THE DANGERS OF GRATING FLOORS: DISPERSION AND EXPLOSION

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This paper describes a series of numerical simulations which explore the potential dangers of grating floors in partially enclosed process operations which involve flammable fluids. The circumstances which are being investigated involve the spill of a liquid or two-phase fluid below the grating which provides the source of vapour which will mix with air to form a potentially explosive vapour cloud.

The only realistic technique available for the analysis of this complex situation is Computational Fluid Dynamics (CFD). However, there are limitations to the use of this technique and this paper examines these very carefully.

The work described in this paper provides lessons to he learnt about possible hazardous situations and about the pitfalls and difficulties which may be met in the employment of highly sophisticated techniques for their analysis.

Keywords: Safety, gratings, flow, dispersion, combustion, C.F.D.

INTRODUCTION

The evaluation of safety of operations which handle flammable materials has traditionally been factored into components, for example, release of flammable material, dispersion of that material, ignition leading to combustion whereby the loss is sustained by damage. However, even within this formalised structure, there are so many variations of possible circumstances that much of the understanding of safety issues follows from the analysis of experience rather than the synthesis of potential scenarios. The purpose of this paper is to demonstrate, using a specific instance, how observations from evidence of eyewitnesses to an accident involving fire/explosion of a release of hydrocarbon can lead to a new view of potential dangers. The approach is, of course, not a novel one since all accident investigations attempt to conclude their inquiries with a number of lessons which the industry should learn but the lesson in this case is new and it is hoped that the way in which the analysis of the experience is developed provides guidelines to the use of a combination of simple concepts of the basic phenomena involved and the subsequent use sophisticated tools to simulated their behaviour.

The accident under consideration is the fire on the offshore platform Piper Alpha on July 6th 1988. The evidence relevant to the present paper involves two areas which were of real concern to the Inquiry held subsequent to the accident by Lord Cullen. The first of these areas relates to the evidence of the only witness to observe the commencement of the explosion itself and involves the description of a precursor flame which spread across the end of the platform just before the witness felt the blast from the explosion. The other area of evidence relates to the absence of alarms from gas sensors which were located in the body of one of the process modules on the platform.

The Inquiry held by Lord Cullen culminated in a report, now known as the Cullen Report, which reached certain conclusions as to how the accident occurred. Subsequent litigation lead to a further examination of the evidence and the judgement at the end of this hearing was in general agreement with these conclusions. It is not our intention to suggest that the wrong conclusions concerning causation were reached but to show how the evidence can be attributed to an alternative explanation which in turn can provide useful lessons which were not identified in the Cullen Report.

EVIDENCE

The Piper Alpha platform is shown diagrammatically in Figure 1 as both plan (1a) and the east elevation (1b). It consists of a tubular steel structure standing on the sea bed and protruding some 68 feet above sea level. The platform was used for drilling wells and as a production platform. Oil production was handled in a number of modules on the 84ft level and the 107ft level. Eyewitness evidence lead the Inquiry to believe that the fire which eventually destroyed the platform was initiated by an explosion in one of two process modules, either Module B or Module C. These modules, are identified in the diagram together with Module A, which enclosed the terminations of the risers from the many production wells, and Module D, which contained the control room, various maintenance workshops and the power unit for the platform.

Module B was employed mainly in the processing of the well fluids which involved the separation of water and gas from the crude oil, the metering of the oil and pumping of the oil into the main oil line to the shore facilities. Module C dealt in the main with processing of the gas stream which to a large extent involved compression in two electrically powered reciprocating compressors and three centrifugal compressors powered by gas turbines. Normally, some of this gas was exported, some was used as fuel and some was used to assist the flow of oil from the wells. In addition certain components of the gas stream were condensed and exported from the platform to shore by injecting them as liquid condensate into the main oil line.

At the time of the explosion around 10 in the evening the wind was blowing from the southwest as shown by the wind arrow.

The inquiry concluded that condensate vapour leaked into Module C and drifted to form a flammable cloud at the east end of the module where the centrifugal compressors were located. When the cloud ignited flame accelerations lead to an explosion which breached fire walls between the modules and caused oil leakage in Module B. The fire in Module B rapidly developed in size and intensity and the rest is history. The main evidence for this interpretation of causation came from eyewitnesses in the control room who heard and dealt with the alarms from flammable gas sensors placed in and around the compressor enclosures at the east end of Module C. These witnesses testified to the absence of any alarms from the gas sensors in Module B. The conclusion that the release of the explosive source of gas was in Module C and its accumulation occurred at the east end of the module would appear to be obvious.

However, the evidence of the Master of a ship located a short distance from the west face of the platform as indicated in Figure 1 (at point X) placed some doubt on this interpretation. The Master was watching the west face of the platform as part of his duties regarding the positioning of his ship alongside the platform. He observed a blue flame which emanated from a location on the west face of the platform near to the boundary between Module B and Module C (the point marked Y). This flame spread across the face of the platform at the same level as the process modules downwind to the edge of the platform beyond module D and upwind to the radiation screen adjacent to Module A (as shown by the pair of arrows on the plan). The flame then faded away and the Master then, almost immediately, felt/heard the blast of the explosion. It is difficult to explain how the flammable vapours moved from a source within Module C to the west face and then drifted both with and against the wind to form a flammable environment through which the flame could spread before the explosion. A simpler, more obvious, explanation was possible if the source of flammable material was in Module B near the west face so that gas could drift to both ends of the module, east and west. At the west end the gas would also drift downwind so that a flammable envelope could exist from the south edge of Module B to the north edge of the platform. At the east end the gas could pass out of the module and be drawn into the air ducts which provided ventilation for the centrifugal compressors thus causing the gas sensors to trigger alarms in the control room. The difficulty with this explanation is the absence of any alarms from the flammable gas detectors in Module B.

Figure 2 shows in a simplified way the type of construction of Module B and a hypothetical layout of the kind of equipment which such a module might contain. No attempt has been made in these preliminary evaluations of the effects of gratings to investigate yet again the way in which the accident occurred on Piper Alpha. The equipment is supported on skids and these rest on the steel plates which form the floor of the module. The base of the skids are made from steel channel sections and the equipment layout is such that the skids form islands across the floor of the module. To provide process operators with easy access across the module and to items of equipment a walkway is placed above these sections. This is made of steel grating which has an open mesh so that air can pass between the lower and upper spaces. The ends of the module, both below and above the grating are open to the ends of the module so that there is free passage for air to flow above and below the grating from one end of the module to the other. Drains are placed in the floor of the module so that oil spillage does not normally accumulate under the grating.

Figures 2a and 2b show the elevation and plan of the hypothetical module and Figure 3a shows a perspective view which will be used to show the results of the evaluation which is described later in the paper.

CAUSATION

A possible series of events was considered to see if it could explain what happened and fit in with the evidence of eyewitnesses. The sequence is described in this section but as a preamble it should be stated that there is insufficient evidence due to the lack of physical evidence and the absence of survivors to offer this explanation as any more than a basis for concerns for future safety of operations designed on the same basis. It is important to note, in connection with our thesis concerning how issues of safety involving speculation can be usefully developed, that at this stage a description is developed which both assists in a explanation which is consistent with the evidence but also has a sound basis in the science which governs the behaviour of the phenomena which are involved.

It is supposed that there is a spill of crude oil below the grating which contains a sufficient quantity of the light hydrocarbons to produce sufficient quantities of vapour. For some reason the normal flow of oil down the drains is blocked and the oil accumulates and spreads across the floor of the module. As it spreads the oil forms quite a large surface for the escape of gases. The difference in ambient pressure between the west and east faces of the module produced by the action of the wind passing the platform provides a driving force which produces air flow in the space above the grating, past the equipment in the module, and below the grating, past the islands formed by the equipment skid bases.

The two flow regimes, below and above the grating will differ due to the differences in flow resistance and the size of the spaces between the walls, floor and ceiling and the items of equipment. If air velocities in the body of the module are of the order of ½ metre per second then simple considerations of Bernouilli's equation suggest that velocities of the order of 1/10th of a metre per second might be expected below the grating. In these circumstances it is quite possible that the flow above the grating could be turbulent whereas the flow below might be laminar. These contrasting conditions would lead to poor dispersion above the source of flammable gas (the spreading pool of oil below the grating) and good mixing in the body of the module where any gas detectors would be located. The presence of the grating would thus produce more than just a partial barrier to the flow of the flammable gases since it would also create conditions which would lead to low dispersion of vapours from the source to the grating and rapid dispersion of any gas which passed through the grating into the body of the module.

It is possible to envisage a steady-state flow regime developing in which the vapours coming off the oil are drawn through below the grating by the pressure differential across the platform and flow into the atmosphere at the leeward face. Any vapours passing through the grating are rapidly mixed in the body of the module so that concentrations never reach alarm levels near the various gas detectors distributed through the module. At the same time, if the wind strikes the platform at an angle recirculation will occur within the module spaces so that flammable vapours will also be dispersed through the opening below the grating on the windward face of the platform. In this way it might be possible to have flammable regions of gas/air mixtures developing at both ends of the module without the initiation of any of the alarms in the body of the module.

Ignition of these gases would lead to the propagation of a flame which might be through a well mixed gas/air cloud as a premixed flame or might be over the surface of a poorly mixed cloud as a diffusion flame. The precise nature of the developments of the combustion thereafter would be very complex as the expansion process associated with the flames would produce gas movements through the module spaces and across the grating boundary.

PROBLEM DEFINITION

Two questions now arise;

"Is this explanation of causation realistic?" and
"Under what circumstances do the conditions leading to such an event exist?".

Both these questions can only be answered by a scientific analysis - with the problem still to be defined in detail. This section of the paper looks at the proposed hypothesis for the causation described above and attempts to define the problem so that an approach can be made to providing answers to the two questions.

Module construction

The geometry of the module (height, width and length), the items of equipment (location, general shape and overall dimensions) installed in the module and the location of the piping (diameter, and locations where there is an appreciable density of pipework) connecting that equipment needs to be defined. The nature of the grating (thickness, size and spacing of web) and its location (height above the module floor and plan of areas of floor covered) must also be determined and the extent to which the space below the grating is blocked by the equipment skid bases must also be included in such definitions.

Source terms

The spill of oil is the first source term to consider. In the context of the hypothesis set out under causation it will be necessary to define the following properties of this source:

The flow rate of the spill;
The properties of the oil in connection with the flashing of the gaseous components

The extent to which the spill spreads to cover part of the floor of the module below the grating

The location of the spill or, alternatively, the location of the pool of oil which forms on the floor of the module as a result of the spill.

The flow of air through the module is the second source term which must be fixed in the definition of the problem. It cannot be defined as a variable since it is necessary to evaluate the way the relative cross sections of the above- and below-grating spaces of the module effect the process. Various levels of sophistication can be introduced at this stage. Should conditions be modelled in terms of global circumstances such as the wind interaction with the platform as a whole which would require the definition of the entire platform structure and the wind speed distribution and direction.? Or, at the next level, is it adequate to define just the wind speed and direction at one face of the module? Or, at the simplest level, is it sufficient to fix a pressure difference between the two faces of the module and analyse the flow through the module using this as the driving force?

In making a decision as to which of these approaches should be employed it is necessary to examine the objectives of the exercise. The simplest model will not allow us to examine the effects of recirculation within the module and will therefore not take into account the reverse flow from the windward face. On the other hand, the full model employing a complete description of the platform and the movement of the wind around it as well as the analysis of the flow through the modules would place a very heavy burden on computational resources. The practical approach will be to take the middle course and then explore the effects of downstream conditions at the leeward face of the module in conjunction with the variations in wind speed and direction on the windward face to allow for the platform as a whole.

Flow and dispersion

The problem must include the flow of two fluids, the air flowing through the module and the gases transferred from the surface of the oil. It is unlikely that it would be necessary to involve the flow of the spill of oil across the module floor.

The problem must include the diffusion and turbulent mixing of the gases in the air flow. It may be necessary to include the more complex behaviour of the diffusion of gases from a liquid surface into a stream of flowing air which would include the effects of concentrations gradients in the space directly above the oil on the source term for gas release from the oil.

Two additional aspects might be relevant to the problem and would require definition at some stage in the analysis. These aspects are related and are connected with the buoyancy forces which would exist as a result of the differences in density between the gases from the oil and air and the presence of heat sources. Thus density differences in the flow processes could be of importance and it might be necessary to introduces the process of heat transfer into the problem as well.

Combustion

Taking the analysis of causation to completion it would be necessary to include all those aspects associated with the fire and/or explosion which would follow on from the ignition of the gas cloud if its concentration reached flammable levels. Such an extension would involve the introduction of innumerable new definitions. Examples include the definition of all the flammable properties of the air gas mixture (such as upper and lower flammable limits, heat of combustion, laminar flame speed, turbulent gas flow effects on flame speed), the location of the source of ignition and the way in which the combustion process would manifest its behaviour outside the module confinement.

Problem solution

The range of processes involved in this problem definition requires the use of very sophisticated tools to provide even the simplest answers. The best solution would involve the complete solution of all the equations governing the behaviour of reacting gases. At the present time Computational Fluid Dynamics (CFD) provides a technique which approaches this goal most closely and in this paper the use of CFD techniques are considered as the only method for the analysis of the hypothesis in a manner which is both realistic and practical. We attempt to show in the following sections how both practicality and realism is achieved.

However, before tackling the analysis of the problem we refer back to the two questions posed at the beginning of this section. The first question asks for a judgement as to whether the hypothesis put forward for causation is realistic and to answer this we take what we have loosely termed the QUALITATIVE *approach. To answer the second question regarding the conditions which lead to* the events described in the hypothesis we apply a QUANTITATIVE approach.

'QUALITATIVE' ANALYSIS

To cover the topic adequately in this short paper we only describe the analysis of the non-reactive events before ignition occurs. In both the qualitative and quantitative approaches a Computational Fluid Dynamics (CFD) model of the module shown in Figure 2 was made. The CFD program used was Phoenics version 3.1 from CHAM Ltd. (1). The program solves the governing equations of heat and fluid flow and is able to model a large range of physical phenomena associated with fluid flow, heat transfer, gas dispersion, combustion processes and other chemical reactions. Furthermore the program also contains a selection of proven turbulence models.

To study the event in a question for a variety of conditions and to allow for a subsequent QUANTITATIVE approach, the initial model was set up as a schematic model of the module. Although all the equipment items were simplified and represented as hexahedra they were placed at the correct locations inside the module. Pipework was not included but as will be seen later modifications to the physical model of the module can be accomplished very easily as the analyses are developed and extended. The simplified model contained in total 4500 computation cells.

For this initial analysis, bearing in mind we are hoping to determine the plausibility of our hypothesis, the problem definition has been kept as simple as possible.

Source terms: The gas vaporisation rate was modelled from the assumed hydrocarbon spillage underneath the grating covering the entire floor space of the module. The gas was considered as a separate phase in the flow but having the same density as *the air thus eliminating the buoyancy forces. Air flow through the module was* based on the simple wind concept with the wind having horizontal velocity components along the axis of the module and perpendicular toit.

The spill of oil is the first source term to consider. In the context of the hypothesis set out under causation it will be necessary to define the following properties of this source:

Flow/dispersion : The turbulence model used was a generalized length scale model suitable for flows within complex geometries with many obstacles. As mentioned above buoyancy forces were neglected and the flashing of gaseous components from the oil was treated as a source term with a constant rate of production not influenced in any way by the flow behaviour. The grating was also modelled using imposed velocity conditions at the grating level.

Others: In addition, in this first approach, the solutions were based on steady state simulations rather than time dependent simulations. Thus the results are those that would have been reached after a sufficient period for them to attain time invariance.

Results

The results shown in Figure 3. There are three perspective views of the module in this figure each opened out to show its interior by the removal of the ceiling and the front wall. The windward face of the module is at the top of each figure and the direction of the wind is from top to bottom and from left to right. The shading on the horizontal plane indicates contours of constant gas concentration. The actual contours can be seen as faint white lines on the background. The shading identifies three levels of concentration. The darkest shade shows effectively zero gas concentration. The light grey shade shows a medium level of gas concentration and the white shows the highest level. In this 'qualitative' approach it is not necessary to define the numerical values of these levels.

Figure 3a shows the gas concentration levels just above the grating. Nearly the entire space in the module body is free from gas. A small patch about three quarters of the way from the air entrance shows concentrations at the medium level but the area extends over a very small part of the module. Figures 3b and 3c show the same concentration levels below the grating with the latter depicting the conditions close to the oil surface and the former a horizontal plane between the oil and the grating. In both these figures the maximum concentration of gas is observed to cover larger and larger areas as the oil surface is approached. At the lowest level the high concentration covers about 1/8th of the floor area and the medium concentrations nearly half the floor area.

Figures 4a and 4b are similar views as 3a and 3c but with twice the air velocity along the axes of the module. Even for this large change in the external conditions the gas concentration distributions at the two extreme levels do not change a great deal. The gas concentrations above the grating are still confined to quite a small location near the centre of the module while the corresponding concentrations of gas below the grating cover roughly the same area of the floor as in the lower velocity case. It would appear from this preliminary 'qualitative' analysis that a tentative conclusion can be drawn that the results of the analysis in terms of gas distribution are not very sensitive to wind speed.

Whilst the above results may not be quantitatively correct, they show that the vaporisation of hydrocarbons from a spill underneath a grating floor may cause high gas concentrations just underneath the grating floor. A further analysis in which the grating was removed shows quite different results which are illustrated in the three gas concentration contour diagrams in Figure 5. These diagrams have the same interpretation as those shown in Figures 3a, 3b and 3c with one exception. In Figure 5 the gas concentration levels associated with each shaded area are half those depicted in Figure 3. An examination of the results also shows that the maximum concentration in the simulation from which Figure 5 was drawn is half the maximum concentration for the simulation shown in Figure 3. This result shows that the gas cloud formed above the oil spill is much more extensive when the grating is not present and the gas concentration throughout the cloud is much more even. The halving of the maximum gas is consistent with the increase in the extended distribution of the gas in the module and is indicative of one of the shortcomings in the 'qualitative' approach adopted in this section. The limitation leading to this result is the fixed nature of the gas production rate chosen for one of the source terms. A more realistic gas source term would have allowed the source rate to increase as the gas concentration driving force between the oil surface and the bulk gas increased. This the expansion of the cloud with the absence of the grating would have enabled more gas to flash from the surface of the oil pool and a more realistic modelling of the flashing behaviour would have produced higher concentrations over a larger gas cloud.

The 'qualitative' approach has shown that there may be a real problem associated with the presence of gratings in process modules when flashing oil spills could occur. This indication is sufficient to encourage the modelling of these phenomena at a more detailed level in order to ascertain more quantitative results both in terms of temporal and spatial distribution. In other words, an attempt to answer the second question, "Under what circumstances do the conditions leading to such an event exist?" is warranted.

'QUANTITATIVE' ANALYSIS

In order to obtain quantitative results using a CFD package it is essential that not only the physical part of the modelling is a correct as possible, but also that the models of phenomena such as turbulence and its effects are at a realistic level. Furthermore, numerical diffusion must be kept to a minimum through the use of a high mesh density and/or the use of a higher order discretisation scheme. This requires a significant increase in the sophistication of the performance of CFD numerical routines and considerable additional computational effort. There is thus the justification for the preliminary work on smaller and less sophisticated models to identify the conditions that could be of special interest. If time dependent simulations are required as in the present case, the computational storage is also an issue, together with time required to analyse the data.

Modern CFD computational packages are very easy to run. The level of analysis we have described as 'qualitative' can be set up very simply and as long as solutions converge results at this level of sophistication can be obtained with comparatively little effort. The greatest burden for the user is the setting up of the system with the proper physical properties of the problem under investigation and the right boundary and initial conditions for a realistic solution. The sophistication of the user interfaces supplied with these packages provides for this ease of use but can lead a unwary user to produce erroneous conclusions when the quantitative aspects become important. It is at this level that expertise in the use of these systems and a thorough knowledge of their fundamentals becomes essential for the correct formulation of the input data for the calculation, the proper operation of the numerical computational system and the efficient interpretation of the very large quantity of numerical results which are produced.

The PHOENICS 3.1 package employed in the present calculations has a number of features which enable some of the difficulties identified to be accommodated without excessive cost or trouble. The CFD computational engine is complemented by a pre-processor and a post-processor which use virtual reality to assist in the entering of data for problem definition and for the interpretation of the results. The pre-processor known as the VR-Editor enables the user to construct a physical picture of his problem on the computer thus defining the problem in numerical terms for the subsequent CFD calculations. The domain for the calculation can be set up and a computer graphics picture constructed by setting up boundaries introducing obstacles and/or sources, selecting fluid properties and defining initial and boundary conditions.

A data file produced by the pre-processor becomes the input file for the CFD calculation. The calculation can be performed on the computer which was used for the pre-processor or may be exported to another more powerful machine to enable very large models to be run efficiently. Alternatively, the file can be sent to a Consultancy practice who have experience in these calculations to benefit from their expertise. The CFD computational package will produce an output data file which can then be dealt with in the post-processor known as the VR-Viewer, which provides an identical virtual reality view of the problem but within which the results can be displayed.

Thus the initiator of the problem can see his analysis through from the start when he is in control of the definition to the end when he can pick those results which best illustrate his conclusions. Initially, the computations can be handled by experts outside his organisation to ensure that the problem has been handled properly. However, as the user gains experience in the use of the system he can either start to do the calculations on his own machine by installing the CFD package. Or he can run his problems remotely on more powerful computers located elsewhere and maintain tight control of their development. This would be achieved by by initiating a larger proportion of the computational controls from his pre-processor but retaining the greater power of a computational machine run by a consultant organisation possessing better computational facilities.

The 'qualitative' results described in the earlier section were obtained using a complete PHOENICS system which included the VR-Editor and the VR-Viewer as well as the CFD package. A computer running on a Pentium 130 with 32 MBytes of memory performed quite adequately without excessive run times when the simple models with a fairly coarse mesh size was employed. The results for a 50 000 cell simulation show similar trends to the smaller models, however, grid independence may not have been reached and a 500 000 cell model is presently being constructed. This model will be used to explore the effects of a number of factors which have been identified in this paper as having an important bearing on the validity of a 'quantitative' analysis. The results of these calculations will be reported at the meeting.

CONCLUSIONS

The dangers associated with spills of oils which can produce gases has been identified as presenting a real risk to the safe operation of process equipment in enclosed buildings which possess void spaces below floors formed from gratings. The problem has been examined employing Computational Fluid Dynamic (CFD) methods and the authors of the paper have concluded that this approach is useful for preliminary studies but must be used with care when realistic quantitative results are desired.

REFERENCES

(1) PHOENICS Version 3.1 user manuals (1998), CHAM Ltd, Bakery House, Wimbledon, SW19 5AU

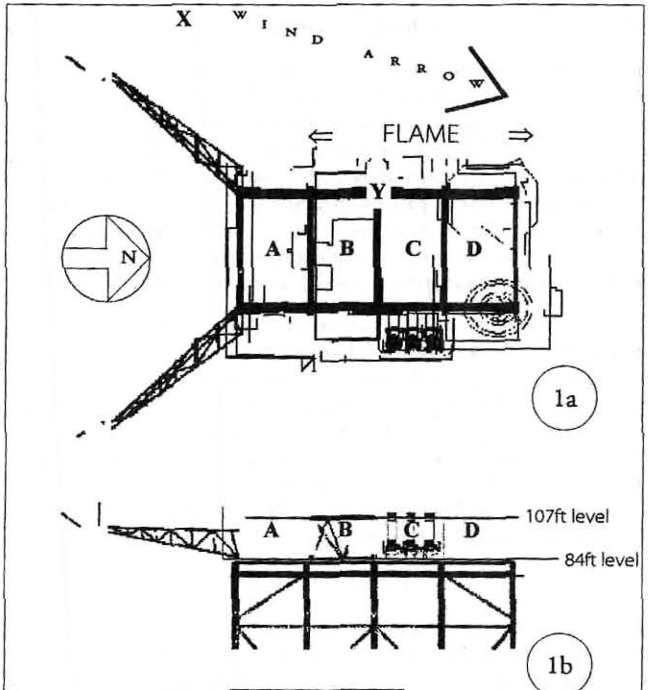


FIGURE 1

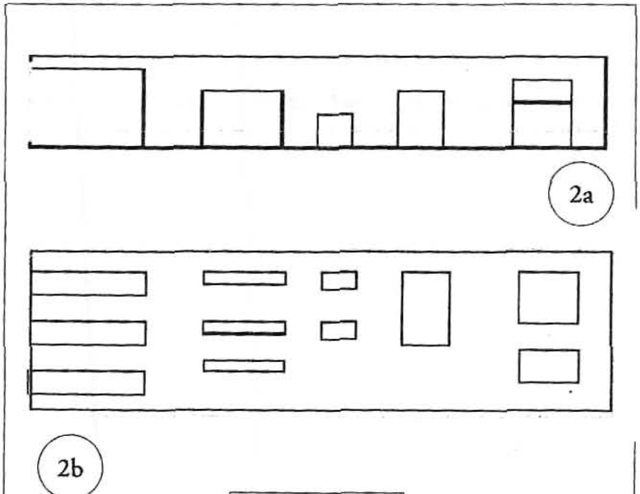
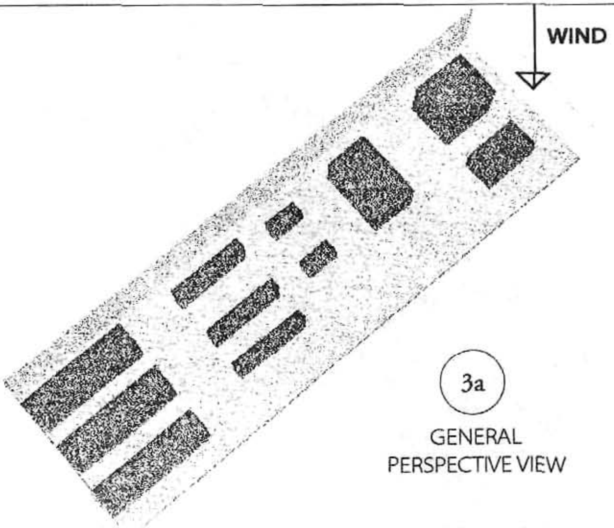
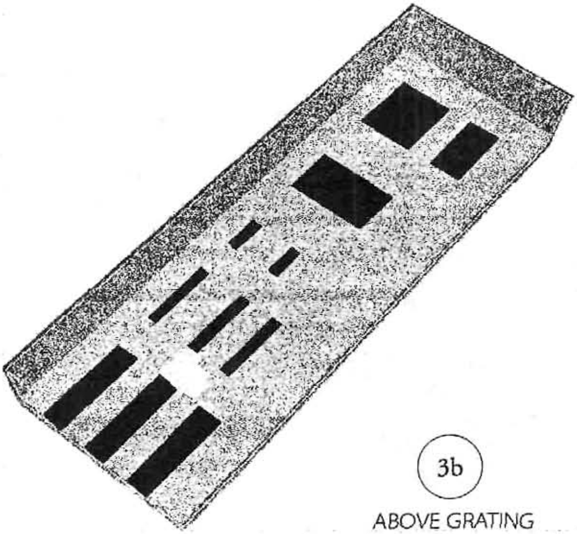


FIGURE 2



3a

GENERAL
PERSPECTIVE VIEW

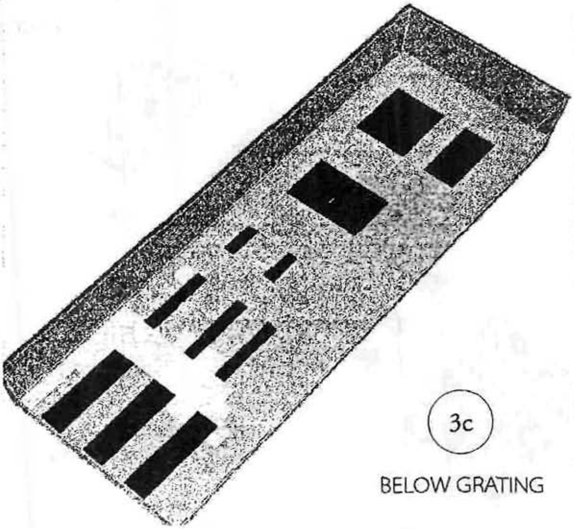


3b

ABOVE GRATING

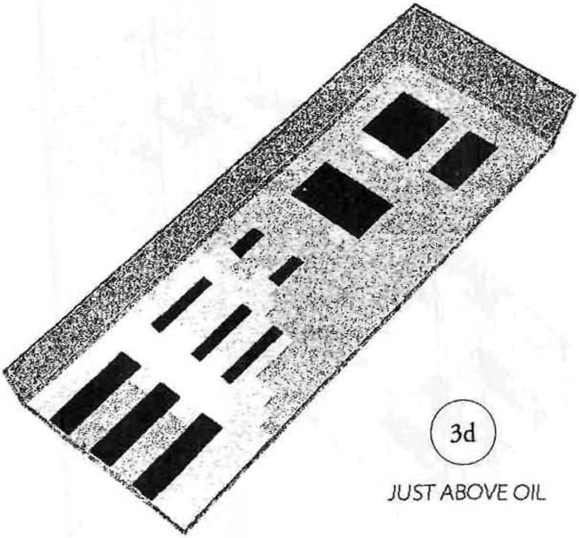
GAS CONCENTRATION CONTOURS
GRATING WITH LOW AIR VELOCITY

FIGURE 3 a & b



3c

BELOW GRATING

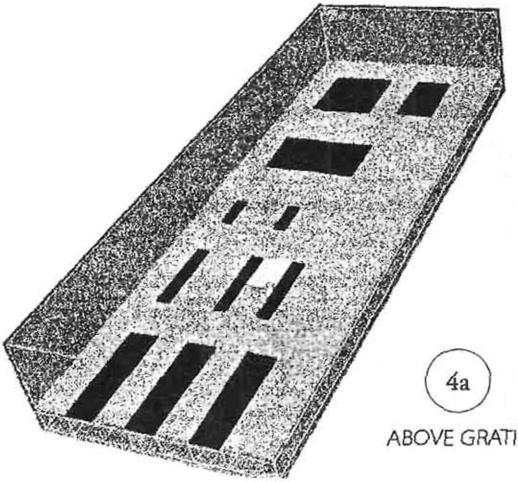


3d

JUST ABOVE OIL

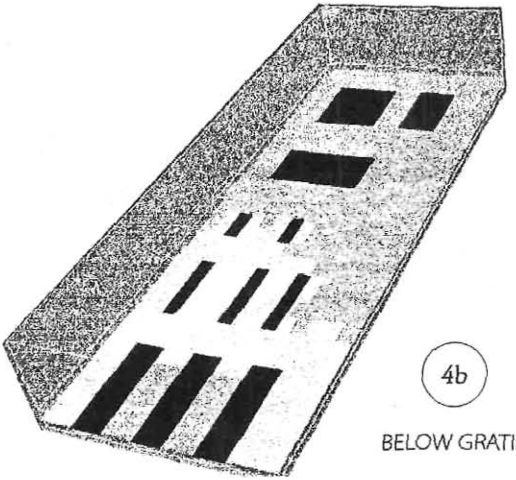
GAS CONCENTRATION CONTOURS
GRATING WITH LOW AIR VELOCITY

FIGURE 3 c & d



4a

ABOVE GRATING

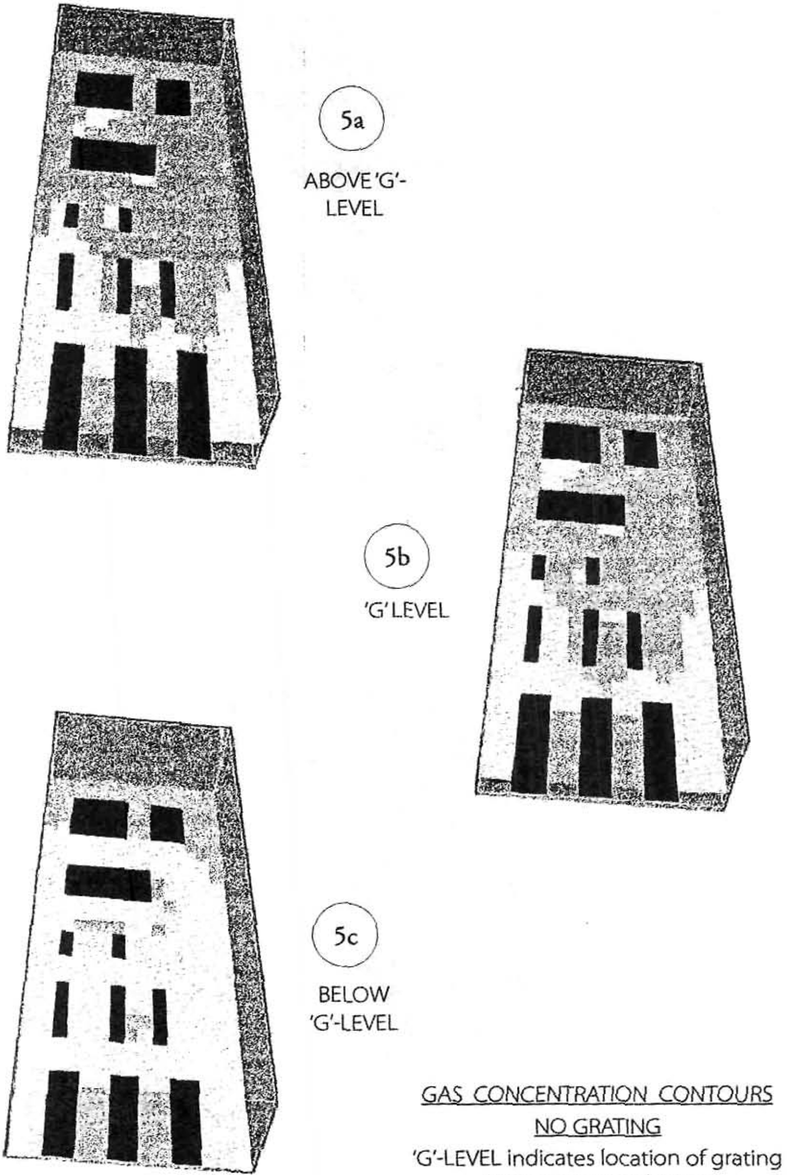


4b

BELOW GRATING

GAS CONCENTRATION CONTOURS
GRATING WITH HIGH AIR VELOCITY

FIGURE 4



5a

ABOVE 'G'-LEVEL

5b

'G' LEVEL

5c

BELOW 'G'-LEVEL

GAS CONCENTRATION CONTOURS

NO GRATING

'G'-LEVEL indicates location of grating in previous simulations

FIGURE 5