THE HSE PROGRAMME OF RESEARCH AND MODEL DEVELOPMENT ON HEAVY GAS DISPERSION

A C Barrell* and J McQuaid**

The major programme of field trials on dispersion of heavy gas clouds organised by HSE at Thorney Island in recent years has received much attention and financial support. However, it is only one part, albeit the most significant part, of HSE's wideranging programme of research and model development on heavy gas dispersion. The programme includes intra-mural and extra-mural work and several projects carried out in collaboration with other organisations. The various parts of the programme are reviewed in this paper. The overall objectives, and the relationship of the individual components to those objectives and to each other, are described. The achievements of the programme to date and the future intentions are discussed.

INTRODUCTION

The estimation of the dispersion of heavier-than-air gases in the atmosphere is an important constituent of procedures for the assessment of major hazards. The need for reliable methods of estimating such dispersion was highlighted in the deliberations of the Health and Safety Commission's Advisory Committee on Major Hazards and in the investigations of risk at Canvey Island carried out by the Safety and Reliability Directorate (SRD) for HSE. These were influential factors in bringing about HSE's major commitment to the improvement of knowledge on the subject. In the early part of the programme, HSE undertook the work entirely on its own account. In recent years, much of the effort has been in collaboration with other organisations, both in the UK and abroad. Throughout the programme, there has been a close involvement of SRD through the Agency Agreement with HSE. The results of the work have been published widely as individual components of the programme have come to fruition. A single, connected account has not previously been given and it is appropriate to do so now, ten years on from the initiation of the programme. This paper will bring together the various facets of the programme. It will show how they relate to each other and will describe the achievements and the prospects from current activities. Much of the work has necessarily been directed towards providing essential scientific information that is not of direct interest to the hazard analyst. While he will wish to be assured that the technology is soundly based, his concern is mainly with the application of the knowledge. The linkages between the scientific investigations and practical problems will be included in the discussion.

* Major Hazards Assessment Unit, Health and Safety Executive,
Magdalen House, Bootle, Merseyside L20 3QZ

** Safety Engineering Laboratory, Health and Safety Executive,
Broad Lane, Sheffield S3 7HQ

THE BASIS OF THE HSE PROGRAMME

HSE has a three-way involvement in heavy gas dispersion work. It needs to be able:

i) to assess the consequences of possible accidents in order to determine broad policy guidelines on the siting of hazardous installations for planning purposes;

ii) to assess the dependability of safety cases prepared by operators of installations in their submissions under the CIMAH Regulations (Health and Safety Commission) (1984)), and,

iii) to relate the available evidence following actual accidents to postulated sequences of events, part of which may involve calculations of dispersion behaviour.

For each of these activities, it is necessary to have available expertise on the latest technology and methods of estimating dispersion that are acceptable representations of the current state of knowledge. If there are serious deficiencies in knowledge, the task of encouraging improvements falls naturally to HSE, given that the subject is of wideranging importance and crosses industry boundaries. Such a situation was identified by the ACMH at an early stage and they requested HSE to institute a programme of research on the behaviour of large-scale releases of heavy gases to the atmosphere. HSE (through the Safety in Mines Research Establishment) had previously been engaged on related research on the effects of negative buoyancy on turbulent mixing. This work had been pursued in the context of the layering of methane in coal mine roadways. It is of interest that results from this work (McQuaid (1976)) have proved useful in the development and validation of mathematical models of heavy gas dispersion in the atmosphere (Colenbrander (1980), Havens (1984)).

The objectives adopted by HSE for the programme were, broadly, to improve the database and thereby to reduce the uncertainties in methods of estimation. In addition, it was desirable that, as far as possible, a consensus amongst users should be achieved (Barrell (1980)). A programme was formulated within that framework. It was recognised that it would be a long-term effort, if only because of the high cost of the research. In the short term, the effort was directed to developing mathematical models based on existing technology to meet the immediate needs such as the Canvey Island investigation and to instituting a programme of preliminary field experiments. Both activities were seen as leading to a closer identification of the problem areas for further work. In the longer term, it was recognised that progress would best be achieved by collaborating with other organisations, once HSE had 'primed the pump'. A detailed discussion of the relationship of the experimental part of the programme to previous work has been given in McQuaid (1979).

THE COMPONENTS OF THE PROGRAMME

Rather than present a straight chronological account, it is more useful to consider the contributions of the individual components to the achievement of the broad objectives described above. The programme is still in progress and, where appropriate, reference is also made to current and planned work. There are inevitably areas which have not been included. Some of these have, of course, been the subject of investigation by other organisations. The topics of significance that remain to be investigated will be considered in a later Section.

Improvement of the Database

At the inception of the programme, the need for reliable dispersion data, especially at large scale, was recognised as a first priority. The form of experiment that was chosen was the instantaneous release of a fixed volume of heavy gas at atmospheric temperature and pressure. The reasons for this choice have been described by McQuaid (1979). The first programme was contracted to the Chemical Defence Establishment (CDE), Porton Down and 42 trials were conducted between 1976 and 1978. The results have been described by Picknett (1981). The Porton Down trials were conceived as preliminary medium-scale field trials, in preparation for the large-scale trials that were judged to be necessary. The trials studied the dispersion of 40 m^3 clouds of gas under a variety of weather and site conditions. They led to the trials of the same design carried out at Thorney Island, West Sussex, between 1982 and 1984. In these trials, the volume of gas released was increased to 2000 m^3. Whilst the Porton Down trials were financed by HSE, the Thorney Island trials were carried out as a multi-sponsored project (called the Heavy Gas Dispersion Trials or HGDT project). NMI Ltd was the principal contractor and the finance (totalling £1.7 m) was provided by a consortium of 38 organisations besides HSE. The various facets of the trials and preliminary analyses of the data have been described in the proceedings of a symposium held in April 1984 (McQuaid (1985)). The trials were originally restricted to the study of dispersion over uniform, unobstructed ground. They were extended to include trials in which the effects of several types of obstruction were studied. In a further extension, the basic design of experiment was changed from an instantaneous to a continuous release mode. The organisation of the project has been described by Johnston (1984).

In total, 29 trials were performed. The data obtained are very comprehensive, including concentration, turbulence and visual records of the clouds and detailed meteorological information. Up to 100 gas sensor records were obtained in individual trials, at distances up to 750 m from the release point. A film of the trials is available (Health and Safety Executive (1982)) which describes the trials' site and instrumentation and illustrates the behaviour of a cloud following release. The availability of the data from the trials was restricted to the project sponsors for a period but they have now been released; details are given by Roebuck (1985). The analyses of the results that have been performed to date indicate, for the unobstructed case, that they can be described by existing modelling techniques and that they are consistent with the results at smaller scales from the Porton Down trials and wind tunnel simulations. The results of the trials with obstructions have not been analysed in detail. They do, however, indicate some marked effects of the obstructions on the concentration distribution and the data will be particularly valuable for developing and validating mathematical and physical models of the phenomena. Similarly, the results of the continuous release trials have not yet been analysed but again the data obtained are very comprehensive and valuable.

The contract with HGDT project sponsors made the facilities at Thorney Island available to any of the sponsors wishing to carry out measurements of their own design during the performance of a trial. In the event, HSE was the only organisation to take advantage of the opportunity. HSE designed an experiment to evaluate the utility of a form of remote sensing using an array of still cameras. The cameras were placed on the periphery of a circle of 700 m diameter and pointed at a fixed position in the path of the cloud. The cameras provided a series of simultaneous photographs which will be analysed to produce a mapping of the evolving outline of the smoke-marked cloud during the period when the cloud is opaque. It is hoped that the records at later times, when the cloud has become semi-transparent, can be used to determine details of the internal structure by an optical tomographic technique. Records were obtained in 7 of the trials without obstructions and in 3 of the trials with obstructions. The experiment provided a separate and low-cost data capture system supplementing the array of concentration sensors. These sensors were necessarily at fixed positions and their usefulness depended on the cloud being advected over them by the wind. The photographic technique, if analysis of the results shows it to be successful, will be of considerable value in future field trials in compensating for any loss of sensor data due to poor alignment with the wind direction at the time of release.

Two further projects separate from the HGDT project were arranged by HSE. They made use of the Thorney Island site facilities and NMI Ltd was again the principal contractor. In the first, the US Department of Transportation (DoT) commissioned a series of trials in which gas was released continuously into a fenced enclosure. The enclosure surrounded the gas container used in the HGDT project, the container serving as a storage tank from which the gas was withdrawn by a fan. The purpose of the experiments was to determine the effect on the concentration distribution of holdup of the gas within the fenced area. Experiments were carried out over a range of windspeeds and initial relative densities. The role of HSE was to act as the contractual link between DoT and NMI Ltd, to provide the gas sensing system and to validate the concentration data. Publication of the results of these trials will be handled by DoT.

The second project arose from a collaboration between the US Gas Research Institute (GRI) and several other organisations to fund a study on the evaluation of 3-dimensional predictive models of heavy gas dispersion. The study is being carried out by Professor J A Havens at the University of Arkansas. HSE, in concert with the UK Departments of Energy and Transport, enlisted as a sponsor of the project. A special arrangement was agreed with GRI whereby the input was to be in the form of the results from a trial commissioned at Thorney Island. The trial was of the same design as in the HGDT series without obstructions. It was conducted at very low windspeed (less than 1 m/s) and provided necessary data for the model evaluation study.

In addition to its direct involvement in the various projects at Thorney Island, HSE has participated in a multi-sponsored project in the US on dispersion of large-scale releases of liquified ammonia. The project was organised by the US Coast Guard and the Fertiliser Institute, with additional funding from European sources. It resulted in 4 trials performed at the US Department of Energy's Nevada test site in August 1983 following earlier unsuccessful attempts at the Naval Weapons Center at China Lake, California. The details of the trials have been described by Koopman (1984). The objective was to study the conditions under which a release of pressurised, liquified ammonia would form a heavier-than-air mixture of ammonia and air and its subsequent dispersion. The circumstances under which such a mixture can be formed had been considered theoretically by Haddock and Williams (1978) and Griffiths and Kaiser (1979, 1982). This work had been done at SRD as part of the background support to the Canvey Island investigation and participation in the US programme was clearly advantageous to HSE in encouraging the acquisition of the data needed to check the theoretical predictions.

At the present time, HSE is not involved in any field experiments on heavy gas dispersion. The intense activity over the past few years has resulted in a large amount of data whose implications for modelling now need to be considered. In addition to the programmes in which HSE has participated, there have also been extensive investigations of liquified gas spills by Shell at Maplin Sands (Puttock et al (1982)) and by the US Department of Energy at China

Lake (Ermak et al (1982)). It will undoubtedly take some years before the data from all the trials have been digested. Experimental effort in the meantime is most likely to be concentrated at wind-tunnel scale, once the scaling rules have been satisfactorily established from the large-scale field data. This is not to say that all problems can be solved at wind-tunnel scale; for some this is a theoretical impossibility (see for example McQuaid (1982)). HSE, in common with other organisations, will be examining the extensive database that now exists to identify whether any significant deficiencies remain.

Development and Validation of Mathematical Models

HSE development of working methods for hazard assessment has concentrated on the simplified box model originally formulated by Van Ulden (1974) and Cox and Roe (1977). These formed the basis of the DENZ and CRUNCH Computer codes developed at SRD which have been the mainstay of HSE hazard assessment work for the past few years. The DENZ code (Fryer and Kaiser (1979)) applies to instantaneous releases whilst the CRUNCH code (Jagger (1983)) applies to continuous releases. The DENZ code predated the Porton Down trials and the results of those trials have since been used to revise the entrainment coefficients originally incorporated in the model (Jagger (1984)). In recent years, the physical model in the codes has been further developed. This work was carried out by SRD under a contract with the Commission of the European Communities (Webber (1983), Wheatley and Webber (1984)). The incorporation of the improved model in a revision of the DENZ and CRUNCH codes for HSE use and the validation of the code using the Thorney Island and other data are currently in progress at SRD. The preliminary processing of the Thorney Island data for the latter purpose has been described by Brighton et al (1985) and Brighton (1985).

Besides the box model, there are in existence a number of more complex models based either on the 3-dimensional conservation equations or depth-averaged forms of these equations. The various models have been reviewed by Blackmore et al (1982) and Havens (1982). The merits of the box model compared to the more complex formulations have been discussed by McQuaid (1984a). HSE considers that its current needs do not justify the substantial effort required to develop its own 3-dimensional code. Not only is the initial development of a code to a user-friendly state very costly but so also is its continuing maintenance and updating and the expenditure of staff effort needed to make best use of it. A review of turbulence models was commissioned from SRD and this has been reported by Farmer (1982). This led to the preliminary formulation of a model (Jagger (1982)) but no further development of this model has been undertaken. In recent years, HSE has adopted a watching brief in this area. Current activities are concentrated on the objective assessment of the validation techniques used by the developers of codes and the development of rigorous benchmark tests for codes. The participation in the GRI project referred to earlier is directly in line with this policy. There are a number of proprietary codes available and HSE's need is primarily to be in a position to judge their reliability rather than having its own in-house code. The objective assessment of complex codes is itself a considerable undertaking and in this area the need for consensus between developers and users of codes is of paramount importance. In the related subject of complex codes for aerodynamic purposes, it has been found necessary to organise an international exercise in which the many available codes are independently assessed against agreed benchmark tests (Kline et al (1981)). It remains to be seen whether a similar exercise will be required for complex codes for prediction of heavy gas dispersion.

Validation of Physical Models

Physical modelling of heavy gas dispersion in wind or water tunnels offers advantages over field experiments (which are themselves small-scale models of releases that might occur in accidents). They are much more economical and they allow closer control over the ambient flow conditions. The instrumentation does not have to be designed to withstand a harsh environment for a long period. The experiments can be replicated, allowing flexibility in the choice and range of instrumentation compared to a field experiment. The latter is essentially a one-off exercise where the whole data capture system has to be deployed each time. Physical models are capable, in principle, of simulating special situations which would be difficult, if not impossible, to study at field scale or to model using available mathematical and numerical techniques. These include, for example, the effects of complex terrain or groups of buildings. These advantages can only be realised if there is confidence that similarity is preserved between the model and full scales. There are fundamental restrictions on the ability to scale all the parameters that influence heavy gas dispersion and some sacrifices have to be accepted. The resulting uncertainties have first to be investigated before physical modelling can be accepted as a predictive tool. HSE effort has concentrated on such an investigation, making use of the field data from the Porton Down and Thorney Island trials. Indeed, the acquisition of data for the purpose of validating physical models was a prime objective of the field trials. The investigation was undertaken following the Porton Down trials but prior to those at Thorney Island. Subsequently, the wind tunnel experiments were compared with the Thorney Island trials when the data from them became available. The work has been performed at the Warren Spring Laboratory (WSL). It has been extensively reported (Hall et al (1982, 1984), Hall and Waters (1984, 1985)) and only the main results will be summarised here.

A choice of 6 trials for wind tunnel simulation was made from the 42 trials of the Porton Down series. The choice was on the basis of the quality of the field data and the need to cover a wide range of windspeed and initial relative density. It was restricted by the limitation that the WSL wind tunnel could only model a neutrally-stable atmospheric flow. The scaling criteria used in most of the experiments were equality of both the initial relative density ratio and the Froude number ($= U/(gL)^{\frac{1}{2}}$ where U is the reference wind velocity, g is gravitational acceleration and L is the length scale). Model windspeeds were maintained above the minimum practical limit by the choice of a relatively large model scale of 1/25.

The alternative approach to overcoming the low windspeed limitation in a wind tunnel is to adopt equality of the Richardson number as the sole scaling criterion. The Richardson number combines the Froude number and the initial relative density ratio. It therefore allows a trade-off to be made between the gas density and the windspeed in the model. The validity of this alternative, which is known as the Boussinesq approximation, had not been established for other than flows with small density differences of the order of a few per cent, such as prevail in naturally occurring flows. A number of the WSL experiments were repeated using higher gas densities and windspeeds to produce equivalent Richardson number models in order to test the validity of the Boussinesq approximation.

In the experiments, data were collected to define the shape and position of the cloud at different times and the concentrations within it. The general conclusion drawn was that the wind tunnel model produced gas clouds which were closely similar to the field experiments in terms of size, shape, spread rates and downwind travel distances. The smoke-marked model clouds also showed a strong visual similarity to the field experiments. The agreement between model and field measurements of concentration was within a factor of 2 or 3 for the more reliable of the field tests. A difficulty in performing comparisons of concentration measurements was the variability between repeat runs. Each of the model experiments was repeated three times and it was observed that the variability was highest for experiments at low Richardson number ie with the smallest negative buoyancy effects. To gain a better understanding of variability levels, large numbers of multiple runs were performed in two cases, one in still air and the other at low Froude number. In the still air case, where 7 runs were made, there was approximately a 30% variation between the largest and smallest concentration. In the other case, for which 20 runs were made, the smallest concentration differed from the largest by almost an order of magnitude. Possible reasons have been suggested by Hall et al (1982). The problem of variability has been the subject of a separate investigation in the HSE programme and will be discussed later.

To investigate the validity of Richardson number scaling, Hall et al repeated some of the simulations performed using Froude number scaling in the main series. They used the greatest available initial density with their test gas (ie 5.74 times that of air) and appropriately adjusted windspeeds. The experiments showed that Richardson number scaling using quite extreme changes in initial density had no significant effect on the size and shape of the gas cloud or its concentration field, at least within the range of experimental parameters examined. They also studied the effect of surface roughness using a much increased aerodynamic roughness height, equivalent to 1.5 m at full scale, compared to the range of 2 to 20 mm in the main series of simulations. With the increased roughness height, the roughness elements were typically about half the depth of the main body of the gas cloud. It was found that the change had a small effect on the gas cloud but the differences could be explained in terms of the changed mean velocities and turbulence levels in the airflow rather than any particular effect due to the presence of the surface roughness elements themselves.

Because of the timing of the WSL project, the simulations of trials in the HGDT project necessarily had to rely on proposed rather than actual conditions. The model scale was 1/40. The subsequent comparisons with trials selected from those actually performed have been reported by Hall and Waters (1984, 1985). In general, the agreement observed for the Porton Down trials was sustained.

The work carried out at WSL has confirmed the validity of physical modelling for dispersion over uniform and unobstructed ground. The technique can thus be used with confidence to investigate effects not readily investigated in the field, such as the influence of the initial shape of the cloud on its subsequent spreading and dispersion. It will also be possible to investigate the effects of low Reynolds number. Such effects may be expected to become important at the small model scales that are necessary to accommodate models of actual installations and their surroundings. The modelling of dispersion in the presence of significant obstructions (ie with a height greater than the depth of the cloud, as was the case in the Thorney Island trials with obstructions) has still to be investigated systematically. A preliminary study has been carried out for HSE by Rottman, Simpson, Hunt and Britter (1985) to be discussed later. Wind tunnel experiments were performed by NMI Ltd as part of the pretrials planning of the HGDT project and some results are quoted by Davies and Singh (1985a). Some of the HGDT project sponsors with wind or water tunnel facilities will be undertaking their own investigations over the next few years. The quality and detail of the results and the variety of conditions covered in the Thorney Island trials provide excellent data for the validation of physical models incorporating obstructions. HSE will be undertaking some limited studies but the details of these have not yet been finalised.

Achievement of Consensus on Data Interpretation

Reference has already been made to the desirability of achieving a consensus on the validation of mathematical and physical models. The first requirement towards this end was the acquisition of data that are accepted as reliable and trustworthy. The philosophy adopted so far by HSE has been to defer the active pursuit of a consensus and instead to direct effort towards removing possible bones of contention that would inhibit the emergence of that consensus. HSE now has a considerable investment in the Porton Down and WSL databases and, with its partnering sponsors, in the Thorney Island database. It is in everyone's interest that the data are not misinterpreted and that any factors that might lead to such misinterpretation are rigorously examined rather than left as questionmarks. Several such factors were highlighted in discussions of the results of the Porton Down trials, including the initial effects peculiar to the release configuration and the effect of variability between trials. Over the past few years, HSE has carried out a number of studies, both theoretical and experimental, intended to support the chosen design of field and wind tunnel experiments. These studies will be briefly reviewed to show how they relate to the main work.

The Physics of Fixed-Volume Instantaneous Releases - The modelling of the fixed-volume instantaneous release requires the specification of the initial conditions and of the manner in which the dispersion progresses through the gravity - influenced to the passive regime. The description of the physical processes involved in accelerating the initially stationary cloud, the entrainment of ambient air into the cloud and the detrainment of gas from the cloud to the air, together with the derivation of associated theoretical frameworks have been and continue to be subjects of study at the University of Cambridge. Supporting evidence has been obtained from small-scale experiments in water channels and the work has drawn extensively on previous work at Cambridge on the motion and mixing of gravity current fronts.

The overall framework is described in Hunt, Rottman and Britter (1984) and divides the evolution of the cloud into four phases, depending on the physical processes that are dominant at different times after release. In the first phase, the cloud motion is strongly dependent on the release conditions, in particular on the initial Richardson number. The motion in this phase was analysed numerically and experimentally and the results have been described in Rottman and Simpson (1984) and Rottman, Hunt and Mercer (1985). The results of the work are in excellent agreement with the observations in the field experiments.

The initial motion progresses to a second phase when the motion has become primarily horizontal. This gravity-spreading phase has been analysed for both zero and non-zero ambient flow velocities. The axisymmetric case without an ambient flow was investigated theoretically by Grundy and Rottman (1985) and they showed experimentally that the front position increases as the square root of the time from release, in accordance with the predictions. Where the gravity spreading occurs in the presence of an ambient flow, it is known from the field experiments that the upwind and downwind fronts of the cloud have very different shapes. The differences in shape and the effects on the cloud motion and mixing are discussed by Rottman, Hunt and Mercer (1985).

In the third phase, called the nearly-passive phase, the gravity spreading is much reduced and the turbulence in the ambient atmospheric flow contributes significantly to the mixing of the cloud. The physical processes occurring in this phase are considered in Hunt, Rottman and Britter (1984). Amongst the questions of interest to modellers are the conditions under which the turbulence tends to sharpen or diffuse the density interface and the possible differences that might exist between the interfacial mixing in an isolated cloud (from an instantaneous release) and a plume (from a continous release). Work in this area is continuing.

The fourth phase is that where the dispersion is passive and is described by any of the well-known prescriptions.

A second investigation in this area was carried out at the University of Liverpool by Chatwin (1983, 1984) on some possible effects of wind shear on dispersion of clouds. He estimated the enhanced mixing that would result from Taylor dispersion (Taylor (1954)) and from the increased cloud surface area due to the leaning over of the cloud. He concluded that the effects of the first did not contribute significantly to the mixing of the cloud. The second factor appreciably changed the total rate of entrainment through the edge of the cloud and could readily be incorporated into a simple box model, if necessary. This was only likely to be the case in the early stages of dispersion before top entrainment becomes the dominant dilution mechanism.

The Statistics of Fixed-Volume Instantaneous Releases - For an instantaneous release experiment, the concentration recorded at a point is highly non-stationary due to the limited duration of cloud presence. The concentration records in the Thorney Island trials characteristically show, in the near field, a rapid rise to a sharp peak as the cloud front reaches the point. Thereafter, there is a complicated return to zero concentration as the cloud drifts away. In the far field, the peak is much less pronounced, but a strong dependence on time is still evident. This behaviour causes problems in comparing the results with predictions. Although mathematical models predict time-average concentrations, it is not always made clear what averaging time should be used in comparing predictions with experiment. For the Thorney Island data, substantial reductions in concentration and particularly in the peak value are obtained as the averaging time is increased above the response time of the sensors (which was around 1 sec). The effect has been investigated by Nussey et al (1985) as part of HSE's intramural programme. They presented the results of a statistical analysis of numerically applying different averaging times to the concentration data. The results provide valuable guidance to modellers.

Clouds released in nominally similar atmospheric conditions (defined by time averages of atmospheric turbulence statistics over 10 minutes) may be expected to exhibit differences in behaviour as an inevitable consequence of the turbulence in the atmosphere. It is obviously necessary to consider the implications when making comparisons of data with models. If a difference exists between the predictions of a model (which conventionally will refer to the mean behaviour over an ensemble of experiments) and the results of an individual experiment, the question arises as to whether this is due to a deficiency in the model or to the random spread about the ensemble mean that would be expected from variability. A theoretical review of this fundamental problem was carried out by Chatwin (1982a, b). The investigation of variability in the Thorney Island experiments is continuing (Carn and Chatwin (1985)). It should be noted that the problem of variability is likely to be less pronounced for heavy gas clouds than for passive clouds, since the inertia of the cloud will attenuate the response of the cloud to the perturbations imposed by large-scale atmospheric motions.

The Mitigation of Heavy Gas Hazards

The major part of HSE's programme has been formulated on the basis of satisfying the information needs identified earlier. It is also important, however, to be able to assess the effects of factors or measures that may mitigate the hazard by reducing the dispersion distance beyond which a heavy gas release may be regarded as no longer hazardous. The two principal items that have been investigated are obstructions or topographical features and water spray barriers. The most relevant application is to releases of flammable gases. With toxic gases, the hazardous concentration levels are generally several orders of magnitude less than for flammable gases. Dispersion distances to safe levels are correspondingly greater and are much less dependent on the conditions at or near the release point. Some further remarks will be made on this aspect later in the paper. It should also be stated that mitigation will be interpreted as referring to a reduction in the distance to a given concentration level. This is achieved by additional mixing with the ambient atmosphere, whether by the high turbulence levels in the wake of an obstruction or by turbulent entrainment by a water spray. For a flammable gas, such mixing may enhance the hazard since, if ignition occurs, the possibilities of high turbulence levels and a premixed cloud would be conducive to high flame speeds. Such considerations will be excluded from the present discussion.

Obstructions and Topography - As a preliminary to deciding on the research that was necessary, a comprehensive review of available information was comissioned from Dr R E Britter of the University of Cambridge. The report on the review (Britter (1982)) discussed the influence of obstructions and topographical features of various scales relative to the scale of the gas cloud. The obstructions considered were buildings, two-dimensional fences and screens of trees. The report provided guidance on parameter spaces within which particular effects would be observed. These effects included, for example, the blockage of a density stratified flow by a two-dimensional fence. The report was valuable in the discussions leading to the trials with obstructions carried out at Thorney Island and the design of the obstructions took account of the guidelines. In the trials, three types of obstruction were included - a 5 m high fence, a 10 m high series of permeable screens to simulate a tree line and an isolated building approximately 9 m cubed. There were, respectively, 4, 2 and 4 trials performed and in one of the trials, the building was upwind of the release point. There was no attempt made to perform parametric studies for each obstruction but rather to obtain a reliable dataset with which models, particularly physical models, could be validated. The results of the trials were in general accordance with expectations in relation to the occurrence of particular physical effects and to the reductions in concentration achievable in the far field (which in this case extended to 500 m from the release point).

In the Thorney Island trials with obstructions, the flow was a transient cloud of heavy gas and therefore differed from the steady layered flow on which the design of the obstructions had been based. In particular, the interaction of the front of the cloud and the fence took the form of an initial splash to a height of around 3 times the fence height followed by a blockage or partial blockage of the main bulk of the cloud. In order to elaborate on the differences between the instantaneous and steady flows, some small-scale experiments in a water channel and supporting analysis using two-dimensional hydraulic theory were carried out at Cambridge. The results are given in Rottman, Simpson, Hunt and Britter (1985). The laboratory experiments confirmed the predictions relating to the effect of the fence on the depth of the bulk of the heavy fluid. The work also included the application of the theory of steady stratified flow to the case of the isolated building and of hydraulic theory to the flow through the permeable screens. Laboratory experiments were carried out on the latter problem and these confirmed the prediction that the depth of the flow decreases as it passes through the screens. A comparison has not as yet been carried out of this work and the results of the field tests but the qualitative descriptions are consistent with the observations. The study has provided physical arguments and supporting analysis for types of behaviour that will be encountered and these will be a valuable input to predictive models. The incorporation of allowances for the effects of simple obstructions into predictive models is a necessary step and forms part of HSE's future programme.

Water Spray Barriers - Work on the effects of water spray barriers was carried out as part of HSE's intra-mural research programme and has now been completed. The application of water spray barriers to the dispersion of gas plumes was reviewed by McQuaid and Moodie (1983) and the results of full-scale trials on the effectiveness of different barrier designs have been given by Moodie (1981, 1984). The technique is clearly inappropriate for instantaneous or short-term releases and there are practical limitations on the size of release for which a water spray barrier would confer worthwhile benefit. They are useful for controlling smaller-scale (up to several kg/sec) steady releases and there are many recorded instances of their value. An assessment of the effect of a water spray barrier on the concentration distribution in a steady plume was carried out by McQuaid and Fitzpatrick (1983). The assessment was based on the combination of the CRUNCH computer code and a simple model of a water spray barrier. Sample calculations showed that the change in concentration induced by the spray barrier diminished quite rapidly with distance downwind. This is in accordance with the limited memory of a turbulent flow. A change in flow conditions near the release point is manifested to an observer downwind as an apparent change in the location of the release point ie the plume appears to originate from a virtual origin. The displacement of the origin becomes a smaller proportion of the travel distance as the observer moves downwind and so the relative change in concentration becomes smaller also. It is for this reason that water spray barriers deployed near the release point will not confer much benefit at the considerable dispersion distances appropriate to highly toxic gases. Furthermore, for flammable gas plumes the effectiveness of a water spray barrier is obviously an optimum when it reduces the concentration to below the lower flammable limit. This should be the aim wherever possible and the results of the investigation reported by Moodie (1984) provide an appropriate design basis.

Technology Transfer

Hazard assessment is a wide field, embracing many technologies, and practitioners must have access to working methods that they can understand and apply without ambiguity. The limitations imposed by simplifications or approximations should be clearly identified whilst at the same time the methods should have a firm scientific foundation. Much of the work described so far is geared to providing that foundation. For everyday applications, the needs of HSE are no different to those of industry. Specialist resources are limited and the casework and policy formation has to be undertaken by practitioners who cannot be expected to be informed on all the complexities across the whole field of hazard assessment. There is thus a need, common to both HSE and industry, for readily applicable methods of estimation such as have existed for dispersion of passive materials for a number of years. The working methods need to be kept up-to-date and appropriate research commissioned as new problems are identified. The close connection between researchers and users in both HSE and SRD ensures that research is firmly linked to practical needs.

There is, of course, a limit to the degree to which the simplification of procedures can be carried without risk of misapplication. It is essential that any simplifications are derived by those who are knowledgeable of the consequences. The work at SRD is firmly directed towards producing computer codes that are usable by the intelligent but not highly specialised practitioner. The DENZ and CRUNCH codes are in that category. For restricted applications, the results produced by the codes can be further simplified for routine use and the work reported elsewhere at this Symposium by Pape and Nussey (1985) exemplifies that approach.

However, it is recognised that familiarity with computerised techniques is a step towards specialisation that may not always be either desirable or necessary. The thought was well expressed by Britter and Griffiths (1982) who stated:

> 'Nevertheless with the many models [of heavy gas dispersion] presently available, the existence of nearly a decade's worth of laboratory experiments in several facilities and the increasing availability of field results, the time is opportune for the assembly of a "work-book" similar to those existing for the dispersion of passive contaminants. Such a "work-book" would, presently, have wide uncertainty limits, but still provide a useful initial screening technique, particularly for users considering a more detailed investigation'.

The preparation of such a work-book is being undertaken by Dr R E Britter in collaboration with HSE. The objective is to provide the intelligent, but probably not well-informed, user with guidelines on calculating the dispersion of heavy gases. It is intended that the work-book will be constructed in such a way that uncertainties are explicitly stated and that it can be easily updated as further information becomes available. The timetable envisages the completion of the first edition of the work-book during 1985.

CURRENT NEEDS

Although this paper is primarily concerned with the extant HSE programme on heavy gas dispersion, it would not be complete without reference to topics that remain to be tackled. The following listing is indicative of currently perceived priorities. It is not intended to be exhaustive. Some of the topics may become redundant, being dependent on the outcome of current work.

The Connection with the Source Term

The programme that has been described was based on the premise that the source term, describing the cloud formation phase, could be separated from the dispersion phase. The reasoning behind that has been described by McQuaid (1979). There has been considerable effort on the specification of the source term concurrently with the work on dispersion. Laboratory experiments on the quantities and rates of release of a superheated liquid from breaches both above and below the liquid level have been carried out by Fletcher (1982, 1984). This work has complemented the programme of the Design Institute for Emergency Relief Systems (DIERS) described by Swift et al (1983), in which HSE has participated. At SRD, the dynamics of an expanding two-phase cloud have been analysed by Jagger and Kaiser (1980), while reviews of underexpanded gas jets and two-phase flashing jets have been reported by Ramskill (1984) and Appleton (1984) respectively. The spreading and evaporation of liquid pools have been analysed by Webber and Brighton (1984) and this work is continuing. The interfacing of the results of these various topic studies with dispersion models will be a logical requirement in the forward programme.

Time-Dependency of the Source Term

It will be clear from the last paragraph that some of the sources that are of interest cannot be classified as either instantaneous or continuous. The dispersion programme has concentrated, for good reasons, on the instantaneous source, although some experiments on continuous releases were performed at Thorney Island. It is conventional to model a continuous release as the integrated effect of a succession of instantaneous releases, a device carried over from models of passive dispersion. The validity of this procedure for heavy gases has not been rigorously examined and it has recently been questioned (McQuaid (1984), Hunt, Rottman and Britter (1984)). Source terms with a varying release rate, or a release rate which is maintained for only a short time compared to the travel time, provide added complexity. The first requirement will be for a screening procedure that will identify when the idealised instantaneous or continuous sources are acceptable representations.

Non-Isothermal Releases

The role of heat transfer from the ground to a cold gas is not yet satisfactorily resolved. However, there are now in existence the isothermal data from the Thorney Island trials and non-isothermal data from the Maplin Sands and China Lake trials. These should serve to clarify whether the large differences in dispersion behaviour attributed to cold gas effects (Fay (1984)) are a reality.

Physical Modelling

The status of the technique has been discussed earlier in the light of the WSL studies. The lack of facilities for modelling atmospheric stability should not pose a restriction. Much understanding of the problems identified earlier can be gained in wind tunnels capable of simulating only a neutrally-stable flow. The evidence from the Thorney Island trials is that atmospheric stability appears to have a much less important effect on heavy gas dispersion compared to passive dispersion. This only applies, of course, over the dispersion distances (suitably scaled) covered by the trials. A heavy gas release will ultimately become as sensitive to stability as a release that is passive from the source.

Co-ordination of Analysis

It is clearly inefficient for many organisations to duplicate effort on the analysis of data. This is especially so for the Thorney Island trials where a large number of the sponsors have acquired the full database in the form of the magnetic tape records of the trials. The number may be expected to increase further as the data become generally available. HSE has made some effort to co-ordinate data analysis (Roebuck (1985)) and some informal arrangements have already been agreed. However, a more organised effort is clearly warranted and should result from the forward programme of the European Commission to be discussed below.

Specification of Meteorological Conditions

Hazard assessments have to take account of the probabilities of occurrence of different weather conditions at the location of interest. The weather conditions are usually specified in terms of easily assessed measures of the dispersive properties of the atmosphere, for example, a reference windspeed and a stability category according to a scheme such as that of Pasquill (1961). The evidence from the meteorological measurements made at Thorney Island is that it is particularly difficult to get a consensus between the various schemes as to the 'stability' of the atmosphere. The measurements and the conclusions from them are discussed in detail by Davies and Singh (1985b) and McQuaid and Roebuck (1985). To offset this difficulty, there is the relative insensitivity of the Thorney Island results to stability, however defined. In any case, the main thrust of developments to improve the classification of stability will take place for the purpose of passive dispersion modelling.

CONCLUDING REMARKS

The programme described in this paper has not been carried out in isolation. Throughout, contacts have been maintained with other organisations working in the field. One of the most productive of these liaisons, probably not well known in the chemical industry, has been fostered by the Commission of the European Communities in its programme on Nuclear Power Plant Safety. This included an Indirect Action or Shared Cost Programme on Gas Cloud Explosions. The HGDT project received substantial support from the programme. Indeed, it was the largest project in the programme and the CEC made the largest contribution to the cost. The model development work (and also that on development of gas cloud explosion codes) at SRD also benefitted. The programme was completed in 1984 and the results have recently been presented at a Seminar (Commission of the European Communities (1984)). Of particular relevance to Major Hazards work is that the Commission is currently considering an Indirect Action Programme on Industrial Risk to run for 4 years from 1985. This will complement a Direct Action Programme already agreed at the Commission's Joint Research Centre at Ispra. It therefore seems likely that the momentum of the last few years on research on heavy gas dispersion and other aspects of hazard assessment will be maintained, to the benefit of industry and the public.

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