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OBJECTIVES AND DESIGN OF THE PHASE I HEAVY GAS DISPERSION TRIALS

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Summary

The Heavy Gas Dispersion Trials (HGDT) project consisted of an extensive programme of field trials on the dispersion of heavy gas clouds at ground level in the atmosphere. The programme was organised by the Health and Safety Executive as a cooperatively funded project with a total of 38 other organisations. Planning commenced in 1979 and the trials were performed between 1982 and 1984 on a site at Thorney Island, West Sussex. The conduct of the trials was contracted to NMI Ltd. The primary objective of the trials was the acquisition of reliable data at large scale with which to test the validity of mathematical and physical models. The basic concept of the trials was the study of the dispersion of fixed-volume, isothermal clouds under a variety of conditions. The trials were divided into two separately funded phases. In Phase I the dispersion was over uniform, unobstructed ground and comprised a total of 16 trials. In Phase II the dispersion took place in the presence of one of three different types of obstacle and comprised a total of 10 trials. This paper describes the design of the Phase I trials and summarises the results obtained.

1. Introduction

The Heavy Gas Dispersion Trials (HGDT) project was undertaken by the Health and Safety Executive (HSE) to remedy the lack of reliable and comprehensive data on the atmospheric dispersion of gases having a density greater than that of air. These gases are commonly referred to, in abbreviated form, as heavy gases. Knowledge of the dispersion of such gases is of importance in the assessment of the consequences of many types of industrial and transport accidents (see for example Britter and Griffiths [1]).

The technology of heavy gas dispersion estimates is quite different to that appropriate to the usual atmospheric pollutants. The need to improve the technological base became apparent in the early 1970s and led to several developments in experimentation and mathematical modelling. These developments have been reviewed by McQuaid [2] and Blackmore et al. [3]. In 1976, HSE instituted a programme of research on the atmospheric dispersion of heavy gases. The principal theme of the experimental part of the programme was the study of the dispersion of fixed volume clouds, initially formed in a container at atmospheric pressure and temperature and then suddenly released. Experiments have been conducted at three different scales. The HGDT project is the large-scale constituent of the programme. Medium-scale field experiments conducted at the Chemical Defence Establishment (CDE), Porton Down have been described by Picknett [4]. Wind-tunnel experiments conducted at the Warren Spring Laboratory have been described by Hall et al. [5]. These experimental investigations have been coordinated with a number of theoretical investigations of particular aspects of the heavy gas dispersion problem and with the development of predictive models (Fryer and Kaiser [6], Jagger [7], Chatwin [8,9], Britter [10], Rottman and Simpson [11], Rottman [12]).

2. Organisation of the HGDT project

The field experiments conducted by CDE (Picknett [4]) were intended as preliminary experiments to provide information for the design of large-scale experiments in which up to 10 tonnes of gas would be released. While the CDE trials were still in progress, HSE requested CDE to conduct feasibility and design studies for the large-scale trials, using the information and experience that had been gained. Early indications were that the cost of the proposed trials would exceed the resources that HSE could make available. Since the information generated by the trials was judged to be of interest to many other organisations, HSE prepared a proposal for a multi-sponsored project and invitations to participate were issued in November 1979. The proposal included details of the organisation, management and technical objectives of the project and the funding arrangements. During this stage, CDE had to withdraw from the project and the role of potential contractor was assumed by the National Maritime Institute (now NMI Ltd.). The organisation of the project and the process of securing the funds to pay for it are described by Johnston [13].

The contract with the project sponsors provided for the establishment of a Steering Committee to meet at intervals of no more than 6 months for the duration of the project. It also established a small Technical Sub-Committee to meet at intervals of no more than 3 months to advise on technical issues arising during the planning and execution of the trials. This committee structure provided a close, continual oversight during the preparation and execution of the trials.

The project was initially confined to conducting trials on dispersion of heavy gas clouds over uniform unobstructed ground. When the project was successfully underway and the experimental system had been proved, a proposal to widen the scope of the project was accepted. A further series of trials was planned to study the effects of several types of obstruction on the dispersion of a heavy gas cloud. This series became known as the

Phase II programme and the original series as the Phase I programme. The Phase II trials commenced immediately on completion of the Phase I programme in June 1983. The Phase II programme is described by Davies and Singh [14].

During the course of the project over 100 organisations were approached regarding sponsorship of the project and, of these, 36 agreed to sponsor Phase I and 33 sponsored Phase II. The complete list of sponsors of Phases I and II is given in the Foreword to this volume.

Following completion of the Phase II programme, some further trials have been undertaken. The availability of the trials site until June 1984 and the proven success of the trials design resulted in a contract from the U.S. Department of Transportion (DoT) for a Phase III programme. This programme is to study the dispersion of heavy gas from within a fenced enclosure for a range of wind speeds and initial gas densities. These trials are not part of the HGDT project and will be reported separately by the DoT. Under an arrangement between several U.K. Government Departments and the U.S. Gas Research Institute (GRI) a single trial of the same design as in Phase I was conducted at very low wind speed. The trial was intended to provide essential data for a multi-sponsored project organised by GRI on evaluation of predictive models of heavy gas dispersion. The results of this trial will be reported separately by GRI. All of these later trials utilised the equipment provided for the HGDT project.

The HGDT project involved a considerable investment in capital equipment. The contract with sponsors envisaged a distribution of the proceeds from the sale of this equipment at the termination of the project. With the agreement of the project sponsors, the equipment was sold to the contractor and the proceeds used to fund a further two trials. In these trials, a new experimental design will be used in which heavy gas will be released continuously from a source at ground level. These trials are due to be performed in 1984. (Note added subsequent to Symposium presentation: Three continuous release trials were performed in June 1984 and will be reported separately.)

Although this paper is concerned only with the Phase I trials, many of the arrangements described apply also to the other trials performed later in the series. The description is necessarily a summary account and full details are contained in McQuaid and Roebuck [15] and in other papers in this volume (Johnson [16], Leck and Lowe [17], Roebuck [18]).

3. Objectives of the Phase I programme

The considerations that led to the choice of a fixed-volume release configuration at ambient temperature and pressure have been described by McQuaid [19]. This choice fulfilled the broad objective of conducting an experiment offering the capability of close control of the release conditions. The technical objectives were twofold:

(i) To obtain reliable data at large scale with which to test the predictive capability of mathematical and physical models. Such data comprise primarily the distribution of concentration as a function of time and position for a variety of weather conditions, and the meteorological parameters required to specify the weather conditions.

(ii) To obtain data with which to improve physical understanding of the mechanisms of heavy gas dispersion and to test the fundamental hypotheses in mathematical models. Such data comprise measurements of turbulent fluctuating velocity and concentration distributions and photographic records of cloud behaviour, in addition to the data needed for (i).

The separation of the data acquisition scheme into these two classes was necessary because of the different types of instrumentation needed. In general, the instrumentation to achieve the first objective will have a less demanding specification in terms of time response and thus will be cheaper than that needed for the second objective. The relative priority assigned to the two objectives was the subject of considerable debate and the disposition of instrumentation finally decided was necessarily a compromise between the needs for adequate coverage of each of the types of measurement and the finance available.

4. The planned programme of Phase I trials

Given that large-scale experiments were required and that these would be expensive, there was a severe limit on the number of experiments that could be included in a firm, contractual undertaking. This number was fixed at five in the planning of the trials. Variables that were capable of control were therefore assigned fixed design values. These were the initial size and shape of the cloud, the ground roughness, the site topography and, in four of the experiments, the initial relative density of the cloud. The principal variables in the design were consequently the atmospheric stability and the windspeed.

The principal considerations in determining the initial size of the cloud were the available downwind extent of the intended trials' site on the CDE ranges at Porton Down, the lower limit of resolution of the gas sensors (which fixed the downwind cloud travel within which measurements could be made for a given size of release), the cost of engineering the gas supply and containment arrangements and the cost of gas for each experiment. Within these constraints, the maximum initial volume that was judged to be feasible was 2000 m^3. This volume represented an increase by a factor of 50 over that in the Porton trials and by about 7.5×10^5 over that in the WSL experiments.

The initial shape of the cloud was determined by the requirement that direct comparison with the Porton trials should be possible (and consequently with the WSL experiments in which the initial cloud was geometrically similar to that in the Porton trials). Although the aspect ratio will influence the initial gravitational potential energy of the cloud, it was decided that its influence could, if necessary, be investigated at smaller scale than in the planned trials.

The aerodynamic ground roughness and the site topography were also determined by the initial choice of trials' site at Porton Down. The site was rough grassland with a slope of less than 1 in 40. When it became necessary to seek an alternative site, the specification laid down a site with similar properties.

In the Porton trials, mixtures of Refrigerant-12 (dichlorodifluoromethane, CCl_2F_2) and air were used, allowing initial relative density ratios up to 4.2. However, only one trial was performed at this value, most of the trials having values between 1.5 and 2.5. In order to retain the maximum flexibility for comparison purposes, it was decided that the fixed value of initial relative density ratio should be 2.0. However, it was also decided that a gas with a large density should, if possible, be selected after other considerations, such as gas sensor technology and cost, were taken into account. Such a choice, in the event of further trials beyond the contracted series becoming possible, would allow a trade-off between windspeed and initial relative density, assuming Richardson number similarity to be valid. This would be an important consideration in attempting to achieve a large Richardson number, given the difficulty of obtaining steady wind conditions at very low windspeeds. In addition to trials with a heavy gas, it was considered highly desirable that the neutrally-buoyant case should be studied. It was intended that any such experiment would be performed as a repetition of a particular heavy gas release, as was done for two of the trials in the Porton series.

Taking all the above considerations into account, the priority lay in the investigation of the effects of wind speed and atmospheric stability. This choice was dictated in any case by the inability to control these as variables and by the indications that their effects were the source of the major uncertainties in predictive models. The selection of the nominal conditions for the trials was determined qualitatively by two considerations:

(i) the needs of Richardson number similarity (for the mixing across the cloud/air interface) and of Monin—Obukhov similarity (for the vertical distributions of atmospheric boundary layer characteristics);

(ii) the desirability of achieving similarity with the experiments at smaller scale (Porton Down and WSL) on the one hand and potential accidents at larger scale on the other.

The requirements of the basic series of 5 trials were therefore set out as follows:

(1) a release at low windspeed under conditions of high stability (thus overlapping with large-scale conditions of moderate windspeed and lower stability);

(2) a release at moderate windspeed under neutrally stable conditions

(thus overlapping with the Porton Down trials under conditions of low windspeed and neutral stability);

(3) a release at high windspeed under neutrally stable conditions (thus overlapping with large-scale conditions of high windspeed and neutral stability);

(4) a release at moderate windspeed under moderately stable conditions;

(5) a passive, or neutrally-buoyant, release in the same conditions as (4), in order to correspond most closely with the neutrally-buoyant releases in the Porton Down trials.

The qualitative descriptions in (1) to (5) were placed in a matrix of stability and wind speed sub-ranges as shown in Table 1 following the same numbering scheme. Although the firm programme envisaged 5 trials only, an additional selection of trials up to a total of 15 was inserted in the matrix with the numbering indicating the order of priority should sufficient finance become available. They were selected to give a better definition of the effects to be investigated and, at the upper end, to widen the scope of the investigation.

TABLE 1

Selected release conditions for the Phase I trials

Pasquill stability condition sub-range	Wind speed sub-range (m/s)			
	0—2	2—4	4—6	6—8
A, B		12	8	
C, D		2, 5, 6	7, 10	3, 15
E, F	1, 9, 14	4, 11, 13		

Notes: Numbers 5 and 13 are neutrally-buoyant releases. Number 14 is at an initial relative density ratio of 4.2.

5. Design of the Phase I trials

5.1 *Introduction*

A design study was commissioned in 1978 from CDE for trials in which up to 10 tonnes of gas would be released. The trials were to be performed at CDE's Porton Down site. The report of the design study was produced in 1979 and included recommendations in respect of the gas containment and gas supply systems, the different types of instrumentation and their disposition on the trials site, and the cost and timetabling of a programme of 5 trials. Before any decisions could be taken on the recommendations, circumstances compelled CDE to withdraw from the project and the National Maritime Institute (NMI, now NMI Ltd.) was appointed as potential contractor. In the subsequent deliberations, some of the recommendations were accepted and some modified or rejected. In this paper, no attempt will be made to record the attribution of design features to the period prior to and following the CDE withdrawal. These details are included in the full report on the trials [15].

5.2 *Choice of gas and gas sensor*

The properties of the heavy gas were specified as follows:

(a) It should be non-toxic and non-flammable so as not to impose an undue restriction on the choice of trials site. It was accepted that the inevitable asphyxiation hazard would impose some restrictions on operations in the vicinity of the gas container. Exposure to this hazard would be restricted to trials personnel and rigorous safety precautions were judged to be entirely practical.

(b) It should have a density relative to air of at least 2.0 and preferably much higher in order to permit trials at high Richardson number.

(c) It should be economical to use, both in terms of its direct cost in tonnage quantities and in the engineering of the storage and evaporation systems required.

(d) It should be capable of detection down to concentrations of around 0.1% (by volume) with commercially available and economical gas sensors able to withstand the outside environment for long periods.

These considerations narrowed the range of options to mixtures of Refrigerant-12 and air, carbon dioxide or nitrogen to satisfy (a) and (b) above, with in addition the possibility of seeding any of these mixtures with a marker gas to increase the number of gas sensing techniques that might be used. The final choice was determined by the availability of gas sensors. The process of selection of both the gas and the gas sensor is described by Leck and Lowe [17]. In summary, the gas sensor chosen was based on the measurement of oxygen deficiency. Two versions of the sensor were produced. A standard sensor for deployment in large numbers had a frequency response of about 1 Hz. A fast-response sensor for deployment in conjunction with sonic anemometers had a frequency response of about 10 Hz. The lower limit of resolution of each sensor was about 0.1% of the released gas. The released gas was chosen to be totally deficient in oxygen and this was achieved by mixing Refrigerant-12 and nitrogen. The sensors, of which over 200 were produced, were subject to rigorous laboratory checks before installation and periodic checks in the field during the trials period. The sensors were individually calibrated and the records from each sensor in each trial were examined and, if necessary, corrected for zero drift before release of the data.

5.3 *Gas supply and containment systems*

The gas storage and supply system was specified to be capable of supplying the full charge of 2000 m^3 of gas in a time of not more than 1 hour for any mixture between pure nitrogen and pure Refrigerant-12. The gas container was required to contain a volume of 2000 m^3 of heavy gas without significant leakage and to release the gas by a mechanism which did not introduce any appreciable disturbing motion or pressure pulse into the gas cloud. The requirement of geometrical similarity with the Porton trials fixed the aspect ratio at approximately 1:1. The gas container in the Porton trials and in the WSL simulations was a cube with a roof which remained in place after the sides of the cube had collapsed to ground level. Hall et al. [5] concluded that the roof inhibited the initial collapse of the cloud due to the restriction it imposed on the movement of air into the vacated space at the top of the container. In view of this, it was decided that exact similarity should be sacrified by specifying that the container lid, if one was used, should be removed shortly before container collapse. It was also decided that a cubical container was not an essential requirement and NMI were given freedom to decide a cross-sectional shape as close to circular as possible within engineering constraints. It was specified that the erect container should be able to withstand and operate in windspeeds up to the maximum trials value of about 8 m/s. After release the container should provide minimum ground obstruction.

The gases were stored in the liquified state and were vapourised separately. The gas mixture was held in a twelve-sided container, 14 m across and 13 m high, fabricated from flexible PVC sheeting. The container was held erect by a system of rigging until a release mechanism operated, allowing it to fall to the ground. Descriptions of the gas supply plant and the gas container are given by Johnson [16].

5.4 *Trials site*

The site chosen was a former Royal Air Force station on Thorney Island in Chichester Harbour, about 40 km east of Southampton. Although there were some obstructions in the form of buildings and trees in the operational area, there was a clear corridor 2 km long and with a minimum width of 500 m. The approach to this corridor was over shallow water to the southwest as was the exit to the northeast. The site was flat to within about 1 in 100. The site details are given in Davies and Singh [20].

The trials site was criss-crossed by two tarmacadam runways approximately 43 m wide. The intervening areas were rough grassland. In the early stages of trials planning, it was provisionally accepted that the possible effects of the surface non-homogeneity would be overcome by covering the runways. The high cost of doing so resulted in a reevaluation. From the point of view of the change of surface roughness, it was concluded that the treatment was not warranted since it was intended that the grassed areas would be mown to maintain an aerodynamic roughness of 10 to 20 mm. Possible differences in surface temperature were judged to have more serious consequences. Some calculations of their effect on dispersion were carried out by Riethmuller [21], using a dispersion model which made allowance for thermal convection within the cloud. These predictions showed that the effects were likely to be too large to be neglected.

Measurements of the surface temperatures of grass and tarmacadam showed that in strong insolation the temperature of the tarmacadam exceeded that of the grass by around 10°C. White-painting of the tarmacadam was found to eliminate (indeed to reverse slightly) the temperature difference. As a consequence, all the runway surfaces over which the cloud might travel, amounting to about 40,000 m^2, were painted white. (They are a distinctive feature of the overhead photographic records of the trials.) Furthermore, the temperatures of the grass and the painted runway were measured and included in the trials data record. A video camera was placed in line with the runway edge to investigate whether any change in the cloud motion was detectable as the cloud crossed the runway boundary. No such change was noticeable, nor was any change evident from the overhead photographic records. In some of the trials the cloud dispersed partly over the grassed area and partly over the runways. These trials can therefore be used, if necessary, to study whether any effect on dispersion is measurable. No such effect has so far been detected.

5.5 *Layout of instrumentation for Phase I*

The design of the sensor array involved many considerations, some of which were mutually incompatible. The design problem was essentially one of maximising the information return, subject to economic constraints.

The difficulties in doing so were of course compounded by the uncertainties concerning cloud behaviour and this precluded a design that could be rigorously defended against all criticism. The choice of final design was an exercise of judgement, making use of all the information available. The description of the evolution of the design will be in three parts. The first part deals with the ground plan of the fixed masts. The second part deals with the location of this ground plan in relation to the fixed features of the trials site and the alignment of the ground plan taking account of wind direction probabilities. The third part deals with the deployment of the sensors on the masts and the degree of flexibility for redeployment of the sensors without incurring significant extra costs.

5.5.1. *The ground plan of fixed masts*

The plan of fixed masts proposed by CDE is reproduced in Fig. 1. Its preparation was guided by the results of calculations of cloud dispersion using the box model described by Picknett [4]. In recognition of the differences that existed between the predictions of dispersion models, it was decided that it would be prudent to consider other predictions of the concentration field. A specification for sample calculations was therefore drawn up and an invitation issued to sponsoring organisations known to possess predictive models. A total of 11 organisations responded to the invitation and widely different predictions were obtained. The range of the predicted maximum concentration that would occur at a given distance from the release point, for stated release and weather conditions, extended

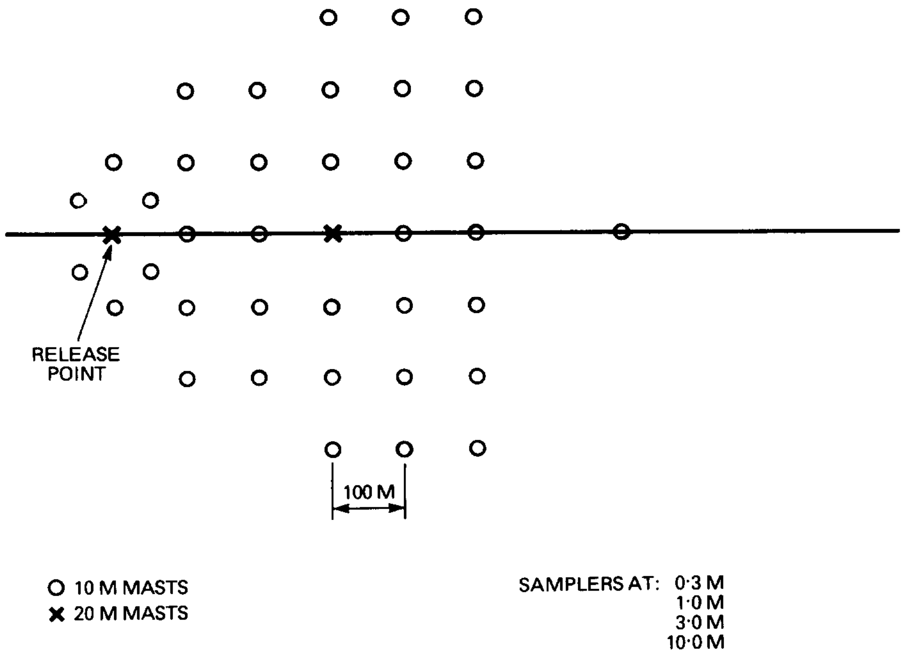

Fig. 1. The ground plan of fixed masts proposed by CDE.

over two orders of magnitude. The details of the results of the exercise are given in [15]. It was concluded that it was not possible to extract a ground-plan design that would efficiently test all predictive models under all conditions. The CDE design was generally compatible with the pattern of the predictions, having no evident deficiency in any one weather condition whose correction would not expose weaknesses under other weather conditions, given a fixed total number of masts. On this basis, the CDE plan was accepted as the final design.

5.5.2. *Location and alignment of the mast array*

The optimum positioning of the mast array required consideration of the interplay between the expected cloud size, the probabilities of occurrence of the design windspeeds by sector and the fixed features of the trials site.

The estimates from the predictive modelling exercise allowed the outlying cloud dimensions, incorporating all the model predictions, to be constructed for particular maximum ground-level concentration levels. It was possible to conclude that an angular spread of ±30° about the mean cloud path would include most of the predictions for a limiting maximum ground-level concentration of 0.5%. The geometry of the ground plan would therefore permit a range of acceptable wind directions of ±20° about the array axis in which the gas cloud would be covered by the masts.

An analysis of meteorological data for the period 1966—75 showed that for any given month, the wind direction probability was fairly evenly distributed over the whole sector of interest (i.e. the 100° sector centred on the clear corridor over the site). The average probability was about 3.5% per 10° sector. This was taken as a design figure in determining the probability of obtaining winds in the acceptance angle corresponding to any chosen combination of spill point and array alignment.

The topography over the whole site was sufficiently flat that it offered no limitations on location of the array. Neither was the presence of the runways considered as a limitation; it was accepted that any necessary treatment of the surface would be arranged. The limitation on usable wind directions was therefore primarily the effects of obstructions on the site. The choice of spill point and of the bearing of the axis of the mast array was determined by the need to minimise the effect of upwind obstructions whilst still providing an adequate downwind field for the gas clouds to disperse without being affected by downwind obstructions. Figure 2 shows the position of the spill point chosen and the alignment of the mast array with respect to the runways. The array centre line is on a bearing of 207°, where the notation is that a wind blowing from the North is at 0°. This choice utilised the full ±20° acceptance range of the ground plan whilst still giving a minimum 100 m clearance between the extreme wind directions and the upwind obstructions.

5.5.3. *Instrument dispositions*

The scheme for sensor deployment that applied at the start of the trials is given in Table 2 and illustrated in Fig. 2. The fixed masts in the CDE ground plan were intended primarily for the standard gas sensors. All but one of the masts in this part of the array were of the same type, designated as the F mast. The remaining mast, designated D, was an F mast with environmental sensors added to give information on the far field weather conditions. Four standard gas sensors were deployed on each of these masts. The lowest sensor was positioned at a height of 0.4 m and the highest at 4 m on masts close to the spill point, 10 m over the bulk of the array and 14.5 m in the far field. In each set, the intermediate sensors were placed at equal height intervals between the lowest and highest sensors.

In addition to the F and D masts, 7 additional masts were deployed. Their locations are also shown in Fig. 2. The instrumentation on each was as follows:

(a) A mast. This mast (the weather mast) had been installed on the site prior to the trials. At the commencement of the trials, the instrumentation consisted of 5 cup anemometers, 5 temperature sensors, 2 sonic anemometers, and one sensor for each of relative humidity, wind direction, solar radiation and barometric pressure. One of the sonic anemometers was placed at 10 m, the usual reference height for measurements of turbulent velocities and vertical heat flux. The second was placed at 2 m to measure conditions close to the ground since the depths of the clouds

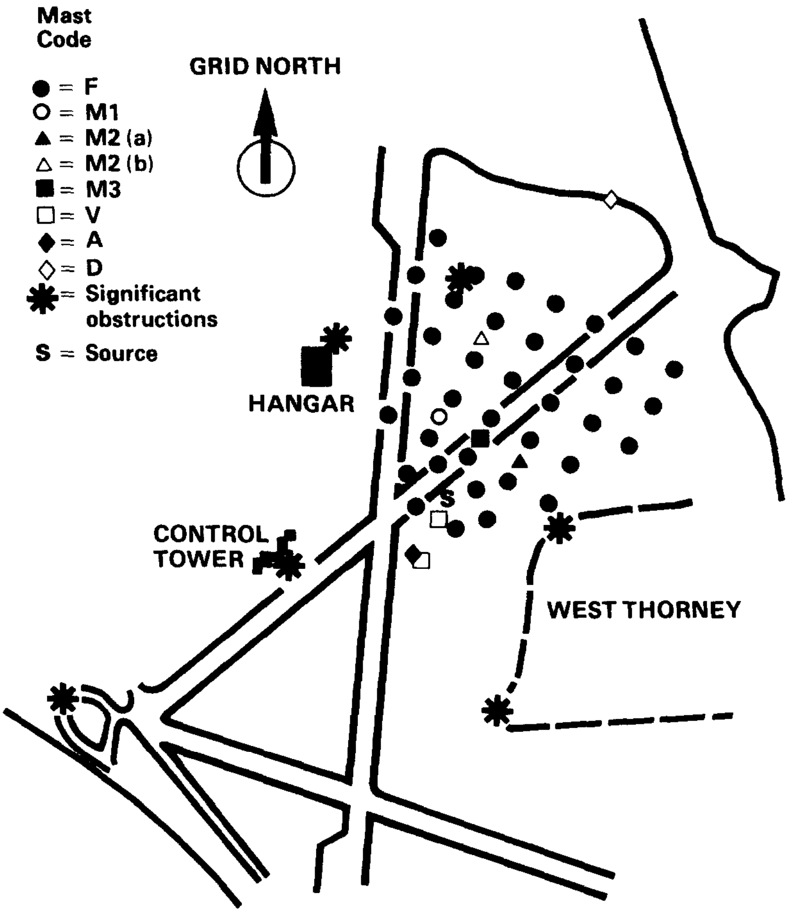

Fig. 2. Identification of types of mast and their location on the trials' site. For the mast code, see Table 2.

in the trials were expected to be no more than a few metres, at least in the near field;

(b) V masts. These masts carried a single potentiometric wind vane at 10 m. These instruments were intended for the application of an eddy forecasting technique recommended by CDE, to aid the judgment of the optimum instant for a release;

(c) M masts. These were trailer-mounted or 'mobile' masts to provide the capability of placing the fast-response instrumentation anywhere in the instrumented field. Each of the 4 mobile masts was provided with 4 standard gas sensors at the same heights as the type F mast. There were 8 sonic anemometers available and the mobile masts were designated as M1, M2 or M3 to correspond to the number of sonic anemometers placed on them. For each of the sonic anemometers other than those at the top of the masts, there was a fast response gas sensor placed at the same height.

TABLE 2

Instrumentation associated with the mast array shown in Fig. 2

Mast Code	Instrumentation
A	5 cup anemometers 2 sonic anemometers 5 thermometers 1 solarimeter 2 relative humidity sensors 1 wind vane
V	1 wind vane
F	4 gas sensors (1 Hz)
M1	1 sonic anemometer 4 gas sensors (1 Hz) 2 gas sensors (10 Hz)
M2 (a)	4 gas sensors (1 Hz) 2 sonic anemometers 2 gas sensors (10 Hz)
M2 (b)	4 gas sensors (1 Hz) 2 sonic anemometers 1 gas sensor (10 Hz)
M3	4 gas sensors (1 Hz) 3 sonic anemometers 3 gas sensors (10 Hz)
D	4 gas sensors (1 Hz) 1 cup anemometer 1 wind vane 1 relative humidity sensor 1 thermometer

The cable attachments to the mobile masts permitted them to be placed anywhere within 100 m of their nominal positions shown in Fig. 2.

Five of the sonic anemometers and three of the trailer-mounted masts were provided on loan by Shell Research Ltd. An offer of the use during the trials of a mobile LIDAR remote-sensing instrument was made by the Central Electricity Research Laboratory. Since the instrument was self-contained, it required no provision to be made for it in the instrumentation plan. Although it was available on the site during the early stages of the trials, it proved not to be possible to use it successfully during any of the trials.

5.6 *Data capture system*

Data collection from some 250 instrument channels at distances of up to 1000 m from the control tower was required. Data terminals distributed over the instrumented field converted the analogue signals to digital format for transmission to a central recording facility located in the control tower. The data capture system is described by Johnson [16]. Each instrument, data terminal and channel had a unique number assigned to it. The location coordinates of each instrument and the data terminal/channel to which it was connected were recorded in a 'housekeeping' file for each trial. This file is an integral part of the data tape record for a trial. Before data tapes are issued, the data is subjected to a validation process, as described by Roebuck [18].

Hard copy summaries of the data tapes have also been produced for each trial [22].

During the trials period, a requirement was identified for supplementary instrumentation to investigate specific characteristics of the gas clouds. Since the channel capacity of the main data capture system was fully allocated, the requirement was met by the provision by HSE of a separate 8 channel portable data logger. The logger comprised an 8 channel multiplexer, 12 bit A/D converter, microprocessor-controlled formatting system and a cassette tape recorder. Each channel was sampled at a rate of 1 Hz. The usage of this data logger is described in [15].

5.7 *Photography*

The Porton trials had demonstrated the value of photographic records and indeed much of the quantitative information from those trials was derived from analysis of such records. It was decided at an early stage that provision for extensive photographic coverage would be included in the design of the Thorney Island trials. The photographic coverage was much more extensive than what was needed for visual effects purposes e.g. the film of the trials [23]. The design of the photographic system took account of a number of scientific objectives.

An important characteristic of the HGDT-type of experiment is its time dependence, arising both from its transient nature and the spatial structure of the cloud. Photographic records were therefore envisaged as providing a valuable aid to the interpretation of the sensor records since both types of record could be time-synchronised from a defined event such as container release. The appearance of particular features in one record could then be correlated with features in the other. Developments in image-processing technology offered promise of more complete quantitative analysis of photographic records than had hitherto been possible. In addition to information on cloud position and geometry as functions of time, there was also the possibility of relating the optical density distribution to the concentration distribution. These considerations were influential in deciding the disposition of still and video cameras in the field. The value of the photographic records for analysis purposes has already been demonstrated [24, 25].

The importance attached to photography imposed two constraints on trials operations. These were that trials should be conducted in daytime and that a helicopter should be available. Although these constraints were intended to be binding, in practice there were occasions when the countdown had proceeded beyond the sensible economical abort point and trials were performed with one or both constraints not satisfied. In general, however, the planned coverage was achieved in most of the trials.

The clouds were marked with orange-coloured smoke by firing up to 4 canisters shortly before release. No provision was made for forced mixing of the smoke and gas in the container. The number of smoke canisters required was determined prior to the trials by some preliminary releases of smoke-marked air. The general requirement laid down was that the cloud should remain visible from above until it was well into the array of instrumented masts.

Video and still cameras were placed in a helicopter flying at a height of 300 m. The helicopter was stationed above the gas container at the time of release and subsequently followed the cloud downwind. Ground-based video, cine and still cameras were placed at various positions on the site, as described in [15]. Some relocations of the camera positions were made during the course of the trials in the light of experience.

6. Meteorological instrumentation

6.1 *Measurement strategy*

The design of the meteorological instrumentation system was determined by the measurements needed to characterise dispersion. The specification of the system is considered in this paper; the description of the results obtained is presented separately in [15] and [20].

The objective of the HGDT project was to acquire data for the use of modellers at large. Their many and varied needs therefore had to be taken into account. As it happens, the requirements of heavy gas dispersion models (and also of passive dispersion models) could have been met by specifying the Pasquill stability category, the wind speed and the ground roughness. This indeed was the framework for the broad specification of the conditions for the trials. However, the Pasquill categorisation scheme was adopted as a convenience for the purpose of the trials planning. There was (and still is) considerable controversy as to the most appropriate turbulence classification scheme to use. Heavy gas dispersion models generally prescribe the physical processes in terms of parameters such as the turbulent velocity and length scales in relationships for entrainment, eddy diffusivities, etc. The models then relate these primary parameters to Pasquill categories or other schemes such as, for example, the temperature difference scheme of the U.S. Nuclear Regulatory Commission (see Sedefian and Bennett [26]) which can in turn be related to the Pasquill categorisation. Modellers are required to do this because, in practical applications, the meteorological data are only usually available in one of those forms. However, it is not defensible for the experimenter to adopt a similar strategy and the only admissable philosophy is to supplement the simplified schemes by measuring the quantities that are explicitly used by modellers. The modellers can then make their own decisions on how to connect their choice of parameterisations to the forms in which meteorological data are available. The design of the instrumentation system and the data reduction procedures therefore took account of both aspects — the need to provide the primary parameters as well as the stability classification for each trial.

6.2 *Classification of atmospheric stability*

The Pasquill scheme utilises meteorological parameters which can readily be observed without the need for elaborate instrumentation. It was decided, however, that the instrumentation on the weather mast should be designed to provide the quantitative information required by other classification schemes.

Wind velocity data were recorded at five heights, decided by the following factors:

(i) The 30 m height of the mast;
(ii) the standard reference height of 10 m common in meteorology;
(iii) the presence of obstructions at ground level due to the mast supports, which fixed the lowest height at 2 m;
(iv) the logarithmic variation of wind velocity with height.

With three of the heights fixed at 2 m, 10 m and 30 m, the remaining heights were therefore at the geometric mean heights of 4.5 m and 17.3 m to obtain equal increments of velocity. Temperature measurements were also made at 5 heights with sensors uniformly spaced between 2 m and 30 m i.e. 9 m, 16 m and 23 m. A wind vane and a relative humidity monitor were placed at a height of 10 m. All of this instrumentation operated on the weather mast for a period of one year preceding the trials. At the start of the trials, two sonic anemometers were added at heights of 2 m and 10 m and a solarimeter at 0.4 m. The specifications of the individual instruments are given by Johnson [16].

The instrumentation permitted quantitative measures of atmospheric stability according to several schemes to be computed. These measures could then be converted to Pasquill categories, for example using the recommendations given in the review of Sedefian and Bennett [26]. The schemes adopted were as follows:

(i) *Wind direction standard deviation* (σ_θ). This is one of two schemes adopted by the U.S. Nuclear Regulatory Commission (NRC) who give recommended ranges of σ_θ for each of the Pasquill categories. The wind direction vane at 10 m provided the data necessary for this method.

(ii) *Temperature difference* (ΔT). This is the second scheme adopted by the NRC. Stability is classified by the temperature difference over a height of 100 m so that extrapolation of the temperature profile measurements was necessary.

(iii) *Gradient Richardson number* (Ri_g) *and bulk Richardson number*

(Ri_b). These two schemes are described by Sedefian and Bennett [26] who give the ranges for each parameter corresponding to the Pasquill categories. The required measurements are obtained from the wind and temperature profile data. In the case of the gradient Richardson number scheme, it is necessary to assume a value of Z_0 but Sedefian and Bennett found that the results of the classification were insensitive to the assumed value of Z_0 in the range 1 to 10 cm.

The application of these schemes in the analysis of the meteorological data from the trials is described by Davies and Singh [20].

6.3 *Characterisation of dispersion in terms of atmospheric boundary layer parameters*

There are a number of recent reviews of heavy gas dispersion modelling e.g. Blackmore et al. [3], Farmer [27], Havens [28], Webber [29], Wheatley and Webber [30]. Indeed, the latter reference lists a total of around 50 models, some of which of course postdate the planning of the present trials. For the present purpose, it is not necessary to describe the details of the schemes in the various models but rather to highlight the input measurements they share. Consideration of the instrumentation requirements of trials for the validation of dispersion models has been given in Section 3 but pertaining only to the instrumentation measuring the properties of the cloud itself. The present discussion relates to the instrumentation to measure the conditions of the ambient atmosphere into which the cloud is released. To some extent, the instrumentation in the cloud will serve a dual purpose in that it also provides data on ambient conditions up to the point at which it is enveloped by the cloud. However, the main concern here is with the instrumentation on the designated weather mast upwind of the spill point.

Dispersion models generally fall into two classes, insofar as the connection between the physical processes governing mixing of the cloud and the structure of the ambient atmosphere is concerned. Firstly, there are the models where the mixing is described in terms of the properties of the ambient atmosphere in the absence of the cloud. All box models, including the more advanced types, adopt this description. The three parameters that encompass all requirements are the reference wind velocity (usually that at 10 m i.e. U_{10}), the ground roughness, Z_0, the friction velocity, U_*, and the stability. The stability can be characterised by a quantitative measure such as the Monin—Obukhov length scale, L, defined as

$$L = -\frac{\rho\, C_p\, T\, U_*^3}{k\, g\, H}$$

where k is the von Karman constant and H is the sensible heat flux.

The quantities needed are thus U_{10}, Z_0, U_* and H. The ways in which they are used to characterise dispersion serve to differentiate the various models. Any three of these quantities will determine the fourth, given the Monin–Obukhov velocity profile applied at the reference height of 10 m, i.e.

$$\frac{U_{10}}{U_*} = \frac{1}{\kappa} \log_e \frac{10}{Z_0} + \beta \frac{10}{L}$$

However, the models generally call for all or any of Z_0, U_* and H to be specified. This in effect leaves U_{10} as the redundant parameter. Since it is the one that is measured in any case, its inclusion is retained despite its formal redundancy.

In the second class of model, to which the K-theory or 'hydrodynamic' models belong, the local diffusivities in the cloud are related to a measure of the local stability analogous to the ambient atmospheric stability but evaluated from the calculated properties within the cloud. The local stability may be defined in terms of a quantitative measure, for example the local Richardson number which is related to the Richardson number of the ambient atmosphere, the local friction velocity and the local turbulent convection velocity scale in the FEM3 model (Chan et al. [31]). The local stability may also be defined in terms of a local Pasquill stability category determined from the calculated local temperature gradient and the NRC relationship between temperature gradient and Pasquill category. This scheme is used, for example, in the SIGMET model (England et al. [32]). Since all these models must necessarily start the calculation by reference to the properties of the undisturbed atmosphere, it follows that the atmospheric properties are also characterised in the above ways. The parameters needed are as before; for example, the Richardson number is related to L and thus to H and U_*.

In the design of the instrumentation system, the measurement of the reference windspeed at 10 m height was already included. There remained the consideration of the determination of Z_0, H and U_*.

6.3.1. *Roughness length*

The wind velocity profile instrumentation permits Z_0 to be determined from fitting of measurements in neutral stability conditions to the logarithmic velocity profile. The assignment of a neutral condition can be made on the basis of the collective evidence from the classification schemes described earlier.

6.3.2. *Sensible heat flux*

The sensible heat flux, H, may be determined from direct eddy correlation measurements or indirectly in a number of ways. The direct method requires high resolution measurements of the vertical velocity fluctuations and the temperature fluctuations. However, the temperature measured by the sonic anemometer cannot be used directly to produce reliable estimates of heat flux in all situations. This is due to possible contamination by horizontal wind velocity components (Kaimal [33]). The Meteorological Office recommended that a separate fast-response temperature sensor (such as a thin platinum wire) should be mounted either within the actual frame of the sonic anemometer or alongside it (Readings et al. [34]). Arrangements were therefore made to implement this recommendation. Subsequent to the decision to include this provision, methods for the correction of the temperature indicated by the sonic anemometer have become available (Schotanus et al. [35], Hasenjager [36]).

The heat flux as measured in the above way is subject to correction for the flux of water vapour. To enable this to be done an additional relative humidity sensor was placed on the weather mast at a height of 30 m. Together with the sensor already placed at 10 m an estimate could then be made of the relative humidity gradient. This additional sensor was deployed from Trial 007 onwards. However, it may be noted that Puttock and Colenbrander in this volume [37] conclude that errors due to the effects of relative humidity gradient on sonic anemometer determinations of heat flux fortunately cancel out.

Of the indirect methods of determining H, the simplest is that proposed by Smith [38]. He suggested that the relationship

$$H = 0.4\,(R - 100)$$

is modestly reliable in all but rather unusual circumstances. In this equation R is the net incoming solar radiation and the units are W/m^2. The measurement of incoming solar radiation was achieved by a solarimeter placed on the weather mast at 0.4 m.

The second indirect method is to use the relationships of Monin—Obukhov similarity theory (Dyer [39]). This requires Z_0 to be known and measurements of the wind and temperature profiles. These requirements are already catered for in the instrumentation scheme to meet earlier needs.

The third indirect method uses the energy balance. The four components of the energy balance are the net radiation, the sensible heat flux, the latent heat flux and the soil heat flux. The net radiation and soil heat fluxes can be measured directly. Instrumentation for these purposes was not included in view of the redundancy already included for the evaluation of H. However, methods are available for estimating these fluxes and also the latent heat flux, based on the classification of the site surface conditions, the air temperature, the incoming solar radiation and the cloud cover. All of these observations are included in the measurement scheme.

6.3.3. *Friction velocity*

As with the sensible heat flux, the friction velocity U_* can be obtained directly or indirectly. One direct method uses eddy correlation measurements and these are provided by the sonic anemometers on the weather mast. It is also possible to measure the surface shear stress directly using a drag plate but no provision for doing so was made in the trials.

The indirect methods rely on the application of Monin—Obukhov similarity theory. There are two cases to consider. The first is where H is known, in which case the determination of U_* follows from the known Z_0 and a measurement of the velocity at a reference height (see for example, Pasquill [40]). The value of H in this determination is the value obtained from any one of the methods described above, other than that using the similarity theory. In the application of the similarity theory, both H and U_* may be taken as unknown and evaluated by iteration, using the known Z_0 and measurements of the velocity and temperature profiles. All the measurements for the evaluation of U_* from similarity theory are included in the measurement scheme.

7. Trials performed in Phase I of the programme

The priority order of trials conditions given in Table 1 was assigned for the purpose of matching financial resources and technical objectives. In practice, it was clear at the commencement of the trials programme in Summer 1982 that the likelihood of being able to perform the full set of conditions was high. The execution of the trials therefore proceeded on the basis of taking weather opportunities as they arose rather than waiting for each priority condition in turn. Thus the numbering in the matrix in Table 1 is not relevant to the actual order in which trials were performed. Only towards the concluding stages, when many of the matrix conditions had been matched with trials performed, was selectivity of conditions introduced.

The trials schedule began with preliminary releases of smoke-marked air to prove the smoke generation arrangements, the container release system and the photographic system. Three such trials were performed (001—003) and do not form part of the trials record. The following trial was a release of 30% nitrogen/70% air mixture to check the gas filling procedure and the gas sensor performance. This trial is included in the trials record as the only neutrally-buoyant release performed. The first heavy gas release (005) was performed on 3 August 1982. It was marked by the first and only failure of the gas container to perform satisfactorily. The container was partially held-up after release, with some loss of gas. The container was subsequently dropped successfully. It was possible to make an assessment of the volume of gas released and the trial is included in the record. During the remainder of 1982, 8 trials were performed, of which one (010) was of limited success due to a late change in wind direction. Prior to the restart in 1983, some changes to the instrument layout were made and a decision taken to omit the remaining planned neutrally-buoyant release and to substitute a release at the lowest initial relative density ratio that was feasible. The programme of Phase I trials was completed in June 1983, with 1 neutrally-buoyant and 15 heavy gas releases on the record. A summary description of each of the trials is given in Table 3.

TABLE 3

Summary description of Phase I trials

Trial number	Date[a] and time	Wind speed[b] (m/s)	Pasquill stability category[c]	Volume released (m^3)	Initial relative density	Number of standard gas sensors which detected gas	Number of fast response gas sensors which detected gas[d]	Number of sonic anemometers in the cloud[e]	Number of sonic anemometers above the cloud[e]
004	15.7.82 12.34	3.8	B	2100	0.99	20	1	1	1
005	3.8.82 14.27	4.6	B	1320	1.65	22	4	3	2
006	4.8.82 19.11	2.6	D/E	1580	1.60	43	2	1	4
007	8.9.82 19.33	3.2	E	2000	1.75	52	2	3	2
008	9.9.82 17.49	2.4	D	2000	1.63	71	1	4	2
009	15.9.82 18.46	1.7	F	2000	1.60	56	4	4	4
010	30.9.82 09.27	2.4	C	2000	1.80	11	0	0	0
011	10.10.82 17.21	5.1	D	2100	1.96	23	0	1	1
012	15.10.82 17.21	2.6	E	1950	2.37	61	2	2	4
013	19.10.82 11.41	7.5	D	1950	2.00	45	2	2	3
014	24.10.82 11.58	6.8	C/D	2000	1.76	46	2	3	2
015	28.4.83 15.29	5.4	C/D	2100	1.41	37	1	1	1
016	28.4.83 18.30	4.8	D	1580	1.68	44	1	1	1

TABLE 3 (*continued*)

Trial number	Date[a] and time	Wind speed[b] (m/s)	Pasquill stability category[c]	Volume released (m^3)	Initial relative density	Number of standard gas sensors which detected gas	Number of fast response gas sensors which detected gas[d]	Number of sonic anemometers in the cloud[e]	Number of sonic anemometers above the cloud[e]
017	9.6.83 19.52	5.0	D/E	1700	4.20	57	3	3	2
018	10.6.83 15.56	7.4	D	1700	1.87	59	2	2	3
019	10.6.83 20.41	6.4	D/E	2100	2.12	62	3	3	2

[a] Day, month, year.

[b] Wind speeds are at 10 m height on the 'A' mast averaged over the duration of each experiment.

[c] Pasquill Stability Categories are assessed from observation, solar radiation, vertical temperature gradient, standard deviation of horizontal wind direction and Richardson number.

[d] Numbers refer only to the fast-response version of the oxygen-deficiency sensor.

[e] Cloud extent defined by records from standard gas sensors.

An exact correspondence between the weather conditions achieved in the trials and those planned in the design intention was not expected. However, for completeness a comparison of the two sets is given in Table 4 where in each element the upper row reproduces the priority numbers from Table 1 and the lower row gives the trials assigned to the appropriate combination of conditions. The data refer to all the heavy gas trials other than the trial with pure Refrigerant-12 (No. 14 in the plan and No. 017 in the trials list). The neutrally-buoyant release (004) was conducted at a windspeed of 3.8 m/s and B stability compared to the plan of 2 to 4 m/s windspeed and C to D stability.

TABLE 4

Comparison of plan and achievement (heavy gas trials at nominal initial relative density of 2.0)

Pasquill stability condition sub-range	Wind speed sub-range (m/s)			
	0–2	2–4	4–6	6–8
A, B		12	8 005	
C, D		2, 6 006[a], 008, 010	7, 10 011, 015, 016	3, 15 013, 014, 018, 019[a]
E, F	1, 9 009	4, 11 007, 012		

[a] Trials 006 and 019 are classified as D/E stability.

The pure Refrigerant-12 release was conducted at a windspeed of 5.0 m/s and D/E stability compared to the plan of 0 to 2 m/s windspeed and E to F stability. Included in Table 4 are Trials 015 and 016 where the target initial relative density ratio had been 1.5 rather than the nominal value of 2.0 for the other trials. The decision to aim for 2 trials at a reduced initial relative density ratio in the 1983 series was taken in the light of the results obtained in 1982. Overall, the achievement was a satisfactory match to the plan.

8. Results of the Phase I trials

Detailed consideration of the results of the trials is given in other papers in this volume and only the broad features are presented here. The detailed results occupy a separate volume for each trial [22]. An adequate summary of the results from many different sensors at many different positions, with each record being highly time-dependent, could necessarily only be presented within the framework of a mathematical model. As has already been emphasised, the trials were conducted without reference to the needs of any particular model description. The reduction of the database into presentable forms will be undertaken by modellers and efforts in this direction are exemplified by [41], [42] and [43]. The emphasis in this paper is on a presentation of results that will give an appreciation of the extent of the database, its reliability and consistency and some distinctive features.

8.1. *Coverage by the gas sensing instrumentation*

Much thought was given to planning the layout of the instrument masts, most of which were embedded in concrete so that the layout could not easily have been changed. The success of the trials therefore rested to a considerable extent on the accuracy of the original judgement. In the event, no changes in the positions of the fixed masts were made and it is pertinent to examine, with hindsight, whether this was justified.

A summary of the coverage achieved by the layout of fixed masts is presented in Fig. 3. This shows the numbers of times that the lowest gas sensor (at 0.4 m height) on each mast detected gas in Trials 005 and 019. The relevant feature in the present context is that the numbers tail off at the sides and downwind edge of the array, being influenced by the lower

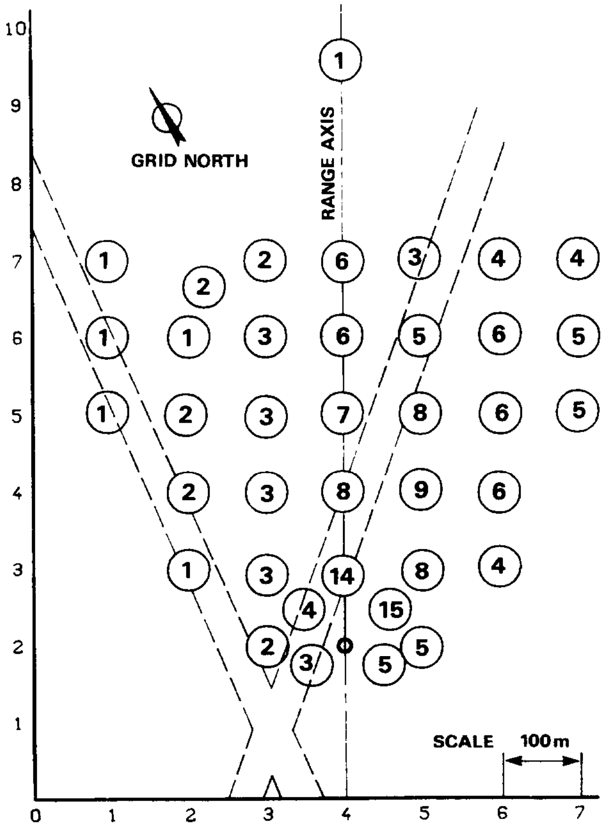

Fig. 3. Numbers of times the sensors at 0.4 m height detected gas in Trials 005 to 019.

limit of resolution of the gas sensors of 0.1% concentration as well as the geometrical size of the clouds. The results demonstrate an excellent match between the capability of the gas sensors and their layout in the field. There is a bias towards higher numbers in the right hand part of the array, reflecting a higher frequency of winds blowing into that sector.

There was much more flexibility built-in to the vertical disposition of the gas sensors, the maximum height being adjustable up to 14.5 m. This flexibility was utilised following Trials 005 and 006, from the results of which it was evident that the clouds were lower lying than expected. The heights of the gas sensors, given in Section 5.5.3, were consequently reduced, except for the lowest gas sensor which remained at 0.4 m throughout. On the masts where the height of the highest sensor had been 4 m, this sensor was removed and the remaining three sensors were placed at 0.4, 1.4 and 2.4 m. On the masts where the highest sensor had been at 10 or 14.5 m, the four sensors were placed at 0.4, 2.4, 4.4 and 6.4 m. A summary of the effectiveness of the vertical disposition of gas sensors on the fixed masts is given in Fig. 4. This shows, for all of trials 005 to

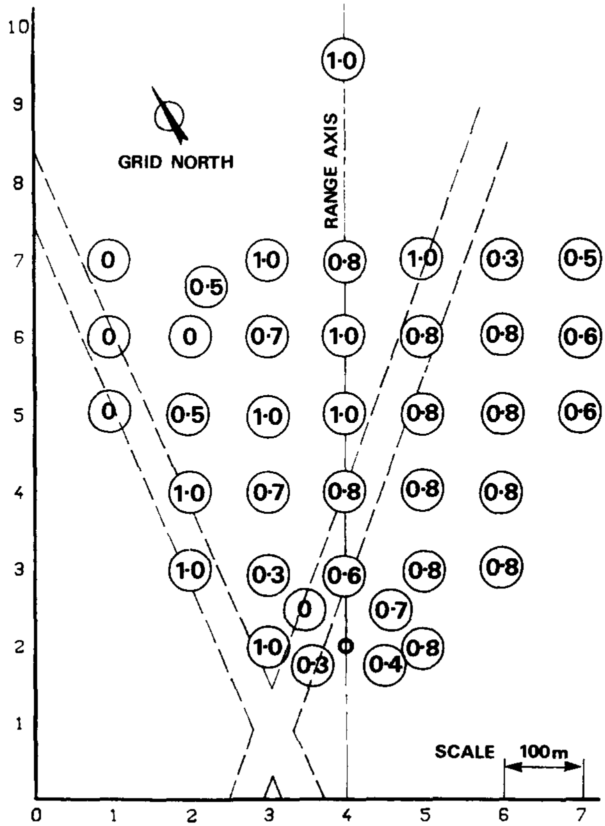

Fig. 4. Probabilities of top sensor detecting gas conditional on the lowest sensor detecting gas for Trials 005 to 019.

019, the ratio of the number of occasions when the top sensor on each mast detected gas as a proportion of the number of occasions when the lowest sensor also detected gas. A low value of this ratio indicates that the gas cloud at the upper level had been diluted below the sensor's lower limited of resolution. Again, the tailing off of the numbers at the sides and downwind edge of the array reflects the match between the gas sensor capability and the chosen vertical layout.

For individual trials, the coverage is summarised in the presentation shown in Fig. 5. Such plots have been produced for all the trials [15]. The example in Fig. 5 is for Trial 014. At each mast in the gas cloud, the peak concentration (from the record averaged over 0.6 s intervals) and the number of sensors on the mast which detected gas are shown. Of interest are the internal consistency of the concentration data (i.e. the peak at any one mast is consistent with those at the neighbouring masts) and the detail available on the vertical distribution of concentration over a large part of the cloud. The conformity of the cloud outline to the mean

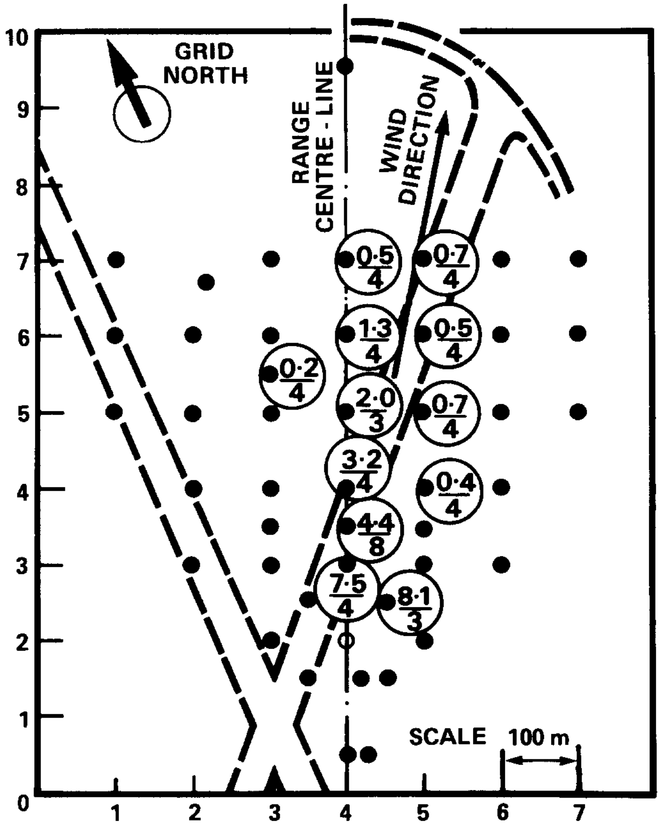

Fig. 5. A summary of the concentration database for Trial 014. The upper figure in each circle is the peak concentration at 0.4 m height and the lower figure is the number of sensors which detected gas at the respective location.

wind direction over the trials period is also an encouraging indication of overall consistency.

The performance of the gas sensors compared to the specification is considered in detail in [17] and only some general remarks are appropriate here. The time records of all the gas sensors in each trial were individually examined and corrections for zero drift applied, where necessary, as described in [17]. Any apparent anomalies were followed up to eliminate, as far as possible, inadvertent wrongful identification of sensors in the housekeeping file, calibration errors, etc. There were very few unexplainable anomalies in the records but where they occur, they have been left in the database.

Although the lower limit of resolition of the gas sensors was nominally 0.1%, in some cases the records gave clear and unambiguous indications below this level. This was due to a lower than average instrument noise level. An example of such a record is shown in Fig. 6. Where it was possible to make a judgement that the excursion above the noise level was consistent with the presence of gas at the sensor, this was done, even though the concentration did not exceed the nominal lower limit of resolution. This was particularly the case for Trial 004 (i.e. the neutrally-buoyant release) where much of the data record relies on such judgements.

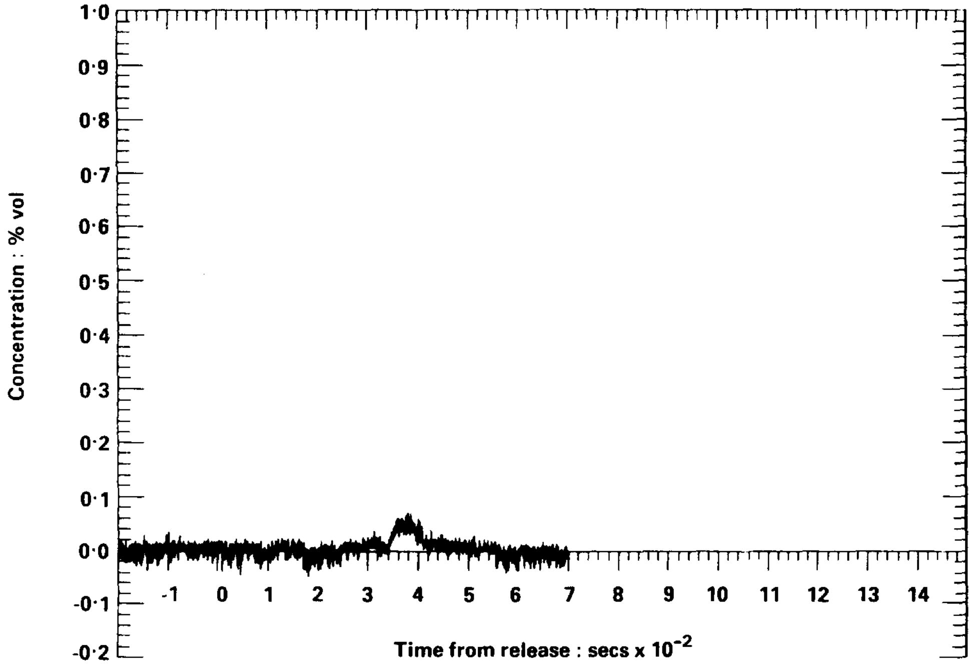

Fig. 6. An example of a gas sensor record with a peak concentration below the nominal lower limit of resolution of the sensor.

Other indications of the accuracy of the gas concentration records are provided in the analyses reported in [41]. In particular, the evaluations of mass balances must be regarded as remarkable by the standards of field experimentation.

A further and potentially fruitful subject of study is the cross-correlation between the distinctive features of individual gas sensor records and the photographic evidence. The sensor records appear to indicate the passage of a well-defined spatial structure past the sensor. The photographic records, especially those from the overhead view, also show a distinctive spatial structure, particularly in the early stages of dispersion. It will be of interest to study how the time-varying record at a given position relates to the time-varying visual appearance of the cloud at the same position. Illustrative examples of the time-varying concentration records are given in Nussey et al. [44], who consider in detail the effect of the averaging time applied to the data, in relation to the sensor's response time.

8.2 *Coverage by the other instrumentation*

The other element of the instrumentation system, besides the array of fixed masts with the standard gas sensors, that was subject to the vagaries of the wind direction was the fast-response instrumentation on the trailer-mounted masts. Although these masts were intended to be mobile and to be positioned to suit the wind direction in each trial, in practice this was never achieved. The masts remained at their initial positions throughout 1982 i.e. for Trials 004 and 014. During the winter shut-down of 1982/83, it was decided that the masts should be moved closer to the release point and that the number of masts should be reduced from 4 to 3. The coverage achieved by the fast-response instrumentation in each trial is included in the data in Table 3. In general, fast-response data were obtained in all trials except 010, which suffered a late change in wind direction which carried the cloud away from the main body of masts. Some preliminary analyses of the results from the fast-response instrumentation and of the comparative performance of the fast-response and standard versions of the gas sensor, are given in [44].

8.3 *Some distinctive features of the results*

The variation of concentration with downwind distance is a characteristic of interest in all forms of dispersion modelling. In the Thorney Island type of experiment, the illustration of this characteristic is not easy, since the concentration at a point varies with time and the form of this variation is itself very dependent on the location. Furthermore, the variation of concentration (however defined) with distance cannot be considered in isolation from the variation with time after release. Despite these difficulties (which current work is addressing) an analysis of the data in a simplified fashion is illuminating. The concentration chosen is the peak value in the record observed at a point. The record is the successive averages over 0.6 s; for the effect of other averaging times on the peak value, see [44]. The downwind distance is taken as the radial distance from the release point to the sensor position. Only the data from the lowest gas sensor at 0.4 m height are considered. Such data, from all the sensors that detected gas in a trial are plotted together, as shown in the example in Fig. 7 for Trial 006. The upper boundary of the data should correspond to the variation along the path of the centroid of the cloud. In any given trial, there were only a few points defining this upper boundary, due to the lack of coincidence of the centroid path and the positions of the fixed masts. The data points assessed by eye as being on the upper boundaries for each trial have been plotted together in Fig. 8. The figure includes the values of the overall Richardson number defined as:

$$Ri = g\frac{\Delta\rho}{\rho_a}\frac{H_0}{U_{10}^2}$$

where H_0 is the initial height of the cloud and is evaluated from the released volume and the initial cloud diameter.

There is no apparent correlation of the data with Ri, a dependence that might have been expected. Such a plot is admittedly crude, since it ignores scaling considerations taking account of the different initial densities and initial volumes in each trial. However, the changes that would be introduced by such scaling are unlikely to be such as to upset the broad con-

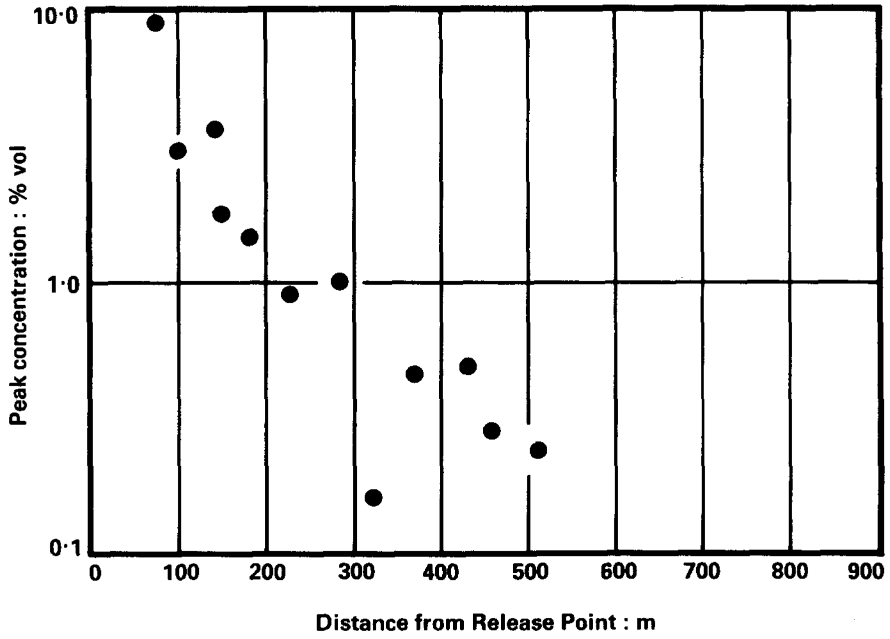

Fig. 7. Peak concentrations from all the sensors in the gas cloud at 0.4 m height. Data from Trial 006.

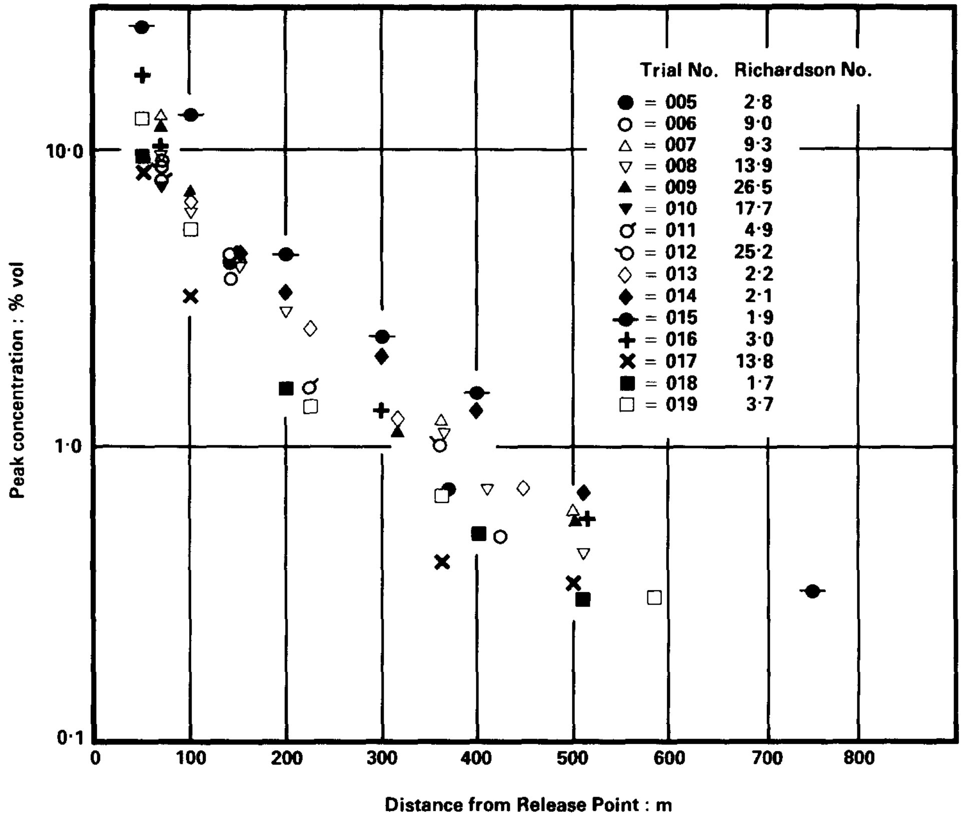

Fig. 8. Peak concentrations on the path of the cloud centroid.

clusion that the peak concentration at a given distance along the path of the cloud centroid is quite insentitive to wind speed and atmospheric stability. This conclusion suggests that the dispersion (or at least this chosen characteristic of dispersion) is dominated by the gravity-driven motion of the cloud over most of the dispersion field covered by the trials.

Other characteristics of general interest are the distribution of concentration with height and the way this distribution changes as the cloud moves away from the release point. Again, the peak data point in the record of 0.6 s averaged values is chosen for illustration. The distribution with height is given in Table 5 for two positions in Trial 016. Near the release point, there is a considerable variation with height, whilst on the mast at the downwind position the peak concentration is more or less constant with height. This behaviour is typical for all the trials.

The effect of the stabilising density gradient on the turbulent structure is important in models based on turbulence closure schemes. The time-dependency of the records presents fundamental difficulties in determining turbulence parameters and it is not yet possible to make any definitive

TABLE 5

Examples of distributions of temporal peak concentration (% Vol.) with height for Trial 016

Height (m)	Distances from release point (m)	
	50	500
0.4	18.0	0.4
2.4	6.1	0.3
4.4	1.6	0.3
6.4	0.87	0.3

statements. This problem is considered by Nussey et al. [44] who tentatively conclude that no effect on the intensities of the turbulent velocity fluctuations is discernible.

9. Concluding remarks

The HGDT project has been supplemented by a number of complementary investigations undertaken by HSE contractors. These were designed to support the project by theoretical and experimental studies of particular aspects of the dispersion of fixed-volume clouds. The results of some of these studies are presented in other papers in this volume. A review of the overall HSE programme on heavy gas dispersion, of which the HGDT project was the principal component, is given in Barrell and McQuaid [45]. Analyses of the data from the Thorney Island trials are also being carried out by other sponsors of the trials. These are summarised in Roebuck [18] and some of the early results are described elsewhere in this volume.

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