise the r.m.s. velocity fluctuations. The natural choice is the local mean U, determined from the sonic anemometer record and averaged over the same period as for the determination of the r.m.s. values. However, the values of the r.m.s. velocity fluctuations themselves are presented so that other normalising velocities may be used if desired.

The results for the three trials are described below.

(a) Trial 45

For this trial, there are nine 3-min periods and the values of σ_w, U, σ_u/U, σ_v/U and σ_w/U at 1 m on the M2 mast at (400, 275) are shown in Fig. 7. The corresponding results for the sonic anemometers at 1 m on the M3 mast at (450, 275) are shown in Fig. 8.

As well as the dramatic decrease in σ_w/U, it can be seen that there is an equally large decrease in the horizontal intensities σ_u/U and σ_v/U. These changes are due to the change in the r.m.s. values and not to any change in U. Indeed the variation in the mean local velocity is quite small though there is evidence, at the first location, that the mean velocity is smaller during the presence of gas. A similar effect was observed by Koopman et al. [7] in the Burro 8 40-m^3 LNG spill test.

That the decreases occur in the presence of gas is clear. In order to confirm that the changes are due to the presence of gas and not to any coincidental change in the ambient flow, the values of σ_w, U and the intensities at a height of 14.5 m (well above any gas) for the two masts are shown in Figs. 9 and 10. There is no decrease during the period for which gas was present at these masts. Any changes during this period are within the 'natural' variability.

Encouraged by these results and by the need to reduce the averaging time still further in order to preserve the 'structure' of the concentration record (see Section 7) the r.m.s. of the velocity fluctuations and the local mean velocity were determined using a 1-min averaging time. The results for the instrument at 1 m on the M2 mast at (400, 275) are shown in Fig. 11. There is now much more variability. While the decrease in σ_w/U and σ_v/U during the presence of gas is still clear, that in the along-wind component σ_u/U is less so.

(b) Trial 46

For this trial, only one sonic anemometer, that at 1 m on the M3 mast at (500, 275) was in the plume. As already mentioned, the w-component channel of this instrument was faulty. However, the values of σ_u, σ_v, U and σ_u/U and σ_v/U can be obtained and are shown in Fig. 12.

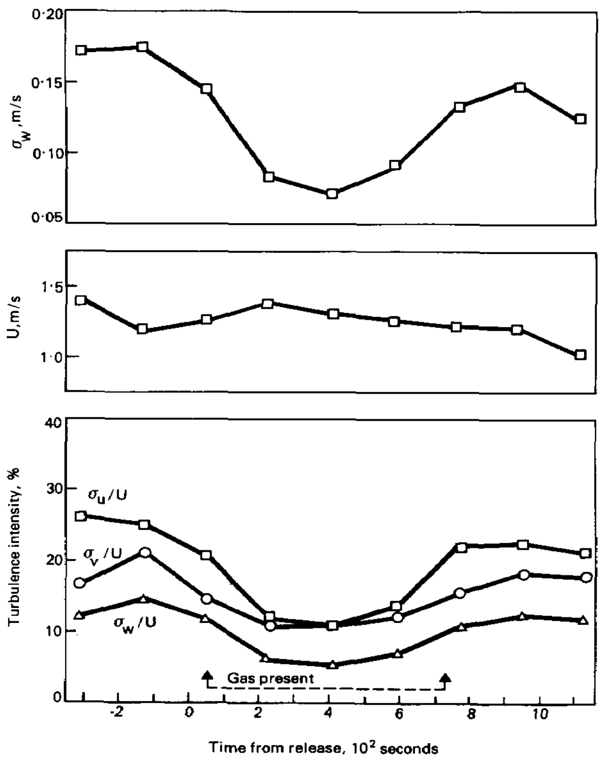


Fig. 8. Trial 45. Turbulence intensities at 1 m on M3 mast at (450, 275).

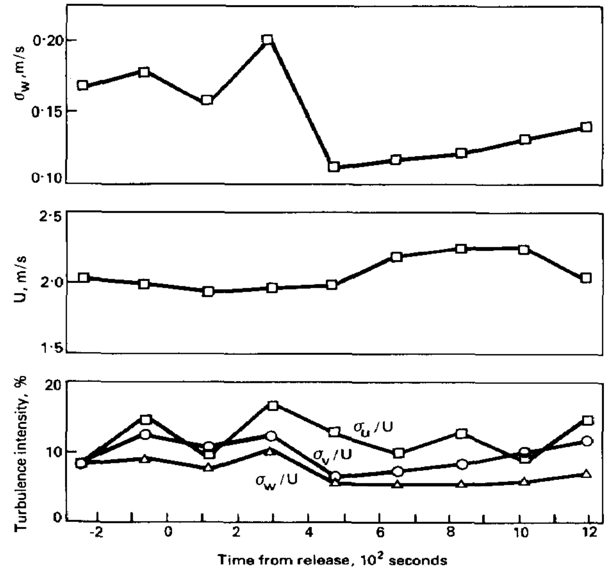


Fig. 9. Trial 45. Turbulence intensities at 14.5 m on M2 mast at (400, 275).

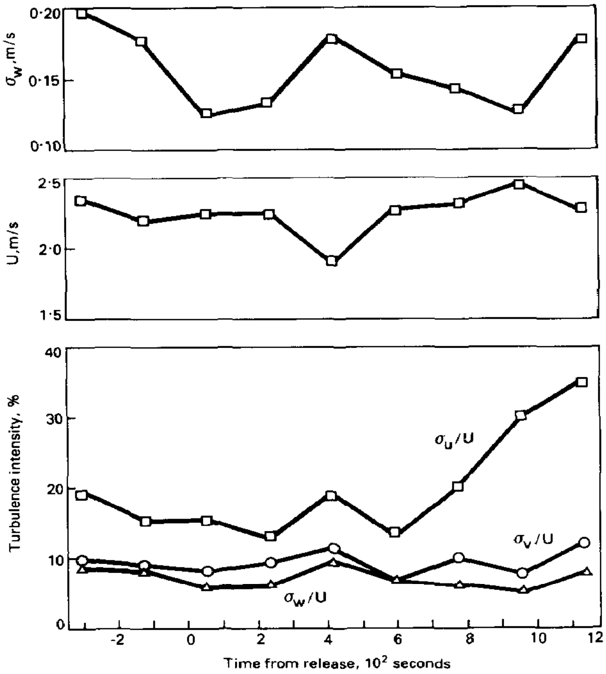


Fig. 10. Trial 45. Turbulence intensities at 14.5 m on M3 mast at (450, 275).

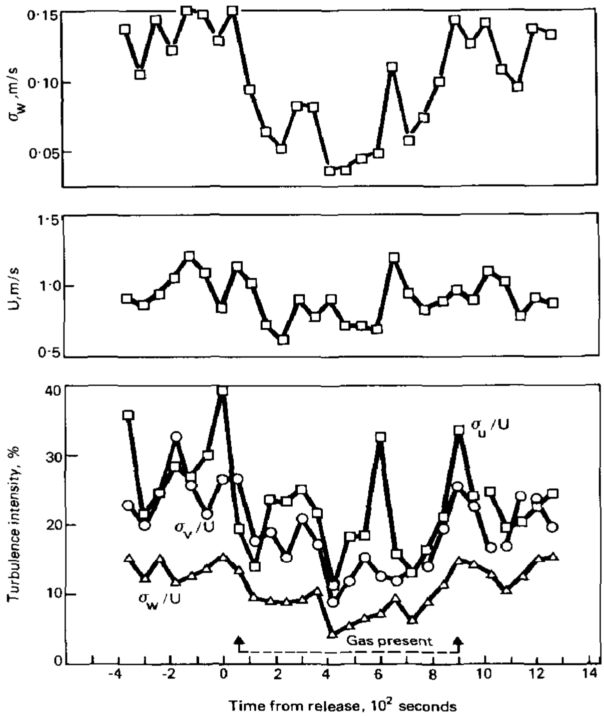


Fig. 11. Trial 45. Turbulence intensities at 1 m on M2 mast at (400, 275): 1 min block averages.

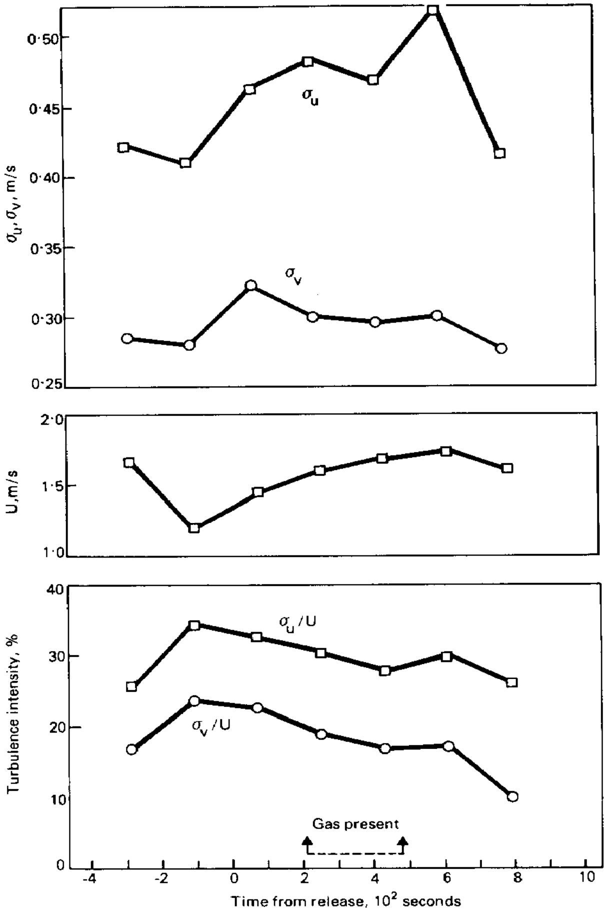


Fig. 12. Trial 46. Turbulence intensities at 1 m on M3 mast at (500, 275).

(c) Trial 47

The results from the sonic anemometers at 1 m on the M2 mast at (400, 275), on the M3 mast at (450, 275) and on the M3 mast at (500, 275) are shown in Figs. 13–15, respectively. (The *w*-component channel of the latter instrument was faulty.)

The dramatic reduction in the turbulence intensities during the presence of gas is generally confirmed by the results from these two trials. Again, there is some evidence that the local mean velocity is reduced during the period when gas is present.

The results for the sonic anemometer at a height of 2.4 m on the M3 mast at (450, 275) are shown in Fig. 16. The gas concentration at this location was very low, being close to the limit of detection of 0.1%; this has been discussed qualitatively in Section 3. The results shown in Fig. 16 confirm that the tur-

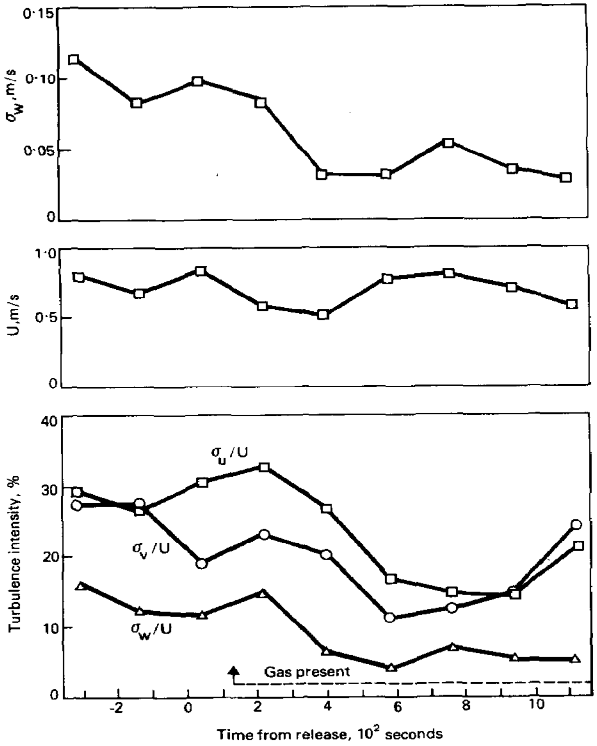


Fig. 13. Trial 47. Turbulence intensities at 1 m on M2 mast at (400, 275).

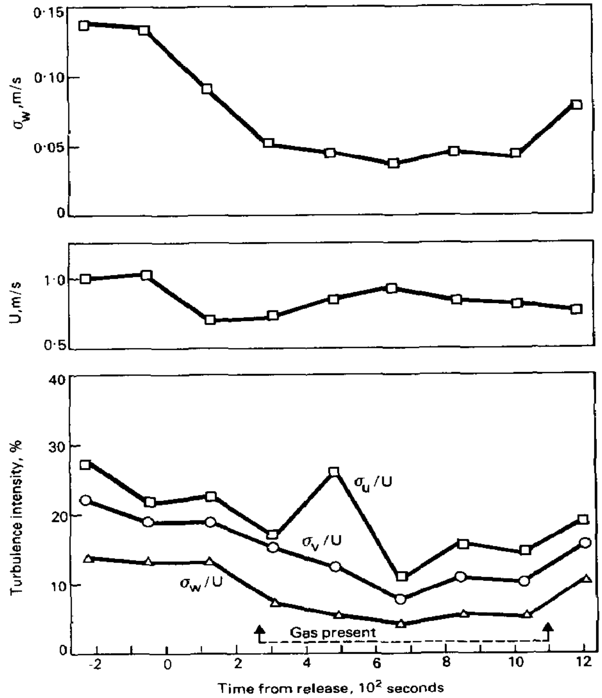


Fig. 14. Trial 47. Turbulence intensities at 1 m on M3 mast at (450, 275).

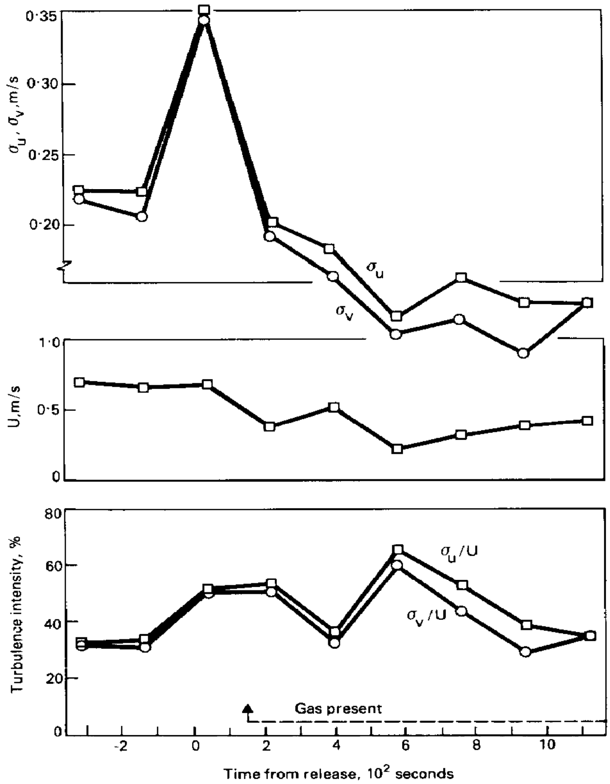


Fig. 15. Trial 47. Turbulence intensities at 1 m on M3 mast at (500, 275).

bulence intensities at this location are greatly reduced despite the very small gas concentration.

5. Turbulence velocity covariances

As well as the turbulence velocity intensities, one would like information on the covariances; $\overline{u'v'}$, $\overline{u'w'}$ and $\overline{v'w'}$. (Quantities like $\overline{c'w'}$ will be considered in Section 7.)

In order to determine stable values of the covariances, one might expect that a longer averaging time than that used to obtain the intensities would be needed. We have used 3-min and 9-min averaging times.

The values of $\overline{u'w'}$ and $\overline{v'w'}$ at the heights of 1 m and 14.5 m at the M2 mast at (400, 275) for Trial 45 are shown in Figs. 17(a) and (b), respectively. As well as the 3-min block averages, 9-min averages are also shown. The values of $\overline{v'w'}$ are very small, as one would expect.

It can be seen that there is evidence that the value of $\overline{u'w'}$ decreases when

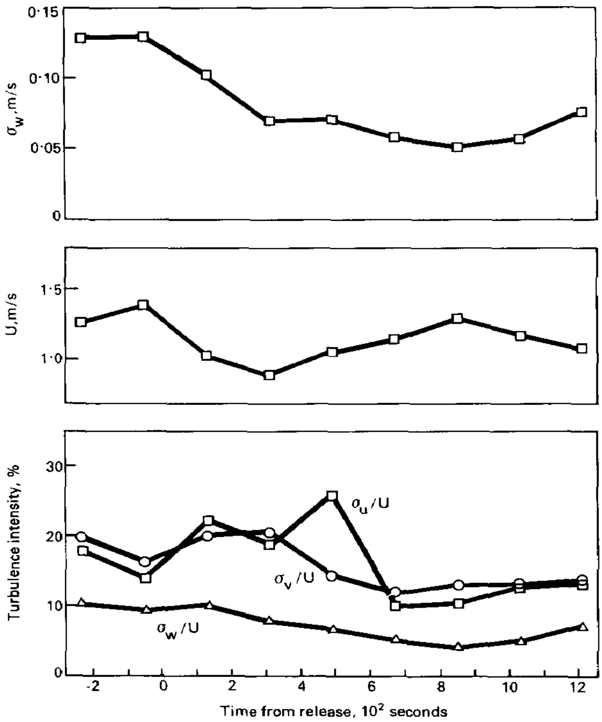


Fig. 16. Trial 47. Turbulence intensities at 2.4 m on M3 mast at (450, 275).

gas is present. The changes in magnitude and sign are significant when compared with the changes occurring at the height of 14.5 m, i.e. well above any gas. The corresponding results at the height of 10 m on the A-mast in Trial 45 are shown in Figs. 18(a) and (b); these values are remarkably constant. Thus, there is good reason for claiming that $\overline{u'w'}$ decreases in the presence of gas.

6. Calculation of a local Richardson number

Having shown that the turbulence intensities are reduced within the plume, an attempt has been made to relate the reduction to a local Richardson number.

In the absence of sufficient data to determine local concentration and velocity gradients, a local Richardson number may be defined as

$$Ri = \frac{g(\rho - \rho_a)\, h}{\rho_a\, u_*^2} \tag{6.1}$$

Here, ρ is the mean density through a vertical section across the plume, h is the mean depth of the plume at that section and time and ρ_a is the density of air; ρ and h can be obtained from the mean concentration distributions in the vertical direction [6]. The determination of u_* is described in the Appendix.

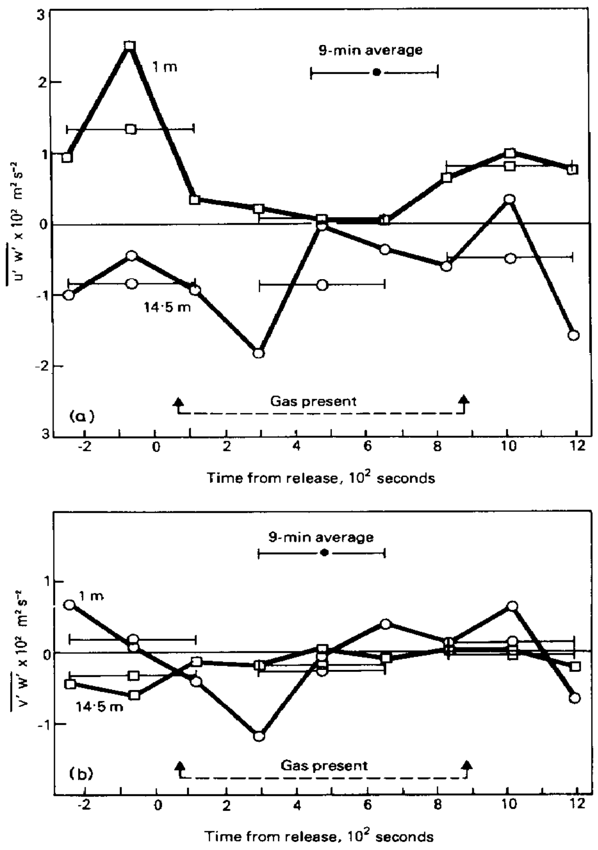


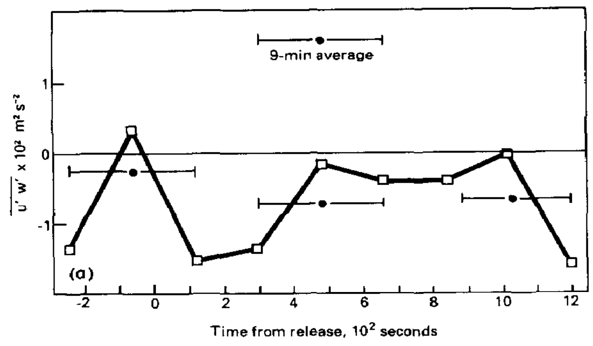
Fig. 17. Trial 45. Covariances: M2 mast at (400, 275); (a) $\overline{u'w'}$ versus time from release, (b) $\overline{v'w'}$ versus time from release.

The variation of the Richardson number with downwind distance is given in Table 1a for each of the two trials. (The distances selected are those at which analysis of the concentration distributions has been carried out by Mercer and Nussey [6].) The results for Trials 45 and 47 are plotted against downwind distance in Fig. 19. It can be seen that the points lie close to a line $Ri \propto x^{-1}$, where x is the downwind distance. This result has been used to obtain the values of Ri at the sonic anemometer locations referred to in Sections 3 and 4. These are given in Table 1b.

One may now consider the change in turbulence intensities in terms of the value of the Richardson number.

For Trial 45, at the M2 mast at (400, 275) the Richardson number is about 50 and the behaviour of the turbulence intensities at this location is shown in Fig. 7.

For Trial 47, at the M3 mast at (450, 275) the Richardson number is about



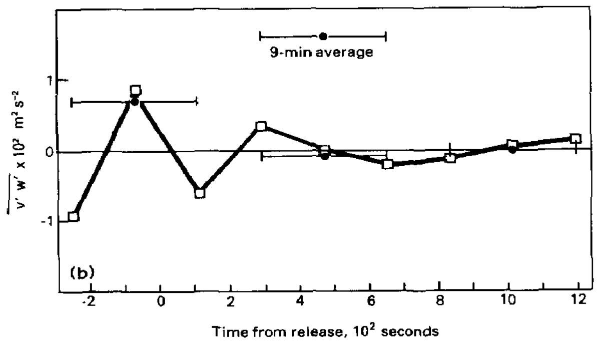


Fig. 18. Trial 45. Covariances: at 10 m on the A-mast; (a) $\overline{u'w'}$ versus time from release, (b) $\overline{v'w'}$ versus time from release.

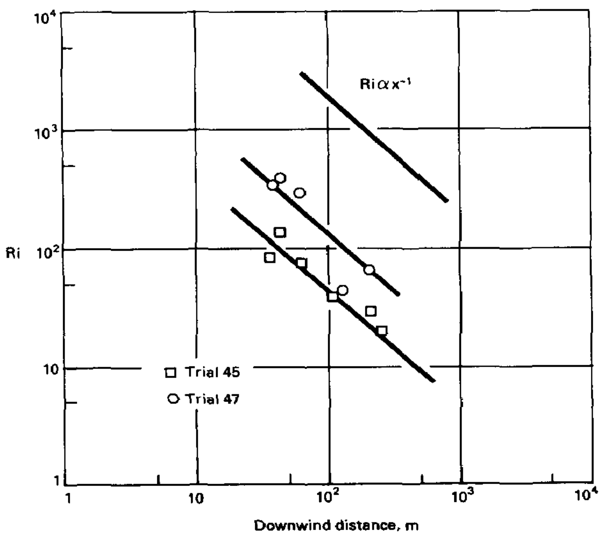


Fig. 19. Trials 45 and 47. *Ri* versus downwind distance.

TABLE 1a

Values of the Richardson number

Trial	Section	Downwind distance (m)	Plume depth (m)	Ri
45	1	36	1.4	82
	2	43	3.0	134
	3	62	2.2	74
	4	107	2.4	39
	5	203	5.0	29
	6	250	7.0	20
	7	467	7.6	5
46	1	53	2.3	14
47	1	38	1.5	340
	2	44	2.1	383
	3	61	2.0	296
	4	126	2.5	44
	5	202	3.9	65

$$Ri = g\frac{\Delta\rho}{\rho_a}\frac{h}{u_*^2}$$

TABLE 1b

Values of the Richardson number

Trial	Location	x (m)	Ri
45	(450, 275)	62	70
45	(400, 275)	90	50
46	(500, 275)	65	<15
47	(500, 275)	38	340
47	(450, 275)	61	215
47	(400, 275)	90	145

340 and the behaviour of the turbulence intensities at this location is shown in Fig. 14. For convenience, σ_w/U for these two locations are shown in Fig. 20.

It can be seen that, even with this large difference in the values of the two Richardson numbers, there is no clear difference in the quantitative change in the values of the turbulence intensities.

7. Mean concentration and concentration fluctuations

As well as the turbulence velocity intensities and covariances, other quantities of interest are the intensity of the concentration fluctuations, σ_c/C and the turbulent transport terms, $\overline{c'u'}$, $\overline{c'v'}$ and $\overline{c'w'}$.

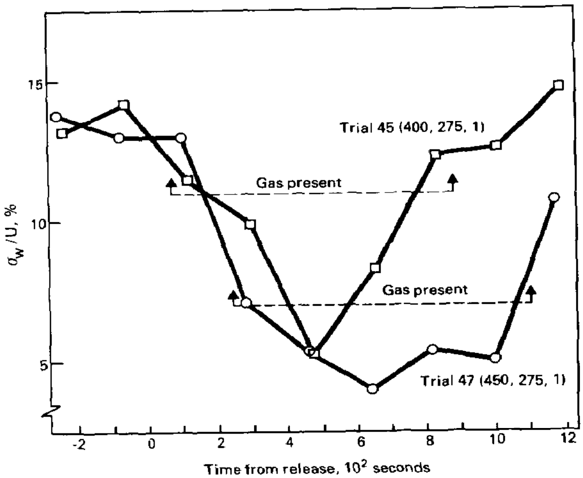


Fig. 20. Trials 45 and 47. w-component of turbulence intensity at 1 m.

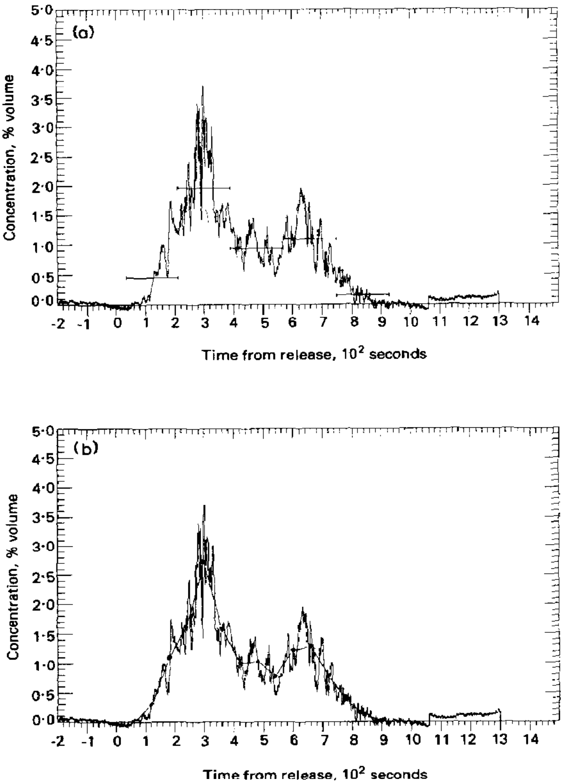


Fig. 21. Trial 45. Gas concentration at 1 m on M2 mast at (400, 275): (a) 3-min average, (b) 1-min average.

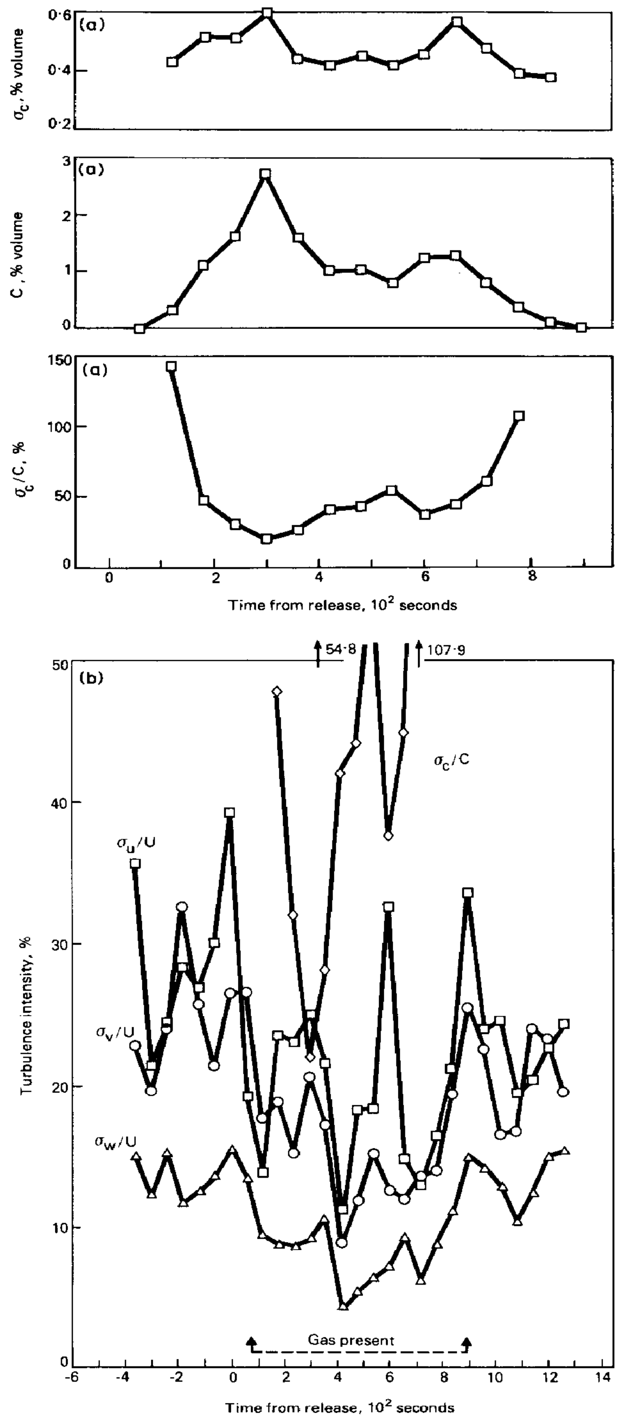


Fig. 22. Trial 45. Concentration (a) and turbulence (b) intensities at (400, 275, 1).

It has been shown in Section 4 that an averaging time of 3-min provides reasonably stable values for the turbulence intensities. However, if one applies a 3-min block average to a concentration record, the 'structure' of the record is completely lost. For example, Fig. 21(a) shows the concentration record from the fast response gas sensor at a height of 1 m on the M2 mast at (400, 275) for Trial 45 with the 3-min average superimposed. Applying a 60 s block mean gives the result shown in Fig. 21(b) and it is seen that a reasonably faithful representation of the underlying 'structure' of the record is thereby achieved.

Using an averaging time of 60 s, σ_c, C and σ_c/C have been calculated for this sensor with the results shown in Fig. 22(a). The values of σ_c are reasonably steady but the values of σ_c/C are highly variable. This can be seen more clearly on Fig. 22(b) which gives the values of σ_u/U, σ_v/U and σ_w/U together with σ_c/C using the same scale as has been used for presentations of the velocity intensities in Section 4. As remarked in Section 4, there is a great deal of variability in the velocity intensities derived with an averaging time of 60 s. The variability in σ_c/C is even greater, reflecting the change in C as well as in σ_c.

Nevertheless, the changes in the velocity intensities are clearly correlated with that in the concentration intensity. This provides a reason to be optimistic that values for quantities like $\overline{c'w'}$ can be derived through using an averaging time of 60 s.

8. Concluding remarks

It has been clearly shown that the turbulence intensities (defined via a 3-min block average) in all three directions are greatly reduced in the presence of gas. Two further (though tentative at this stage) results have been obtained. Firstly, the turbulence intensities at heights where little or no gas was detected show a marked reduction over the period when gas was present at lower heights. Secondly, the quantitative behaviour of the turbulence intensities is surprisingly independent of the value of the local Richardson number. This result is counter-intuitive; the method used to determine the local Richardson number could be improved and further work is needed.

Results have also been obtained on the velocity covariances. Because of the greater difficulties in defining an averaging time for these quantities, the results obtained so far are tentative. There is need for further work to be carried out on this and on the determination of quantities like $\overline{c'w'}$.

Finally, an interesting observation is that the results for the local Richardon number Ri as a function of downwind distance x, in Trials 45 and 47 clearly indicate that Ri decreases as $1/x$ for $Ri > 20$. Clearly, this result requires the assumption that the values of the local Richardson number are correct. Should these be substantiated, the observation would provide a good test of model performance, since the Richardson number involves both the concentration and the depth of the plume.

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Appendix

Description of the ambient wind field

Davies and Singh [8] and Puttock [9] have described the meteorology of the Thorney Island site and analysed the meteorological data for the Phase I trials.

The meteorological conditions for the continuous release trials are given by McQuaid [1]. Trial 46 can be regarded as having been conducted in neutral stability conditions, while Trials 45 and 47 took place in stable conditions. The velocity profile for neutral conditions is, in the usual notation,

$$U=\frac{u_*}{k}\ln\,(z/z_0) \qquad \text{(A1)}$$

This profile has been fitted to the data obtained from the instruments (cup-anemometers and sonic anemometers) on the meteorological station (the A-mast) for Trial 46. For Trials 45 and 47 attempts were made to fit the profile appropriate to stable conditions [3]

$$U=\frac{u_*}{k}\,(\ln\,(z/z_0)+5\,z/L) \qquad \text{(A2)}$$

where L is the Monin–Obukhov length.

However, anomalous results for u_*, z_0 and L were obtained (see Puttock [9] for a discussion of the problems involved). It was decided therefore to fit a neutral profile to Trials 45 and 47 as well. The values of u_* and z_0 so obtained are given in Table A1; they are reasonably consistent with those obtained by Davies and Singh [8] from an analysis of the Phase I trials.

The turbulent root-mean-square (r.m.s.) velocities in the downwind, cross-wind and vertical direction σ_u, σ_v and σ_w, respectively, have also been determined at the A-mast at heights of 2 and 10 m. These values together with the intensities σ_u/U, σ_v/U, σ_w/U and the values of σ_u/u_*, σ_v/u_* and σ_w/u_* for the three trials are given in Table A1.

According to Monin–Obukhov similarity, the values of σ_u/u_*, σ_v/u_* and σ_w/u_* are functions only of z/L in the surface layer. Thus, in neutral conditions, these normalised standard deviations should be constants, independent of height or roughness [10]. Empirically, it is also found that this is practically so for stable – though not too stable conditions. Panofsky and Dutton [10] give average values for σ_u/u_*, σ_v/u_* and σ_w/u_* (obtained from a number of micro-meteorological observations) of 2.39 ± 0.03, 1.92 ± 0.05 and 1.25 ± 0.03, respectively.

TABLE A1

Environmental conditions and turbulence intensities

	(a)		(b)		(c)	
	Trial 45		Trial 46		Trial 47	
u_*, m/s	0.14		0.20		0.08	
z_0, m	0.019		0.009		0.007	
Sensor height (m)	2	10	2	10	2	10
U (m/s)	1.55	2.13	2.52	2.93	1.07	1.37
σ_u (m/s)	0.365	0.335	0.532	0.662	0.265	0.240
σ_v (m/s)	0.324	0.398	0.378	0.390	0.184	0.221
σ_w (m/s)	[a]	0.158	[a]	0.334	[a]	0.107
σ_u/U	0.235	0.157	0.211	0.226	0.247	0.175
σ_v/U	0.209	0.187	0.150	0.133	0.172	0.161
σ_w/U	[a]	0.074	[a]	0.114	[a]	0.078
σ_u/u_*	2.61	2.39	2.66	3.31	3.31	3.00
σ_v/u_*	2.31	2.84	1.89	1.95	2.30	2.76
σ_w/u_*	[a]	1.13	[a]	1.67	[a]	1.34

[a] w-component channel not functioning.

It can be seen from Table A1 that apart from the values for σ_u/u_* in Trials 46 and 47, the results are in reasonable agreement with the values given by Panofsky and Dutton [10].

Another method of obtaining a value for u_*, then, is to average the values of the standard deviations σ_u and σ_v at the two heights and divide by the quoted ratios for the normalised standard deviations. This results in values for u_* of 0.17, 0.23 and 0.11 m s^{-1} for the three Trials 45, 46 and 47, respectively. These values are all within 20% of the values which were obtained by fitting a logarithmic neutral mean velocity profile. If these two sets are then averaged, we finally have the values; 0.15, 0.21 and 0.09 m s^{-1}, respectively.