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FIELD EXPERIMENTS ON DENSE GAS DISPERSION

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Summary

This paper comprises a review of field experiments which have been performed to study the dispersion of dense gases in the atmosphere. Tests are compared by deriving and using parameters which indicate the effective scale of the various experiments, and the extent to which density effects influence the dispersion. The instrumentation used is also specified in each case. In addition, a description is given of the recent tests conducted by Shell Research Ltd. at Maplin Sands, which involved spilling up to about 25 m^3 of refrigerated liquid propane and LNG onto the sea. Available information on other experiments now at the planning stage is reported.

1. Introduction

As public concern has grown about the postulated consequences of accidental releases of large amounts of flammable or toxic gases, so have scientific efforts increased to quantify these consequences. A major part of this effort has been the performance of field experiments to study dense gas dispersion. The density aspect is important because most of the gases which are stored in quantity in liquefied form would be denser than air if released accidentally because of either high molecular weight or low temperature.

In this paper we review field experiments which may provide information on the dispersion of dense gases in the atmosphere. Other aspects of the experiments, such as measurements of evaporation or combustion, are not considered here.

Section 2 discusses in some detail the reasons for doing field experiments on this topic, the types of experiment which are done, and the ways in which the results are applied. To enable us to categorise the experiments which have been done, space is devoted to the derivation of criteria to distinguish which spills are effectively instantaneous or steady state. Parameters are also derived to describe, in a dimensionless form, the effective scale of the various experiments. This is not a straightforward exercise, and other parameters might be

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suggested. However, it is desirable to have some means of comparing the size of the experiments and of showing in which cases density effects were not strong enough to affect the dispersion.

The major details for all the experiments are presented side by side in Tables 1a—1c. The information believed necessary to assess the similarities and differences between the experiments is shown here, including details of the type and scale of spill, the source configuration and surrounding topography, and the extent of instrumentation. The tables are accompanied, in Section 3, by descriptions of the experiments.

One series of experiments, with which the authors were involved, is described at greater length in Section 4, since details of these spills have not previously been published. These are the Maplin Sands Trials conducted by Shell Research Ltd. during June to November 1980.

Experiments currently being executed, and future work, are discussed in Section 5.

2. Background

2.1 Why perform field experiments?

Field experiments on dense gas dispersion are performed because there is a great need for data to confirm or contradict theoretical dispersion predictions. A survey by Havens [1] in 1978 showed the wide range of predictions made by a number of models which had at that time been proposed to describe dense gas dispersion. All such predictions can be plausible if there are no experimental results with which they can be compared.

Laboratory experiments can also be useful. These are of two types. First, there are those which try to isolate some process occurring in the dispersion and study it in detail [2—6]. However, particularly in the case of the entrainment of air into the gas cloud, there is no general agreement about the way in which the laboratory results should be scaled to dispersion in the atmosphere.

The other relevant laboratory experiments involve detailed simulation of dense gas spills in a wind tunnel or water flume. Such work is described in detail elsewhere in this volume [7]. These experiments normally do not model a number of effects, particularly the thermal aspects — enhanced mixing due to thermal motions and the transition to buoyancy of methane as it warms and mixes with air. Also, since dense gas clouds can be very wide and flat (a width to height ratio of 100 is easily attained), the Reynolds number based on the height of a cloud in a wind tunnel is often lower than is desirable. Thus although wind tunnel and water flume experiments can be useful and their limits of usefulness may be extended in the future, this will only be when they themselves have been checked against reliable field data.

2.2 Measures of spill size: a criterion for density to be important

For the purposes of comparison, it is convenient to have a measure of the extent to which "dense gas" effects influence any spill. The two most obvious features of a dense gas spill are the gravity spreading of the gas, and the

inhibition of vertical mixing by the density gradient formed. (This does not preclude the existence of other mechanisms by which the density can affect dispersion.) For a continuous release, a suitable measure of the gravity spreading is the ratio of the initial spreading velocity to the ambient mean velocity, U:

$$N_L = \frac{\sqrt{g'H_0}}{U} \quad * \tag{2.1}$$

where the initial cloud height

$$H_0 = \frac{Q}{UD}, \tag{2.2}$$

$g' = g\frac{\rho_g - \rho_a}{\rho_a}$ where g is the acceleration due to gravity, ρ_a and ρ_g are the density of air and the initial density of the gas, Q is the volume flow of gas from the source, and D is the crosswind width of the source. The same expression (2.1) can be used for the instantaneous case, with

$$H_0 = \frac{V}{\pi R_0^2} \tag{2.3}$$

where V is the initial gas volume, and R_0 is the initial radius of the cloud.

A suitable measure of the effect of the density difference on vertical mixing is an initial layer Richardson number, which relates the stabilising effect of the density to the kinetic energy of the ambient turbulence; this requires g', a layer thickness H_0, and a turbulent velocity scale, for which the friction velocity u_* can conveniently be used, giving

$$Ri_0 = \frac{g'H_0}{u_*^2} \tag{2.4}$$

Apart from a difference in the velocity scale used, this is the square of the number N_L. Of the two possibilities, we shall use Ri_0 as a measure of the extent to which density effects may be unimportant, significant, or dominant in any spill. The reason for this choice is that gravity spreading is already fairly well understood, and field experiments are undertaken more to elucidate the details of the mixing process. The notation $Ri_0{}^C$ and $Ri_0{}^I$ can be used to distinguish between values of the parameter derived for continuous and instantaneous spills, derived from (2.2) and (2.3) respectively.

The calculation of Ri_0 unfortunately requires some decision to be made about the initial horizontal area of the gas cloud in each case in order to derive a value for H_0. For unconfined spills of liquefied gases this is not straightforward; we shall use the maximum area obtained from a pool spread calculation [8] for instantaneous spills. For continuous spills we calculate the equilibrium pool diameter.

A choice which would avoid the above problem is the use of the cube root

*This is the square root of the ratio used by Britter [2], L_B/D in his notation.

of the initial gas volume as a length scale, giving

$$\mathcal{R}i_0 = \frac{g' V_0^{1/3}}{u_*^{\,2}} \tag{2.5}$$

Since an initial high cloud quickly slumps lower, this can be said to measure the relative scale of spills without dependence on the configuration at the chosen initial moment. Fay [9] has used $\mathcal{R}i_0$ as a major parameter in a modelling study which deals primarily with the asymptotic dispersion behaviour at long times, independent of what happens in the early stages. However, any quantity of gas can be released without exhibiting density effects if it is spread over a large enough area, and so it is necessary to take account of the value of H_0 when comparing experiments.

For a small enough spill, the gas density will be unimportant; it is therefore useful to derive a criterion by which we may eliminate from consideration experiments which do not show density effects. Britter [2] in water flume experiments with a continuous source found the plume was essentially passive (in lateral spread) for $N_L^{\,2} \ll 0.1$, which corresponded to $Ri_0 \ll 40$. The plume was not observed to extend upwind of the source for $N_L^{\,2} < 0.02$ ($Ri_0 < 8$). As far as vertical mixing is concerned, the laboratory experiments of Kantha, Phillips and Azad [5] and McQuaid [10] show a dependence of entrainment on stratification which seems to approach a constant for a Richardson number less than about 5. Thus, in round numbers, we suggest that for experiments with $Ri_0 < 10$ density effects are not important.

2.3 Approaches to scaling

In the design and interpretation of dense gas field experiments there appear to be two prevalent philosophies. The first regards an experimental spill as an analogue of a postulated spill, relying on scaling arguments, particularly Froude number scaling, to transform the results. We have already discussed the possible choice of N_L or Ri_0 as dimensionless groups describing a spill. N_L is an inverse Froude number based on a velocity scale U, and Ri_0 is the inverse square of a modified Froude number based on a velocity scale u_*. The distinction between these two illustrates a problem: there may be more parameters which are relevant but not represented in a single dimensionless group. The ratio of U and u_*, for instance, is dependent on surface roughness. Heat transfer, and mixing due to thermally induced motion, are other processes which might be important, but which are dependent on other parameters.

The alternative approach is more closely related to mathematical modelling. This regards the experiments as tests of the models developed, which should be based on an understanding of the physical processes involved. It is still necessary that experiments are performed which are large enough for any mechanism which will affect the largest possible spill to be exhibited. Sufficiently extensive measurements of the experiments are required to check that each mechanism is correctly modelled. Such checking is needed in case two errors in the model happen to cancel out, at the scale of the experiment, in their effect on the gross results, even though they would not cancel at a large

scale. This approach is the one we ourselves have taken.

A third possibility is that the tests are at the actual scale of some possible accidental releases. Indeed, although it is important to be able to predict the consequences of the largest plausible release, a greater probability may be attached to releases smaller than this. For some smaller releases, it is not necescary to scale the experimental results at all.

2.4 Instantaneous and continuous

Two types of release have already been mentioned: instantaneous and continuous (or steady-state). There is also an intermediate category, a release over a finite time not short enough for the spill to be effectively instantaneous but not long enough for a steady state to be reached. We derive below criteria for categorising releases in these respects.

For the full understanding of dense gas dispersion, both ideal experiments need to be performed. Steady-state spills allow the study of a number of features of dense gas dispersion without the extra complexities of time dependence. Furthermore, many accidental releases are likely to be slow, effectively steady-state, leaks from pipes or vessels. However, releases over short times introduce time-dependent aspects which are not covered by the steady-state spills, and so rapid release experiments also need to be performed.

An understanding of the two extremes alone does in fact allow an upper limit to be placed on the maximum concentration at a given distance for any spill. An intermediate spill, over a short but significant period of time, will give concentrations lower than the same quantity of material spilled faster or, in particular, instantaneously*; it will also give concentrations no greater than those of material spilled at the same rate for a longer period of time, i.e. steady state. Thus the concentrations from both extreme calculations are conservative estimates of the dispersion from an intermediate spill. Nevertheless, better estimates should be available by modelling the time dependence explicitly. A number of models attempt this [11,12].

There still remains the question of how to decide when a spill in a field experiment is effectively instantaneous or steady-state. A release at a steady rate over a limited period of time will give the same concentrations as an infinitely long release (at least in an ensemble average sense) provided the extra spreading at the front and rear of the cloud formed does not affect the centre. That much is necessary, and provides our basic criterion for a steady-state spill. It is convenient if the spill lasts long enough for the whole plume from source to the lowest concentration of interest to be present simultaneously. This would give a second, simpler, criterion — that the spill lasts at least as long as it takes for the gas first emitted at a constant rate to dilute to the lowest concentration of interest; but that is more restrictive than strictly necessary. On the other hand, it may be desirable to perform longer spills if only to achieve a suitable averaging time for the stochastic behaviour of the plume. We certainly designate as steady-state any spills which satisfy the second criterion

*This may not be true in very low winds, where the bulk of the mixing may be due to turbulence generated by the slumping motion of the cloud.

above, taking a final concentration of 2%*. For those which just fail by that criterion, consideration is given as to whether they are nevertheless effectively steady-state in terms of the spreading at the front and rear not dominating the whole cloud. In fact few of the experiments considered are close to the borderline.

Another criterion is needed to decide when a vapour release is effectively instantaneous. The effect of increasing the release period is to elongate an initially circular cloud in the direction of the wind. This elongation is approximately $U_B T_R$, where T_R is the time taken for the release and U_B is the bulk velocity of the cloud, which may be lower than the ten-metre wind velocity U. To avoid excessive elongation of the cloud, $U_B T_R$ should be less than $2R$ where R is the cloud radius at some significant time. Since it is easier to use basic, known parameters, it is better to express the criterion in terms of U rather than the unknown U_B. The proposed criterion is, then, that UT_R should be less than the radius of the cloud when the gravity spread velocity has dropped to one tenth of the velocity, U, i.e.

$$UT_R < (U/10)^{-1}\sqrt{g' V/\pi}$$

$$\frac{T_R U^2}{\sqrt{g' V/\pi}} < 10 \qquad (2.6)$$

The factor of ten is rather arbitrary, but has been chosen to separate two of the spills performed at Maplin (see Section 4); one spill, for which the left hand side of eqn. (2.6) was 5, gave a nearly circular cloud, while another, at a value of 25, had a very elongated cloud.

2.5 Type of release

The way in which material is released into the atmosphere is significant, as well as the time over which it is released. The majority of experiments which we review in this paper concerned release of liquefied gases. Such spills fall into two major categories. The liquid spills performed on land were all into bunds of some type, i.e. the area over which the liquid could spread was limited by walls. The instantaneous land spills are characterised by an initial high rate of evaporation followed usually by a long period of decreasing evaporation rate as the surface cools. They are representative of dispersion following a loss from a bunded storage tank but do not provide the instantaneous source of gas convenient for modellers.

Sudden releases of liquefied gas onto water (all were unconfined) produce a source with a rapidly increasing vapour production rate due to the spreading of the liquid pool [8]. The radius of the pool reaches its maximum (probably determined by viscous and surface tension effects) not before most of the liquid has evaporated. After that the evaporation rate very rapidly decreases. In low winds such a spill may qualify as an instantaneous release of

*At concentrations of a few percent, density effects appear to become unimportant; also this is the level below which most flammable gases cease to be flammable.

gas, as defined in Section 2.4.

The source characteristics of such a spill, instantaneous or continuous, are also important. A high jet of LNG for example may evaporate before it hits the water surface, obtaining its latent heat of vaporisation from air entrained into the jet. Compared with LNG which has obtained its latent heat from the water, and then entrained the same amount of air, the first plume would be considerably colder. This would affect the density and thus the subsequent dispersion. Violent motion at the source can also effect entrainment of air.

The third category of experiment is the release of material already in a gaseous form as a cloud initially of considerable height. These experiments have all been performed on land. They have the advantage of providing the most idealised initial conditions for the development of models. They may, however, have less relevance to evaporating liquid accidents than might be desired; the initial height of the cloud may introduce features into the dispersion which are not present otherwise. In particular there is a tendency for most of the mass to be concentrated in a "doughnut" formed by the slumping head. Nevertheless, the possibility of accidents which produce this initial condition, such as failures of pressurised storage vessels, means that these experiments have a direct relevance as well as theoretical interest.

2.6 Material spilled

In a majority of the experiments reviewed here the material spilled was liquefied natural gas (LNG, usually more than 95% methane). The reason for this is that the experiments were performed to improve knowledge of LNG hazards in particular. However, LNG does not provide the simplest, basic dense gas cloud from which to develop a theoretical understanding. Compared with an isothermal, high molecular weight gas such as freon, LNG has the additional possibility of convective motions with associated mixing, and it can become buoyant as a result of heat transfer from the surface or the effects of ambient humidity. A change in source conditions which causes more evaporation of the LNG in the air will result in a lower heat content of the cloud as described in the last section; this can make the difference between eventual positive and negative buoyancy.

In surveying the range of materials spilled in relation to the thermal effects involved, we see that the simplest case is afforded by an ambient temperature dense gas, such as freon. Liquid propane, although not reaching the ideal of no thermal effects, also very nearly represents this same isothermal case since the thermal effects are only one third of those for LNG and it retains strongly negative buoyancy even if warmed to ambient temperatures. LNG experiments quantify the other thermal and buoyancy effects mentioned. Liquid nitrogen experiments, of which there are very few examples, represent an intermediate case where the strong thermal effects are present, but the complication of the plume becoming buoyant is not.

In addition to experiments with LNG, propane and freon, other materials have been spilled to assess their particular properties. Ammonia, although not

denser than air even at its boiling point, can form a dense cloud if the release produces an aerosol which then evaporates in the air [13]. Experiments with chlorine have been concerned primarily with its evaporation rate or with trials of hazard reduction methods [14].

2.7 The Tables

A complete list of the field experiments on dense gas dispersion of which we are aware is contained in Tables 1a, 1b and 1c. The division into three groups is made for the reasons given in Section 2.5. The other obvious division, between instantaneous and continuous, is not made because there is in reality a continuum of release rates between effectively instantaneous and effectively steady-state. For each experiment, it is indicated in the Table whether the spills meet the criteria of Section 2.4 as instantaneous or steady-state, or are intermediate between these. For liquefied gas spills, the liquid may be spilled very fast but evaporate too slowly for the evolved gas cloud to be effectively instantaneous. If the liquid spill time is less than the evaporation time* for that quantity spilled instantaneously, the spill is designated "instantaneous liquid". If the evaporation time is short enough to satisfy the criterion (Section 2.4) for an instantaneous gas cloud, the spill is also described as "instantaneous gas".

For instantaneous and steady-state spills the dimensionless parameters $Ri_0{}^{I}$ and $Ri_0{}^{C}$ are calculated, to give an impression of the effective scale of the releases. It should be noted that dense gas effects are not important when $Ri_0{}^{I}$ and $Ri_0{}^{C}$ are less than 10, and the importance of the density induced flow relative to ambient atmospheric conditions increases with increase in these numbers.

TABLE 1a

Land spills of liquefied gases into bunds

	Year	Ref.	Material	No. of tests	Quantity (m^3 liquid)[b]	Rate (m^3 min liquid)[b]	Duration (min)
Air products	1966—7	[16]	Oxygen	11	—	0.04—0.15	30—250
AGA/TRW	1968	[17]	LNG	18	0.2	—	0.2
Gaz de France	1972	[18]	LNG	>40[a]	up to 3	—	—
Gaz de France	1972	[18]	LNG	1	—	0.16	4.5
Battelle/AGA	1974	[19]	LNG	42 (14 ignited)	0.4-51	—	0.3—0.5

See Table 1c for footnotes.

*Defined as the interval between the times when 10% and 90% of the liquid has evaporated, according to a pool spread (if on water) and evaporation calculation.

It is of course possible to achieve very large values of these parameters by performing experiments in very low winds. However, such low winds tend to be highly variable in direction and strength and the result may not be a good analogue of larger releases in stronger, steadier winds. For this reason we have excluded experiments in winds below an arbitrary limit of 2 m/s in the calculation of Ri_0^{I} and Ri_0^{C}, although a footnote in the table shows where this restriction has excluded higher values of the parameters. Subject to this proviso, the greatest value of Ri_0^{I} or Ri_0^{C} achieved by each set of experiments is noted.

The surface onto which liquids were spilled is also stated in each case, owing to its importance for evaporation.The surrounding topography, structures or natural features, is described to the extent that it may influence gas dispersion.

Finally an attempt is made to indicate the extent of measurements made for each experiment. This is done by a simple count of instruments of the four main types:

(a) Gas concentration sensors of any type except dosage samplers.

(b) Cloud temperature sensors.

(c) The number of scalar meteorological parameters measured, including ambient surface or water temperature etc.

(d) The number of cameras used, whether still, ciné, video, or infrared. Other instruments, such as those for liquid level or pool spread or combustion measurements, are not covered.

It should be appreciated that this information can be misleading. The numbers given are the maximum available, and all may not have been used for every spill of a series. There can be great variations in the proportion of instruments covered by an individual spill and there can be differences be-

Type	Ri_0^{I} max	Ri_0^{C} max	Surface	Surrounding topography	Source	Sensors			
						Conc.	Temp.	Met.	Photo.
Steady state	—	300[e]	Soil	1 m^2 bund	Evaporation maintained by water spray	6	5	4	—
	—	—	Wet & dry clay; steel	2 m^2 bund				3	1
Instantaneous liquid	—	—	Soil	Bunds 9 m^2—200 m^2	Tipping bucket				
Steady state	—	0.15	Soil	200 m^2 bund					
Instantaneous liquid	—	—	Wet & dry soil; polyurethane foam	Bunds 3 m^2—450 m^2 some with high walls		36	26	9	

TABLE 1b

Unconfined spills of liquefied gases on water

	Year	Ref.	Material	No. of tests	Quantity (m^3 liquid)[b]	Rate (m^3 min^{-1} liquid)[b]	Duration (min)
Bureau of Mines	1970	20	LNG	51[a]	0.04—0.5	—	—
Bureau of Mines	1970	20	LNG	4	—	0.2—0.3	—
Bureau of Mines	1972	21	LNG	13 (6 useful)	—	0.2—1.3	Up to 10
Esso/API	1971	22	LNG	17	0.09—10.2	—	0.1—0.6
Shell 'Gadila'	1973	23	LNG	6	27—198	2.7—19.8	10
Shell Maplin	1980	Section 4 this paper	Propane	11 (3 ignited)	—	2—5	4—8
Shell Maplin	1980	Section 4 this paper	LNG	13 (4 ignited)	—	1—5	1.5—10
Shell Maplin	1980	Section 4 this paper	Propane	3 (1 ignited)	15—25	—	—
Shell Maplin	1980	Section 4 this paper	LNG	7 (3 ignited)	5—20	—	—
China Lake 'Avocet'	1978	32	LNG	4	≃4.5	4	
China Lake 'Burro'	1980	24	LNG	8	40	12—18	2.2—3.5
China Lake 'Coyote'	1981		LNG	(5 ignited, 10 RPT tests)	3—28	6—19	0.2—2.3
China Lake	1981		Ammonia		—	—	—
Frenchman Flat	Planned 1984		LNG		Up to 350	—	—

See Table 1c for footnotes

Type	Ri_0^I max	Ri_0^C max	Surface	Surrounding topography	Source	Sensors			
						Conc.	Temp.	Met.	Photo
Instantaneous liquid, perhaps inst. gas	—	—	Water	60 m pond	Tipping bucket	0	0	1	5
Steady state	—	10[e]	Water	60 m pond		12	0	1	5
Steady state	—	200	Water	70 m wide lake with 20 m high walls		30	0	√	√
Instantaneous liquid, three inst. gas	1200[e]	—	Sea	Barge present	Jet 7 m from surface pointing 30° upwards	18	2	9	2
	—	900	Sea	Ship	Jet 18 m from surface. Moving ship in 4 trials	0	0	2	3
Steady state	—	600	Water	Sea, or 300 m pond surrounded by flat sands; shore 350 m upwind	At surface or up to 3 m above surface	200	70	45	7
Steady state	—	40							
Instantaneous liquid, instantaneous gas	1700[e]	—			Sinking open barge				
Instantaneous liquid	—	—							
—	—	—	Water	Irregular; level for 25 m downwind of source, then 7 m rise in 80 m	1 m jet down onto submerged splash plate	11	24	17	√
Most steady state, one borderline inst. gas	(3000)	25				90	100	76	4
—	—	—				—	—	—	—
—	—	—				—	—	—	—
—	—	—				—	—	—	—

TABLE 1c

Instantaneous releases of gas on land

	Year	Ref.	Material	No. of tests	Quantity	Rate	Duration	Type
DGA, Netherlands	1973	25 26	Freon 12	2	1000 kg (2400 m^3 at density 1.25[c]	—	—	Instantaneous gas
HSE Porton	1977	27	Freon density 1.03—4.2[c]	35	40 m^3 gas	—	—	Instantaneous gas
HSE Thorney Island	Planned 1982	28	Freon, density 2[c]	—	2000 m^3 gas	—	—	Instantaneous gas

[a]Total includes laboratory evaporation tests.
[b]In terms of liquid volume; for initial gas volume these values should be multiplied by approximately 250 (LNG, propane, or oxygen).
[c]Density relative to air.
[d]Dosage measurements also made.
[e]Ignoring spills performed in wind speed less than 2 m/s, which would have given higher Ri_0.

tween the accuracy, range and time response of various instruments. Nevertheless, it is useful to present the figures as an indication of the instrumentation used in each case.

The experiments listed in these tables are described in more detail in Sections 3, 4 and 5.

3. Past experiments

3.1 Field experiments before 1970

Few dense gas dispersion experiments were performed prior to 1970. ICI and BP sponsored some chlorine dispersion experiments at the Chemical Defence Establishment in 1967.

Air Products [16] spilled liquid oxygen into bunds at sites in California in 1966 and 1967 and maintained a steady evaporation rate by using a water spray. These steady-state tests often lasted for several hours and allowed one portable oxygen analyser to be used at many locations in addition to continuous measurements at five fixed sampling points.

Early LNG work was performed in 1968 by TRW Systems Group for the American Gas Association [17]. About 0.2 m^3 of LNG was used in each of 18 experimental spills into a 2 m^2 bund with three types of surface. Evaporation rates and methane concentrations were measured. The concentration sensors were mounted on a trolley so that they could be moved closer to the bund as the evaporation rate decreased during an experiment. Unfortunately the validity of data from the concentration sensors above the flammability

Ri_0^I max	Ri_0^C max	Surface	Surrounding topography	Source	Sensors			
					Conc.	Temp.	Met.	Photo
2000	—	—	Sand	Liquid flashed in 5 sec with much entrainment	1[d]	0	9?	?
4000[e]	—	—	Flat grassland; z_0 from 2 to 200 mm; some on sloping land	Cube, tent with falling sides	10[d]	0	42	3
—	—	—		Cube, tent with falling sides	—	—	—	—

limit is uncertain. A correlation was obtained in which the plume width and height were independent of distance, but concentration decreased inversely with distance from the dike.

3.2 Bureau of Mines

Experiments with LNG were carried out by the U.S. Bureau of Mines [20] in 1970 and 1972. The 1970 instantaneous spills were performed to measure liquid pool spread and evaporation and did not include concentration measurements. Experiments were filmed in which up to half a cubic metre of LNG was tipped onto an artificial pond from a bucket. Four steady-state experiments were also run in that year, with gas concentration measured fifteen metres downwind. The spill rates were about 0.05 m^3/min and the wind speeds in three cases about 2 m/s and once well below 1 m/s. Use of Gaussian dispersion equations to correlate the data gave a ratio σ_y/σ_z of five, which was interpreted as showing density effects to be present.

In 1972, further steady-state experiments [21] were performed on a strip mine lake in Pennsylvania which was 100 m wide but enclosed by steep walls 20 m high and 150 m apart at the top. Sensors able to measure up to 9% methane were placed at three downwind distances, arranged in horizontal and vertical lines of six. The flow rates in the six good experiments ranged up to about one cubic metre per minute. Again high values of σ_y/σ_z were found.

Also reported in 1970 and 1972 was the ratio of the peak concentration observed to the mean concentration over the whole experiment for each sensor. Values up to twenty were found. (We discuss this aspect of experimental data, in relation to model predictions, in Section 4.5.)

3.3 Esso/API spills

In 1971, a series of spill tests was carried out on Matagorda Bay, Texas by Esso Research and Engineering under the auspices of the American Petroleum Institute [22]. The spill location was at sea 2 or 3 km from a low-lying peninsula, which would have had negligible effect in the wind, and 10 km from the mainland.

LNG was discharged from a barge which carried a cryogenic tank of about fifteen cubic metres capacity. The release was through an elevated nozzle pointing upwards at an angle of about thirty degrees. In the ten small spills of about 0.9 m^3 the discharge was completed in about 6 s. The seven larger spills, of between 2.5 and 10.2 m^3, took up to 35 s. Instrumentation for measurement and control of the spill was located on this barge.

Two rows of catalytic gas sensors and some thermistors were deployed downwind of the spill barge on small floats cabled to an instrument barge. Mounted on the instrument barge was a 16 m meteorological mast. The atmosphere was generally stably stratified during the experiments.

Using a criterion that the spill time should be much shorter than an evaporation time, the Esso group concluded that only their smaller spills were "instantaneous" with respect to the liquid evaporation. Using our weaker criterion (Section 2.7) all qualify as "instantaneous liquid" spills. Additionally on three occasions the wind was low enough for "instantaneous gas" spills. However, for two of these the cloud did not pass over the lines of sensors.

The results were analysed in terms of Gaussian plume profiles. It was clear that the width to height ratios of the plumes (σ_y/σ_z) were greater than those appropriate to neutrally buoyant releases from point sources over land in any atmospheric conditions.

3.4 Gaz de France tests at Nantes

An extensive series of tests was carried out at Nantes in 1972 by Gaz de France in order to investigate the consequences of spilling LNG into a bund [18]. More than 40 experiments were performed to study evaporation, dispersion and combustion of the gases. Most of these tests consisted of the tipping of up to 3 m^3 of LNG from an open vessel into a bund with area between 9 and 200 m^2. The effect of bund wall height on dispersion was investigated. A steady plume was studied in one continuous spill at a rate of 10 m^3/h.

It was noted that, since evaporation from a soil surface rapidly decreases as the soil cools, the maximum hazard occurs soon after the LNG is spilled, when there is the greatest evolution of vapour. Provided enough liquid is spilled, the rate at which vapour is produced is proportional to the surface area of the bund; so the hazard distance is principally dependent on this area. The exact extent of instrumentation used is not clear from the published details but a "large number" of gas sensors was used, together with several thermocouples.

A consequence of the rapid decrease in evaporation was that the initial visible cloud was observed to separate from the plume which remained after the

initial burst of vapour. It was found from the concentration measurements that the flammable region was always contained within the visible cloud, in line with calculations for relative humidities from about 50% upwards which were encountered. One unexpected observation was that in a number of experiments the cloud showed a tendency to lift off from the ground in its later stages.

The results were compared with a model based on a Gaussian puff formula of Sutton, modified to take account of the fact that the gas was not evolved instantaneously. Various hypotheses were suggested which might account for the occasional buoyant behaviour of the cloud.

3.5 Shell spills from S.S. 'Gadila'

In 1973 Shell scientists conducted the largest experimental spills of LNG yet performed, although the primary purpose of the tests was not the study of the detailed dispersion characteristics of the clouds formed [23]. As part of the commissioning trials of the LNG carrier 'Gadila', several trials were made to test the effectiveness and safety of the recommended procedures for emergency cargo jettisonning. Each of the six tests lasted ten minutes and involved the release of up to 200 m^3 of LNG from a nozzle at the stern of the ship 18 m above the water. For two of the tests the ship was stationary; in the others it was moving at up to 10.5 knots. The wind speed (at 30 m) varied from 1.9 to 5.1 m s^{-1}, with a stable atmosphere. The relative humidity was high, between 80% and 85%. The two stationary tests were filmed by a ciné-camera at sea level, and helicopter-mounted ciné and infra-red cameras.

Because the LNG was released in a horizontal jet high above the sea, it is believed that all evaporated before reaching the water surface. Consequently the initial conditions assumed for the calculation of Ri_0 in Table 1 are derived from the observed dimensions of the jet as it reaches the surface, and the calculated density of the appropriate methane/air mixture.

At the high relative humidity prevailing, the cloud would have been visible for some distance beyond the flammable region. The visible cloud was observed to be 1370 m long for test 4 (7.6 m^3/min of LNG in a 5.1 m/s wind) although beyond 1000 m the vapour was very inhomogeneous. The plume height was of the order of 8—10 m, and the maximum width 300 m at 750 m downwind. At a release rate of 19.3 m^3/min in a 3.9 m/s wind (test 6), the plume was more coherent and uniform over the entire length, with height generally 10—12 m and maximum continuous width 550 m. At the end of this test, the visible plume length was 2250 m and still increasing.

3.6 Battelle/AGA

Further experimental spills of LNG into bunds were performed in 1974 by Battelle Columbus laboratory, sponsored by the American Gas Association [19]. They used a test site at Capistrano near San Clemente, California where a 300 m by 100 m area was cleared and levelled. The 28 dispersion experiments comprised 17 with a 2 m bund, for a few of which an insulated

floor was used, 9 with a 6 m bund, of which six used high bund walls, and 2 with a bund of 24 m diameter. In all cases the LNG was spilled in 20—30 s. Unfortunately, the liquid tended to spill partly outside the bunds.

The gas sensors used were catalytic devices, which have the disadvantage of having a double valued calibration, i.e. a given output corresponds to two possible concentrations. Thirty-six of these were deployed, together with thermocouples, at four distances up to 300 m from the spill. Thermocouples were also used in the soil under the pool and downwind.

The spillage of LNG outside the bunds complicated the analysis of the results, and photographs of the visible cloud were used to assess the effect of high bund walls and of insulating the floor. However, the concentration measurements were used by Battelle to derive a correlation for maximum concentration in terms of downwind distance, wind velocity and bund area, as well as being available for analysis by other participants in the AGA LNG programme. (See other Sections of the report, Ref. [19].)

3.7 Dutch freon release

The first test to involve the almost instantaneous release of a large quantity of dense gas, rather than evaporating liquid, was performed by the Ministry of Social Affairs (DGA) in the Netherlands, and reported by van Ulden [25] and Buschmann [26]. 1000 kg of freon-12 was evaporated "quasi-instantaneously". This material has a density 4.2 times that of air. However, intensive mixing with air occurred during the first few seconds of expansion and after about five seconds it was estimated that the cloud had a volume of about 2400 m^3. The density of this freon/air mixture would then be about 1.25 times the density of air. The wind speed (at 10 m) was 3 m/s with a logarithmic profile and the surface layer was exactly neutral.

From a maximum height of about 5 m the cloud slumped to a minimum height around 20 cm before increasing in height again. At 1000 m from the release point the height was nearly 10 m. The shape of the cloud remained roughly cylindrical with some elongation in the direction of the wind.

Dosage measurements were made on arcs at 100 m, 500 m and 1000 m from the release point, with one continuous concentration measurement at 100 m.

As a result of this experiment van Ulden [25] derived the first slab model assuming a cylindrical cloud. The data showed that the constant c was equal to 1 in the expression for the frontal velocity.

$$U_f = c\sqrt{g'H}$$

The rate of mixing at the front could not be determined with reasonable accuracy from the data, although the best fit was given by

$$\frac{dV}{dt} = 0.05 \times 2\pi RH\, U_f$$

3.8 HSE/Porton spills

A series of freon releases was carried out for the British Health and Safety Executive by staff at the Chemical Defence Establishment, Porton Down [27,29]. The objective was to release rapidly a large quantity of vapour as an initially high cloud, but introducing as little disturbance to the cloud as possible during the release. The method devised was to contain freon, or a freon/air mixture, in a cubical tent of about 3.5 m dimension. The spill was initiated by allowing the sides of the tent to drop, concertina-fashion, to the ground; the gas then began to slump and move with the wind. The top of the tent remained in place.

The experiments were performed on flat grassland with roughness of 2, 10 and 20 mm., and on a few occasions sloping land was used in order to observe the effect of the slope. Various ratios of freon to air allowed a range of initial densities from 1.03 to 4.2 times the density of air, and in addition two neutral buoyancy cloud releases were made.

The majority of gas observations were dosage measurements, made by bag or diffusion samplers. Typically 120 such samplers were deployed, at four distances from the release point. However, these do not give information on instantaneous concentrations, and average cloud concentration was usually estimated from the visible dimensions of the cloud, although there were a few continuous concentration monitors deployed. The cloud was marked with smoke and photographed from the top of a 15 m mast using a fish-eye lens to give a wide plan view. Two ciné cameras observed the profile of the cloud at different distances from the release points.

The cloud was always found to slump and dilute very fast initially; even in very calm conditions the concentration decreased by a factor of ten in the first six seconds. A raised outer rim to the expanding cloud was usually a prominent feature. The presence of the tent prior to an experiment caused a region of almost stagnant air in its wake, with a resulting tendency of the cloud to develop into a horseshoe shape.

The results were analysed by comparison with a cylindrical slab model, and by contrasting similar experiments to ascertain the individual effect of changes in cloud density, wind speed, ground slope or roughness. Of these, only ground roughness changes (by a factor of ten) were found to have no marked effect. No effect of the presence of clouds on the vertical turbulence intensity was detected; these measurements were performed in clouds of up to 2.5% gas concentration.

4. Maplin Sands tests

4.1 Introduction

In 1978, Shell Research Ltd. felt that there was still a need for well instrumented spills of substantial quantities of liquefied gases in well defined conditions. Accordingly, at the beginning of 1979 detailed planning started for a series of steady-state and instantaneous liquid spills of up to twenty cubic

metres of LNG and refrigerated liquid propane. These gases were chosen both because the company has a particular interest in the handling of these materials, and because complementary information can be provided by the two gases to aid our understanding of dense and cold gas dispersion, as mentioned in Section 2.6.

The site chosen was at the Proof and Experimental Establishment of the British Ministry of Defence. Their ranges at Maplin Sands on the north bank of the Thames estuary provide an area of tidal sands some 20 km long and up to 3 km wide to which public access is restricted. This was therefore an ideal flat site, covered by water at high tide and subject to prevailing off-shore winds, where dispersion and combustion experiments could be carried out safely.

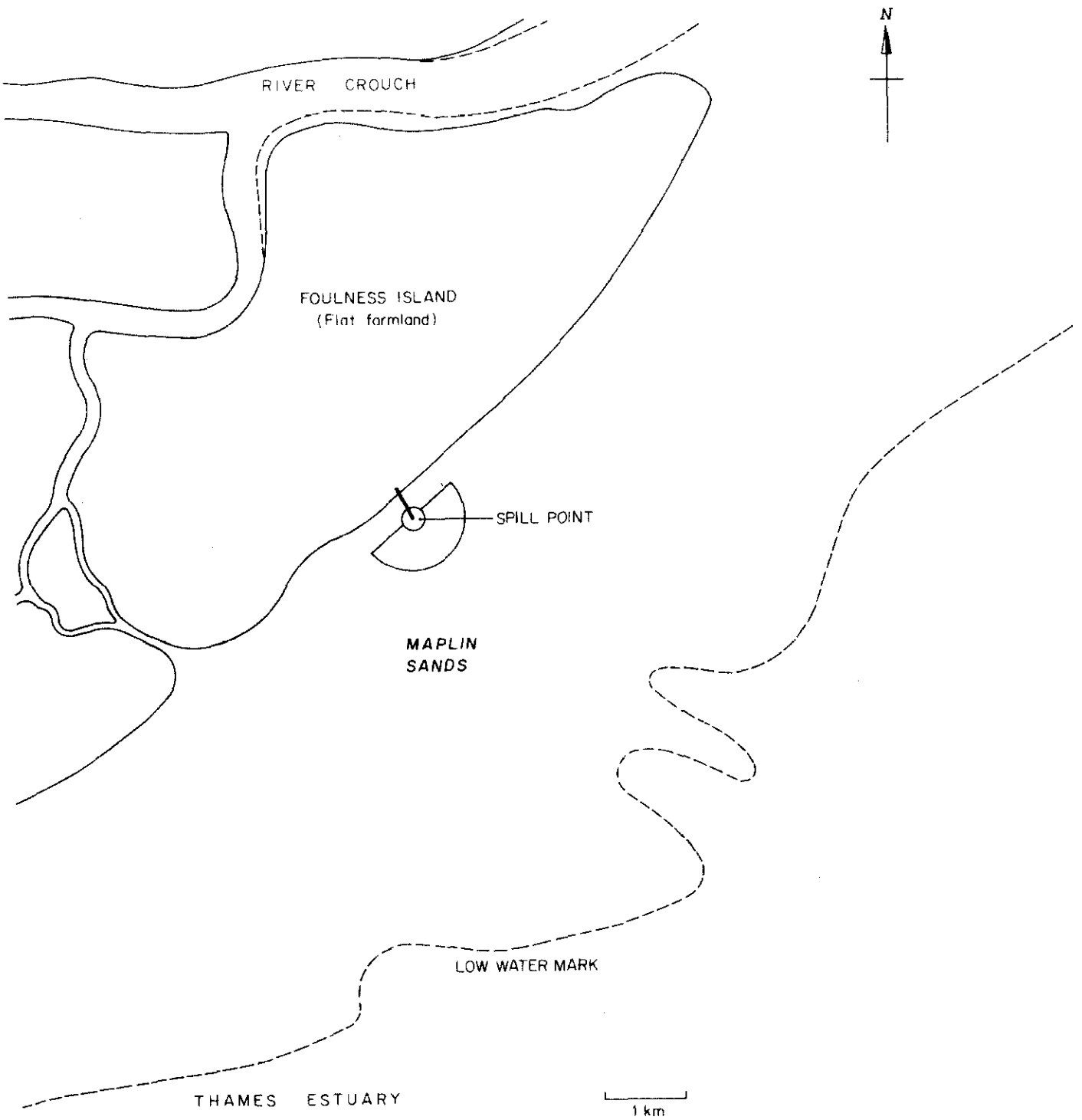

Fig. 1. Location of test site on Maplin Sands.

In all, 34 spills were performed during the late summer of 1980. Of these, 11 were ignited. The combustion aspects of the programme will not be discussed here, although some of the combustion spills provide useful dispersion data; in particular, continuous spill combustion experiments were identical to dispersion experiments until the moment of ignition.

4.2 Site description and engineering

The spill point chosen was 350 m offshore from the southeast facing coastline of Foulness Island (Fig.1). At high tide there was at least a 300 m fetch over water after the 5 m high sea wall. The need to wait for the conjunction of suitable offshore winds and high tide would have greatly restricted the number of opportunities for spills. So a dike was constructed to retain a 300 m diameter shallow pond around the spill point at low tide. Since the slope of the sands is about 1 in 1000 and the height of the dike is only about 0.75 m at its highest, an almost ideal flat site was also available at low tide.

Onshore, the gas handling plant included three 25 m^3 cryogenic tanks to hold LNG or propane, plus two tanks for liquid nitrogen. The liquid nitrogen was used to cool the liquefied gases to prevent excessive boil-off, and to provide a driving pressure for the delivery of the liquefied gas to the spill point. A 150 mm diameter insulated cryogenic line led from the storage facility to the spill point and continuous spillages were performed directly from this line. In the latter part of the programme, a pipe end was attached which allowed delivery of the cryogen at the surface with negligible vertical momentum.

Considerable importance was attached to the ability to perform an ideal instantaneous-liquid spill without significant obstruction to the atmospheric flow. This was achieved by means of an octagonal submersible barge 12 m across which could be raised by pumping air into buoyancy chambers and lowered by flooding the chambers. The open depression on the top had a capacity of more than 20 m^3 of cryogen. As the barge sank water would suddenly flood over the edge into the top displacing the liquefied gas onto the sea surface.

4.3 Instrumentation

Instruments were deployed on 71 floating pontoons most of which were equipped with 4 m masts. The pattern of deployment (Fig. 2) was chosen to give optimum coverage of the field likely to be occupied by the largest envisaged instantaneous spill and allowing for all wind directions with an offshore component. (Spills were restricted to offshore wind conditions for reasons of safety.) For one series of continuous spills, which give shorter distances to given concentration than instantaneous spills of the same total quantity, a modified array was used. Pontoons were moved from parts of the far field to double the density of coverage in the near field up to 180 m.

In total there were about 360 instruments in the array. Mounted on a standard pontoon, in addition to combustion instruments, were three gas sensors (at 0.5 to 0.9 m, 1.4 m and 2.4 m above the sea surface) and one fast response

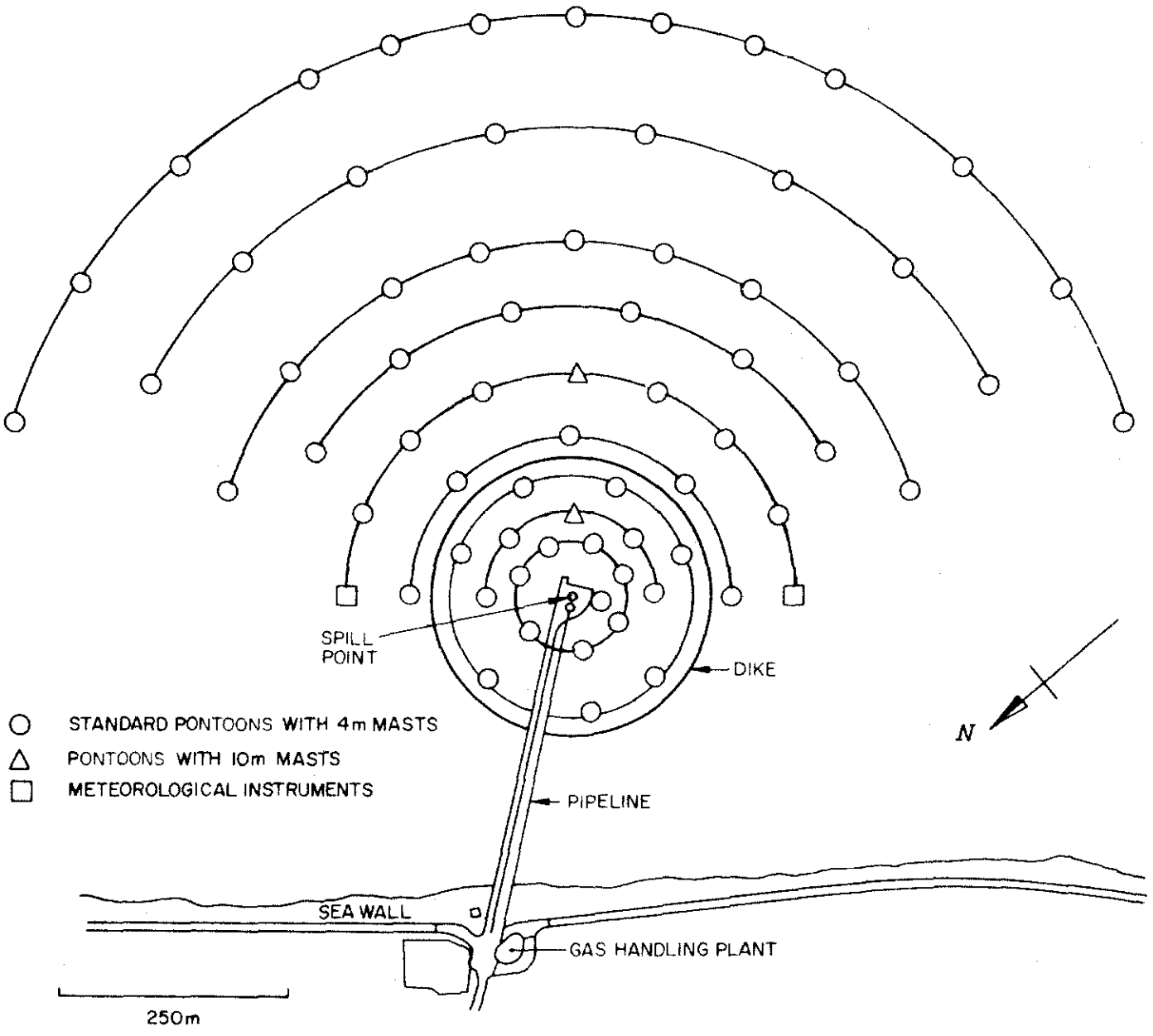

Fig. 2. Layout of sensor stations at Maplin.

thermocouple close to the lowest gas sensor. The gas sensor is a device based on measurement of the heat loss from a filament under free convection. Two special pontoons each had ten-metre masts, six gas sensors, one thermocouple and two three-axis sonic anemometers. Two further sonic anemometers were mounted on ordinary pontoons.

Another two special pontoons were devoted to meteorological measurements. These provided vertical profiles of temperature and wind speed up to ten metres, together with measurements of wind direction, relative humidity, insolation, water temperature, and wave height.

The signals from all these instruments were sampled ten times per second (30 Hz for the thermocouples), digitised on the pontoons and relayed by cable via multiplexers to the computers onshore. Disc storage was used for the data during an experiment, followed by transfer to tape for transport to the Shell mainframe computer near Manchester. The extensive software which had been developed for data analysis was available on this computer, accessible from our "home" laboratories at Thornton and Amsterdam.

The spills were photographed from three locations: two land-based towers providing orthogonal views, plus a helicopter overhead. From each position still photographs and videa recordings were taken. The overhead photographs have since been analysed by a "Magiscan" image analyser which could read the position of the visible cloud. After perspective correction this information has been added to the main computer data set.

4.4 A description of the tests performed

At the time of writing, analysis of the data is at an early stage, and only limited, preliminary results are available. These will be given in the next Section (4.5). However, we are able to detail the spills performed and to give some qualitative observations. In the following we shall use what be believe to be a logical order for analysis, rather than the chronological order of the experiments.

Basic information on the useful dispersion spills is given in Table 2. Eleven continuous propane spills were performed, of which three were ignited. The last few spills used the surface release nozzle, and therefore gave the best defined spills. One spill (45) in a very low wind showed considerable upwind spreading of the gas. However, there are indications that for part of the spill period the wind field was not uniform, with velocity decreasing considerably with distance from the shore.

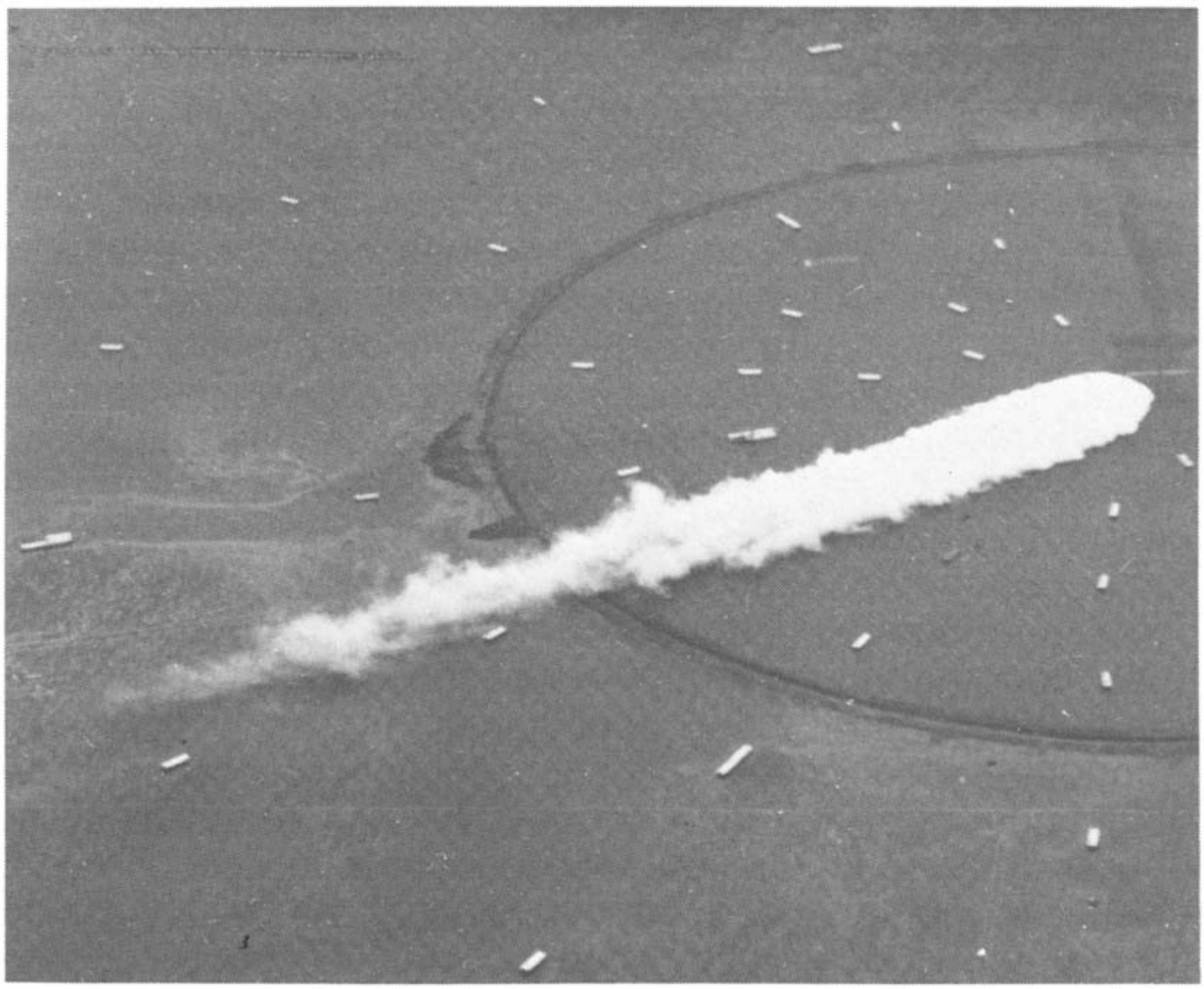

Fig. 3. Spill 56 — continuous LNG spill at 2.5 m^3/min in a 4.8 m/s wind.

TABLE 2

Spills at Maplin likely to provide useful dispersion data

Spill no.	Spill		Wind speed (m/s)	Source location	Comments
	Rate (m^3/min)	Duration (min)			
Continuous propane					
43	2.3	5.8	5.8	0.5 m above water level	
45	4.6	6.8	2.2	0.25 m above water level	Unusual atmospheric conditions
46	2.8	7.8	7.9	At water level (improved pipe end)	
47	3.9	4.5	5.2	At water level	
50	4.3	4.0	8.3	At water level	Ignited
51	5.6	3.7	7.8	At water level	Ignited
52	5.3	3.3	7	0.15 m below water level	
54	2.3	5.0	3.6	At water level	
55	5.2	4.0	5.7		
Instantaneous propane					
60	27 m^3	—	1.2	Sinking barge	Photographic data only
63	17 m^3	—	3.4	Sinking barge	Only near-field data
Continuous LNG					
12	1.0	10.7	2	2—3 m above water level	Low and non-constant spill rate and wind
15	2.7	6.7	3.9		
29	3.5	5.4	5	Near water level	
34	2.9	3.5	8.5		
35	3.8	4.5	10.0		
37	3.9	5.0	4.9	0.25 m below water level	Highly buoyant cloud. Missed sensors
39	4.5	2.3	4.5	0.25 m above water level	Ignited
56	2.5	1.5	4.8	At water level (improved pipe end)	
Instantaneous LNG					
22	10 m^3	—	5	Sinking barge	Ignited; prior to this, a useful dispersion test
23	7 m^3	—	5	Sinking barge	Momentary ignition

All the continuous propane plumes exhibited obvious density effects, producing low, wide plumes; this behaviour was more marked in lower winds. After the initial drop near the source the visible cloud could be seen growing in height downwind. On some occasions a "head" could be seen at the edges of the plume, remaining visible farther than the gas in the centre.

Thirteen continuous LNG spills were performed. Of these, eight will probably provide data useful for dispersion analysis. Some, at least, of these plumes appeared higher and narrower than those from similar propane spills (Fig. 3). From an initial comparison between two spills with delivery close to the water surface and others with an elevated source, the plume behaviour seems to be noticeably dependent on the source type. There was also one spill in which the LNG was discharged as a jet under the water, and this produced a totally buoyant plume which passed above even the nearest sensors at 40 m.

Of the three instantaneous propane spills performed, two are interesting from the point of view of dispersion. Spill 60 took place in a very low wind (1.2 m/s) and produced an ideal cloud, almost perfectly circular, spreading from the spill point (Fig. 4). It is therefore regrettable that the data collection system failed entirely on this occasion. However, an excellent photographic record was obtained of this remarkable spill. Spill 63 was also in a fairly low wind (3.5 m/s) and again started as a roughly circular cloud before moving off downwind. The cloud was very low initially, with a raised head around the circumference, and it could be seen to be growing in height as it moved downwind.

Two of the instantaneous LNG spills (numbers 22 and 23) are of particular interest. These were well controlled spills and provide useful dispersion data, even though the cloud of spill 22 was eventually ignited. The wind speed was higher (5 m/s) than for the propane spill 63, and in each case the cloud produced was very elongated, resembling the continuous spills more than the low-wind instantaneous.

4.5 Some preliminary results

The results of these experiments analysed so far cover six well-defined steady-state spills.

A problem posed by the continuous spills is the meandering of the plume. The array of measuring stations (Fig. 2) was set out as described to cover our largest instantaneous spills and any offshore wind direction. Restriction to a smaller acceptable range of wind directions would have further reduced the number of spills which could be performed in the three months available. The steady-state plumes in all but low winds were so narrow that they could pass completely between sensor stations occasionally, although not for the whole of any experiment because of variations in the wind direction. Thus any one sensor might see the plume only intermittently and there were times when the plume did not pass over any stations at a given distance.

If model predictions are to be compared with the data, it must be decided exactly what gas concentrations the models are intended to predict. The long-

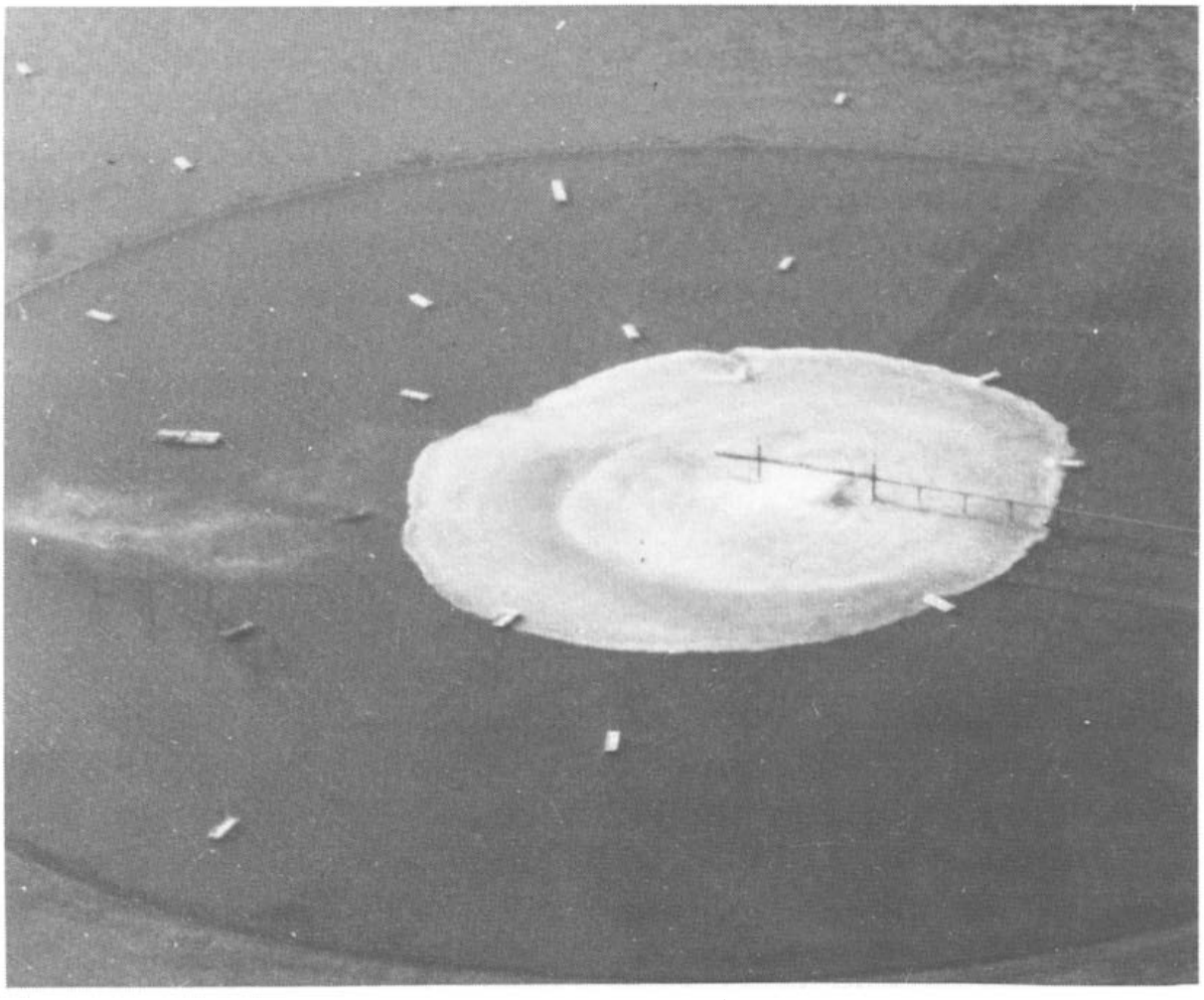

Fig. 4. Spill 60 — instantaneous propane spill of 27 m^3 in 1.2 m/s wind.

term average concentration at a fixed location downwind of the source is reduced by meandering of the plume. However, meandering of the plume does not change the average maximum concentration inside the plume.

A model dealing with flammable dispersion should therefore not predict long-term average concentrations at fixed locations. On the contrary, the value of particular interest in flammable gas plumes is the maximum concentration in the plume at a given distance from the source, whatever its angular position may be. This concentration can conveniently be referred to as the "centreline concentration", though it does not necessarily always occur at the centre of the meandering plume. If model predictions are in terms of "mean concentrations", then the predicted plume-centre concentration should be compared with the mean of this "centreline concentration", measured in the experimental plume. The long-term average concentration at any fixed point may be much lower, but that fact has little significance for the assessment of flammable gas hazards*. The crosswind variation in concentration predicted by the model is then assumed to be taken relative to a moveable centreline.

To measure the relevant mean concentration it is necessary to obtain measurements of the "centreline concentration" at each instant, and subsequent-

*For toxic gases, however, the long-term average concentrations at fixed locations may be relevant; a slightly different approach to modelling is then needed.

ly to average the values. This can only be done if there were several sensor stations across the plume at each distance, requiring perhaps an order of magnitude increase in the number of sensor stations, which was not possible in practice. Averaging the intermittent signal at any sensor does not give the required result. It is more useful to take the maximum observed concentration, since the "centreline" concentration would be observed as the "centre" of the plume meandered over a sensor. The sensor stations were close enough that the plume centreline rarely failed to pass over one for at least part of the spill time. In fact, there were usually sensors in the plume for a large part of the spill time (the plumes themselves normally lasted for more than 200 s). In these circumstances the maximum signal obtained can be assumed to be above the mean of the "centreline concentration" as defined.

Maximum values of the gas concentration signals at each distance have been obtained for five of the spills. (The data were first smoothed using a three-second moving average to eliminate high frequency noise spikes; the sensor time constant is about three seconds.) For the other spill analysed, the wind speed was so low that the plume width was much greater than the sensor spacing and useful mean values can be obtained. From these concentrations, interpolation gives a parameter of particular interest, the distance to lower flammable limit (LFL, 5%v for LNG, 2.1%v for propane). The values obtained are shown in Table 3, labelled "peak" where maximum concentrations were used.

For comparison we have run the model HEGADAS. This model is described by Colenbrander [11] and in less detail by Blackmore et al. [30] in this volume. The steady-state version of the model assumes similarity profiles of concentration in the vertical and crosswind directions once the gas has left the source. Vertical mixing is proportional to a function of a bulk Richardson number which is derived from laboratory dense layer experiments together with neutral atmospheric dispersion experiments for the passive limit.

A necessary input to the model is the value of the friction velocity, u_*.

TABLE 3

Comparison of LFL distances for six continuous spills with predictions from HEGADAS

	Spill no.	Measured LFL distance, (3 s average) (m)	Predicted LFL distance HEGADAS mean (m)
Propane	46	245 ± 35 (peak)	140—220[b]
	47	340 ± 80 (peak)	355—540[b]
	54	400 ± 100 (mean)	295[c]
LNG	56	110 ± 30 (peak)	235[c]
	39	130 ± 20 (peak)	200—390[a,b]
	15	150 ± 30 (peak)	235—320[a,b]

[a]Range due to uncertain effect of non-ideal source configuration.
[b]Range due to uncertainty in ambient conditions.
[c]Using average surface roughness.

This can be calculated from the wind speed and roughness length, if known, but we have measurements of turbulent velocities and therefore obtain u_* directly. The values obtained from the six sonic anemometers vary to some extent, and use of the full range of values obtained results in a range of predictions. For the LNG spills with an elevated source there is also uncertainty in the amount of LNG which evaporated in the air, and this widens the range of predictions.

From Table 3 it can be seen that the LFL distances predicted for LNG are too great (i.e. are conservative). This may be due to the fact that the published HEGADAS model does not include the effects of heat transfer to the gas cloud from the sea surface. Detailed comparison of the data with a model version including these effects will show whether the difference can be explained in this way. The propane data are in better agreement with the model predictions but the range of predictions is wide at present for the reasons given above. It is to be hoped that a full study of the meteorological data will provide better definition of the ambient conditions and so permit a smaller range in the model predictions. A full assessment of any model, however, requires detailed comparison with the data rather than concentrating on a single measurement such as LFL distance, and this full assessment is currently being undertaken.

5. Current and future experiments

5.1 China Lake

The continuing programme of tests conducted in the United States at China Lake, California, is described in some detail elsewhere in this volume [24]. Comments here will be restricted to the 1980 forty-cubic-metre tests, in order to point out the differences from the Maplin tests, and to explain the derivation of the information presented in Table 1.

China Lake is a desert site involving primarily dispersion over land. The LNG is spilled onto water and then leaves the pond 25 m from the source; the terrain thereafter slopes irregularly, with a rise of 7 m in the next 80 m. The 1980 tests each involved forty cubic metres of LNG spilled over a period of about three minutes. In the high winds prevailing in all but one of the tests (apparently a wind at 10 m greater than 6 m/s), this spill was long enough to give a steady state as defined in Section 2. For the remaining spill the mean wind speed measured at 8 m was 2.6 m/s. Calculation shows this spill to be just on the borderline for the "instantaneous gas" definition of Section 2. Only in this spill, with an Ri_0^{I} of about 3000, were strong density effects observed.

5.2 Thorney Island

The U.K. Health and Safety Executive is co-ordinating a multi-sponsored experimental programme to take place in 1982 at Thorney Island on the south coast of England [28]. The site is a disused airfield on a low-lying island

about 2 km across. For the wind directions which will be used, the wind will be coming off the sea and over about 1 km of flat ground to the release point. As with the previous HSE experiments at Porton Down, ambient temperature freon will be used, initially contained in a cylindrical tent and mixed with air to a density twice that of ambient. The quantity of mixture used in each of five spills will be about 2000 m^3, which requires a tent 14 m high whose sides will collapse concertina-fashion to release the gas. Concentration measurements will be made at an array of about 40 sensor stations. The tests should be completed by the end of 1982.

5.3 Frenchman Flat

Preparations are being made in the United States to perform spills of up to 350 m^3 of LNG [31]. The site proposed is at Frenchman Flat in the Nevada desert, and it is hoped that a large spill can be carried out there in very low winds. Such an experiment, an order of magnitude larger than the 20—40 m^3 of Maplin and China Lake, would give greater confidence in the modelling of the largest postulated accidents, such as loss from a 25000 m^3 tank on an LNG ship.

5.4 Complex terrain

The experiments described, and most mathematical models, have been concerned with dispersion on a flat surface. In the presence of an obstacle such as a building or a ship, the dilution of released gas would be enhanced. At present, this can only be approached by wind tunnel or water flume simulation or by using the very conservative calculation for a flat surface. Similarly, wind tunnels are used to assess the influence of topographical features. The only field experiments in this area have been a few of the releases at Porton. Further experiments dealing specifically with these aspects would provide greater confidence in the scaling procedures to be used in these analogue techniques and aid the development of mathematical models.

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