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THE EFFECT OF AVERAGING TIME ON THE STATISTICAL PROPERTIES OF SENSOR RECORDS

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Summary

The paper presents the results of an analysis of the sensitivity to time smoothing of the concentration records from the Thorney Island trials. It is shown that averaging times greater than about one second can have significant effects on the concentration records. The observed peak is then attenuated to an extent which is greater than the uncertainty associated with the instrumentation. The loss of information is dependent on the chosen averaging time and needs to be considered in any comparison of the measurements with the predictions of models.

The paper also reports on a preliminary analysis of the turbulence records both inside and outside the cloud. It was not possible from the results of this analysis to delineate any influence of the dense gas on the turbulent structure within the cloud.

Introduction

In the Thorney Island trials, the selection of an instantaneous release mode was made on the basis of a number of criteria as described in [1]. The choice does, however, produce difficulties in interpretation and analysis of the data due to the unsteady nature of the flow. These difficulties need to be addressed in the context of the information requirements of predictive models. In particular, the extraction from the very large database of representative 'average' quantities characterising the cloud must first be performed before the data can be usefully compared with predictions. One approach is to derive suitably defined cloud averages, as has been done by Brighton [2]. An alternative, more fundamental, approach is to consider point values within the cloud. This approach is particularly relevant to the processing of the data for comparison with models which predict the internal structure of the cloud. This paper is concerned with the second approach.

The sensitivity of the concentration records from the Phase I trials to time smoothing is examined with a view to establishing ground rules for model validation work. A preliminary analysis of the turbulence records has also been performed with a view to determining whether there is any

measurable effect on turbulence parameters due to the presence of the dense gas.

It is inevitable that time averaging will attenuate the concentration record and the value of say, the peak concentration (i.e. the maximum concentration in a sensor record extending over the duration of the trial) will depend on the averaging time adopted. Moreover, since the record is not symmetrically distributed about the peak, the position of the peak may be significantly affected and this will be especially so when the largest peak is relatively sharp. It is essential therefore to have some indication of the effect of averaging time on the logged concentrations. Otherwise the task of assessing the level of agreement between a model and an experiment becomes difficult since good agreement could be a matter of judicious choice of averaging time.

The need to achieve a consensus view on the ordering and presentation of experimental data for model validation purposes is well recognised in the field of complex turbulent flows [3]. The study reported here does not set out to solve the problem in its entirety but rather to produce evidence that caution needs to be exercised and to recommend averaging times that could be considered to result in reasonable representations of the Phase I trials data base of gas concentration records.

The question of averaging time is also pertinent to the objectives regarding the provision of data to further the understanding of the physical processes involved in heavy gas dispersion and to test hypotheses concerning these processes that are made in mathematical models. This is because box models and numerical models require information on the mean and turbulent properties of the ambient wind field which will itself be an unsteady flow over the short duration characteristic of the passage of an instantaneous cloud. Numerical models also involve parameterisation of the turbulent processes within the gas cloud. It is thus necessary to describe the turbulence both in the ambient flow and in the cloud. The paper discusses the problems involved in analysing turbulence in an unsteady flow and presents some results.

2. Description of the concentration records

As a preliminary tc the data analysis, it is useful to look first at the types of concentration record observed in the trials. Concentrations are expressed as a percentage of the initial concentration which is taken to be 100%. The concentration records consist of data sampled at 20 times per second and organised into blocks of 12 data points. This provides a convenient first choice of averaging time of 0.6 s. Such averaged data are obtained simply as the mean of the data in each block and the averaged value is assigned to the time corresponding to the mid-point of the data block.

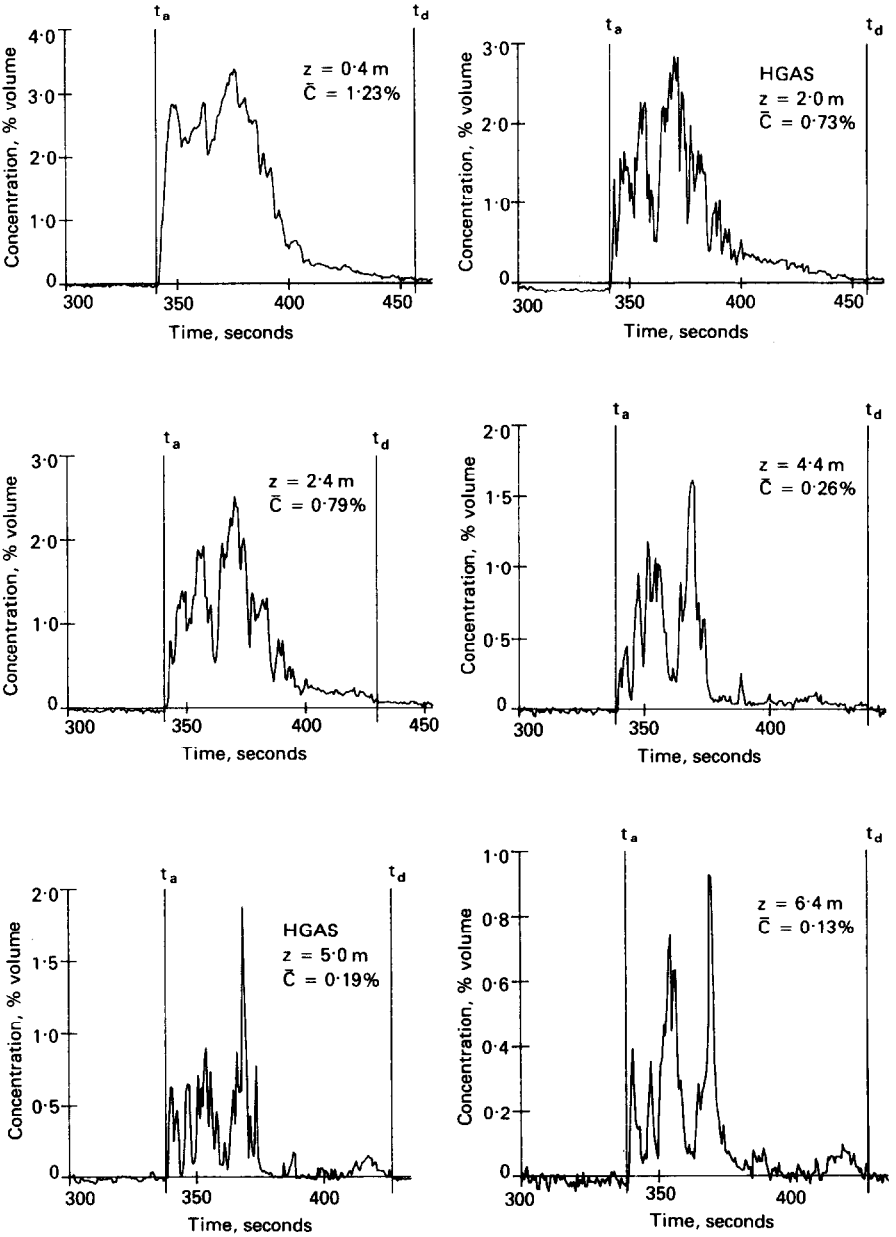


Fig. 1. Trial 19: Variation in concentration levels with height at X = 475 m, Y = 275 m for an averaging time of 0.6 s. The times shown are with respect to the start of the data collection period.

2.1 Characteristic features and their variation with height and downwind distance

Typical concentration records based on this 0.6 s averaging time are shown in Fig. 1. The figure shows the variation in concentration levels with height at a particular downwind location for Trial 19. The selected mast is about 100 m from the source and was one of the mobile masts which included two of the fast-response gas sensors denoted HGAS in the figure. The high level of fluctuation may be due to the spatial structure imparted to the cloud on release in combination with turbulent fluctuations (i.e. the superimposition of an essentially deterministic flow on a stochastic one). The mean concentrations, $\bar{C}$, shown for each height, is the average concentration over the duration of the cloud — the times shown are relative to the start of logging, the release occurring at 319.5 s. The arrival time, t_a, at the sensor is that when the concentration rises above, and remains above, the lower limit of resolution (0.1%) of the sensor. The departure time, t_d, is defined conversely.

Of particular interest are the peak concentrations i.e. the maximum concentration advected past each sensor. In Fig. 1 the peak concentration varies by about a factor of 4 between 0.4 m and 6.4 m and the peak-to-mean ratio by about a factor of 10. It is also interesting to note that the structure of the records at, and above 2 m, is broadly similar and that the standard gas sensors (denoted GAS in the figure) show similar features to the fast-response instruments (denoted HGAS in the figure), but the fast response instruments show more fluctuations.

Basically there are two types of concentration record: those showing relatively low levels of fluctuation (top left hand corner of Fig. 1) and the rest. At a particular height examination of other records shows that the degree of fluctuation in the concentration record tends to decrease with distance from the release point. These features are of course dependent on averaging time as will be shown in Section 3. The records selected for Fig. 1 are fairly representative of those obtained in all the Phase I trials.

2.2 Distribution of the peak concentrations over the Phase I trials

For a 0.6 s averaging time, the distribution of the peak concentrations that were observed in the Phase I trials is summarised in Table 1. The table shows, for each trial analysed, the number of sensors detecting gas (both standard and fast-response types), the number detecting a maximum concentration of less than 1% and the number detecting a maximum of more than 2%. The next three columns show the lower quartile, median, and upper quartile of the distribution of maximum concentrations and the final column shows the highest concentration observed by any sensor. (Trials 4 and 5 were not included in the analysis as the validated data tapes were not available at the time the analysis was conducted.)

For example, in the case of Trial 12, 41 sensors detected peaks of less than 1% and 12 sensors detected peaks of more than 2%. 25% of the sensors

TABLE 1

Distribution of peak concentration (0.6 s average) over the sensor array for trials 6 to 19

Trial No.	No. of sensors detecting gas	No. of sensors detecting less than 1% of gas	No. of sensors detecting more than 2% of gas	Peak concentration (%) distribution			
				Lower quartile	Median	Upper quartile	Highest in trial
6	46	34	5	0.26	0.40	0.89	9.2
7	57	37	10	0.28	0.65	1.55	13.2
8	73	49	13	0.23	0.66	1.18	9.3
9	62	38	10	0.22	0.54	2.65	12.3
10	11	1	9	2.03	3.88	4.66	7.6
11	23	10	7	0.16	1.20	2.58	7.9
12	65	41	12	0.17	0.37	1.65	11.6
13	47	20	15	0.69	0.92	2.21	7.6
14	50	30	10	0.40	0.57	1.41	6.9
15	38	15	15	0.35	1.33	3.18	25.6
16	45	27	10	0.44	0.56	1.72	17.9
17	62	42	15	0.22	0.36	1.49	82.3
18	60	34	18	0.35	0.66	3.98	88.2
19	67	32	24	0.34	0.92	2.50	89.7

detected 0.17% of gas or less and 50% detected peaks of 0.37% or less. The highest concentration observed by the sensor array was 11.6%. For Trials 6 through 19, 705 sensors detected gas of which 58% detected less than 1% of gas and about 25% detected more than 2%.

3. The effect of averaging time on concentration records

It will be apparent from the results shown in Fig. 1 that the data record will depend on the averaging time chosen, which was 0.6 s for the data illustrated.

Many of the sensor records exhibit significant attenuation of the peak concentration as the averaging time increases. A typical example is shown in Fig. 2. An averaging time of about 3 s reduces the peak based on a 0.6 s average by about a factor of 2, whilst significant features of the structure of the record are lost for a 10 s averaging time.

Given the variations in the properties of sensor records illustrated in Fig. 2, how is the averaging time to be decided? If modellers declared the averaging time appropriate to their models, there would be no difficulty. In the general absence of such information the first approach must be to assess the significance of the problem in the hope that the assessment will point to guidelines for future analyses.

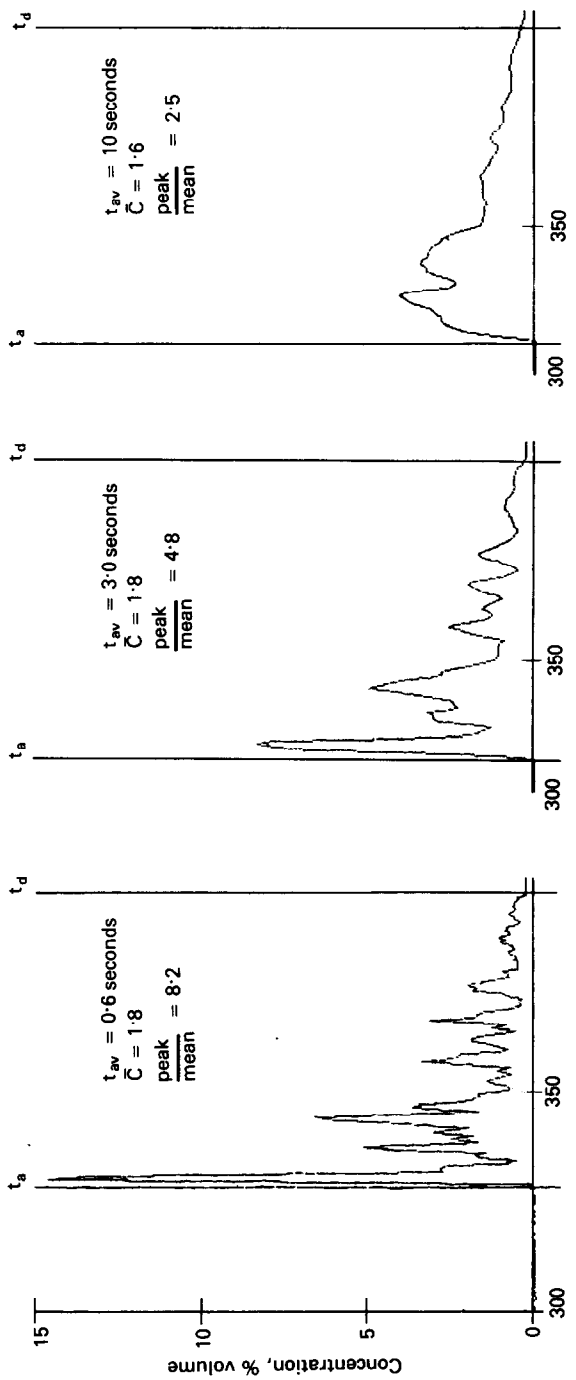


Fig. 2. Trial 19: Variation in peak concentration with averaging time, t_{av}. HGAS sensor at X = 400 m, Y = 250 m, Z = 2.0 m. The times shown are with respect to the start of the data collection period.

The record used as an illustration in Fig. 2 shows that the mean value of concentration over the duration of cloud presence at a particular location is not significantly affected by averaging, provided that the averaging time is much less than the duration of cloud presence. This conclusion is quite general for all the data. However, the mean value of concentration so defined is not pertinent to model validation and hazard analysis work. Of greater importance is the influence of averaging time on other characteristics of the record more closely associated with the specification of the hazard. For flammable clouds, the peak concentration (and the averaging time associated with it) will be important in defining the maximum extent of the combustible region of the cloud (see for example [4] and [5]). For toxic clouds, Griffiths and Harper [6] have shown the importance of the time variation of concentration in determining the toxic effect. Our assessment will therefore focus on the effect of averaging time on the measured peak concentration. Analysis of the effect on the intensity of the concentration fluctuations (a much more difficult problem) has not yet been performed in any detail.

3.1 Basis of the assessment of the effect of averaging time

A rational basis for this assessment, at least in the first instance, is that there should be no loss of relevant information as a result of the averaging process. This does not preclude the use of an averaging time which does result in such a loss provided the analyst is aware of that loss and makes a compensating adjustment in his model predictions. Whether the adjustments are valid depends of course on the ultimate use of the model, and specifically whether the information lost results in an unquantifiable uncertainty in the assessment of the hazard.

The concentration records are obtained from instruments with a finite response time and an inherent measurement inaccuracy. A first requirement is therefore that the averaging time should exceed the rise time of the sensors, which was about 0.3 s for the standard gas sensors used in the trials. The uncertainty in measurement is given by Leck and Lowe [7] as ±5% of reading for concentrations greater than 2% and ±0.1% concentration for concentrations less than 2%. An averaging time which attenuates the record outside the lower bound of these limits therefore inevitably results in a loss of information. This will be accepted as a measure of the averaging time above which suitable qualification will be necessary in any comparison of the data with model predictions. It is appreciated that shorter averaging times may result in a loss of information but this is not readily quantifiable. For larger averaging times, the data have been examined to assess the magnitude of the attenuation of the peak concentration and this provides a guide to judgements of the validity of model comparisons using large averaging times.

The concentration records represent a sampling of the sensor output at a much higher frequency than the frequency response of the sensors. Hence

any fluctuations present on the records that are at frequencies greater than the sensor frequency response arise from noise in the circuitry and the data logging system. The use of an averaging time greater than the rise time of the sensors will eliminate the high frequency noise. Above this averaging time, of course, the noise will be indistinguishable from genuine fluctuations reflecting concentration fluctuations. The frequency response of the gas sensors is thus of central importance and will be discussed prior to presenting the results of the data analysis.

3.2 Frequency response of the gas sensors

All but eight of the gas sensors deployed on the mast array are standard gas sensors, with a nominal frequency response of about 1 Hz (i.e. an exponential time constant of 0.16 s and a 10—90% rise time for a step change of 0.35 s). The remaining eight gas sensors are fast-response instruments with a frequency response of 10 Hz (i.e., a time constant of 0.016 s and a nominal rise time of 0.035 s). The response times quoted above were obtained under laboratory conditions in the manner described by Leck and Lowe [7] and only instruments exhibiting the nominal rise times (or better) were deployed in the field.

The laboratory conditions may not have been representative of those in the field which are of course not known, their determination being the object of the exercise. However, some idea of sensor performance may be gained by comparing the outputs of a number of sets of sensors with different response times that were in close proximity if it can be assumed that the input signals are essentially similar. Some of these comparisons make use of the record from the temperature channel of sonic anemometers as this should behave as a gas sensor in the presence of gas. (The temperature channel essentially determines the speed of sound, a, in the gas. Since $a \propto \sqrt{[T/M]}$ an increase in concentration and hence molecular weight, M, is recorded as a decrease in the temperature T.)

Two kinds of analysis have been carried out on some of the data from sensors in close proximity. Firstly, a comparison has been made between the data and the results of an idealised analysis. The variation in the attenuation of peak values with input frequency and sensor response has been calculated for sensor exponential time constants of 0.016, 0.16 and 0.64 s and a sinusoidal input signal. The results of the calculations are shown in Fig. 3. The actual input signal to sensors in the field is of course irregular. Nevertheless, a comparison of the data from pairs of sensors with different frequency responses and the results from the idealised analysis in Fig. 3 may provide collateral evidence in support of the performance claimed in [7]. Thus, under the assumption that HGAS sensors give a better estimate of the true concentration we have estimated peak ratios (i.e. GAS/HGAS) from the trials data books (i.e. 0.6 s averaged data) and the band width of peaks from raw data plots. (It should be noted that about two thirds of HGAS peak concentrations were attenuated by less than 15% when averaged

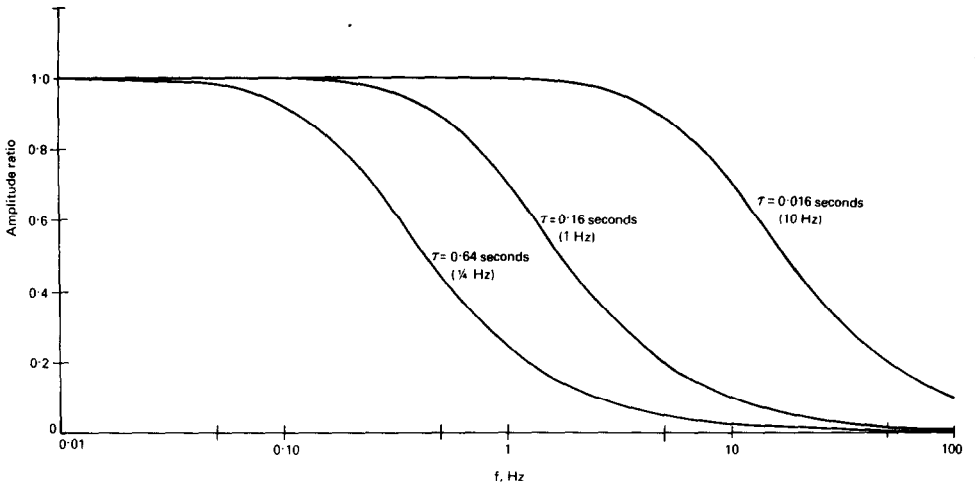


Fig. 3. Amplitude ratio, $1/\sqrt{[1 + (2\pi f\tau)^2]}$ for a perfect sinusoidal input as a function of frequency, f and exponential time constant, τ.

TABLE 2

Peak ratio (PR) for HGAS and GAS sensors in 'close proximity'

Trial No.	Location coordinates (m)					
	X,Y	Z			$PR\left(\frac{HGAS2}{HGAS1}\right)$	$PR\left(\frac{GAS*}{HGAS}\right)$
		HGAS1	HGAS2	GAS		
6	500,350	—	3.6	3.6	—	1.7
7	500,350	2.0	2.4	2.4	0.92	0.92
8	300,350	2.0	—	2.4	—	1.18
9	300,350	2.0	—	2.4	—	1.8
9	500,350	2.0	2.4	2.4	1.56	0.8
9	300,550	2.0	—	2.4	—	0.3
12	500,350	2.0	2.4	2.4	1.04	0.5
13	500,350	2.0	2.4	2.4	0.94	0.95
14	400,350	2.0	—	2.4	—	0.8
15	400,250	2.0	—	2.4	—	0.7
16	400,250	2.0	—	2.4	—	0.8
17	400,250	2.0	—	2.4	—	0.15
18	400,250	2.0	—	2.4	—	0.72
19	400,250	2.0	—	2.4	—	0.36
19	475,275	2.0	—	2.4	—	0.88

*where two HGAS records are available the one at the same height as the GAS sensor has been used

over 0.6 s and the largest attenuation was about 40%.) Secondly, the power spectra of the output for some GAS, HGAS, and sonic-anemometer temperature channels have been determined to support the above analysis.

Thus, for Trials 6 through 19 we have identified all the HGAS/GAS pairs of sensors in close proximity and assessed the peak ratio from the trial data books. The results of this analysis are given in Table 2 which shows that:

(i) where two HGAS sensors were on the same mast at heights of 2.0 and 2.4 m, the peak concentrations were in good agreement, except in one case where a 50% difference was observed;

(ii) on the 15 occasions when GAS and HGAS sensors were in close proximity the standard sensor recorded peak concentrations greater than the fast-response sensor in 3 cases (80% greater in one case), whereas a ratio less than unity would be expected.

The idealised response curves in Fig. 3 indicate an expected amplitude ratio of about 0.9 for an instrument with a time constant of 0.16 s. This is based on a typical persistence of the peak of about 1 s (between the times of occurrence of half the peak on the rise and fall sides) giving a frequency of about 0.5 Hz for the fitted sinusoid. About half of the peak ratios in Table 2 are in the expected region. However, the wide variation from the value of 0.9 demonstrated in Table 2 suggests that there can be significant concentration variations over small distances which may invalidate any attempt to compare the sensor records for sensors in close proximity. This is especially true near the source where intense local variations will be present.

Further evidence of the difficulties involved in carrying out any assessment of sensor performance in the field can be gained from the power spectra for some of the sensors listed in Table 2. These power spectra were computed for contiguous blocks of 30 s duration from the 20 Hz data, beginning at the start of the main recording period. Durations of 30 s were chosen as a compromise between the need to compute statistically reliable estimates of spectral density and the recognition that the spectral density is itself evolving in time. Figures 4 (a), (b), and (c) show cumulative spectral densities for records from Trial 7 in time slices of 30 s for a period when gas was present for, respectively, the temperature channel of a sonic anemometer, fast-response and standard gas sensors at approximately the same height. Figure 4 (d) shows the cumulative spectral densities for a HGAS sensor on the same mast, but 0.4 m higher than the sensor in Fig. 4 (b) for the same time periods. The traces are numbered to indicate their temporal order. These traces demonstrate that there is significant temporal variation in the frequency characteristics of the signal.

These plots also show that the proportions of power observed by HGAS sensors in the 1—10 Hz band is lower than that for the temperature channel of the sonic anemometer which indicates that the frequency response characteristic of the sonic anemometer is better than the HGAS sensors.

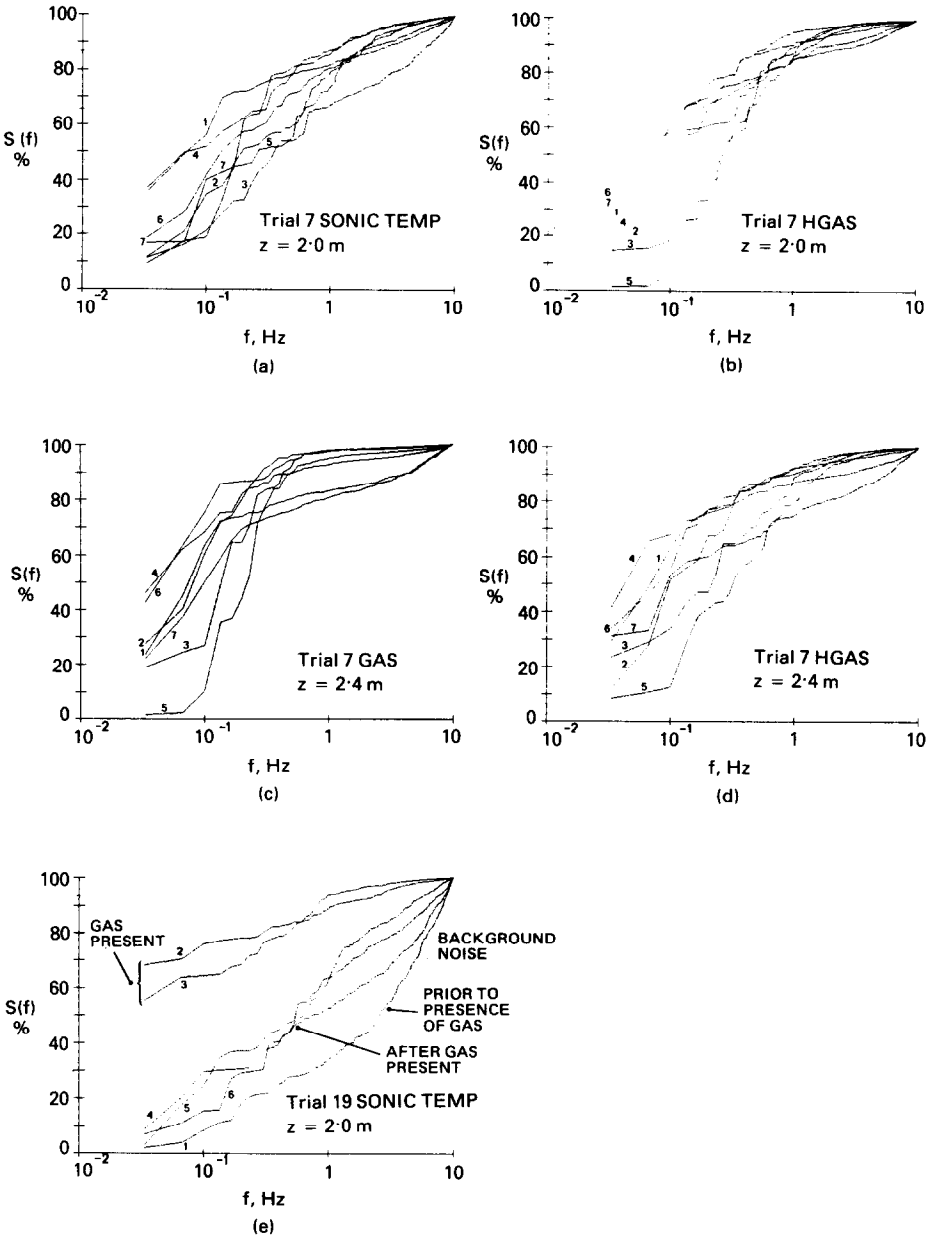


Fig. 4. Cumulative spectral density, $S(f)$ i.e. percentage of total power up to and including that at frequency, f, as a function of frequency.

When gas is present, typically about 25—60% of the power is in the 0.1 to 1 Hz range and less than about 20% of the power is above 1 Hz.

A further example for a sonic anemometer temperature channel is given in Fig. 4(e) for Trial 19 for periods before, during and after gas was present.

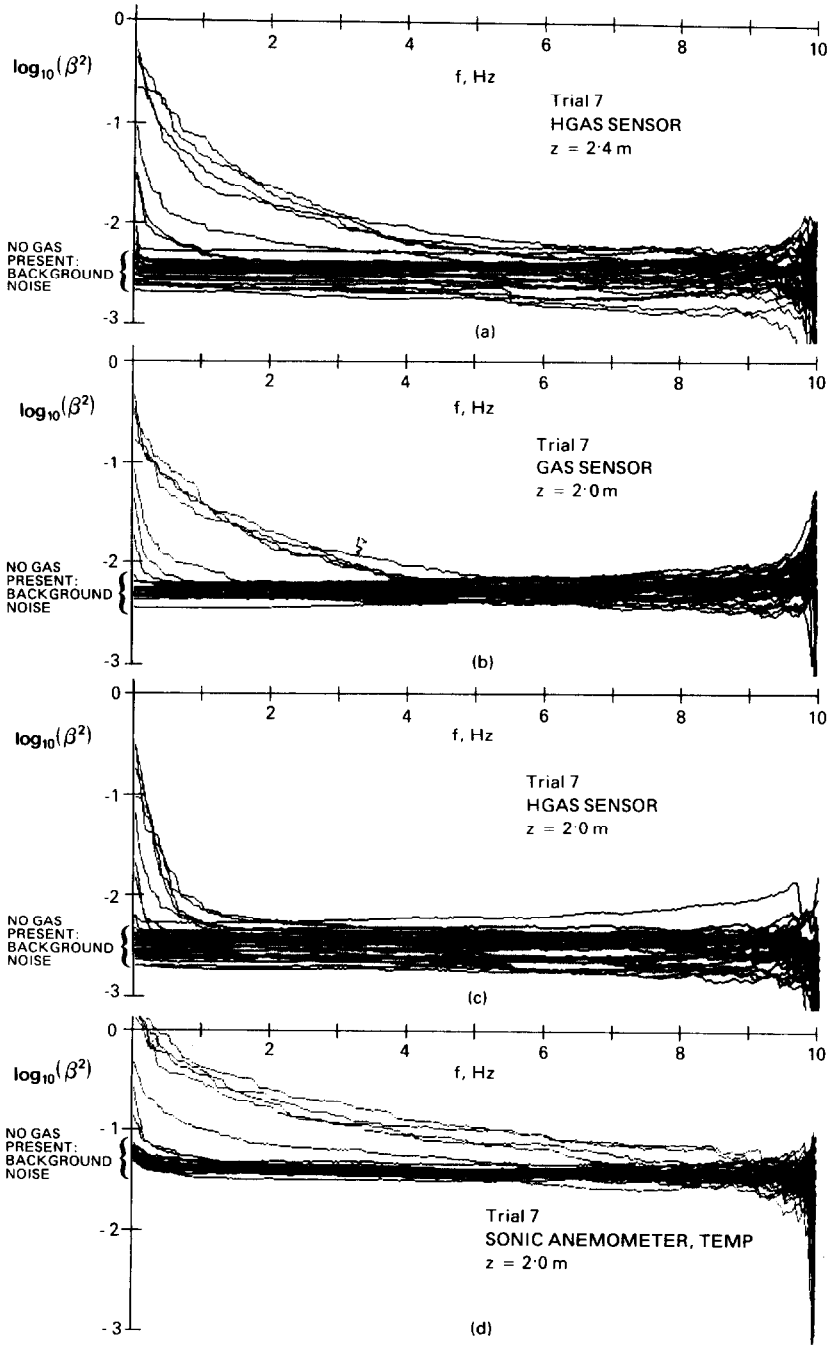


Fig. 5. Lanczos partial sums of power spectra, β^2 as a function of frequency, f.

This figure also shows that the proportion of power for frequencies beyond 1 Hz generated by the background noise is about 70% to 90%; this is typical of the sonic anemometers and both types of gas sensors. The plots also indicate that the input to sensors in close proximity could be quite different and that the time series are not stationary.

The power spectra derived from each of the 30 s slices of data have also been processed using a procedure described by Lanczos [8]. The Lanczos criterion for discrete spectra is defined as

$$\beta_k^2 = (N - k + 1)^{-1} \sum_{i=k}^{N} (a_i^2 + b_i^2) \quad (k = 0\ (1)\ N)$$

where a_i, b_i $(i = 0\ (1)\ N)$ are the discrete Fourier cosine and sine coefficients. β_k^2 is the average power above the discrete frequency k. Clearly, for white noise, the value of β_k^2 is roughly independent of k, except when $k \approx N$, in which case there will be sampling fluctuations. If, on the other hand there are pronounced power bands in the spectrum up to a cut-off frequency of $k = k_0$, say, then for $k > k_0$, β_k^2 will be roughly constant as before, but for $k < k_0$, β_k^2 will tend monotonically to β_0^2, the normalised total power, as $k \to 0$. Plotting β_k^2 against frequency, f, for the sensors shown in Fig. 4 for Trial 7 suggests (see Fig. 5) that in the case of HGAS sensors their output begins to deviate from the background noise in the 5—8 Hz range; and the corresponding figures for GAS sensors are 1—2 Hz and for sonic anemometers about 9 Hz. The value of this frequency varies within and between sensor records and trials but the figures quoted are typical.

Taking the results of the spectral analysis into account and given the likely input range of frequencies and the amplitude ratios listed in Table 2, we must conclude in the light of Fig. 3 (albeit for a sinusoid) that we have found no convincing evidence from the trials data to suggest that the sensors were not performing to the stated response characteristics. There are indications, although these are not conclusive, that the gas sensor performance in the field was to specification and did not deteriorate over the long time span of the trials. Moreover all gas sensors were checked in the laboratory during the winter of 1982/83 and no evidence of deterioration or change in performance was observed after 6 months in the field. Reference should also be made to the tests reported in [7] in which smoke-marked Refrigerant-12 was released in a ventilated underground roadway. Concentration records from both types of gas sensor were compared with the record from a sensor based on a light-scattering principle. This sensor had a frequency response of the order of 100 Hz. The results of these tests confirmed the gas sensor response characteristics as determined from laboratory measurements. We therefore accept that the field performance of the gas sensors is not markedly different from the stated [7] performance characteristics.

3.3 Variation of peak concentration with averaging time

In this Section we look at the effect of averaging time on the peak concentration levels in order to aid judgement on the value of averaging time (t_{av}) that satisfies the criteria discussed in Section 3.1.

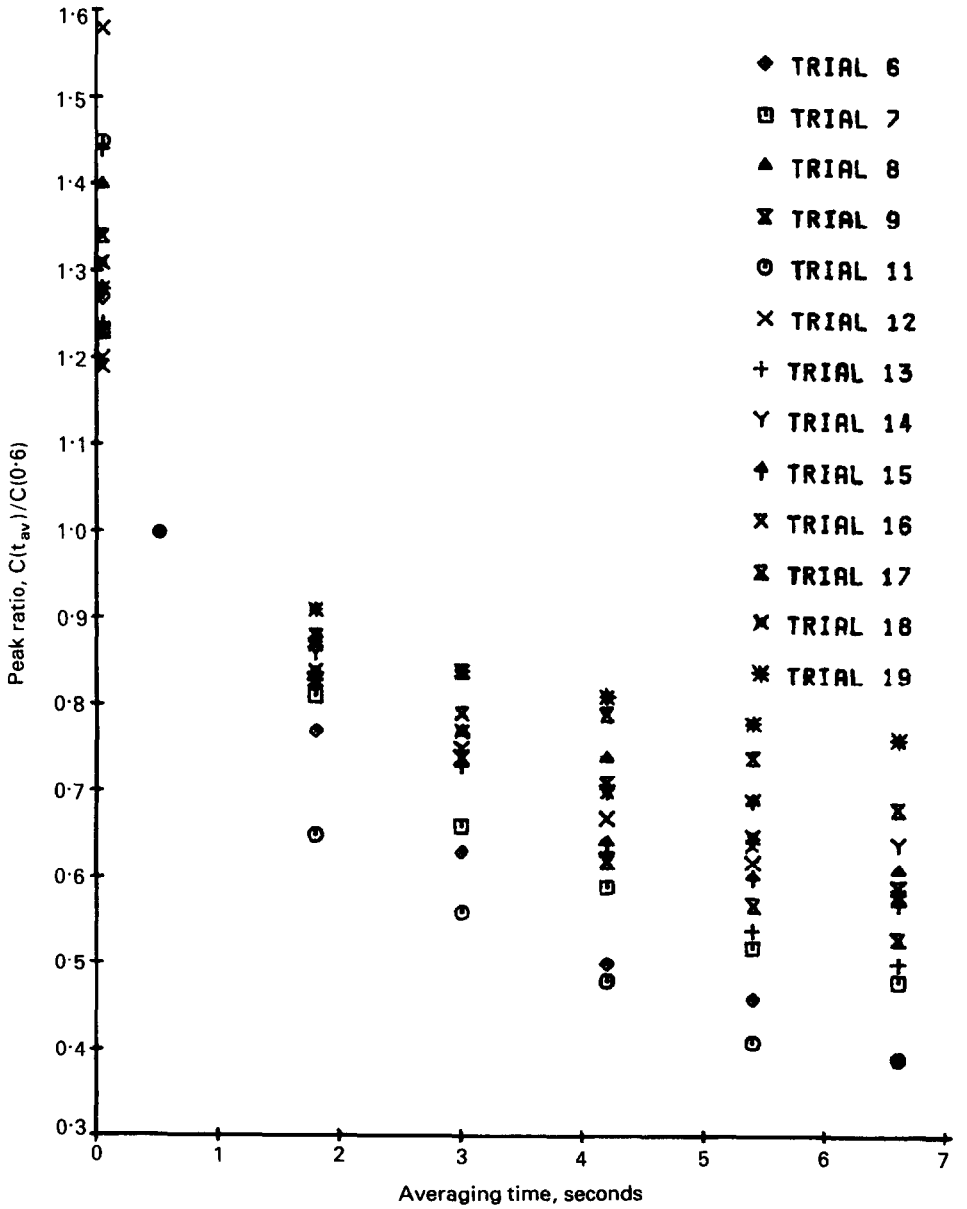


Fig. 6. Effect of averaging time on peak concentrations in the range 0.1% to 1% for Trials 6 to 19 relative to a 0.6 s average. For the points shown 25% of the peaks show greater attenuations.

In Appendix I we give estimates of the peak ratios for the raw data (i.e. $C(20\ \text{Hz})/C(t_{av})$ that are to be expected if t_{av} is to suppress (filter out) signal noise. However, because the noise level is different for different sensors and because the attenuation will also be affected by the sharpness

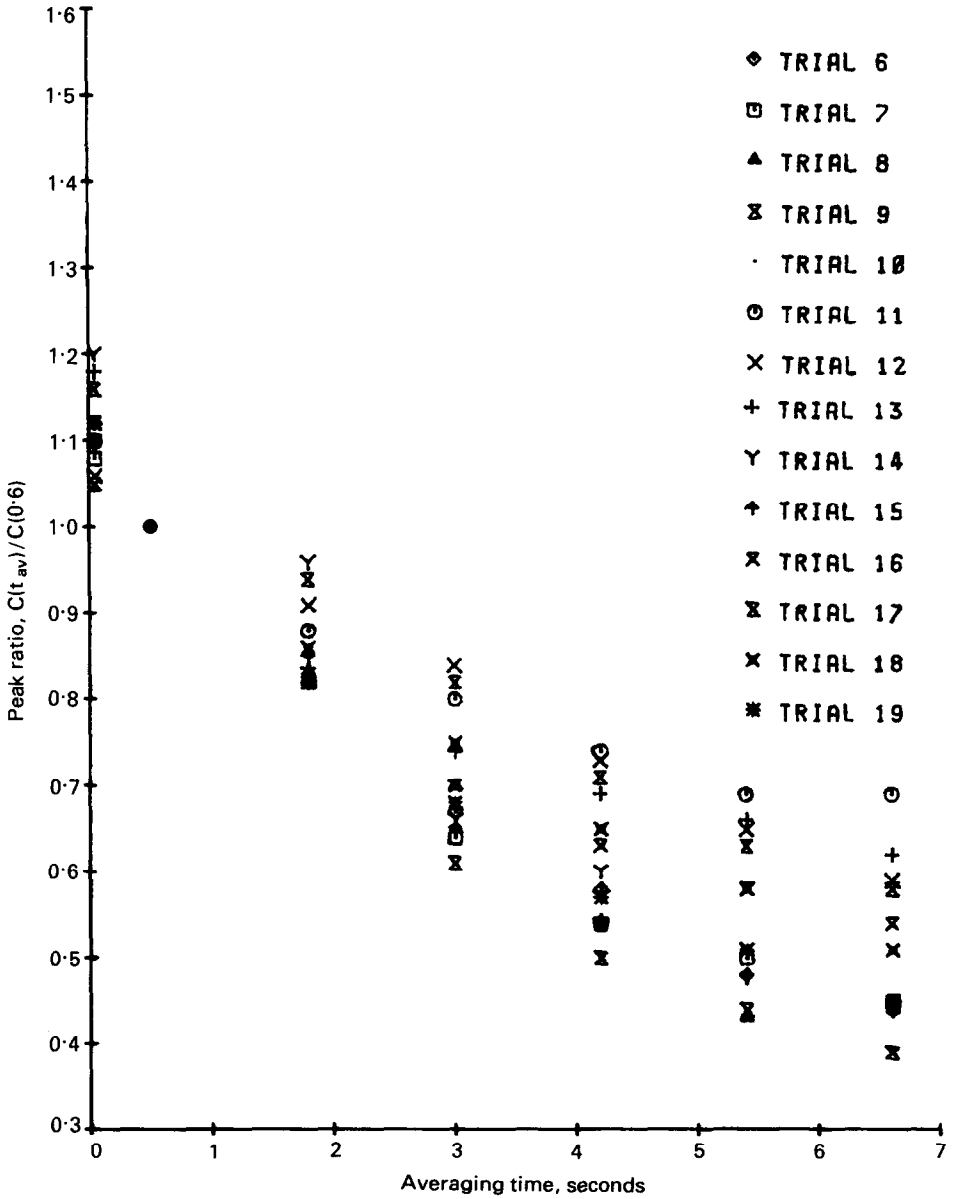


Fig. 7. Effect of averaging time on peak concentrations in the range above 1% for Trials 6 to 19 relative to a 0.6 s average. For the points shown 25% of the peaks show greater attenuations.

of the peaks and the level of concentration fluctuation, a judgement will need to be made about what averaging time should be applied to the concentration records which would be representative of the full range of trials. In order to aid such judgement we have systematically looked at the effect of averaging time on peak concentrations for all gas sensors deemed to have detected gas in Trials 6 through 19. The method of averaging adopted for each sensor is described in Appendix II.

This averaging process has been applied to each sensor record using averaging times of 0.6, 1.8, 3, 4.2, 5.4 and 6.6 s. The maximum peak concentration within a sensor record was obtained from the raw 20 Hz data. Peak ratios of $C(20\ \text{Hz})/C(0.6)$ and $C(t_{av})/C(0.6)$ were then derived, trial by trial, for each sensor record and for the above averaging times. The results were then partitioned into two groups according to whether the smoothed 0.6 s peak was less than 1% or not. For each group of sensors the results for each peak ratio were ordered in descending peak ratio order to enable the distribution of peak ratios over each group of records to be derived.

The results of this analysis showing the variation of peak ratio with averaging time are summarised in Figs. 6 and 7; it being axiomatic that all peak ratios pass through the point (0.6, 1). Values plotted to the right of this point are lower quartiles; values to the left are upper quartiles. Hence 25% of the sensors show peak attenuations greater than those implied.

We see, in fact the peak attenuations for the raw 20 Hz data (i.e. $C(20\ \text{Hz})/C(0.6)$) are in the range we would expect, given that the lower quartiles for the 0.6 s peak concentrations for the various trials range between 0.13% and 0.31%. The data shown are consistent with an r.m.s. noise level of between 0.03% and 0.1% being adequately suppressed by an averaging time of 0.6 s (see Appendix I). In fact the two points for the unaveraged data showing the greatest peak ratios represent trials with the smallest lower quartiles for the 0.6 s peak concentrations (i.e. relatively poor signal-to-noise ratios), while the point with the corresponding lowest peak ratio represents the trial with the highest lower quartile which is self-consistent. In consequence 0.6 s represents an averaging time that is reasonably consistent with the criterion that noise should be suppressed.

For averaging times of about 3 s and longer it is seen from Fig. 6 that there are significant attenuations of peaks for at least 25% of the sensors for some trials — almost by a factor of 2 at 3 s. It should be noted that the variation in peak ratio shown in Figs. 6 and 7 with respect to any of the other averaging times can be obtained by dividing the peak ratios shown by the corresponding peak ratio $C(t_{av})/C(0.6)$. Bearing this in mind and given that 0.6 s is sufficient to suppress noise and is greater than the rise time of the sensors, it is our judgement from Fig. 6 that an upper limit on the averaging time of about 1 s is necessary if the attenuation of the peak is not to exceed the stated accuracy of the sensors for a majority of the records.

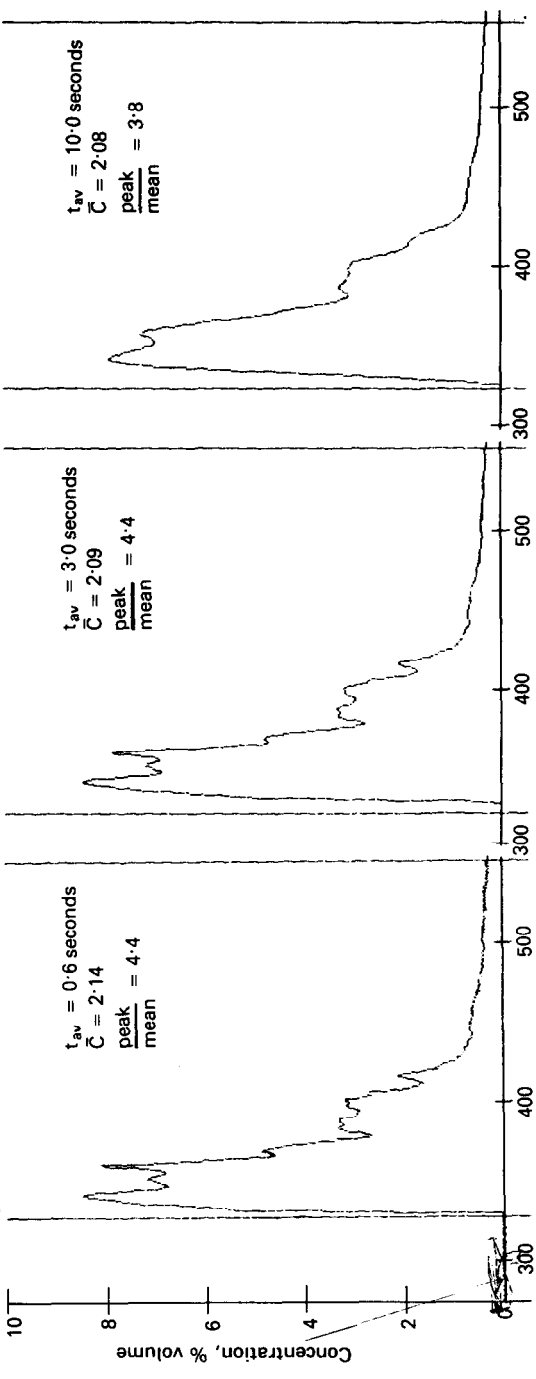


Fig. 8. Trial 17: Variation in peak concentration with averaging time, t_{av}. GAS sensor at X = 40 m, Y = 250 m, Z = 0.4 m. The times shown are with respect to the start of the data collection period.

To complete the analysis we have looked at the 1% and above peak concentrations, Fig. 7. The point to note here is that again the peak ratios for the raw data are consistent with the signal and noise levels i.e. peak ratios of about 1.07 (see Appendix I). As before, there is significant attenuation of the peaks as the averaging time increases (more so than before) and the figure again confirms that the use of averaging times greater than about 1 s would attenuate the observed peak concentrations below the stated accuracy of the sensors for a large proportion of the sensors.

Of course some peaks (namely in records that show relatively little fluctuations) show little attenuation with averaging time, an example is shown in Fig. 8; the peak/mean ratio varies by about 10% as the averaging time increased from 0.6 s through to 10 s. On the other hand, some peak excursions are of a duration little more than the rise time of the instrument so that the real peak has already been attenuated in the record. Also, since some records exhibit considerable fluctuations in concentration and because a sharp peak is attenuated more severely than a broad peak, the position of the peak (temporally, within the record) can be significantly affected, as shown in Fig. 2. For comparison of concentration records with models we therefore recommend adopting the smallest averaging time consistent with the criteria discussed in Section 3.1 i.e. one of about 0.6 s.

For the calculation of quantities such as c'^2 from the HGAS records in which a fair amount of high frequency power is present, a straightforward application of uniform-weight averaging to derive the fluctuation $c'(t)$ could lead to a serious loss of information. The reason for this is that in the frequency domain a uniform-weight digital filter possesses a roughly triangular power transfer function, as opposed to the ideal rectangular power transfer function. This difficulty may be overcome by the use of more refined digital filters whose power transfer functions are more nearly rectangular. The derivation of such filters is described, for example, by Bloomfield [9].

4. Analysis of the turbulence records

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 test hypotheses concerning these processes that are made in models. This section is concerned with some methods of analysing the data in order to meet this objective.

Box models, and numerical 'three-dimensional' or 'turbulence' models require information on the ambient mean and turbulent wind field. In addition, some numerical models have to parameterise the turbulent mass and momentum fluxes that appear in the Reynolds averaged equations. The way in which this is done may differ from model to model. Thus, as well as testing the overall predictive capability of a model, the Thorney Island data may also be used to test the 'sub-models' of the turbulent mass

and momentum fluxes within the cloud. Clearly, a first step in this analysis is to ascertain whether the presence of the dense gas has a measurable effect on the turbulent structure within the cloud. Should this turn out to be the case, further work would be required to quantify the effect in terms of some parameter such as a local Richardson number.

A difficulty with attempts to assess the effect of gas on the turbulence is that the dispersion of an instantaneous release of heavy gas at Thorney Island is a complex unsteady turbulent flow. The time for gas to advect past a sensor is of the order of 100 s; furthermore, in these times, the gas concentration at a particular sensor exhibits considerable variation reflecting the structure of, as well as the turbulence within, the cloud (see Fig. 1).

Statistical rigour dictates that the turbulence quantities should be obtained *via* suitably defined ensemble averages, i.e. by means of replicated experiments. This is clearly not practicable (for logistic and economic reasons) on the scale of the Thorney Island trials.

Indeed in most studies of turbulent flows, replicated experiments are rarely performed, if only because of the large number of times that are required to produce stable averages (see for example Carn and Chatwin [10]). Instead, time averages are used and an ergodic hypothesis invoked to equate time to ensemble averages. For the strict application of the ergodic hypothesis, the turbulent flow is required to be statistically stationary in time and homogeneous in space. These conditions may be attainable in a wind-tunnel but cannot be attained in the atmosphere. In studies of atmospheric turbulence and atmospheric diffusion therefore, the approach that is adopted is 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 and to show that these motions are independent, i.e. that there is a 'spectral gap' [11, 12]. In these studies time averages of the order of tens of minutes are common.

In the case of the Thorney Island trials, however, a particular sensor will be exposed to gas for a period of typically 100 s, during which period the concentration record exhibits large variations. The definition of an appropriate averaging time in this situation clearly presents great difficulties and hence the determination of meaningful turbulence quantities is a problem. Nevertheless, some attempts have been made at determining turbulence quantities and to see if they are affected by the presence of gas.

4.1 Description of the ambient wind field

Davies and Singh [13] have described the meteorology of the Thorney Island site. The turbulence intensities presented by them were produced by averaging data from the weather mast upwind of the release point over the duration of a trial, typically 20 min. In order to ascertain the effect of a much lower averaging time on the calculated turbulence intensities, we have looked at the records of the sonic anemometers at 10 m on the weather mast and calculated the variation in intensities (i.e. $\sigma_u/\bar{U}$, $\sigma_v/\bar{U}$, and $\sigma_w/\bar{U}$)

with averaging time for different time periods throughout a trial. These intensities were normalised with respect to a localised (in time) moving average wind speed, also determined from the sonic-anemometer record. The argument for using a localised mean is that as $t_{av} \to 0$ the localised mean wind speed $\bar{U} \to U$ so that $u' \to 0$ and hence the longitudinal intensity will tend to zero for small values of t_{av}. For consistency the same procedure is applied to the lateral and vertical components. We feel that this approach is justified as no other method commends itself in the presence of a flow whose statistical properties are time dependent.

The results are typified by those shown in Fig. 9 for the vertical intensity in Trial 19. The traces relate to three windows of 250 s within which the averaging time has been varied from 10 s up to 250 s. The value obtained by NMI [13] by averaging over the whole data collection period of about 20 min was 0.07 which is in good agreement with those shown in Fig. 9.

The figure shows that, for each time window, the intensity stabilises for averaging times between about 50 and 100 s — typically 60 s which is in agreement with the value reported by Rodean and Cederwall [14] in a similar analysis for the China Lake experiments. The fact that the three windows show different levels indicates that the intensity is varying throughout the trial. This variation is greater for the longitudinal and lateral components than for the vertical component as is shown in Fig. 10. It is this kind of random variation in the ambient field which makes it difficult to

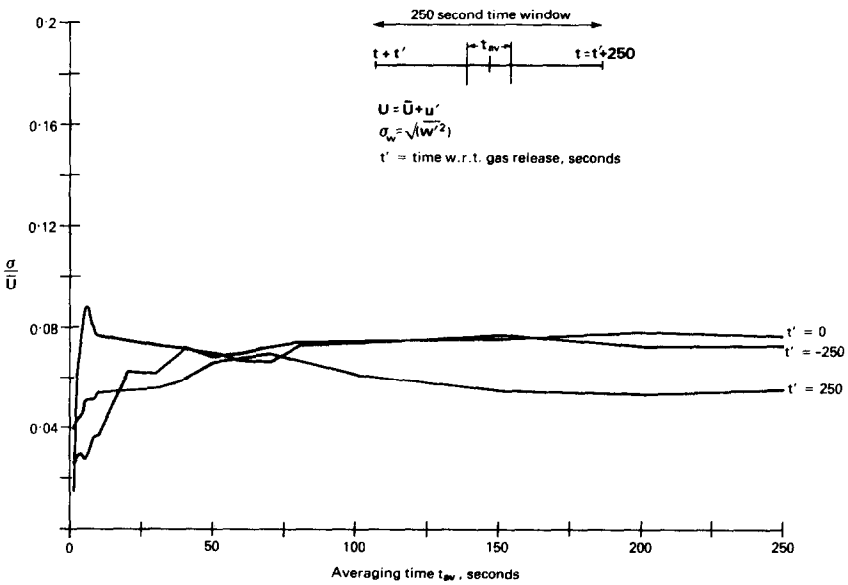


Fig. 9. Trial 19: Variation in the vertical intensity, $\sigma_w/\bar{U}$, with averaging time t_{av} for the sonic anemometer at 10 m on the weather mast. The traces relate to three windows of 250 seconds.

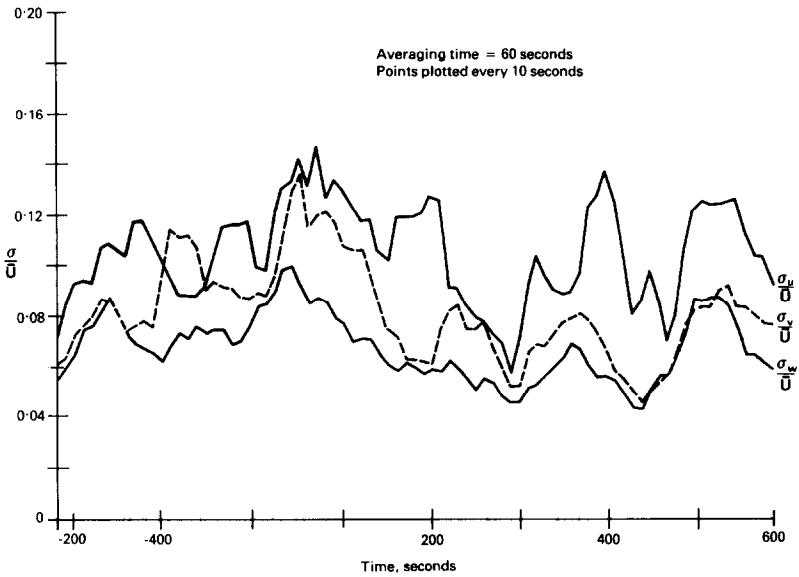


Fig. 10. Trial 19: Variation in the longitudinal, lateral and vertical intensities with time for the sonic anemometer at 10 m on the weather mast. The averaging time is 60 s and the times shown are with respect to the gas release.

distinguish the influence of the dense gas on turbulence within the cloud. Note also, that the averaging time of 60 s is comparable with the period for which a sensor detected gas, and during this period the gas concentration shows considerable variation.

4.2 Effect of gas on the turbulence

In order to answer the question of whether the presence of gas has an effect on the turbulence, the quantities referred to earlier, namely the turbulence intensities and the mass and momentum fluxes, need to be determined both within and outside the gas cloud. It is here that we face the fundamental difficulty of determining an appropriate averaging time for the Reynolds decomposition in an unsteady turbulent flow whose overall time scale is comparable to those of the largest turbulent eddies. Since it has been shown above that the turbulence intensities in the ambient flow are reasonably stable for an averaging time of 60 s, this time has been used to define the turbulence intensities within the gas cloud — even though the gas is present at a particular sensor for a comparable period. Because of these difficulties, fluxes have not been calculated; the aim has been simply to attempt to determine whether the presence of gas affects the turbulence intensities.

A simple approach is to present the results in a form where the time dependence is not shown explicitly. This has been done by producing a 'scatter-plot' of gas concentrations from the fast-response sensors averaged

over 0.6 s (for the reasons given in Section 3, though averaging times between 0.1 and 1 s produce similar results) against the fluctuating turbulent velocities u', v' and w' respectively. Using sonic anemometer data, these fluctuations are simply defined as the departures of the instantaneous value at the centre of a 60 s time-window from the mean value over that window. Should the presence of gas have an effect, one would expect the magnitude of the fluctuations to be different at high concentrations.

Attention was first focussed on those sonic anemometers that were exposed to the highest concentrations of gas for the longest durations ie those instruments at a height of 2 m (the lowest height at which sonic anemometers were sited) on the M2 mast at location (400,250) for Trials 15, 18 and 19. The gas concentration record at this location for Trial 15 is shown in Fig. 11; the other two are similar in terms of gas persistence. Scatter plots for Trial 15 showing $\bar{C}$ against u', v' and w' are shown in Figs. 12(a), (b) and (c) respectively. The time period covered in the scatter plots is a 200 s slice centred on the period when gas was present, typically 30 to 100 s for these three trials. Each plot therefore contains 4000 points. In some cases, the magnitude of u' and v' appears to be considerably smaller at high concentrations with some evidence of a bias to a non-zero mean value. Note, however, that there were very few points at the high concentration levels (20 points represent 1 s of data); the significance of these results is therefore doubtful as the observed pattern cannot be regarded as representa-

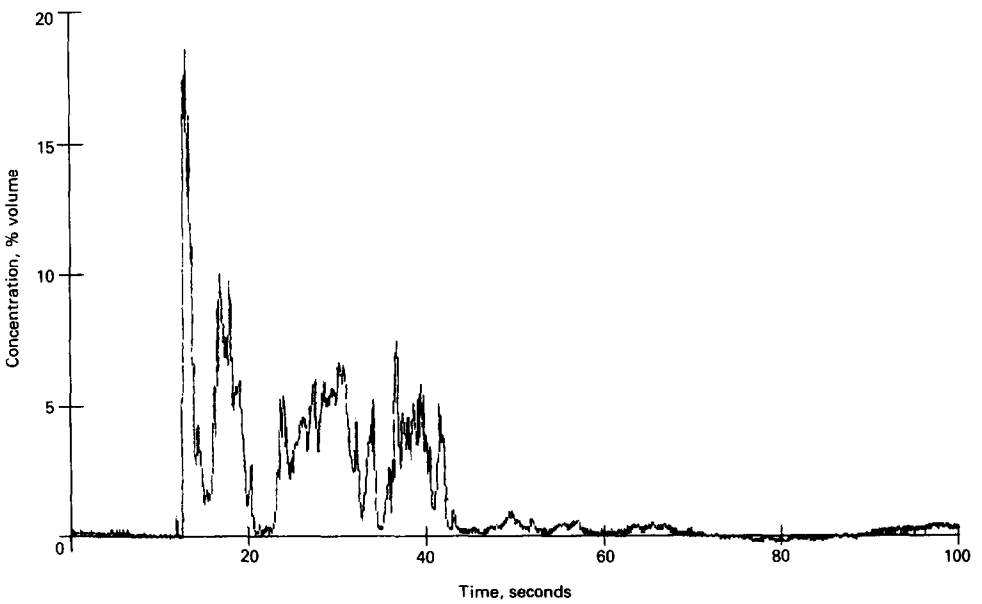


Fig. 11. Trial 15: Gas concentration record. HGAS sensor at X = 400 m, Y = 250 m, Z = 2.0 m. The times shown are with respect to the gas release.

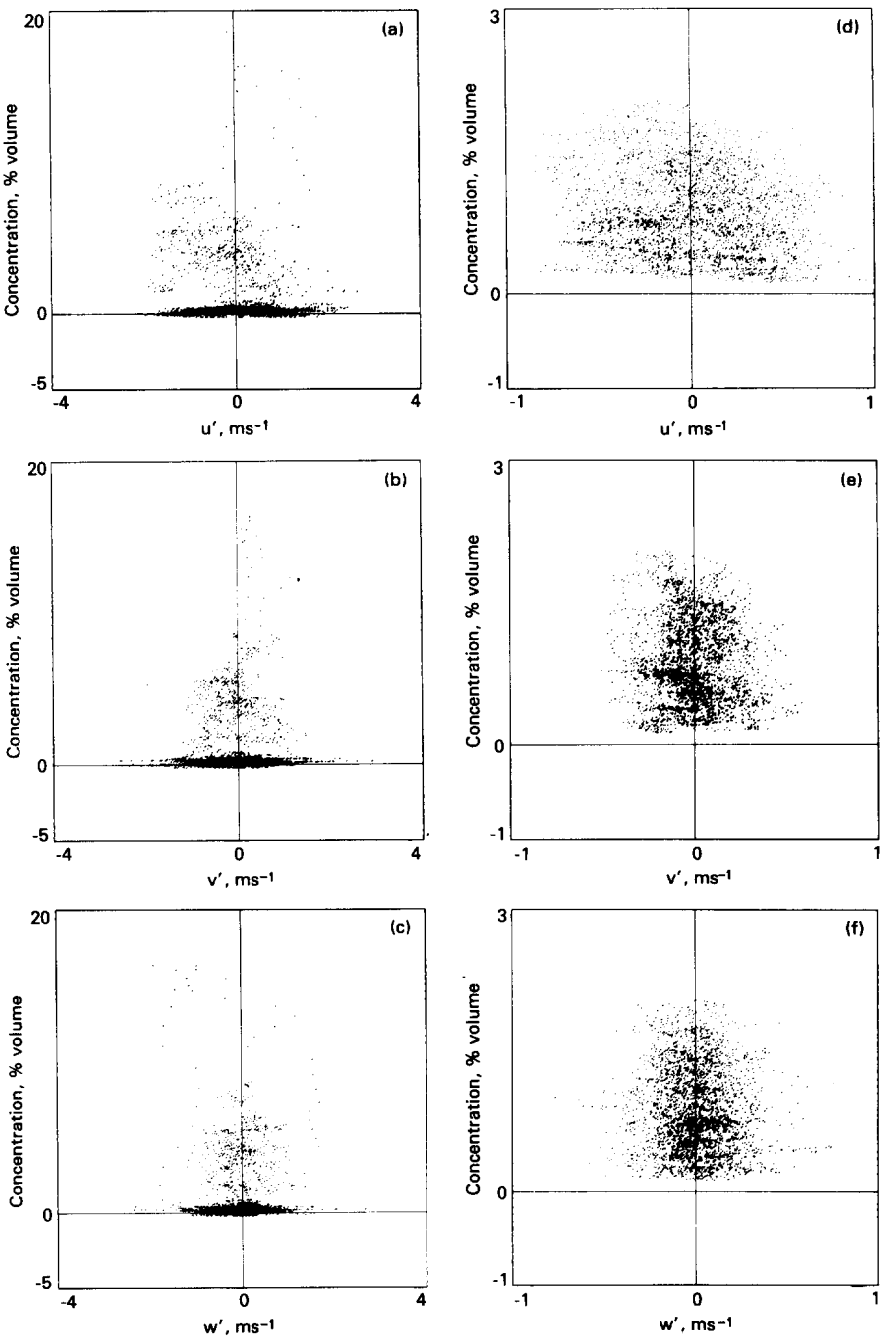


Fig. 12. Scatter plots for Trial 15: (a) u', (b) v', (c) w' and for Trial 7: (d) u', (e) v', (f) w'.

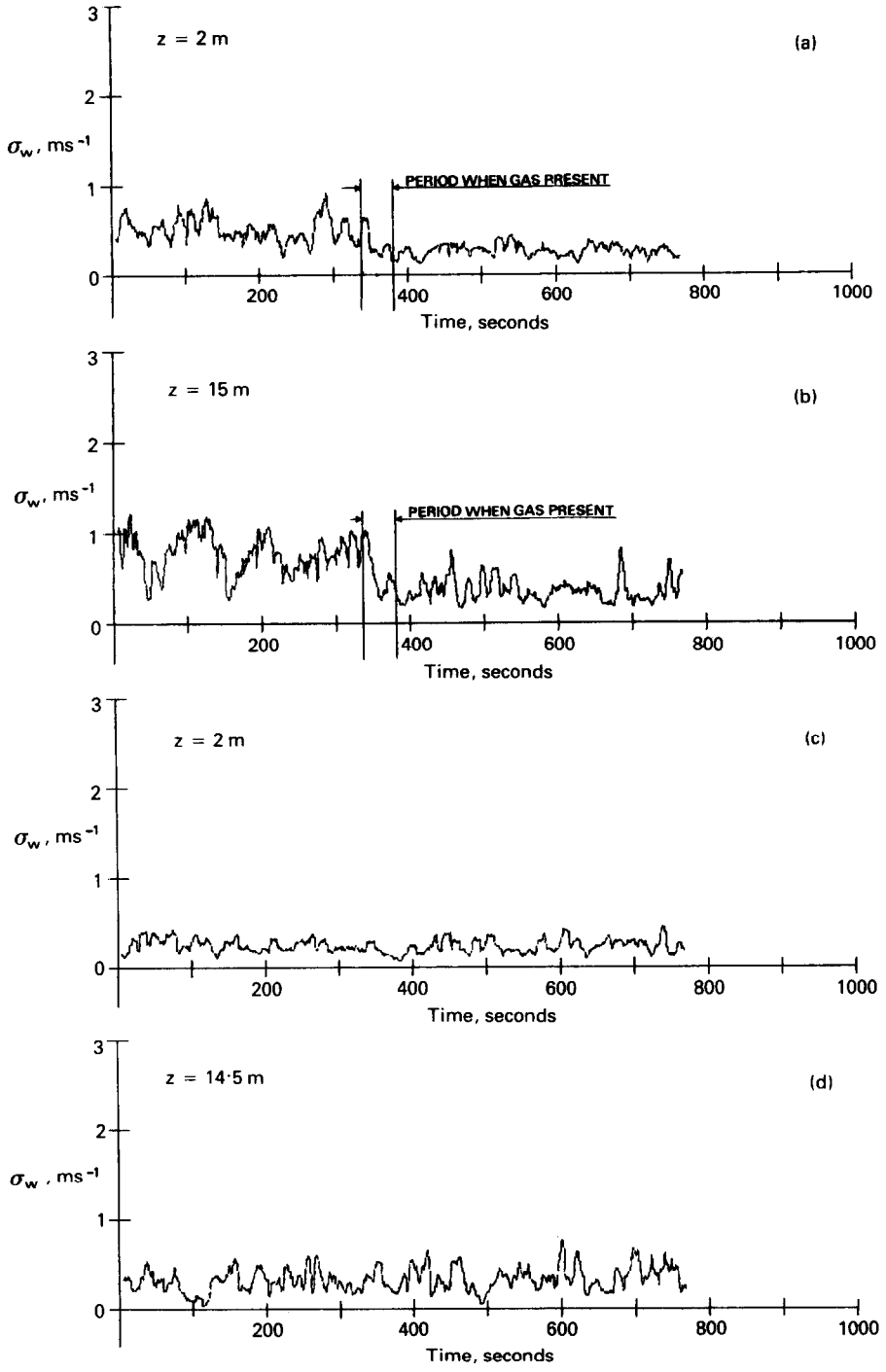
tive of that which would be obtained if these concentration levels persisted for a longer time. Moreover, the observed behaviour is not consistent across the three trials.

TABLE 3

Summary of results from 'scatter-plots'

Trial No.	u'	v'	w'
7	No change detected	No change detected	No change detected
13	No change up to about 2%. Some tendency to more negative and slightly smaller deviations above 2% (about 5 s of data)	No change up to about 2%. Some tendency to more positive and slightly smaller deviations above 2% (about 5 s of data).	Very little change
15	No change up to 6%. Above 6%, mainly positive fluctuations but no significant change in magnitude	No change up to 6%. Above 6%, (only 1—2 s of data) the fluctuations are positive and smaller	Very little change
17	No change up to 2%. Above 2%, more negative but slightly smaller fluctuations but too few data points (about 5 s of data)	Some tendency to more negative fluctuations at concentrations up to 2%. All fluctuations above 2% are negative, but represent only about 5 s of data	No change detected
18	Some tendency to more negative fluctuations above 4% but no change detected in the magnitude of the fluctuations	No change detected	No change up to 6%. Above 6%, about 3 s of data show more negative fluctuations but no significant change in magnitude
19	No change up to 7%. Above 7%, about 1 s of data show no change in magnitude of negative fluctuations. Only 7 positive fluctuations above 7%	No change up to about 6.5%. More negative, but no significant changes in magnitude of fluctuations above about 6.5%.	No change detected

Fig. 13. Trial 15: Variation in the standard deviation of the vertical component of the wind velocity, σ_w, with time. Sonic anemometers; (a) at X = 400 m, Y = 250 m at a height of 2 m, and (b) at 15 m, (c) at X = 325 m, Y = 275 m at a height of 2 m and (d) at 14.5 m. The averaging time is 10 s and the times shown are with respect to the start of the data collection period.


z = 2 m
(a)
σ_w, ms^{-1}
PERIOD WHEN GAS PRESENT
Time, seconds
z = 15 m
(b)
σ_w, ms^{-1}
PERIOD WHEN GAS PRESENT
Time, seconds
z = 2 m
(c)
σ_w, ms^{-1}
Time, seconds
z = 14·5 m
(d)
σ_w, ms^{-1}
Time, seconds

A similar analysis has been carried out on the sonic anemometers for Trials 7, 13 (each at location (500,350), and 17 (location 400,250). The gas concentrations in these cases are much lower than in Trials 15, 18 and 19 — peak concentrations of 2 or 3% only. The results for Trial 7 are shown in Figs. 12(d), (e) and (f). No effect of the presence of gas on u', v' or w' is apparent. A repeat of the analysis for averaging times of 0.1 and 1 s for gas and 10 and 100 s for turbulence records also showed no apparent effect. The results for the six trials are summarised in Table 3.

A second approach is simply to calculate the turbulence intensities using an averaging time of 60 s and to see whether a difference can be detected when gas is present. The difficulty here, of course, is that since the intensities derived from a 60 s average are not constant over the duration of a trial, one cannot know whether any differences that might be apparent are due to the presence of gas or are correlated with the changes in the ambient flow or some other effect. Figure 13(a) shows, for the sonic anemometer at a height of 2 m on the M2 mast in Trial 15, the variation in σ_w derived from a running mean of 10 s (60 s gives a similar picture). It appears that the standard deviation is reduced in the presence of gas and remains relatively low after the gas has passed. That the effect is due to the presence of dense gas is not clear since it has not been observed in any other trials and the sonic anemometer on the same mast at 15 m (i.e. well above the gas cloud) shows similar changes, as shown in Fig. 13(b). Examination of the intensity levels at other locations (Fig. 13(c) and (d)) shows that the mean intensity level remained at the lower level throughout the trial.

Our conclusions from this analysis of six trials is that it has not been found possible to clearly delineate the effect of dense gas on the turbulence structure. Moreover, the interpretation of the output from a sonic anemometer in the presence of dense gas is not straightforward. An analysis by Foster [15], shows that the inaccuracies are 0 (±0.10 m/s) in gas concentrations of a few percent. Such differences do not affect the conclusions drawn from our analyses, but underline the problems one may face in calculating turbulence quantities.

5. Conclusions

It has been shown that averaging times greater than about 1 s can have significant effects on the concentration records resulting in attenuation of the observed peak concentrations below the stated performance characteristics of the instruments. In the case of point values of the concentration averaged over the duration of the cloud presence, the amount of smoothing applied to the record is not significant. However, because of the importance of peak concentrations for hazard assessment, unless an averaging time is adopted that results in an acceptable representation of the full data base, averaging time could become yet another disposable constant in the valida-

tion exercise. We recommend on the basis of our examination of all the gas concentration data from the Phase I trials that any analysis or comparison with models needs to be suitably qualified if an averaging time greater than about 0.5 to 1 s is applied to the data from the standard gas sensors. Shorter averaging times are appropriate for HGAS sensors which exhibit very sharp peaks (Section 3.3 and Appendix II).

With regard to the implication for the physics of complex models our analysis for six trials has not found any significant differences between the turbulence intensities in the cloud and the ambient field at the locations where records were logged. Moreover, because the averaging times required are similar to the time for which gas was present we feel that any attempt to compute fluxes from the data would need careful consideration and interpretation.

Acknowledgement

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Appendix I

Peak degradation and noise suppression

The use of time averaging, as well as reducing the magnitude of any noise component, will also reduce the magnitude of any peaks present in the data.

It is axiomatic that a sharp peak will be attenuated more than a broad peak. If noise is to be suppressed without loss of signal resolution, we need to choose a value of averaging time, t_{av}, which is consistent with the criteria discussed in Section 3 and results in a degradation of the recorded peak concentration that is the same order of magnitude as the r.m.s. noise level. Any larger value of t_{av} would increase the signal-to-noise ratio at the expense of signal resolution, while smaller values would have the reverse effect.

Consider now a gas sensor immersed in a uniform atmosphere of 0.15% gas and the output from the sensor is sampled and recorded at 20 times a second. If the r.m.s. noise level (the power of which is mostly at relatively high frequencies compared to the signal (e.g. see Fig. 4(e)) is of the order of 0.1% we would expect, after smoothing, *peak* ratios, i.e. C(raw data)/$C(t_{av})$ of the order of (0.15 + 0.1)/0.15 i.e. 1.7. If the noise level was 0.05% *peak* ratios of about 1.3 would be expected. Similarly for sensors in 1.5% of gas we would expect peak ratios of about 1.03 to 1.07.

We have looked at a small sample of the raw data and confirmed that the r.m.s. noise levels are of the order of 0.03 to 0.11%. Indeed the basic resolution (±1 bit) of the 12 bit digital measuring system [16] is equivalent to a concentration of about ±0.025%. Thus by comparing the calculated peak ratios $C(20\ \text{Hz})/C(t_{av})$ with those that would be expected based on an estimate of the signal to noise ratio it is possible to make a judgement about the value of t_{av} that should be adopted.

Appendix II

Time averaging procedure

Each of the concentration records contains contiguous blocks of 12

readings (at a sampling frequency of once every 20 s) representing 0.6 s slices of data. The analysis of the sensitivity of the concentration records to applied averaging time was conducted using arithmetic averages over these data blocks. Each sensor record of 0.6 s blocked average values was scanned to find the maximum value in the series i.e. $C_{max}(0.6) = C_k$. The mean values for averaging times in multiples of 0.6 s were then computed with C_k as the centre. Thus the 1.8 s peak concentration was defined as

$$C_{max}(1.8) = (C_{k-1} + C_k + C_{k+1})/3,$$

the 3 s peak concentration as

$$C_{max}(3.0) = (C_{k-2} + C_{k-1} + C_k + C_{k+1} + C_{k+2})/5$$

and so on.

There is, of course, an alternative way of defining peak values, according to which $C_{max}(1.8)$, for example, is simply the maximum value of the time series derived from the original 20 Hz series by performing a running mean operation with a window of 1.8 s. There is no a priori reason why the 'running mean' peak concentration thus produced should coincide with the 'blocked mean' value as defined above. However, to perform running mean calculations on the original 20 Hz data for all the trials would have been computationally very costly whereas the calculation of blocked means on the 0.6 s data was quite feasible.

To assess the effect of using running means as opposed to blocked means to compute peak values, a separate analysis was performed using the records from 18 fast-response instruments taken from eight different trials. For the $C(1.8)/C(0.6)$ and $C(3.0)/C(0.6)$ peak ratios, about half of them were less than those obtained using blocked means. The peak ratios $C(20\ Hz)/C(0.6)$ for two thirds of this sample were very similar, but in general the trend was for the blocked means to show greater peak ratios. (In five cases they were identical or less). In four cases the $C(20\ Hz)/C(0.6)$ ratios for the blocked means was significantly greater (1.07 cf. 1.02, 1.21 cf. 1.14, 1.23 cf. 1.11 and 1.42 cf. 1.28) than that obtained using a running mean and for this reason we recommend the consideration of a different smoothing procedures [10] for processing the fast response data. In terms of Figs. 6 and 7 these 4 sensors would be in the group of sensors showing the worst degradation. Furthermore, we have re-calculated peak-to-mean ratios for the plots shown in Fig. 2, based on running means. The corresponding values of 8.1, 4.7 and 2.5 are almost identical with those shown in the figure.

Taking all these considerations into account, it was felt that the use of blocked means rather than running means was justified, in order to assess the value of the averaging time that should be applied to the vast majority of sensors for model validation purposes.