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FUTURE DIRECTIONS OF DENSE-GAS DISPERSION RESEARCH

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Summary

The estimation of the dispersion of dense gases in the atmosphere is a major factor in the assessment of the hazard posed by loss of containment of flammable and toxic gases. Furthermore, the forensic investigation of accidents is often assisted by such estimates. This paper discusses the dispersion of dense gases from the point of view of the information needs of such users of predictive models. The interfaces with other phases of the assessment are described in order to assist the discussion of information needs. The steps that are being taken by the Health and Safety Executive to remedy some of the deficiencies are described.

1. Introduction

Over the past ten years or so, interest has grown in industrialised countries regarding the possible consequences of the large-scale release of flammable or toxic gases into the atmosphere. This interest has been fostered by the increasing scale, in number and extent, of industrial and transport operations involving these materials. The occurrence of a number of disastrous accidents (for example, the Flixborough explosion [1] and the Mississauga chlorine accident [2]) has focussed attention on the potential risks of these operations. One consequence has been the introduction of legislation, or proposals for legislation, in a number of countries requiring that the potential risks should be assessed [3,4,5].

In the United Kingdom, the draft Hazardous Installations (Notification and Survey) Regulations [4] contain this provision in Regulation 6(1):

> "If after consideration of a hazard survey report and of any other information available to it the Health and Safety Executive is of the opinion that there is, or may be, an exceptional risk to the health and safety of persons, whether at work or not, it may by notice to the person responsible for the survey require him to make a detailed assessment of any one or more of the matters set out in Schedule 4 which it may specify in the notice; and the responsible person shall send a report of the assessment to the Executive".

The listing in Schedule 4 of matters about which a detailed assessment and report may be required includes, amongst others, the magnitude of any hazard, the number of persons whose health or safety might be affected by the hazard and emergency plans.

Consideration of such matters necessarily requires information on the dispersion behaviour of released materials in the atmosphere. Indeed, in a review of the current position in the UK, Barrell [6] anticipates that a number of assumptions will be common to many hazard surveys and identifies as specific examples:

> "... assumptions about dispersion of toxic vapours in various weather conditions, assumptions about the vulnerability of populations to thermal radiation from fireballs and overpressure from explosions, etc. It would seem sensible therefore for us to find a way to collaborate to reach a consensus view on assumptions of this kind, to avoid the unnecessary duplication of effort that would result from companies working wholly independently of one another and of HSE".

In the first of the examples quoted above, the dispersion information is a direct input, while in the others it is a necessary prerequisite for a combustion calculation in those cases where delayed ignition is postulated.

For some highly toxic materials, the released quantity will generally be small and an assumption of passive dispersion will be valid. In most cases, however, it is now appreciated that this assumption is not justified. This is because of the large quantity that might be released and because many of the gases of concern possess a density in excess of that of air either because of high molecular weight, low temperature or through being mixed with finely dispersed liquid droplets. The subject of dispersion of such dense (strictly, denser-than-air) gases is thus central to quantitative assessment of the consequences of a release of hazardous material.

Legislative requirements are necessarily concerned with hypothetical accidents. The forensic investigation of accidents that have occurred is the inverse problem. Here the involvement of dispersion calculations is threefold.

Firstly, the sequence of events during the accident may not be obvious. Any information that can be gained from relating observed consequences to postulated accident sequences can be valuable in identifying causes of the accident and therefore in drawing lessons to avoid a recurrence.

Secondly, in the case of a possible chronic effect, it is necessary to be able to estimate the exposure of the population so that remedial action, if possible, can be taken. This is, however, more likely to be the case with releases of highly toxic materials such as occurred, for example, at Seveso [7].

Thirdly, the information available from an accident, although generally sparse, can sometimes be useful as a means of validating predictive models. Such use of forensic information has been made by Kaiser [8].

Although most emphasis in work on dense-gas dispersion is currently placed on its role in the assessment of major hazards, there are other no less important fields of application. Examples of these include the quantitative classification of areas in which particular types of electrical equipment may be used in the presence of flammable gas, the behaviour of lighter-than-air gases in confined spaces and the covenanted release of dense gas from elevated sources such as vent stacks. The first of these topics will be discussed as an illustration of a less well-known field of application of dense-gas work.

2. Large-scale releases of dense gas

2.1 The assessment procedure

The procedure for estimating the consequences of a given accident has components corresponding to the following three phases:

(i) The initial formation of a cloud or plume.

(ii) The dispersion of the cloud or plume to the point where it ceases to present a hazard.

(iii) The consequences if the cloud or plume is ignited (in the case of a flammable gas) or passes over a population (in the case of a toxic gas).

The factors pertaining to each phase that are of importance to assessment procedures will be reviewed. Methods of analysis will not be included since these are the subject of other papers in this issue.

2.2 The formation phase

The processes in this phase determine the 'source term' for the dispersion phase. This term is specified by the quantity of gas (for a sudden or 'instantaneous' release) or the rate of evolution of gas (for a 'continuous' release), together with the geometry of the source. Two types of loss-of-containment accident are of prime importance, both involving gas which is initially in a liquefied state.

The first is where the gas is maintained as a liquid by storage under pressure at a temperature above its saturation temperature at atmospheric pressure (often referred to as its 'normal boiling point'). The storage temperature is usually the ambient atmospheric temperature. Examples of gases commonly stored or transported in this way include chlorine, ammonia and liquefied petroleum gases such as propane and butane. Engineering limitations on the size of pressure vessels mean that individual storages of this type are limited to not much more than 150—200 tonnes.

The storage temperature can also be below ambient temperature but still above the normal boiling point of the material. The storage condition is maintained by refrigeration, referred to as 'partial refrigeration' in this case. Because of the lower pressures, sizes can be larger, ranging up to about 2000 tonnes.

The storage temperature can sometimes be above ambient temperature, although this is generally as a result of the material undergoing a process rather than being in store. Often in such cases the material is liquid at ambient temperature and pressure. Where the material is flammable, loss of containment is hazardous if the flash point of the material is below the storage temperature. Examples of this circumstance are where a flammable liquid is used as a heat-transfer fluid and liquid-phase oxidation processes such as the cyclohexane oxidation process involved in the Flixborough explosion.

These examples of pressurised storage conditions are not all-embracing but they do represent the circumstances most commonly found in practice. The stored energy may cause the liquefied gas to be ejected violently if a loss of containment occurs. There is a variety of possible release conditions depending on whether the breach is above or below the liquid level, the size of the breach in relation to the cross-section of the vessel, the storage conditions and the physical properties of the material. A detailed discussion of the various circumstances, with particular reference to ammonia as an example, is given by Griffiths and Kaiser [9]. A general feature that is attributed to this phase, and that has been observed in experiments and in accidental releases, is the evolution of a rapidly expanding two-phase cloud (or jet, for a breach of limited dimensions). The phase composition of this cloud depends on the initial stored energy represented by the superheat of the liquefied gas (the difference between the storage temperature and the normal boiling point). This dependence has been shown by Fletcher [10]. As the superheat increases, so vapour—liquid disengagement in the vapour space of the vessel decreases and an increasing proportion of the liquid is entrained by the erupting vapour and is carried out of the vessel. The expanding cloud reaches a maximum size whose final composition depends on the rate at which it entrains air and on the size distribution of the entrained liquid. Fletcher [10] has observed that some of the liquid is in the form of large drops, which fall back to the ground and so do not contribute to the cloud that is formed. The understanding of the various processes is still poor, introducing uncertainty into the statement of the initial conditions for the dispersion calculation. Jagger and Kaiser [11] have attempted to link a model of the cloud formation phase with that for the dispersion phase, but the lack of experimental evidence is presently a considerable inhibiting factor.

The second type of loss-of-containment accident of importance is where the gas is maintained by refrigeration as a liquid at atmospheric pressure (usually referred to as 'fully-refrigerated' storage or cryogenic storage). Vapour formation in this case is governed by heat transfer to the liquid from the surfaces with which the liquid comes into contact. There is rather less initial dilution of the vapour by entrained air during the formation stage than is the case with a flashing liquid. Indeed, any dilution that there might be is ignored in estimating the initial cloud or plume properties. The initial conditions will be time dependent as, with increasing time from release, the contacting surfaces reduce in temperature and the heat transfer rate falls. This is especially so if there is a secondary containment, such as a bund, able to retain all the released liquid.

The estimation of the rate of vapour formation, and hence the specification of the initial conditions for dispersion, is believed to be on a satisfactory basis for the case where the boiling point of the liquid is well below ambient temperature, as for example for liquefied natural gas. A proviso to this statement is, of course, that the thermal properties of the contacting surfaces are known.

For liquids with a boiling point close to ambient temperature, heat transfer from the wind assumes importance and there is rather more uncertainty about the vapour evolution rate. Examples of such liquids include propane, butane, chlorine and ammonia.

So far as dispersion of dense-gas clouds is concerned, the point of obvious relevance is the sensitivity of the dispersion to the initial condition of the cloud. Sensitivity tests of models of dispersion can give information on the response of the models to adjustment of the assumed initial conditions. These indicate, as might be expected, that the hazard range for a flammable gas does depend critically on the assumptions for the mass of air entrained and the initial geometry of the cloud simply because the dispersion phase may be very short lived. Jagger and Kaiser [11] conclude that whether this is so depends on the initial mass released, the importance of the dispersion phase increasing as the initial mass increases.

For toxic clouds, the results of dispersion calculations are much less sensitive than in the case of flammable gases because of the much extended dispersion phase before the cloud is rendered harmless. Variations in the assumption for the mass of air entrained, and thus for the initial density of a cloud of given total mass of source gas, do not result in significant differences in the distance over which the cloud is hazardous. This is because a reduction in initial density is accompanied by a reduction in the mixing produced by gravity spreading, counterbalancing the advantage of the lower dilution factor necessary to achieve the desired reduction in concentration. Another way of saying this is that it is the total negative buoyancy in the initial cloud that matters, and this is independent of the initial dilution.

The measurement of the vapour production rate from spills of liquefied gases presents a difficulty in performing experiments in which dispersion from such spills is to be studied. This is the principal reason why the Health and Safety Executive has opted to concentrate its experimental dispersion programme on releases of pre-formed clouds of gas at ambient temperature and pressure.

2.3 The dispersion phase

Over the past few years a number of predictive models have been developed for dense-gas dispersion. They all rely for their empirical information on a narrow base of experimental data. The models generally agree with the experimental observations, but they disagree with each other when used to forecast what might happen in situations that have not been subject to experimentation. The available experimental information is not reliable and detailed enough to allow 'good' models to be distinguished from 'bad' ones, or indeed to assign well-defined values to disposable constants in models of the same basic type.

The principal deficiency at the present time is, therefore, the absence of a body of reliable data. HSE has instituted a programme of experiments and has opted to concentrate on instantaneous clouds of gas at ambient temperature and pressure for reasons which are discussed in McQuaid [12]. The study of continuous releases will form a later stage in the programme. This Section will discuss the considerations that influence the design of the experiments and will describe the experimental arrangements.

The programme is in three parts:

(i) Moderate-scale field experiments.
(ii) Large-scale field experiments.
(iii) Wind-tunnel experiments.

Part (i) has been completed and is described in Picknett [13]. It consisted of 42 trials in each of which 40 m^3 of gas was released. The influences of initial relative density, wind speed, stability, ground roughness and ground slope were investigated. The experiments were performed at the Chemical Defence Establishment, Porton and are known as the Porton trials.

Part (ii) is planned to take place in 1982 and will involve the release of 2000 m^3 clouds of gas. The experiments will be performed by the National Maritime Institute at Thorney Island and will be referred to as the Thorney Island trials. The experimental arrangements will be described later in this Section.

Part (iii) consists of wind-tunnel simulations of some of the experiments performed in part (i) and to be performed in part (ii). The simulations of the part (i) experiments were at 1/25th scale whilst those of the part (ii) experiments were at 1/90th scale. The experiments were performed during 1981 at the Warren Spring Laboratory (WSL). They will be referred to as the WSL experiments.

The programme therefore represents a co-ordinated series of experiments of the same basic type conducted at three different scales. The selection of the conditions for the Thorney Island trials and the WSL experiments is governed by a number of considerations. The Porton trials have provided a large body of data at one scale. It is clearly desirable that the other experiments should be performed under conditions which ensure that all the results can be directly compared with each other, so that effects of scale change can be identified. The results can then be compared to determine:

(i) Whether the change of scale results in some effect which was not previously appreciated.
(ii) Whether a model validated at the smaller scale remains valid. If it does not, this would indicate that particular assumptions have broken down, for example, that the entrainment is not causally connected to the intensity and scale of turbulence in the way postulated in the model. Supplementary information on the details of the flow structure then becomes valuable in elucidating the reasons for the observed departure.

In considering the selection of experimental conditions needed to determine the effects of scale of release on dense gas dispersion behaviour, it is useful to review the procedures that must be adopted in order that similarity will be preserved from one scale to another. The parameters that are considered relevant to the dispersion of a quantity of dense gas are:

ρ_a, ν_a	density and kinematic viscosity of air
ρ_g, ν_g	density and kinematic viscosity of the dense gas
l	length scale
g	gravitational acceleration
z_0	aerodynamic roughness of the ground
L	length parameter characterising the atmospheric stability condition
h	initial height of the dense-gas cloud
α	ground slope
U	wind speed at a reference height

From the theory of similitude, the following list of dimensionless groups can be obtained:

ρ_g/ρ_a	density ratio
$U/(gl)^{1/2}$	Froude Number (F)
Ul/ν	Reynolds Number (R)
ν_g/ν_a	kinematic viscosity ratio
z_0/l	roughness parameter
L/l	stability parameter
h/l	source shape parameter
α	ground slope

Provided all the relevant quantities have been included and the values of all these dimensionless groups are arranged to be the same on each scale, then experiments conducted at one scale will be representative of conditions at the other scale. The laws expressing behaviour that are deduced from observations at one scale can be applied at other scales over the same range of the dimensionless groups encompassed by observations. The empirical coefficients that are found to be applicable at the scale of the observations should also apply to other scales.

The scale of the Thorney Island trials is still small compared to that of possible full-scale accidental releases. It is desirable that the change from full scale to the scale of the observations should leave the dimensionless groups in the same range so that extrapolation should not be necessary. If such extrapolation is necessary, it would be hoped that the better definition of the scale effects that would result from comparisons over the scale range of the three model experiments would retain validity up to the full scale.

As is well known, however, it is physically impossible in this particular problem to change the scale, i.e. the value of l, and maintain all the dimension less groups constant. A sacrifice must be accepted and it is usually argued that equality of the Reynolds number is not essential provided the flow is turbulent at all points in the flow field.

Thus in changing from one scale to another, the corresponding velocity is determined from equality of the Froude number. This means that if the scale is increased, the representative velocity (which is usually referred to a fixed height) must be increased in proportion to the square root of the ratio of the scales (and the height to which it refers is increased in proportion to the ratio of the scales).

In addition to the physically impossible condition described in the above paragraph, it is also not possible on practical grounds to simulate some conditions at two different scales. It is clear from the last paragraph that low wind speed conditions at large scale will be difficult, if not impossible, to represent at smaller scales. Furthermore, in order to obtain similarity of the approach flow, it is necessary that the ratio of the velocities at any two heights at one scale should equal that at the corresponding scaled heights at the other scale. (A similar consideration applies to all other flow variables that influence the problem.)

The velocity distribution in the vertical plane is described by the Monin—Obukhov similarity law [14]:

$$\frac{u}{U_*} = \frac{1}{\kappa} \log_e \frac{z}{z_0} + \beta \frac{z}{L}$$

where u is the velocity at height z, U_* is the friction velocity (defined as the square root of the kinematic surface shear stress) and κ, β are empirical constants. Accepting this relationship, it can be shown that the above condition is satisfied if the roughness, z_0, and the stability length parameter, L, are both adjusted in direct proportion to the change in scale. Provided that the distributions of turbulence properties are also determined solely by z_0 and L (and that is the usual assumption), then the same statement applies to these distributions as to the velocity distribution. This means that:

(i) The velocity and the turbulent-property distributions corresponding to small roughness conditions at large scale (e.g. the surface of the sea) cannot be represented at smaller scales.

(ii) Similarly, very stable conditions (which correspond to low positive values of the stability length parameter, L) at large scale cannot be represented at smaller scales.

The existence of these limitations does not appear to have been explicitly acknowledged in previous programmes of field trials. The limitations must be recognised and trials should be designed to cover as wide a range of the variables as possible in order to minimise any extrapolation that might be necessary. It would appear, however, that there can be no question of being able to represent, at a model scale, the conditions that cause most anxiety, i.e. release under stable conditions over a surface of small roughness.

It follows also that the Thorney Island trials can only be validly compared to individual experiments in the Porton trials where the roughness was less, and the stability more extreme. The WSL experiments are restricted to neutrally stable conditions and this excludes the smallest-scale experiments from the scale range over which the effect of the stability parameter can be investigated.

A further restriction on the conditions that can be studied is usually imposed by the need to perform trials on a fixed site. This means that the influence of ground slope cannot be investigated in the Thorney Island trials.

However, limited studies of the effect of ground slope were included in the Porton trials and the WSL experiments so that again part of the scale range is covered.

The initial density ratio can take values up to a maximum of 4.2, given the use of Refrigerant-12 (dichlorodifluoromethane, CCl_2F_2) as the source gas. This is the heaviest available gas that is economically acceptable for field trials. It was used in the Porton trials and will be a component gas in the Thorney Island trials. Only one trial was performed at the maximum value in the Porton series, the largest number of trials being associated with values between 1.5 and 2.5. In the Thorney Island trials, a fixed value of 2.0 for the initial density ratio will be adopted as a general rule. Some trials at larger values may be included at later stages. The initial density ratio is not usually regarded as having a separate influence, according to the Boussinesq approximation. It is combined (after rearranging it to be relative to air) with the Froude number to give the densimetric Froude number. The WSL experiments will allow the comparative validity of Froude number and densimetric Froude number scaling to be evaluated.

In addition to experiments with dense gas, it is highly desirable that a trials series should include experiments with neutrally buoyant clouds. These experiments should be performed as repetitions of particular dense-gas experiments and should serve to provide base-line comparisons for the effects of the initial relative density. This was done for two of the experiments in the Porton trials. The Thorney Island trials will have the unique capability of measuring concentration for neutrally buoyant experiments with the same instrument array as for the dense-gas experiments.

Finally, the influence of the source shape (represented by the parameter h/l) is manifested in the initial gravitational potential energy of the cloud. The shape parameter can be combined with the initial relative density ratio and the Froude number to give a parameter

$$\frac{\rho_g - \rho_a}{\rho_a} \cdot \frac{1}{F^2} \cdot \frac{h}{l}$$

which expresses the ratio of the potential energy per unit volume in the initial cloud to the kinetic energy per unit volume in the approach flow. It seems plausible to regard this parameter as characterising the dynamic effects of the initial potential energy. Thus for experiments at equal relative densities and equal Froude numbers, maintaining the shape parameter constant should ensure that the potential energy effects are similar at the different scales. The shape parameter is the same in each constituent part of the HSE programme so that comparison of the results will not be vitiated by the effects of the initial potential energy. It follows, however, that the results of the three sets of experiments, and any analytical models validated by their results, will only be applicable at other scales if the shape parameter is the same (on the assumption of course that the shape parameter does have an effect). However, the effect of shape parameter can be investigated at small scale and this may be the subject of later investigations.

The considerations discussed above are relevant to the behaviour of a cloud subject to the influence of negative buoyancy. Eventually as the density of the cloud approaches that of air, the dispersion behaviour will be asymptotic to that observed for passive materials. The progress to passive dispersion is important to the estimation of toxic gas cloud effects, where exposure to concentrations below 100 p.p.m. may be of interest. There is an absence of information that could be used to establish the criterion for transition to passive behaviour. The Porton trials were not very helpful in this respect. The need to cover the transition range has been a factor in the design of the Thorney Island trials.

Much hope is being placed in the Thorney Island trials for resolving current uncertainties in dense-gas dispersion. Future developments over the next few years will depend on the outcome of the trials since many organisations have subjugated their own interests and have come together in order to permit the organisation of a comprehensive programme that meets their common needs. It seems appropriate therefore, in this discussion of future developments, to describe the proposed trials and this will be done in the following Section.

3. The Thorney Island trials

3.1 The concept of the trials

This was decided by the recognition that progress seemed most likely to be achieved by separating out the uncertainties of the cloud formation stage, as has been discussed by McQuaid [12]. In the planned trials, as in the Porton trials that preceded them, the source conditions are closely controlled. Attention is concentrated on studying the dispersion of clouds of known initial composition and geometry.

3.2 Description of the trials

Control over the source conditions is achieved by preforming a cloud of known composition within a container or tent which can be rapidly removed. The container in the trials will be an upright prism, 13 m high, and of hexagonal cross-section. The major dimension of the cross-section is 14 m giving a tent volume of about 2000 m^3. The tent will be fabricated from sheet plastic and the sides will be folded to ground level by suitable rigging. A quarter linear-scale model of the tent and rigging was successfully tested early in 1981.

In the majority of the experiments, the tent will be filled with a mixture of 68% nitrogen and 32% Refrigerant-12 by volume to give a mixture density twice that of air. The gas will be marked by smoke.

Several systems will be employed to provide data on cloud position, geometry and composition over a range up to about 1.5 km from the point of release. These will comprise:

(a) An array of sensors at fixed locations.

(b) Video and cine film records.
(c) LIDAR scanning.

The sensor array will employ 38 masts in a grid of 100 m mesh size. The arrangement of the grid in relation to the release point has taken account of forecasts of cloud behaviour obtained from existing predictive models and of the wind direction probabilities at Thorney Island at the time of year when the trials will be performed. Each mast will have four gas sensors. The sensors will be commercially available oxygen deficiency sensors. The use of nitrogen on its own as source gas will provide a neutrally buoyant cloud which can be studied with the same sensor array as the nitrogen/Refrigerant-12 clouds. The frequency response of the gas sensors will be better than 1 Hz. A number of sensors will be deployed with a faster response. These will be co-located with turbulence monitors. Data from the sensors will be transmitted in digital form to a central recording station. All data channels will be time-synchronised so that co-variances and correlations of the sensor outputs can be computed.

The Porton trials demonstrated the value of good visual records and the Thorney Island trials will draw on the lessons learned from them. The overhead view of the cloud will be recorded on videotape from a helicopter. A high-speed cine camera to the side of the release point will record the initial stages of the cloud collapse and slumping. Several motorised still-cameras will record the side view of the cloud at different locations over the downwind range. A side-view video camera will also be employed. Computerised image-processing techniques applied to these records should provide an efficient means of extracting quantitative information on the changing cloud geometry.

The third system will be a LIDAR instrument. This will be located upwind of the release point and will fire through the cloud parallel to its direction of travel. The firing rate will be about 1 per sec and the spatial resolution will be about 7.5 m. In the initial stages of the cloud dispersion the firing will necessarily be in a fixed direction but later some scanning in the horizontal or vertical planes will be possible.

The Thorney Island type of experiment is of course only possible when the wind vector is within an angular window whose arc is fixed by the chosen geometry of the sensor array. For a given total number of sensors, the geometry is a compromise between the need for a high spatial density to maximise the 'information content' of an experiment and the need for a wide angular window to minimise the waiting time. Such a decision is not easy. It is helped by the availability of meteorological data over a number of years at the site and by forecasts from predictive models. However, even if the mean wind vector is within the angular window of the sensor array on the chosen day, short-term fluctuations in the wind direction might take the cloud outside or partially outside the window if the timing of the release was ill-judged. Improving the quality of this judgement may be possible by making use of information on the approaching wind structure obtained from an upwind location. This technique, known as eddy forecasting, is being studied for possible application during the Thorney Island trials.

4. Electrical area classification

The major current interest in dense-gas dispersion work is the dispersion of large-scale releases in the atmosphere. However, there are other less well-known topics where it is hoped that the spin-off from the interest generated by the atmospheric dispersion studies will have significant influences on development. The particular example of electrical area classification will be discussed in this Section.

The assessment of major hazards is concerned with hypothetical releases of gas in circumstances that are otherwise safe in everyday experience. There are other circumstances where the presence of a flammable atmosphere is not an unusual occurrence. The need to operate electrical equipment in such a situation, with the attendant risk of igniting the gas, has given rise to the practice of classifying or zoning areas where flammable atmospheres may be present. This classification does not at present rely on quantitative estimates of dispersion distances. The development of such estimation methods presents an interesting problem to fluid mechanics specialists, requiring information not only on the time-mean dispersion behaviour of a dense gas but also on the short-time fluctuations about this mean.

A draft British Standard Code of Practice on the topic has been in preparation for some time [15]. Consideration is being given to the use of the results of a limited investigation [16] carried out 30 years ago on the flammable atmosphere in the vicinity of an aircraft undergoing refuelling. The dispersion relation recommended by Katan is an empirical modification of Sutton's equation [17] for dispersion of a passive material from a point source. It is now accepted that the behaviour of dense gases, particularly the gravitational spreading, cannot be accounted for in this way.

There is a need to achieve a favourable balance between the benefit to safety and the extra cost of the specialised electrical equipment that must be used in the presence of a flammable gas. In the absence of reliable methods of estimating gas dispersion, there can be no reasonable assurance that a favorable balance is being struck. The basis of the current practice will be described. Further details can be found in Schoen [18], Hill [19] and in British Standard 5345 Part 1 [20].

The classification procedure is based on the recognition that in the vicinity of any plant handling a flammable liquid or gas there will be a probability that a flammable atmosphere will exist. The flammable atmosphere could be due, for example, to ever-present causes or to occasional leaks from connections in pipework. The classification of zones surrounding the plant is based on an assessment of the above probability. Thus BS 5345 Part 1 [20] defines three zones:

Zone 0: An area in which a flammable gas-air mixture is continuously present or present for long periods.

Zone 1: An area in which a flammable gas-air mixture is likely to occur in normal operation.

Zone 2: An area in which a flammable gas-air mixture is not likely to occur in normal operation, and if it occurs it will exist only for a short time.

In current practice the extent of the zone is decided by recommended fixed distances for different kinds of plant. For the draft British Standard Code of Practice [15], the possibility is being examined of determining the extent of the zone by first estimating the release rate for identified sources of leakage. The distance to the point where the mean concentration (averaged over a time of 3 minutes) has fallen to the lower flammable limit might then be estimated.

Once the zoning has been defined, the type of electrical equipment that may be used can be decided by reference to BS 5345 Part 1 [20]. Electrical equipment is classified by the protection concepts (i.e. protection against ignition of a flammable gas-air mixture) incorporated in its design. The protection is, in some cases, based on statistical concepts. As a general rule the cost of the equipment increases with the degree of protection, so that there can be considerable economic implications in the zoning decision.

Recent work on the ignition probabilities in methane jets by Birch et al. [21] is of direct interest to this zoning procedure. They showed that the envelope corresponding to the lower flammable limit does not define the flammable boundary for complete ignition of a methane jet. Chatwin [22,23] has discussed this work in the context of dense-gas dispersion. Most flammable gases are denser-than-air so that the work of Chatwin is directly relevant.

It seems only rational to expect that the probabilistic approach practised in the electrical aspects of the problem should be matched by a similar approach in the fluid mechanics aspects.

It is hoped that this discussion of a problem of great practical importance, but perhaps little known to research workers in the field of dense-gas dispersion, will stimulate interest so that the quantitative designation of hazardous zones can be placed on a firmer foundation.

5. Discussion

In relation to both hazard assessment and the conduct of experiments there are a number of dense-gas dispersion topics, not so far mentioned, where developments are desirable.

Models in current use for predicting dense-gas dispersion are concerned with time-averaged effects. This is satisfactory for the case of toxic clouds where information on the human response is so sparse that concentrations averaged over a few minutes are adequate to distinguish levels of effect, especially away from the immediate vicinity of the source. For flammable gases, however, the combustion behaviour depends on the turbulence properties as well as on the time-mean properties. There is still considerable uncertainty concerning the deflagration behaviour of unconfined flammable gas clouds and various suggestions have been made to explain the high turbulent-burning velocities estimated to have occurred in some accidental explosions.

Abdel-Gayed and Bradley [24] have shown in laboratory experiments that the turbulent-burning velocity is proportional to the turbulence intensity in the unburnt gas. The turbulence intensity that might be expected to exist in a dispersing cloud would be too low to provide an explanation. Two mechanisms by which the intensity might be enhanced sufficiently have been suggested. The first of these postulates that the enhancement occurs as a result of the gas flowing around obstacles. Increased turbulence in the wakes of such obstacles (which might be structures in a plant area or topographical features) couples with a combustion feedback mechanism to produce an accelerating flame. Such flame accelerations have been observed in the laboratory by Moen et al. [25]. The second suggestion also postulates a feedback mechanism that occurs in the absence of obstacles. The enhancement of turbulence is attributed to a self-induced buoyancy analogous to that in an atmosphere in unstable equilibrium. The hypothesis is described by Bray and Moss [26].

Both of the above suggestions have obvious implications for dense-gas dispersion work in that they require information on the turbulence levels in the unburnt gas. Workers on the dispersion aspects must therefore widen their perspectives, both as regards the measurement of turbulence in experimental trials and the inclusion of predictions of turbulence distributions in analytical models. The Thorney Island trials will have provision for the measurement of fluctuating velocities and concentrations.

Field experiments on atmospheric dispersion are very expensive. Significant factors in the cost are the high capital cost of a fixed array of gas sensors and the running cost of staff on standby during periods when the wind direction is not aligned with the sensor array. It is highly desirable that this inflexibility should be reduced. Methods of scanning a cloud by remote-sensing instruments provide a promising means of achieving that end, if a limitation of the objectives of the experiment can be accepted. Point measurements with high time resolution can only be obtained by fixed sensors at the present time. However, information on concentration distributions within the cloud, such as could be obtained with a scanning system, would suffice to provide data for validation of predictive models and for evaluating the variability of cloud concentration distribution parameters about their ensemble-averaged values. The spatial resolution and the scanning rate (which would effectively determine the averaging time) vary with the system employed. In addition to the established LIDAR system already mentioned, systems have been developed and described by Gifford [27], Walther [28], Lilienfeld et al. [29] and Santoro et al. [30]. Some of these systems show promise of being very economic by comparison with a fixed array of sensors. An optimum arrangement would be to have a fixed array coupled with one or more scanning systems which might be deployed during standby periods. The optimum design of sensing arrangement would depend, of course, on the balance between the cost of conducting experiments with scanning instruments and the value of the limited information that would be obtained.

Finally, some remarks may be appropriate on a topic that may become of future importance if trends in the passive dispersion field are indicative. This is the controversy that has arisen over the past few years on the method to be used to classify the turbulent state of the lower atmosphere. Predictive models of dense-gas dispersion that are in current use adopt different methods of relating dispersion behaviour to parameters characterising the atmospheric turbulence. For example some box models relate entrainment coefficients to turbulent length and velocity scales which in turn are related to broad ranges of Pasquill stability categories. Others relate distributions of eddy diffusivities to vertical temperature gradients and these in turn are also related to Pasquill stability categories. Clearly if the two different ways of using the Pasquill categories described in these examples do not characterise the same turbulence field, then predictions by the models in a given Pasquill stability condition will not be comparable with each other. For the Thorney Island trials a climatological recording mast has been set up at the trials site in advance of the commencement of the trials. The data from the mast will be used to compare various classification schemes that have been proposed (see for example Sedefian and Bennett [31]). During the trials the local meteorological conditions will be monitored in detail so that any future consensus on the scheme that should be used can most likely be accommodated.

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