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THE PHASE II TRIALS: A DATA SET ON THE EFFECT OF OBSTRUCTIONS

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Summary

This paper describes the design and objectives of the second phase of heavy gas dispersion trials conducted at Thorney Island. In this phase, 2000 cubic metre volumes of gas with densities relative to air varying between 1.9 to 4.2 were released instantaneously to disperse in the presence of three types of obstruction. The criteria used in selecting the obstructions and sample data for each type are presented and preliminary indications of the effect of the obstructions are given. Conditions during each of the ten trials conducted during this phase are presented.

1. Introduction

During the conduct of the Phase I heavy gas dispersion trials at Thorney Island in 1982 (McQuaid [1]), a joint HSE—NMI proposal was presented to sponsors suggesting a Phase II programme of tests. Whereas Phase I was conceived to aid the development and test the validity of mathematical models of dense gas dispersion, Phase II was primarily aimed at providing a data set with which to compare physical modelling in a wind tunnel. The Phase I programme had provided a significant investment in equipment and systems for gas release and data acquisition. Utilising this investment and the proven success of the trials execution methodology the Phase II trials provided a valuable extension at relatively modest cost.

The Thorney Island facility was designed to represent an idealised large scale experiment. In Phase I the flat site remained unobstructed and the release system provided an instantaneous release comprising a 2000 m^3 cylinder of gas of aspect ratio one. In Phase II this instantaneous spill was allowed to disperse in the presence of obstacles. The trials were necessarily limited in number (ten) and were not intended as a parametric study of obstructions; rather the intention was to produce a representative range of the fluid dynamic phenomena likely to occur when a dense cloud disperses over a complex built environment. It was judged that within the category of instantaneous spills, the Phase II programme would generate a satisfactory set of situations against which wind tunnel testing methods could be validated.

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This paper gives an outline of the trials conducted and provides some examples of the effects of certain obstructions. Further details of the site, meteorology and methods used in Phase I are given in Johnson [2] and Davies and Singh [3] , whilst a comprehensive discussion of the rationale and background to the complete heavy gas dispersion programme is provided by McQuaid and Roebuck [4] in HSE's report to the trial sponsors.

2. Choice of obstructions

In selecting the obstructions, consideration was given primarily to the range of fluid dynamic situations likely to be encountered during model tests on heavy gas dispersion over typical sites. Discussions with potential sponsors of the Phase II programme led to the conclusion that the main situations that should be examined were those obtained during the following:

(a) Flow and dispersion over a solid barrier as may be used to arrest or delay the passage of a gas cloud. (Here, based on the work of Britter [5], it was expected that depending mainly on wind speed, the height of the barrier and the density of the gas cloud, conditions varying from a completely blocked* flow to an unblocked flow could be obtained.)

(b) Flow and dispersion through a permeable barrier such as that provided by a row or several rows of trees. (To examine this, porous fences were used in two combinations to provide two sufficiently different 'view factors' or blockages.)

(c) Flow and dispersion in the vicinity of buildings. (Since the aim of these trials was not to simulate a prototype situation but to obtain a data set on fundamental effects, an isolated building was chosen.)

Having decided on the three obstacles to be used it was then essential to choose the dimensions and location of the obstructions such that they would be consistent with the scale of releases at Thorney Island and at the same time would provide a range of flows of interest.

At Thorney Island, 2000 m^3 of gas was released in about 1.5 seconds. Although this quantity of gas is orders of magnitude smaller than that possible in an accident, nonetheless the release rate lies within the range likely during a full-scale release. For the purposes of determining the dimensions of obstacles during these trials therefore, the Thorney Island trials were regarded as being "full-scale".

Dimensions of the obstacles were provisionally chosen based on a knowledge of full-scale obstructions together with the criteria given by Britter [5] to obtain certain flow effects. To confirm the early choices and finally to determine the size and locations of the obstacles, a brief series of wind tunnel tests were carried out (Davies [6]).

A fuller description of the sequence of events during the planning period

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*In a blocked flow the gas cloud is reflected by the barrier to be carried over subsequently only when sufficiently dilute.

is given by McQuaid and Roebuck [4]. Essentially the wind tunnel experiments confirmed that 50 m was a suitable downwind location for the obstructions. At distances around 100 m the cloud was generally too dilute to exhibit strongly heavy gas effects. For a solid fence of height 5 m, blocking was clearly observed at low wind speeds (around 2 m/s) and little buoyancy effects were seen at speeds above 6 m/s. This was in line with the observation in Phase I that typically the cloud had a depth of about 4 m at this distance downwind. For the permeable screens it was clear that a complicated flow was inevitable. Combinations of cloud transmission, reflection and flow over the barrier existed in a balance dependent on wind speed and cloud density. For the isolated building upwind of the source it appeared that a small separation would be needed to observe strong wake effects on the source over and above the enhanced mixing processes due to increased turbulent stresses.

These considerations led to the selection of the size and location of the various obstacles and to the formulation of the trials programme as shown in Table 1. The programme was intended to cover the basic flow phenomena so far discussed and in addition two trials were planned to examine the effects of initial density. It was hoped that Trials 9 and 10 would provide

TABLE 1

HGDT Phase II programme

Trial	Obstruction	Cloud density relative to air	Wind speed (m/s)	Distance of obstruction from source (m)	Remarks
1	5 m solid fence	2	< 2	50	Blocked flow.
2	5 m solid fence	2	2–6	50	Intermediate case.
3	5 m solid fence	2	6–8	50	Cloud passes over fence.
4	10 m porous screen	2	2–6	50	Complete visual occlusion.
5	10 m porous screen	2	2–6	50	Partial visual occlusion.
6	Building (10 m)	2	<2	50	Little dilution by building.
7	Building (10 m)	2	5–8	50	Small buoyancy effects.
8	Building (10 m)	2	2–6	−20	Strong building wake effects.
9	5 m solid fence	4.2	2–6	50	Effect of density in relation to model scaling.
10	Building (10 m)	4.2	2–6	50	Comparison with cases 1, 2 and 6.

data relevant to the not infrequently used modelling practice based on initial Richardson number (defined in Appendix I). The demands of Froude scaling are model wind speeds equal to full-scale values reduced by the square root of the model scale. Under some circumstances this brings physical modelling up against the constraint of the lowest speed that the facility can reliably sustain, hence the need to relax the density ratio similarity and compensate with increased velocity. Whereas this practice is reasonably well established for buoyant, momentum dominated stack emissions, its range of validity for heavy gas dispersion simulation is less well understood.

The programme outlined in Table 1 was finally checked against meteorological records and the Phase I experiences to determine the risk of achieving a specific trial. In the event, the full programme was basically completed as planned (Appendix I).

3. Trials with an impermeable barrier

The solid fence used during the trials consisted of tarpaulin sheets hung over a frame of scaffold. The fence, shown in Figs.1 and 2, was 5 m in height and was located on a 180° arc, 50 m from the source.

As planned, four trials were conducted with this obstruction; the conditions that prevailed are summarised in Table 2. (Further details of all trials conducted during Phase II are presented in Appendix I). The first three

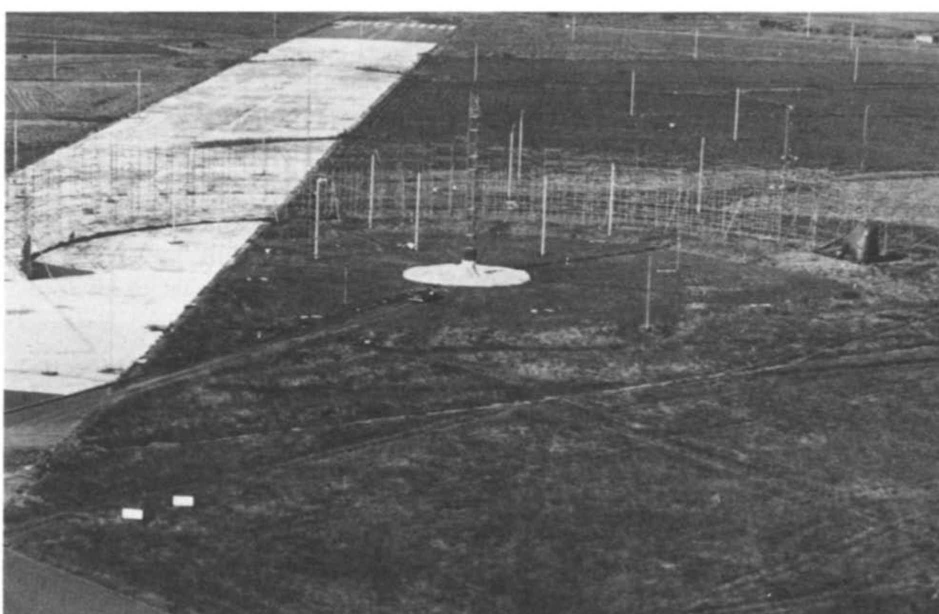


Fig.1. The Thorney Island trials site with scaffold framework at 50 m from the spill position.

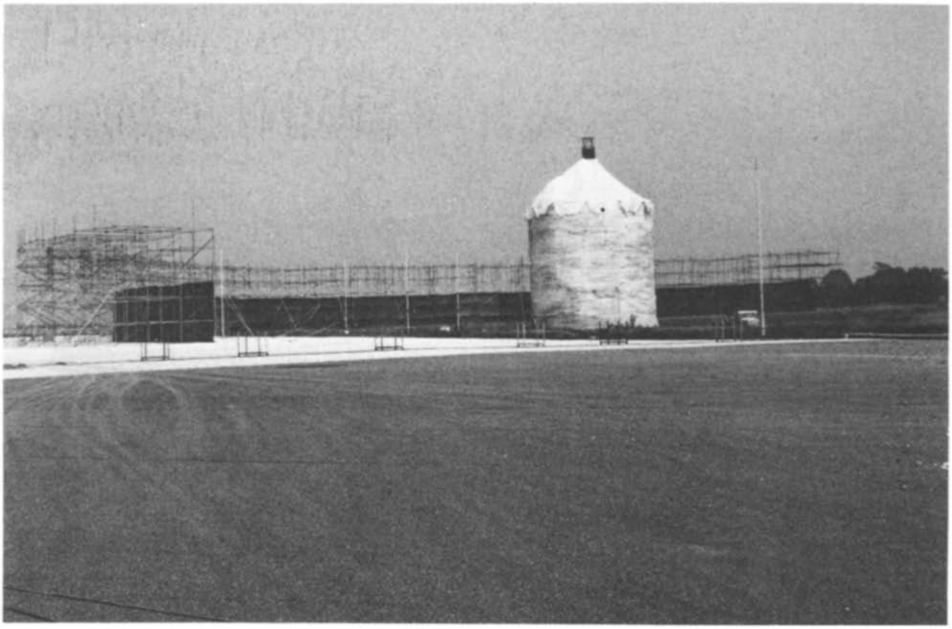


Fig.2. Obstruction 1 : 5 m high impermeable barrier.

TABLE 2

HGDT phase II. Trials with a 5 m solid fence, 50 m from the source

Trial No.	Relative density (ρ/ρ_a)	Wind speed at 10 m (m/s)	Cloud bulk Richardson number (Ri_B)
025	1.95	1.4	61.8
021	2.02	3.9	8.8
020	1.92	5.7	3.5
022	4.17	5.9	8.1

$Ri_B = (\Delta\rho/\rho_a)gH_0/\bar{U}_{10}^2$

where $\Delta\rho = \rho - \rho_a$, ρ = initial cloud density, ρ_a = density of air, g = acceleration due to gravity, H_0 = initial cloud height, $\bar{U}_{10}$ = mean wind speed at 10 m.

trials listed in Table 2 correspond to Trials 1 to 3 of Table 1, and so provide data for conditions of complete (or almost complete) blocking*, partial blocking and virtually no blocking of the gas cloud. Figure 3, taken during Trial 021 shows the case of partial blocking where the fence is responsible

*During Trial 025 (the case of complete blocking) the wind direction changed shortly before gas was released. The result was that whilst the gas cloud was indeed blocked by the fence, there was additionally a component of the wind opposing its motion down range.

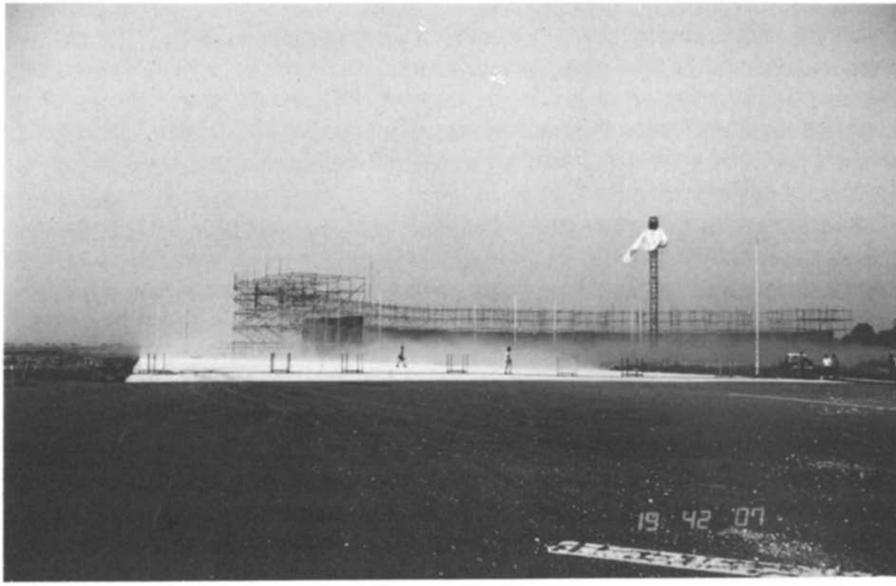


Fig.3. Trial 021: Partial blocking of the cloud by the 5 m barrier.

for delaying the passage of the cloud by reflecting the initial wave but the wind speed is such as to gradually pick up the gas and carry it over the fence. During Trial 020 where the wind speed approached 6 m/s virtually no blocking was observed and gas was readily swept over the fence as shown in Fig.

Fig.4(a). Trial 020: Largely unblocked cloud advection in presence of 5 m barrier.

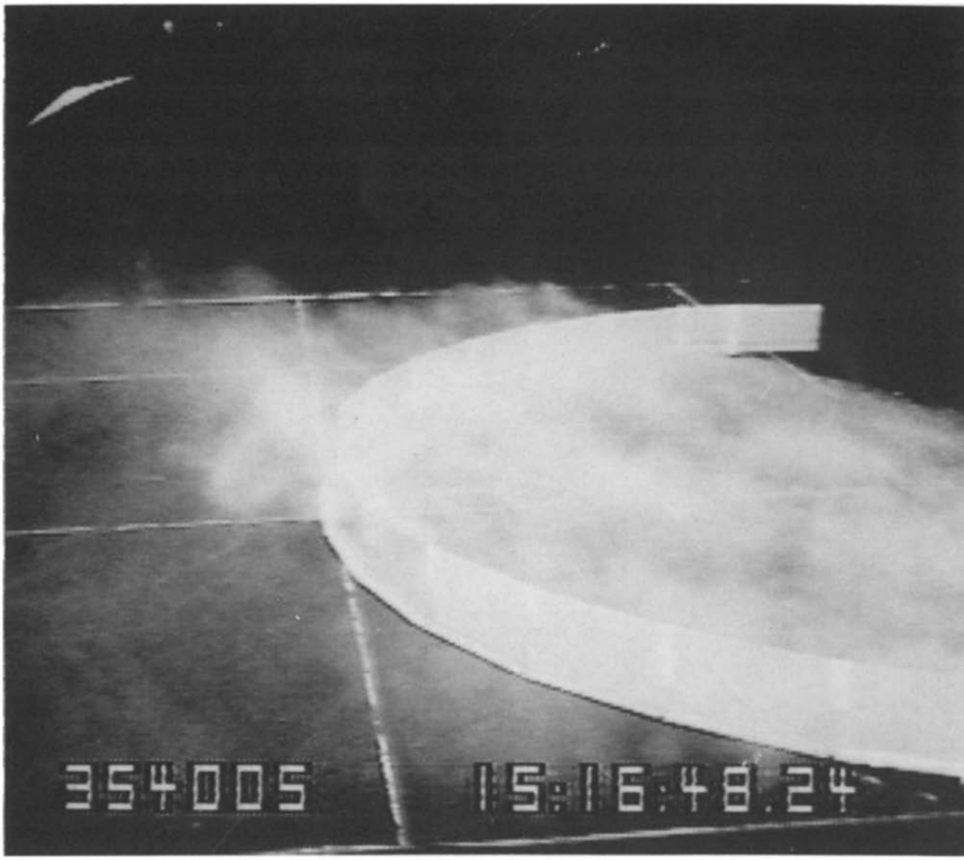


Fig.4(b). Wind tunnel simulation 020: View of unblocked condition modelled in NMI No. 7 tunnel.

4(a) (during the trial) and Fig.4(b) (during a wind tunnel simulation of the trial).

The effectiveness of the fence in diluting the gas cloud can be seen in Fig.5. Here, peak concentrations on the centre line of the gas cloud during Trials 019 (a release in Phase I) and 020 are compared. These spills had similar values of initial cloud Richardson number $(\Delta\rho/\rho_a)gH_0/\bar{U}_{10}^2$; their initial densities differed by about 10%. It appears that though little blocking occurred in Trial 020 the presence of the fence was effective in increasing the amount of dilution. These results (and similar presentations later in this paper) are intended to be indicative of gross effects, since scaling considerations will apply to the parameters plotted. These arise from the differences in initial density and released volume between trials.

The fourth trial conducted with this obstruction, Trial 022, was intended to examine the effect of initial cloud density; a source gas consisting of Freon-12 only was used, giving an initial density (relative to air) of about

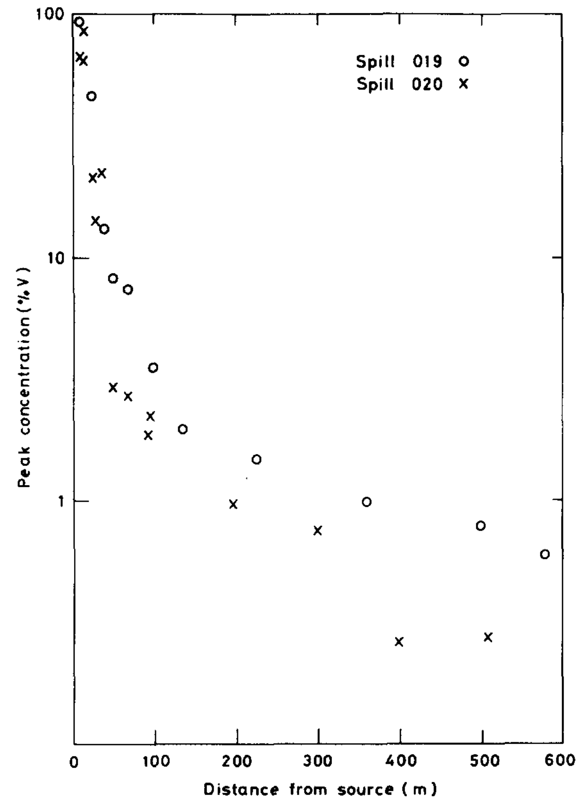


Fig.5. Peak centre-line concentration with (020) and without (019) the 5 m barrier (o: 019, Ri_B = 3.7; x : 020, Ri_B = 3.5).

4.2. During this spill, considerable blocking was observed. This is clearly evident in Fig.6, taken from a wind tunnel simulation of the spill: the gas cloud was reflected by the fence and produced the wave seen in the photograph. Not all aspects observed during this spill were evident during Trial 021 in spite of their similar initial cloud Richardson numbers. Examination of peak values of gas concentration highlights the differences between results during the two spills. Figure 7 for example, shows that the 1% and 0.5% concentration contours during the two spills differ substantially. Ostensibly the fence blocks the denser gas cloud more effectively leading to lower concentrations downwind of the fence.

This result supports the view expressed by Britter [4] who suggested that simulation based on initial cloud Richardson number (modified Froude number), where the density ratio is not modelled correctly, may lead to errors in the vertical scale of the cloud so that phenomena such as blocking may not be correctly simulated. Separately, of course, the mixing processes during the density driven slumping phase are likely to differ with initial density and Fig.8 shows that for dispersion over unobstructed terrain also

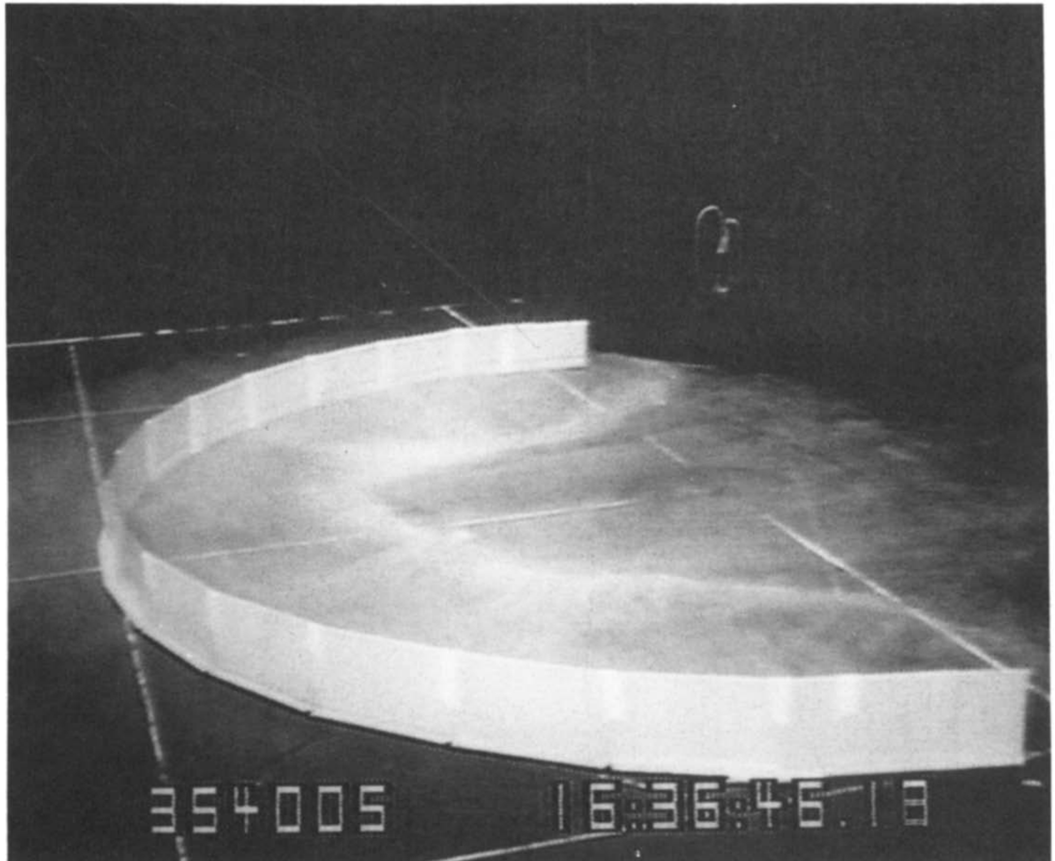
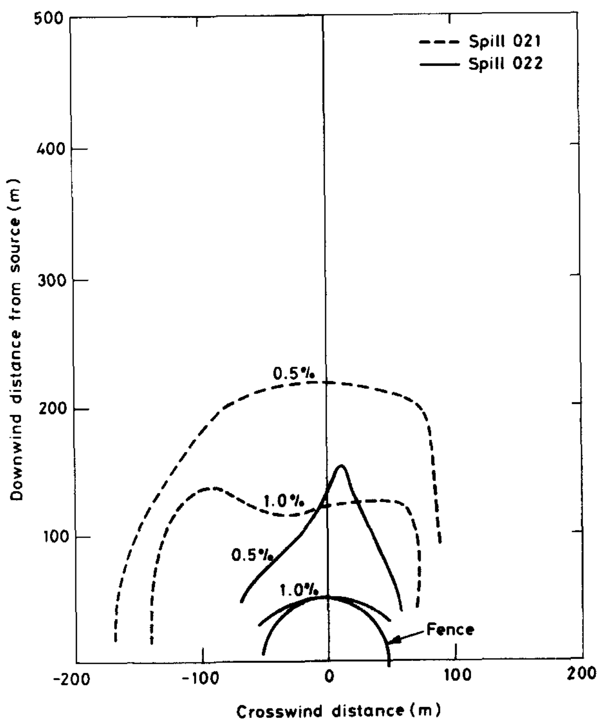


Fig.6. Wind tunnel simulation 022: Blocked flow due to 5 m barrier.



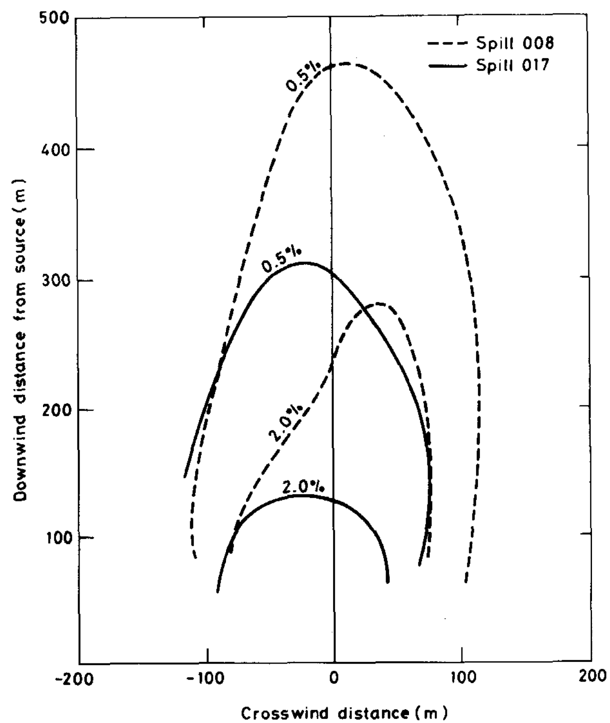


Fig.7. Peak concentration contours for Trials 021 (ρ/ρ_a = 2.0, Ri_B = 8.8) and 022 (ρ/ρ_a = 4.2, Ri_B = 8.1).

Fig.8. Peak concentration contours for Trials 008 (ρ/ρ_a = 1.6, Ri_B = 14.0) and 017 (ρ/ρ_a = 4.2, Ri_B = 13.7).

the denser gas (Trial 017) is diluted more quickly than the less dense gas (Trial 008).

4. Trials with permeable screens

The porous fences consisted of military camouflage nets draped over rows of scaffold, as shown in Figs.9 and 10. The fences were 10 m in height and were positioned on 180° arcs, with the first row located 50 m from the spill point; subsequent rows were positioned at 3.3 m intervals.

Two trials were conducted with this obstruction and represented cases of partial (Trial 023) and total visual occlusion (Trial 024). These features were obtained using 2 rows and 4 rows of nets and the release conditions are described in Table 3.

In addition to the standard environmental measurements made during each trial, measurements of the velocity profile behind the nets were also made during these trials. These measurements were necessary in order that the characteristics of the nets during each trial could be defined. The results of these profile measurements are shown in Fig.11, where data have been compared with the upstream velocity profile for each spill. In both cases the data have been non-dimensionalised by the velocity at 10 m upwind of

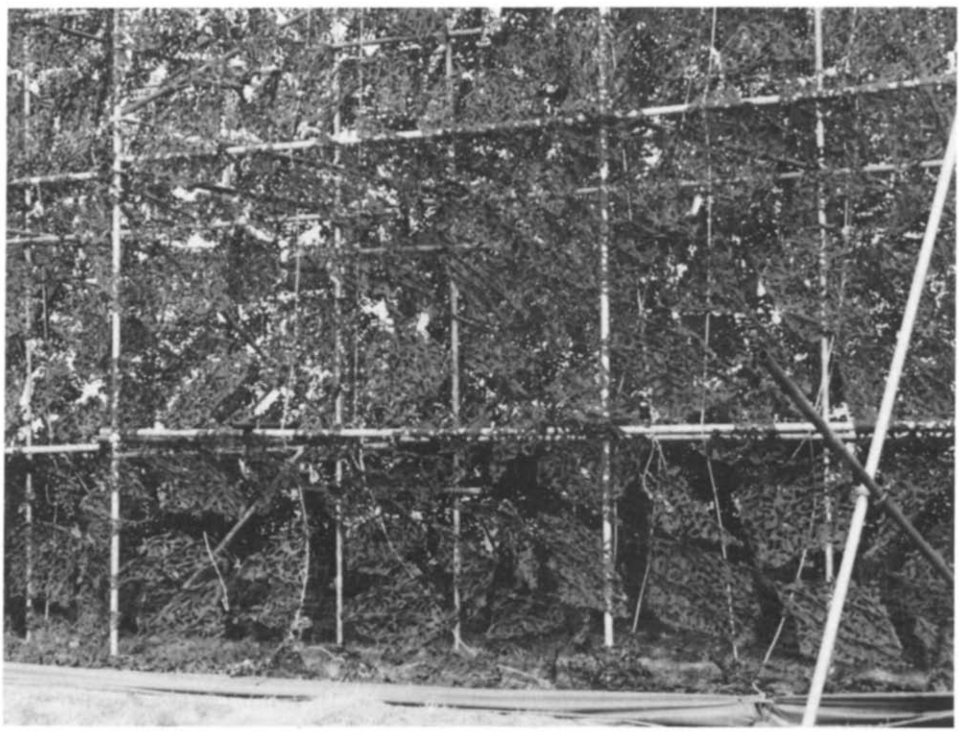


Fig.9. View of netting for the permeable obstruction (Obstruction 2).

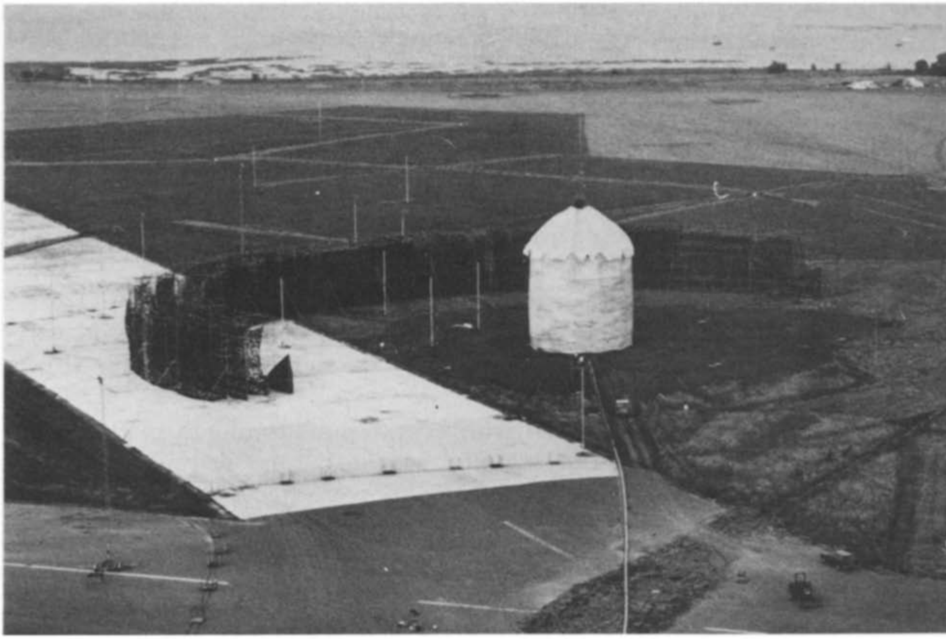


Fig.10. Four screens comprising the 10 m permeable obstruction.

TABLE 3

HGDT Phase II. Trials with 10 m high porous screens at 50 m from the source

Trial No.	Relative density (ρ/ρ_a)	Wind speed at 10 m (m/s)	Cloud bulk Richardson number	Remarks
023	1.80	5.8	3.0	2 rows of screens
024	2.03	6.8	2.7	4 rows of screens

the screens. To further characterise the nets, wind tunnel tests were carried out on a single piece of camouflage net to determine the pressure drop coefficient. The data obtained, shown in Fig.12, suggest that at the speeds at which the trials were conducted, the pressure drop or resistance coefficient was about 3.3 in a uniform wind.

Although a visual impression of the effect of porous screens on the gas cloud may be obtained from Fig.13 (taken during Trial 023 when two rows of nets were used) more detailed information on the effect of the fence can only be obtained from the gas concentration measurements. Based on the pre-trial wind tunnel tests, it was expected that the main effect of porous fences would be in delaying the passage of the gas cloud rather than in affecting the concentration magnitude at ground level. Figure 14 for example,

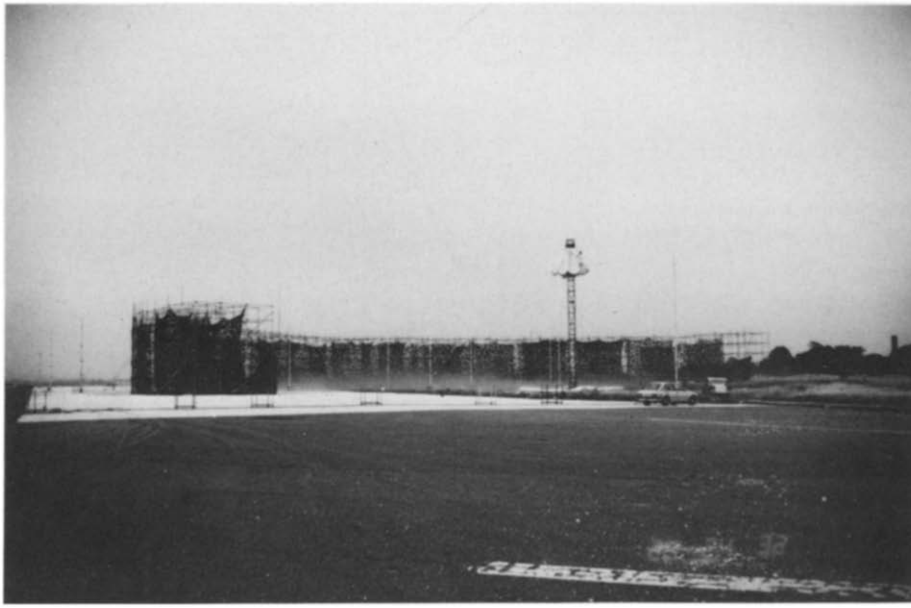
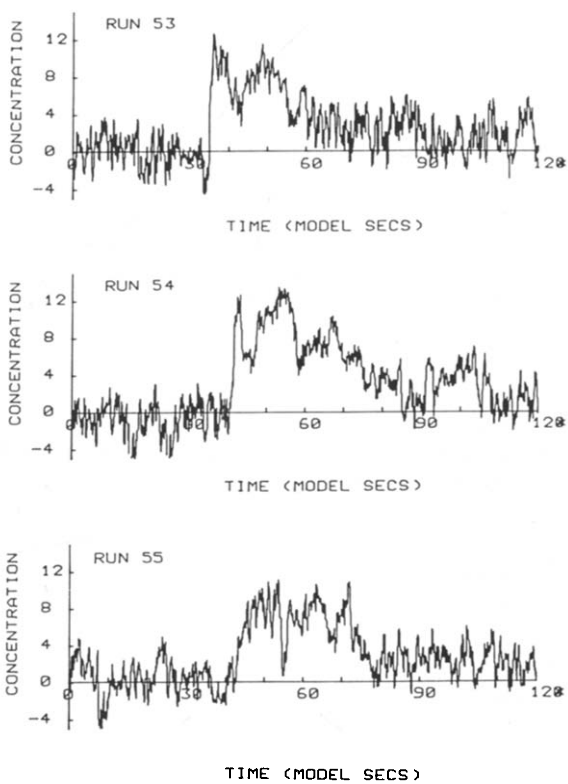


Fig.13. Trial 023: Cloud dispersing past partially visually occluded obstruction.



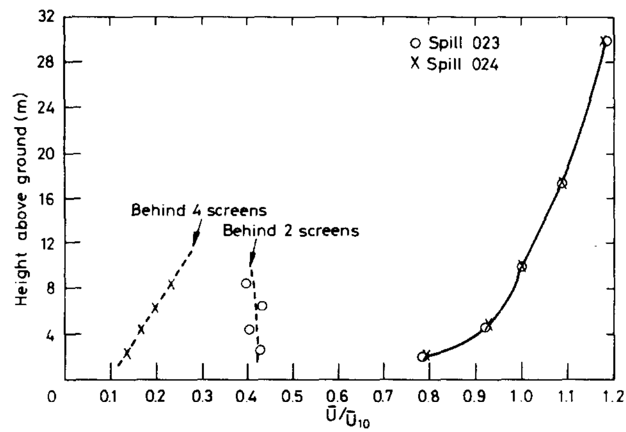


Fig.11. Comparison of velocity profiles up-wind and immediately down-wind of the porous screens.

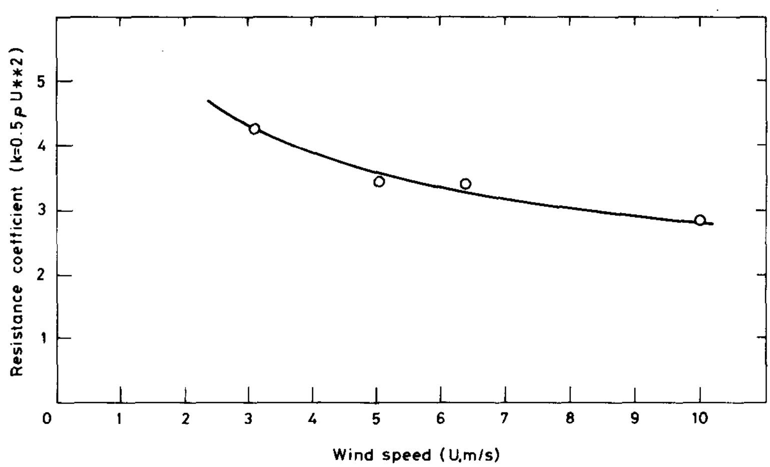


Fig.12. Pressure drop coefficient (k = 0.5 ρU^2) across a single screen.

taken from Davies [6], demonstrates that as the view factor or visual occlusion increased, the time for gas to arrive at a reference position behind the fence was increased. (The number of screens in these wind-tunnel simulations was not the same as in the full-scale trials, but the qualitative conclusion is not affected).

Data from the trials, as shown in Figs.15 and 16 also demonstrate that the porous fences had relatively little effect on peak, ground-level concentrations. The depth of the cloud at the fence position was noticeably increased over that observed in the unobstructed trials, demonstrating the effectiveness of the fences in vertically distributing the gas. The effect of the fences can also be seen in Fig.17. Here, peak concentrations at ground

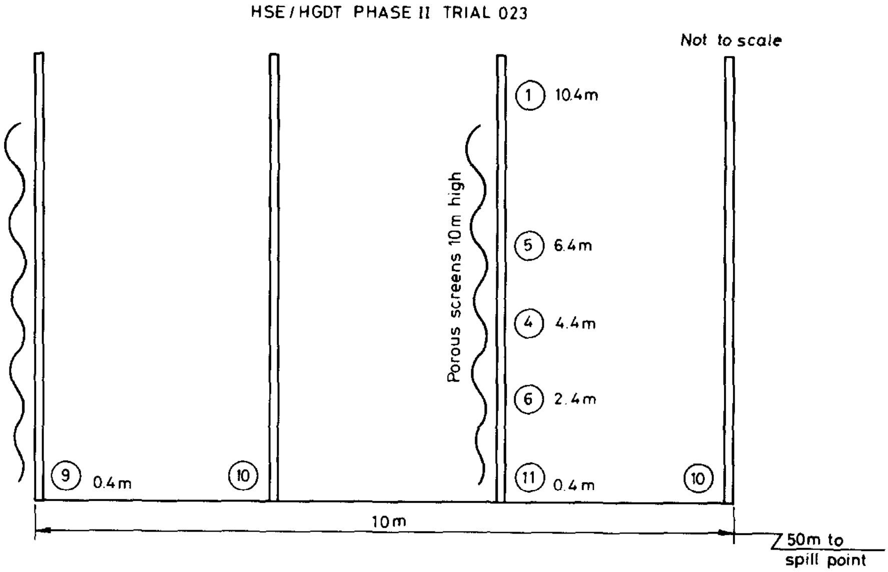


Fig.15. Peak values of gas concentration in the vicinity of two rows of screens.

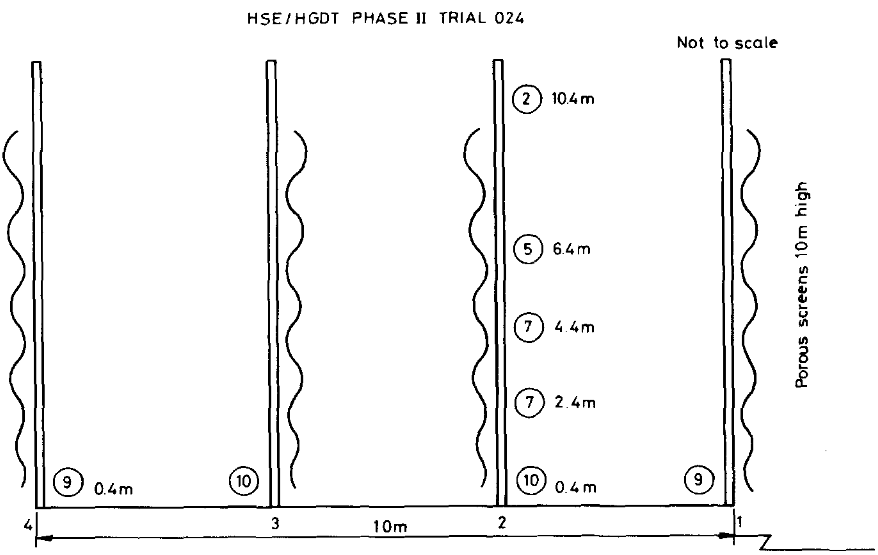


Fig.16. Peak values of gas concentration within 4 rows of porous screens.

Fig.14. Concentration time histories at $X = 75$ m, $Z = 0.2$ m for (A) an open site, (B) a 3 screen fence and (C) a 5 screen fence in a wind of 2 m/s, in wind tunnel simulations (Davies [6]).

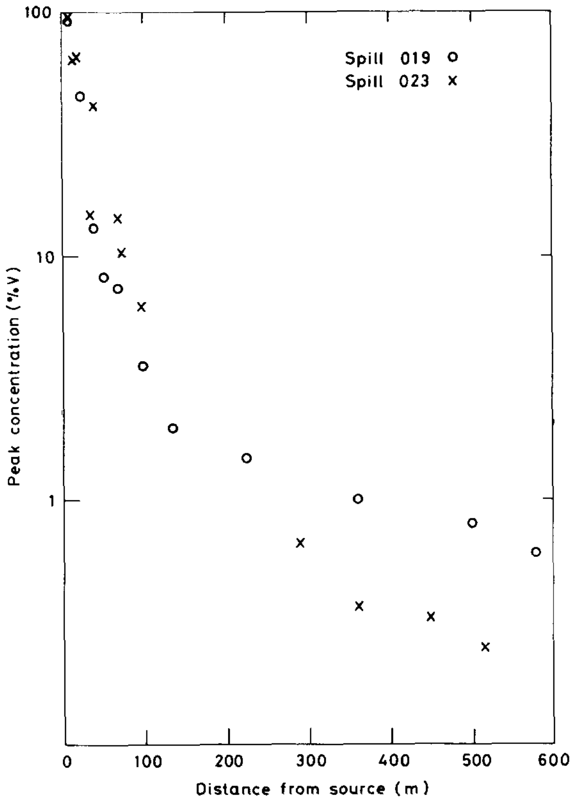


Fig.17. Peak centre-line concentrations with (023) and without (019) the 10 m permeable barrier (o: 019, Ri_B = 3.7; x :023, Ri_B = 3.0).

level during Trial 023 (with two rows of nets) are compared with data from Trial 019 (an unobstructed release during Phase I). In the near field (0 to 50 m) the porous fence had little effect at ground level and may even have caused an increase in peak concentrations just behind the nets. At greater distances, however, the obstruction did have the effect of noticeably reducing the peak concentration.

5. Trials with an isolated building cube

The 9 m cubical building used during this series of trials is shown in Figs. 18 and 19 and consisted of plastic sheets attached to a wooden frame. The complete structure was mounted on a trailer and was moved to the required position shortly before the release of gas. In both photographs of the building transducers are visible, mounted on the building sides and top. This distribution was to ensure that local measurements of gas concentration and wind speed and direction could be made.

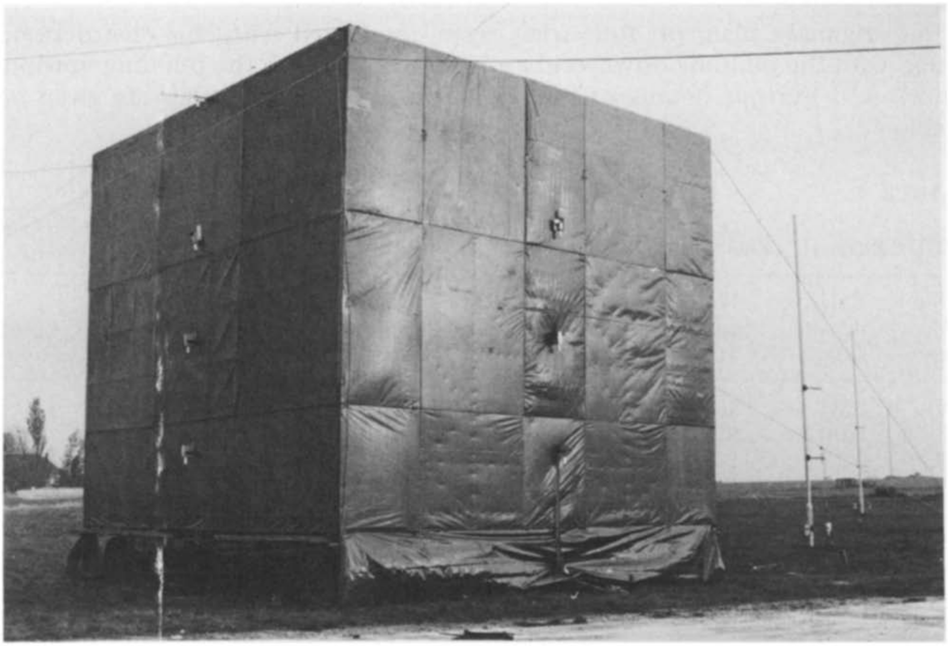


Fig.18. Obstruction 3: The mobile building.

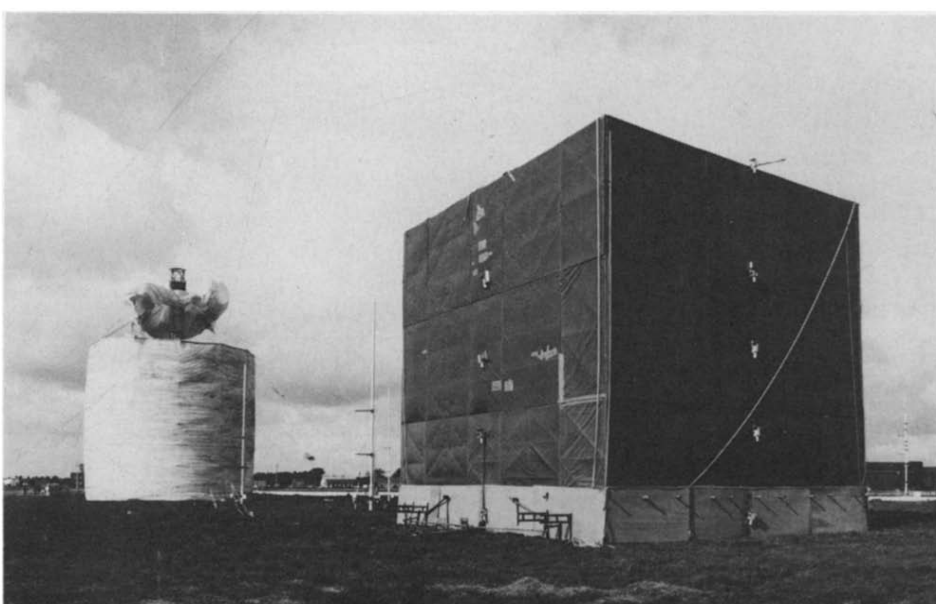


Fig.19. View of 9 m building cube downwind of source container.

As originally planned, four trials were conducted with this obstruction; three with the building downwind at 50 m and one with the building upwind at 27 m*. Further details of the conditions during these trials are given in Table 4.

TABLE 4

HGDT Phase II. Trials with an isolated 9 m cubical building

Trial No.	Relative density (ρ/ρ_a)	Wind speed at 10 m (m/s)	Cloud bulk Richardson number	Position of the building (m)
26	2.00	1.9	34.8	50
28	2.00	9.0	1.5	50
27	4.17	2.2	71.0	50
29	2.00	5.6	4.0	−27

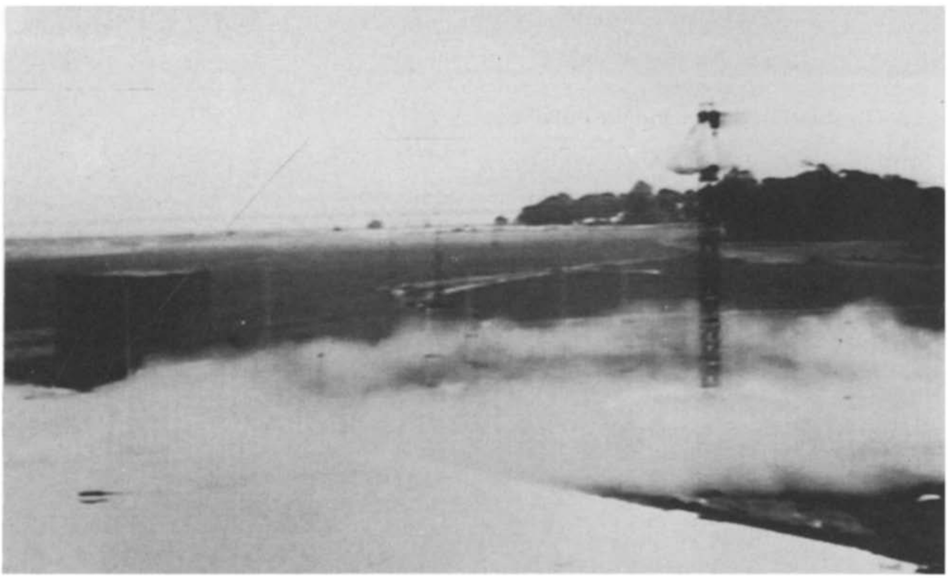


Fig.20. Trial 026: Cloud passing around the obstruction in a low wind.

Of the three trials carried out with the building downwind, two examined the effect of wind speed. In Trial 026, the wind speed was relatively low and the cloud was swept around the sides of the building without much obvious mixing. As Fig.20 shows, the height of the cloud appeared to be almost un-

*A separation of 20 m from the rear face of the cube to the upwind surface of the source container.

Fig.21. Trial 028: Cloud sweeping past the obstruction in a high wind.

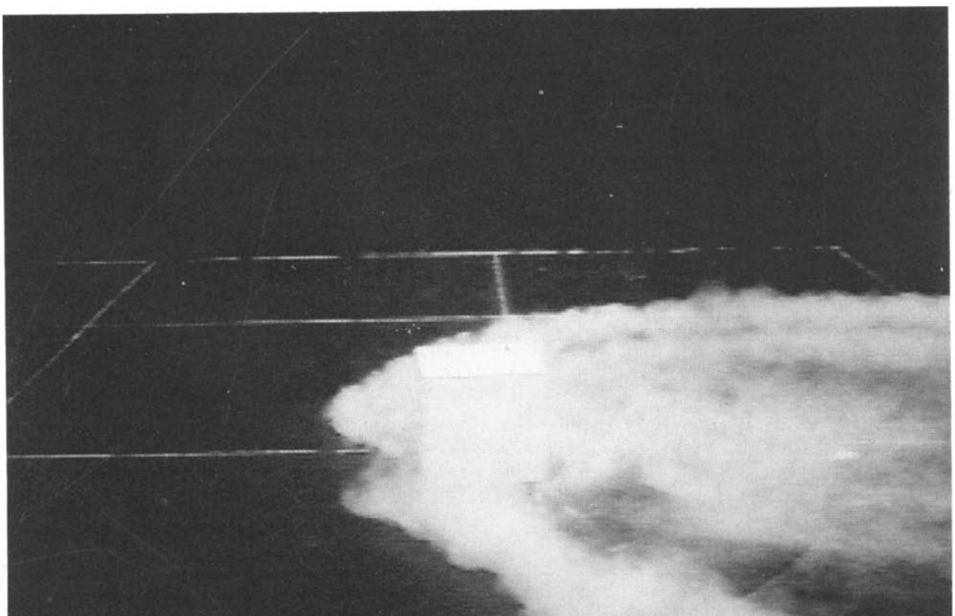


Fig.22. Wind tunnel simulation 026: Comparison with Fig.20.

influenced by the building. At the higher wind speed during Trial 028, however, the cloud was much more influenced by the building with obvious signs of enhanced mixing. During Trial 028 the building was almost completely engulfed by the gas cloud, though this is not immediately apparent from the photograph in Fig.21. Figures 22 and 23 show the contrast more clearly in the wind tunnel simulation.

The third trial conducted with the building downwind, Trial 027, was intended to examine the effect of initial density; for this reason Freon-12 was used as the source gas. Unfortunately, shortly before gas was released, the wind direction changed and during the release the building was not downwind of the source. Nonetheless there was interaction between the building and the gas cloud so that useful data relevant to the effect of this obstruction was obtained.

The fourth trial examined the effect of the building when positioned 27 m upwind of the source. Results obtained showed that the gravity front travelling upwind was entrained by the low pressure region in the wake of the building such that gas entered the wake and was drawn up the rear face of the building. This can be seen in Fig.24, taken from the wind tunnel

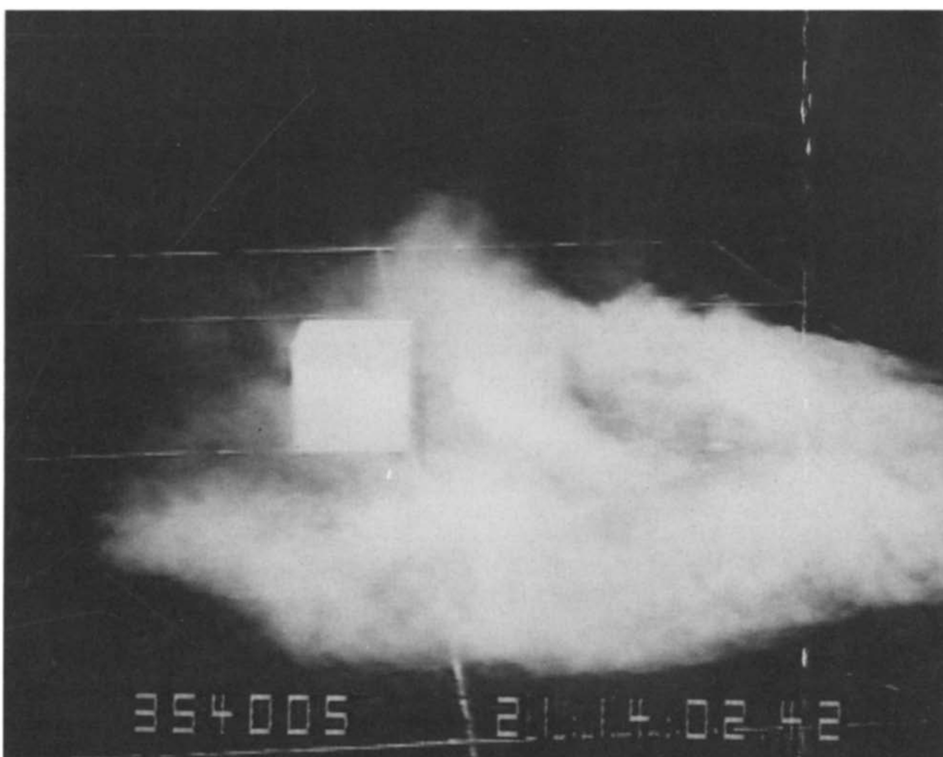


Fig.23. Wind tunnel simulation 028: Comparison with Fig.21.

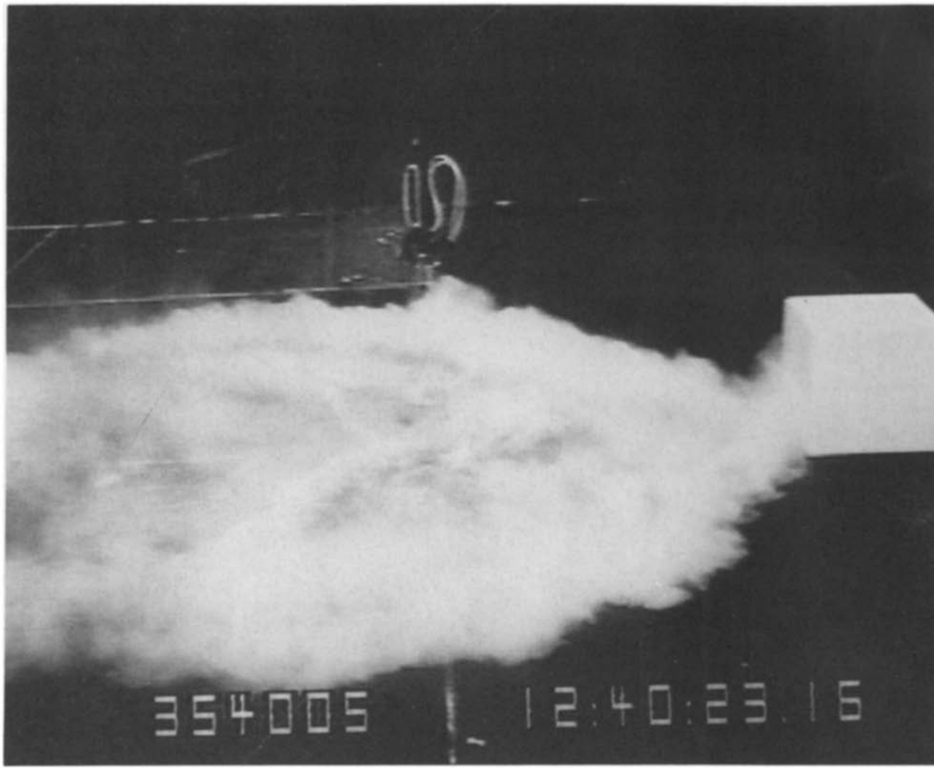


Fig.24. Wind tunnel simulation 029: Entrainment of cloud into wake of upwind building.

simulation of Trial 029. Very little gas was observed to travel around the sides of the building.

A further brief indication on the effect of the upwind building may be obtained from Fig.25. Here, a comparison of the peak ground-level concentration in spills 029 and 019 shows, at first sight, surprisingly little effect of the upwind building.

6. Conclusions

Ten trials were conducted during the second phase of gas dispersion tests at Thorney Island, and comprehensive data on the effect of selected obstructions on the dispersion of heavy gas has been obtained. The trials do not represent a parametric study on the effect of obstructions but provide information on dispersion phenomena likely to occur during accidental releases of heavy gas on complex sites where walls, trees or buildings may be present. The data set is now available for comparison of modelling techniques and for detailed studies of the fluid dynamic interactions in these complex flow.

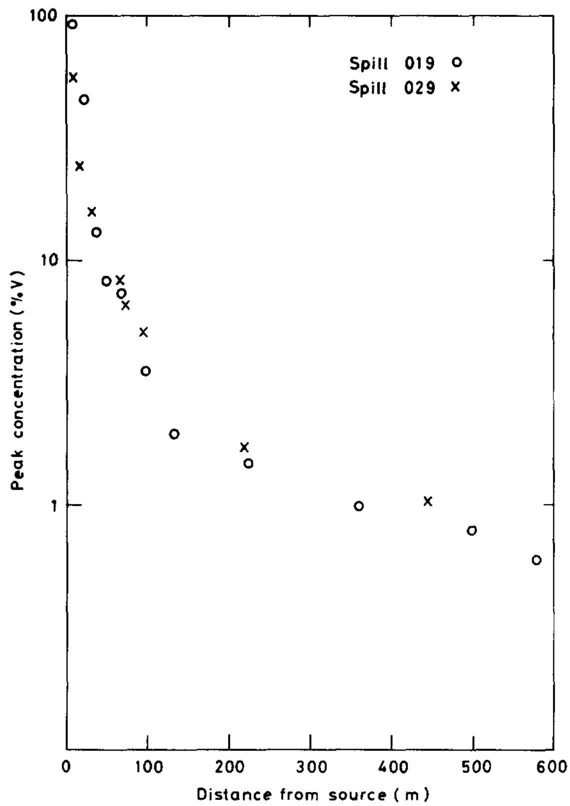


Fig.25. Peak centre-line concentrations with (029) and without (019) the building upwind (○, 019, Ri_B = 3.7; ×, 029, Ri_B = 4.0).

Appendix I

Details of trials conducted during Phase II, HGDT, Thorney Island

Trial No.	Date	Release time	$\bar{U}_{10}$ (m/s)	$\bar{\theta}_{10}$ (degrees)	ρ/ρ_a	Released volume (m^3)	Ri_B	R (W/m^2)	Cloud cover
020	15/07/83	15.10:52	5.7	−6.5	1.92	1,920	3.5	686	0/0 (hazy)
021	15/07/83	19:41:36	3.9	−6.1	2.02	2,050	8.8	96	0/0 (hazy)
022	25/07/83	19:00:15	5.9	−7.6	4.17	1,400	8.1	157	2/8
023	15/08/83	20:24.03	5.8	28.6	1.80	1,960	3.0	3	1/8
024	16/08/83	20:05:17	6.8	28.8	2.03	1,925	2.7	9	4/8
025	31/08/83	20:12.01	1.4	−124.5	1.95	2,000	61.8	0	3/8
026	24/09/83	11:35:43	1.9	5.0	2.00	1,970	34.8	271	7/8
027	24/09/83	17:06:01	2.2	137.3	4.17	1,700	71.0	6	6/8
028	5/10/83	11:15:51	9.0	41.9	2.00	1,850	1.5	230	5/8
029	6/10/83	19:02:40	5.6	27.0	2.00	1,950	4.0	3	6/8

$\bar{U}_{10}$ = wind speed at 10 m
$\bar{\theta}_{10}$ = wind heading at 10 m relative to axis of fixed mast array
ρ/ρ_a = initial density of released gas, relative to air
Ri_B = initial cloud bulk Richardson number = $(\Delta\rho/\rho_a)\, gH_0/\bar{U}_{10}^2$ where $\Delta\rho = \rho - \rho_a$, H_0 = initial cloud height
R = insolation
$\sigma_u/\bar{U}_{10}$ = turbulence intensity in along-wind (u-component) direction
$\sigma_v/\bar{U}_{10}$ = turbulence intensity in cross-wind (v-component) direction
$\sigma_w/\bar{U}_{10}$ = turbulence intensity in vertical (w-component) direction

This paper has briefly introduced the background to the planned programme and has tried to illustrate some early results. The presentation is intended to be indicative rather than comprehensive — a great deal more analysis is required to digest the data fully.

Generally the classes of flow described in Table 1 were observed in the trials and qualitatively similar visualisations have been produced in an NMI wind tunnel. Where the circumstances of the trials were poor for photography, wind tunnel photographs have been included.

In all cases these simulations were performed with a match to the trial gas density. This may be particularly important for instantaneous releases where it has been shown from both Phase I and Phase II trials that initial density is important as a separate parameter influencing dispersion.

References

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$\sigma_u/\bar{U}_{10}$ (%)	$\sigma_v/\bar{U}_{10}$ (%)	$\sigma_w/\bar{U}_{10}$ (%)	Atmospheric stability	Type of obstruction
12.5	10.3	9.3	C/D	5 m high, solid fence at 50 m
15.7	10.1	8.0	D/E	5 m high, solid fence at 50 m
12.0	9.3	6.5	D/E	5 m high, solid fence at 50 m
17.8	10.4	7.9	D/E	2 rows of porous screens, 10 m high
14.6	9.9	7.0	D	4 rows of porous screens, 10 m high
18.1	27.8	10.1	F	5 m high, solid fence at 50 m
—	27.3	13.1	B	9 m building, 50 m downwind
—	12.1	7.6	D/E	9 m building, 50 m downwind
15.8	9.9	6.6	D	9 m building, 50 m downwind
14.3	10.3	6.9	D	9 m building, 27 m upwind