Explosion Mechanism Advisory Group report

Explosion Mechanism Advisory Group report

Buncefield Major Incident Investigation Board

Contents

Summary *iv*

Introduction *1*

Scope of review *2*

Conclusions *3*

Recommendations *4*

Appendices
1: Technical considerations: Report of the Advisory Group on the explosion mechanism *5*
2: Scope of further work to determine the explosion mechanism in the Buncefield incident *14*
3: Map of the Buncefield depot and a selection of relevant photographs indicative of the damage *20*
4: Membership of the Advisory Group *30*

References *31*

Summary

The Buncefield Major Incident Investigation Board (MIIB) has been overseeing a comprehensive investigation of the incident and has published a number of reports on its findings. One important aspect of the incident was that a severe explosion took place, which would not have been anticipated in any major hazard assessment of the oil storage depot before the incident.

The Board invited a team of explosion experts from academia and industry to form a working group to advise on the work that would be required to explain the severity of the Buncefield explosion.

The Advisory Group identified a number of possible explosion scenarios but within the time available could not fully test them against the considerable amount of information available. Nevertheless, the Group has concluded that there is a strong likelihood that the cause of the severe explosion at Buncefield can be explained, although this will require further, more detailed work. However, it is the opinion of the Group that a comprehensive explanation is unlikely to be found without the conduct of further experimental and theoretical research.

It is recommended that a joint industry project be initiated with the task of completing the assessment started by the Advisory Group and, on the basis of its findings, defining the requirements of the research to be carried out in a second phase of the project.

Guidance to industry and the Health and Safety Executive (HSE) should be a primary deliverable of the project.

Introduction

1 The Buncefield Major Incident Investigation Board (MIIB) has been overseeing a comprehensive investigation of the incident and has published a number of progress reports[1-3] and an initial report[4] on its findings.

2 The progress reports identify that the incident occurred following a spillage of unleaded petrol from one of the storage tanks. However, one important aspect of the incident was that a severe explosion took place, which would not have been anticipated in any major hazard assessment of the oil storage depot before the incident.

3 In its initial report, the MIIB stated that:

> 'Further work is needed to research the actual mechanism for generating the unexpectedly high explosion over-pressures seen at Buncefield. This is a matter of keen international interest, and participation from a broad range of experts, as well as the industry, is essential to ensure the transparency and credibility of any research programme. The Board will consider further recommendations about the nature and scope of such work.'

The MIIB therefore invited explosion experts from academia and industry to form a working group to advise on the work that would be required to explain the severity of the Buncefield explosion. The first meeting of this Advisory Group was held in December 2006. The Group then had three subsequent meetings to review evidence and agree a report to the MIIB.

4 In its report *Recommendations on the design and operation of fuel storage sites*[5] the MIIB stated:

> 'We have asked the panel to advise us whether research is justified and if so the scope of such research, likely methods of funding it, and its governance arrangements, to ensure a satisfactory outcome. We have asked the panel to present its findings to us shortly after Easter and we shall make our recommendations known soon afterwards.'

5 This report is the response to this request and provides a summary of the technical issues examined by the Advisory Group along with its conclusions and recommendations.

Scope of review

Review process

6 The Advisory Group has carried out a preliminary assessment of the forensic evidence obtained following the incident and of the results of experiments carried out by the Health and Safety Laboratory (HSL). The objective of this assessment was two-fold:

- to determine whether a sequence of events could be identified that would explain why such severe explosion pressures were generated; and

- if this was not possible, to recommend to the Board what further actions would be required to explain the explosion severity.

7 In conducting the assessment, the Group made reference to previous fundamental laboratory-scale and large-scale experimental work. Although there was a preference to seek an explanation based on known mechanisms, the Group did not close itself to other potential means of generating the explosion. A summary of the technical issues considered by the Advisory Group is provided in Appendix 1.

Explosion mechanisms

8 An explosion can be produced when a gas cloud is ignited within a confined volume such as a building. As the flame propagates through the gas cloud it produces hot combustion products. The confinement prevents expansion of these combustion products and as a consequence, the pressure increases. In general, this continues until the confining structure fails, in some cases catastrophically.

9 This mechanism does not explain the type of explosion that occurred at Buncefield as the majority of the cloud was not confined. It is recognised that two 'confined explosions' did occur, but these events alone could not explain the severity of the overall explosion.

10 There are two known mechanisms for generating an explosion in a relatively unconfined vapour cloud. One is a deflagration, where the flame accelerates to high speed, which requires a mechanism for generating the flame acceleration. It has been shown in large-scale experiments that this can be provided by turbulence generated as the explosion propagates through pipework congestion typical of process plant.

11 In the case of Buncefield, this pipework congestion was not present to any significant degree and not at all in some areas where high pressures were produced. Trees and undergrowth were, however, present along both sides of Buncefield Lane. It is possible that these acted as a means of accelerating the flame in a manner similar to congested pipework regions on process sites.

12 The second mechanism is a detonation, which if sustained, can be much more damaging. It may arise from the coalescence of a strong shock wave and a fast-moving chemically reacting front. Together, this can undergo a transition to propagation faster than the speed of sound and produce over-pressures at the front in excess of 10 bar. It can also arise from the high temperatures and pressure generated by a shock wave in a confined, high flame speed deflagration or directly from strongly focused shock waves in a very reactive mixture. One possibility considered was the initiation of a detonation as a result of an explosion venting from either of two confined explosions. However, at Buncefield there was no clear evidence of even localised detonations.

Conclusions

13 The Group attempted to explain the explosion event at Buncefield using deflagration, detonation or a combination of both. It also examined other possible means of flame acceleration. However, it was not possible to identify a single scenario that could explain all aspects. In this the Group was limited by:

- uncertainty regarding the composition of the vapour cloud;
- apparent ambiguities in some of the forensic evidence;
- uncertainty regarding the explosion severity required to cause the level of damage observed, particularly to cars and buildings;
- the time available, as the possible scenarios could not be properly tested against the considerable amount of information available; and
- the difficulty of distinguishing between unburned gas flow ahead of the flame and burned gas flow, in the other direction, away from it.

14 Nevertheless, the Group concluded that there is a strong likelihood that the cause of the severe explosion at Buncefield can be explained. However, this will require further, more detailed work. It is the opinion of the Group that this should in the first instance involve the continuation of the assessment already started, fully testing a range of scenarios against the forensic evidence and the current scientific understanding of explosion mechanisms.

15 It is also the opinion of the Group that a full explanation is unlikely to be achieved without the conduct of further research.

Recommendations

16 It is recommended that a joint industry project be initiated that will, in its first phase, have the objectives of completing the assessment started by the Group and, on the basis of this, of defining the requirements for further research. This research – experimental and theoretical – would then be completed in a second phase of the project. Guidance to industry and HSE should be a primary deliverable of the work.

17 A proposal for the joint industry project has been prepared by the Group and is detailed in Appendix 2. The cost of the first phase of the project is estimated at not more than £200 000. The second phase of the work cannot be priced at this stage.

18 Governance of the project should be through a steering committee comprising stakeholders from industry and HSE, as regulator. The first phase of work would be conducted primarily by a technical committee, one member of which would act as project manager.

19 The Group recommends that this project should be initiated as soon as possible, with the first phase to be completed in early 2008. The additional experimental and theoretical work should then be completed within the following 18–24 months. To facilitate the first phase of the project being completed to schedule, it is suggested that there should be a maximum of ten sponsors. Broader support may be required for the second phase of the work.

Appendix 1

Technical considerations: Report of the Advisory Group on the explosion mechanism

1 To progress research into the mechanism that may have generated the high explosion over-pressures the Board wishes to receive recommendations concerning the nature and scope of that research with a view to ensuring the credibility of any research programme.

2 Paragraphs 5–8 of this appendix outline how over-pressures might be attained in combustion, while specific explosion scenarios are discussed in subsequent sections. This examination revealed several limitations in the current understanding of the relevant phenomena and the requested recommendations appear in paragraphs 37–38.

3 In the course of its work, the Group examined various scenarios for the initiation of two explosions that are suggested by CCTV records (see paragraphs 9–13) and for the subsequent flame propagation. Only one of the explosions was of seismic magnitude. In addition to information from CCTV records, the Group was aided in its studies by details of damage to buildings, tanks, cars, trees and shrubbery, all supplied by HSL. Examples of the damage are given in a series of photographs in Appendix 3. HSL also supplied the results of tests on cars exposed to explosive over-pressures. From the details of the damage sustained, the approximate over-pressures causing the damage were estimated. The Group was presented with these estimates which enabled isobars to be constructed showing over-pressures on a map of the site (see paragraph 39 and Figure 1). However, it should be noted that there is significant uncertainty regarding the magnitude of the over-pressures at the sources of the explosion that were considered and throughout the car park area.

4 HSL also presented results of computational fluid dynamics (CFD) computations concerning the way the vapour from the spilled fuel dispersed across the site. These proved to be difficult computations because, contrary to the situation in most CFD studies, the vapour flows and wind velocities were very small. Nevertheless, a combination of CCTV and computational evidence gave an indication of the changing depth of the fuel–air cloud. The variation of fuel–air concentration in the cloud was unknown but it would probably range from excess fuel at the ground to excess air at the top, with the most reactive mixture somewhere between. Where preliminary analysis has been carried out, worst-case stoichiometric conditions were assumed.

Over-pressures in combustion

5 The Group was able to estimate over-pressures generated by a variety of mechanisms. Some further details are given in paragraph 39. These included over-pressures across a flame, those arising from the degree of confinement and also the dynamic pressures arising from the gas flow ahead of the flame. High rates of change of heat release rate can generate strong acoustic waves and the associated pressure amplitudes were estimated, as well as the shock wave intensities at which pressure pulses and reaction fronts would coalesce in damaging detonations. These estimates of over-pressures were made for a variety of scenarios of explosive flame propagation and were compared with those derived from the observed damage. The comparisons gave guidance on the nature of flame propagation and the most probable scenarios are reported here.

6 An important feedback mechanism occurs when a turbulent flame propagates across obstacles. This causes turbulence in the flow of unburned mixture ahead of the flame. This turbulence increases the turbulent burning velocity, which in turn generates more turbulence ahead of the flame. This feedback results in flame acceleration and the eventual attainment of a maximum turbulent burning velocity (and maximum flame speed). Over-pressures also increase with flame speed. The maximum burning velocity is normally attained when any further increase in turbulence would reduce the burning velocity as a result of flame quenching. For the Buncefield event, maximum burning velocities and flame speeds (the vector sum of burning and gas velocities) were estimated theoretically and from the somewhat limited experimental data available on burning velocities and Markstein numbers.

7 High turbulent burning velocities can create a strong shock wave ahead of the flame, with associated elevations of pressures and temperatures. These elevations might reduce the auto-ignition delay time sufficiently to cause auto-ignition and detonation. Computations suggested that the maximum turbulent flame speed for near-stoichiometric butane–air in a confined duct was about 1200 m/s. This could generate a shock wave ahead of the flame with a pressure of 11.7 bar and a temperature of 825 K, sufficient to induce auto-ignition and consequent detonation. A similar mixture of pentane–air was unlikely to auto-ignite.

8 Shock wave interactions with the flame front can also induce higher flame speeds, in excess of the ambient speed of sound, and their intersections can create ‘hot spots’, both mechanisms aiding transition from deflagration to detonation.

Ignition

9 Though there is some uncertainty regarding ignition, the Board’s reports indicate that the emergency generator cabin, on the south side of the Northgate building and the emergency pump house, close to the north side of Bund A, both contained potential ignition sources. These locations are given in Apendix 3, Figure 3. Both buildings show evidence of having been subjected to an internal confined explosion.

10 CCTV evidence indicates that two explosions occurred with a time interval of one or two seconds between them, with the second being the severe explosion event. These explosions could have been separate explosions within the two buildings; however, other explanations are likely, as described in the following sections.

11 The Group considered that there was evidence to support the view that the first ignition occurred at a source in the emergency generator cabin, on the south side of the Northgate building, after a sufficiently flammable mixture had built up there. This conclusion was reached on the basis of both the forensic evidence and the belief that the emergency pump house was probably located within a fuel-rich part of the vapour cloud. An explosion in the emergency generator cabin and its aftermath are considered in paragraphs 14–25. Another scenario in which the first ignition occurred in the vicinity of the emergency pump house is examined in paragraphs 26–31.

12 The potential for a link between the two ignition sources was discussed by the Group. For example, an explosion in the emergency pump house could have had an effect on the local power supply that then resulted in electrical switching in the emergency generator cabin. However, at this stage any conclusion would be speculative at best.

13 The Group was aware that other ignition sources were possible, for example, one of the empty tanks suffered an internal explosion. Within the time available, it was not possible to consider alternative ignition sources in any detail. This should form part of any further work.

Explosion in the emergency generator cabin and its aftermath

14 Ignition was followed by a 'bang-box' explosion inside the generator cabin. This generated a high over-pressure, together with a fast-moving flame in an external cloud. Previous large-scale experiments suggested over-pressures of no less than 200 mbar and flame speeds in the region of 150 m/s. These studies also showed that when the external cloud contained obstacles, the over-pressure could be substantially higher. In the present case, fragments of the brickwork from the walls around the emergency generator cabin would have been propelled across the Northgate car park. It is possible that this could explain the observed abrasion of the trees and lamp posts on the side facing the generator building at the south end of the car park, but it is unlikely to explain such evidence at the north end of the car park. The Porsche car just outside the displaced doors of the cabin was severely damaged.

15 Blast from this explosion could be responsible for some of the car damage in the area south of the Northgate car park. The Group considered potential sequences of events following the explosion in the emergency generator cabin. These scenarios are described below.

Deflagration within the trees and shrubs

16 Large-scale experimental evidence indicates that, unless a transition to detonation occurs, a high-speed flame venting into an unobstructed area will rapidly decelerate. Thus the flame would propagate with diminishing speed across the south of the Northgate car park and enter the tree line along Buncefield Lane.

17 Consideration was also given to a jet flame initiating turbulent combustion in the boundary layer of a mixture of fuel and air. Computations showed that once the momentum of the initiating jet had declined, so also had the flame speed in the boundary layer, as observed in large-scale experiments.

18 Once the flame entered the trees and shrubs, it would accelerate rapidly up the tree line, reaching high speeds at the northern end. Damage to the trees and undergrowth was extensive and became progressively worse as Three Cherry Trees Lane was approached and continued eastwards along Cherry Tree Lane. Because of the feedback mechanism, which causes the flame to accelerate as it propagates, this tends to confirm that the flame was moving in a northerly direction. The trees and shrubbery would have acted as obstacles to the gas flow ahead of the flame, induced by the expansion of combusting hot gases, generating turbulence in the flow. The flame would also fold around the larger obstacles, such as tree trunks, developing a much larger surface area. The combination of the large flame area and a high turbulent burning velocity over that area would have resulted in a greatly increased rate of combustion. This would have caused the flame to accelerate to its maximum flame speed, possibly in the region of 400 m/s, creating a high over-pressure at the flame front and an additional over-pressure due to the semi-confined nature of the explosion. It is estimated that the magnitude of the total maximum over-pressure would be no less than about 1000 mbar. This pressure magnitude in the area of the trees is not inconsistent with some estimations of over-pressures.

19 In this scenario, the damage to the trees also suggests that the flame accelerated in a southerly direction down Buncefield Lane from the point of entry, but in this direction it travelled less far before reaching the edge of the flammable cloud. Therefore it did not accelerate to the same extent in this direction and would not have produced such high over-pressures here.

20 An important anomaly was a number of severely damaged cars in the south-east corner of the car park, at a point where the flame would enter the tree line. The flame speed would have been low at this point and associated over-pressures would be less than those estimated from the car damage. The pattern of damage between the Northgate Building and Fuji Building would also need some explanation, as this appears to change relatively suddenly, which does not appear to be consistent with a gradually decaying pressure wave.

21 In this scenario, the first explosion would be an explosion in the emergency generator cabin and the second more severe explosion would occur in the trees and shrubs towards the north end of Buncefield Lane and continuing east some distance along Three Cherry Trees Lane, where the vegetated verges were wider. The explosion in the emergency pump house would occur once the flame reached this area but would not have been observed on the CCTV.

Direct initiation of a detonation

22 An alternative scenario is that the explosion venting from the emergency generator cabin underwent a transition to detonation, possibly as a result of pressure and flame interaction with the Porsche car parked just outside the east end of the cabin. There was general agreement within the group that localised detonations might occur; however, a consensus could not be reached on the likelihood of these being sustained over the length of the car parks.

23 This scenario can explain the relatively even level of damage across the full car park area. It also offers a potential explanation for the apparent sudden change in the level of damage at points close to the edge of the cloud. Given the limited height of the cloud, pressure decay might be expected to be rapid.

24 However, the level of damage to the Northgate and Fuji buildings does not appear to be consistent with the very high over-pressures associated with a detonation front, even given the very short duration of this pressure pulse. There is insufficient information available to determine conclusively whether the severe damage caused to some of the cars is consistent with a detonation front or not. Because of the severe fire damage east of Buncefield Lane and in the vicinity of Bund A there was only limited data on over-pressures in this region.

25 The Group gave some consideration to the possibility of a combination of this scenario and the previous one. This is either a detonation in a limited section of the cloud to the south end of the car parks before the deflagration occurring in the trees and shrubs or a detonation occurring after flame propagation to the north end of the trees and shrubs. No clear evidence could be found to support either occurrence, but equally they could not be definitively excluded.

Explosion in the vicinity of the emergency pump house and its aftermath

26 Although there is no clear evidence that the first ignition occurred inside the emergency pump house, it is possible that incendive sparks were generated there after the activation of the site emergency system, and that these created the first ignition and explosion. The fuel–air mixture extended to a depth of more than 4 m from the area of the emergency pump house, at the apex between Three Cherry Trees Lane and Buncefield Lane, and extended down to the southern limit of Bund A. This large amount of fuel created the potential for a large explosion, although the gas dispersion analysis suggests that it was likely to be a fuel-rich mixture.

27 As with the description given in the previous section, where ignition was considered within the emergency generator cabin, ignition in the emergency pump house could have resulted in either:

- flame propagating towards the tree lines at both the north end of Buncefield Lane and along Three Cherry Trees Lane to the north of the site; or
- direct initiation of a detonation.

28 The possibility of direct initiation of a detonation was considered unlikely due to the expected fuel-rich concentration of the cloud in the vicinity of the emergency pump house and the pattern of damage. This possibility was therefore not considered further by the Group.

29 The first case would result in flame acceleration in a southerly direction in the tree line along Buncefield Lane. This is, in effect, the reverse of the process described in paragraphs 16–21 and equal magnitude pressures are possible in each case. This scenario has the benefit of providing a possible explanation of the high level of damage to cars parked at the south-east corner of the car park.

30 It is worth noting that in the third progress report[3] on the incident, abrasion on the south side of posts and trees was taken to indicate a flame propagating north from the south end of the car park. The abrasions were taken to be as a result of a fast flame propagating towards the posts and trees. It was recognised by the Group that these abrasions could also have been caused by solid particles entrained by the high velocity of the burned gas, moving in the opposite direction to the propagating flame. The burned gas would tend to have significantly higher velocities than the unburned gas which would both enhance entrainment and intensify abrasion damage. Therefore the abrasions could also be indicative of a flame moving south from the north end of the car park/tree line. A difficulty with the scenario of a southerly spread of flame along the Buncefield Lane line of trees is the contrary evidence in paragraphs 16–21.

31 Alternatively, the explosion within the pump house may have been initiated on the arrival of a deflagration that had propagated from the emergency generator cabin. This second internal explosion would have occurred about one second after the first, the time for a deflagration to propagate between the two centres at a speed of 400 m/s. A detonation would take about a quarter of this time.

Alternative means of pressure generation

32 Because of the high concentration of fuel in the vicinity of the emergency pump house, there was the possibility of the creation of an intense fireball which would enhance mixing with air. Overall, the burning would probably be of a rich mixture, which, together with the large size of the fireball, would enhance the development of Darrieus-Landau flame instabilities that significantly increase flame front wrinkling. This would produce a large rate of change in the heat release rate, which could produce strong acoustic waves. These, through the baroclinic instability, would further wrinkle the flame, providing a feedback mechanism to enhance still further the rate of change of heat release rate and the generation of even stronger acoustic waves. These instabilities could create pressure oscillation amplitudes of 1000 mbar, which would contribute to increased over-pressures in the car parks.

33 In this case, the tree trunk damage in the Northgate car park might be indicative of a strongly induced flow into the base of a rising fireball. In this regard, the absence of soot on the tree trunk is noteworthy.

34 Another possibility was that this was followed by a second ignition at the emergency generator cabin. This would lead to the northward flame propagation along the line of trees on Buncefield Lane. In the absence of flame propagation towards the emergency generator cabin from the north, this scenario depends upon the statistical coincidence of a random spark in the generator building occurring one or two seconds after the first ignition. With the complex combined geometries of topography and flames, circumstances might arise in which flames could approach each other from different directions. This could lead to rapid burning of the trapped gas and the generation of strong acoustic waves that could further enhance burning. Sufficiently strong shock waves in a high pressure and temperature environment could induce detonation.

35 However, given the unusual nature of the Buncefield explosion, the Group could not reach a view on the likelihood of either of these occurring.

Conclusion

36 The Group found that it was not possible to describe definitely the nature of the severe second explosion. Given the time constraints, it was not possible to review fully what was a considerable amount of evidence and there is therefore still work to do in this area. Continuation with this assessment would help to define the necessary further work to determine the cause of the severe explosion in the Buncefield incident.

Recommendation for future research

37 In the course of the investigations certain areas emerged for necessary further research. Some of this research is of a more fundamental nature and some of it involves large-scale tests. The major areas identified to date for such work are:

- car damage as an indicator of explosion over-pressures;
- structural damage caused to buildings (similar to the Northgate and Fuji buildings) by high magnitude, short-duration shock wave;
- more data on burning velocities and Markstein numbers of key explosive mixtures at higher temperatures and pressures;
- more data on ignition delay times of key explosive mixtures at lower temperatures and pressures and on deflagration to detonation transition;
- the nature of premixed turbulent combustion in boundary layers;
- experimental and theoretical study of 'bang-box' ignition of external vapour clouds containing higher hydrocarbons;
- single and two-phase vapour cloud explosions in hydrocarbon–air mixtures;
- experimental and theoretical modelling of flame acceleration by finely spaced obstacles (to represent undergrowth) and tree-type obstacles;
- CFD simulation of vapour cloud formation, appropriate to low and no-wind conditions;
- study of flow of burned gas behind the flame, as well as of unburned gas ahead of the flame and their effects in abrasive damage.

38 Further research should be justified and prioritised to deliver a fuller descriptive and scientific understanding of the explosion scenario of 11 December 2005. This must be based on a more detailed assessment of the forensic evidence. The main primary deliverable from further work is revision of safety guidelines, based on an improved awareness of the complexities of the explosion and the accompanying fire hazards, that can be applied by industry.

Annex to Appendix 1: Estimations of over-pressures

39 Estimates of the dynamic over-pressures provided by HSL fall into five different categories, listed below. Such pressures can be quite high, but are difficult to assess because they require knowledge of the gas velocity, drag coefficient and the duration of the impulse.

- Estimates from **damage to building structures**.
  - These cover damage to windows, panelling, brickwork, doors, roofs, walls, internal floors, and bending and buckling of steel frames, and ripped-off panelling. They suggest over-pressures of no more than 200 mbar.

- Estimates of over-pressures at sources of ignition and '**bang-boxes**'. These are not quantified with much certainty, but are likely to be significantly in excess of 200 mbar.

- Estimates from **car damage** initially ranged up to 1000 mbar. However, more recent work by HSL suggested over-pressures in excess of 2000 mbar.
  - Some uncertainty is associated with the initial tests, as the procedures were unable to record the pressure at which the damage occurred. Instead, damage was correlated with the maximum over-pressure attained in the test. In general, the damage correlates better with the pressure difference between the inside and outside of the cars than with the higher final pressure in the test chamber.
  - Maximum values of the differences between external and internal pressures in the tests were about 200 mbar. This is also the approximate value that might be anticipated theoretically for the onset of buckling damage, due to an externally applied pressure. This matter is important because the damage to vehicles was almost exclusively 'crush damage', arising from a near equal over-pressure on all sides.
  - An important exception to this interpretation is the over-pressure estimate for the severe damage to the car in one of the tests, from a near-instantaneous pulse. The over-pressure in this experiment was quoted by HSL to be 'at least' 2000 mbar. This damage is almost, but not quite, as severe as that suffered by cars in the Fuji building car park. It is worthwhile to differentiate between cars that predominantly suffered from a relatively low level of 'crush damage' (which were outside the apparent region of the origin of pressure generation) and those that suffered more extensive damage (which tended to be within this region). The damage to the cars in the latter region was considerably higher, with some being extensively crushed and others having some of their panels partially torn off the body of the car.
  - It is also noteworthy that many of the tyres on cars in the high pressure region had their tyres deflated. This may have been due to the seal being broken by a high external pressure. Given the typical inflation pressure of car tyres, this might suggest an over-pressure in the explosion in excess of 2000 mbar.

- Estimates from damage to **trees, lamp posts and telegraph poles** along Buncefield Lane suggest over-pressures of 1000 mbar.

- Buckling forces on a **tank roof**, such as at Tank 12, were analysed. These show that collapse can occur with an external over-pressure of 100 mbar.
  - An attempt has been made to summarise over-pressures on the map in Figure 1, with overlaid isobars of 1000, 300, 150 and 40 mbar. Regions with pressures above 1000 mbar are shown shaded.

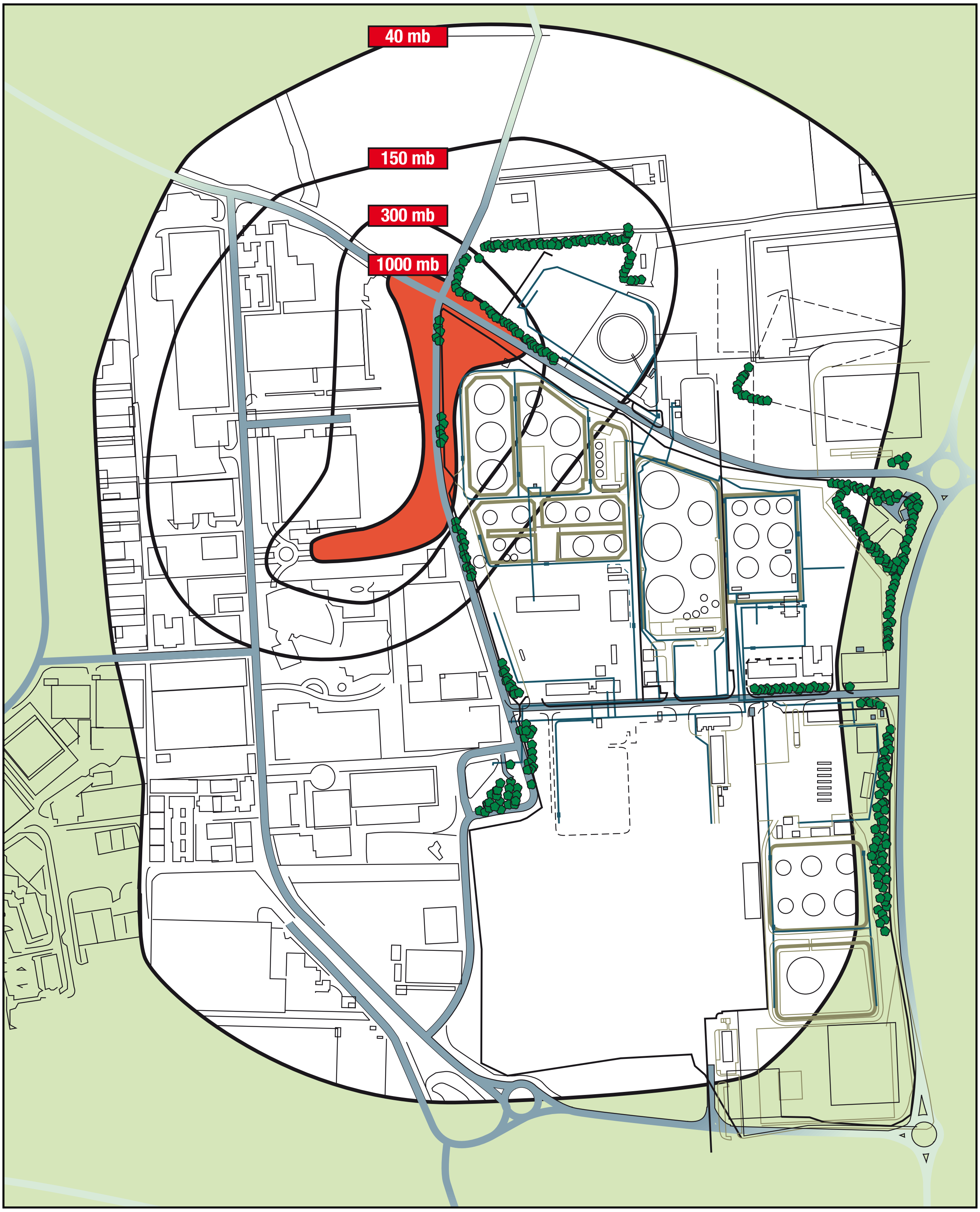

Figure 1 Map of the area around the Buncefield site showing approximate over-pressure isobars. These are based on the distribution of damage caused to buildings (including the pump house and the emergency generator cabin), tanks and vehicles as recorded by the primary investigation team. Inevitably, there are large error bars, particularly associated with the 1000 mb contour. It was noted that the damage to vehicles across the car park was remarkably uniform, but there is no information available on over-pressures that are required to cause such damage. The red shading corresponds to an area in which there were convenient markers that provided strong forensic evidence that the over-pressure was greater than 1000 mb. This does not preclude the possibility that such over-pressures were achieved beyond this area.

Appendix 2

Scope of further work to determine the explosion mechanism in the Buncefield incident

1 At around 06.00 on Sunday 11 December 2005, a number of explosions occurred at Buncefield Oil Storage Depot, Hemel Hempstead, Hertfordshire. At least one of these initial explosions generated significant and damaging blast pressures. The subsequent fires engulfed over 20 large fuel storage tanks across a high proportion of the site. There were no fatalities, but 43 people were injured and significant damage occurred to both commercial and residential properties in the vicinity as well as to the local environment.

2 The MIIB has been conducting a comprehensive investigation of the incident and has published a number of progress reports on its findings.[1–3] These reports identify that the incident occurred following a spillage of unleaded petrol from one of the storage tanks. The Board went on to publish its own initial report[4] based on the findings in the three earlier reports. The initial report also sets out the Board's four main areas of concern arising out of the incident.

3 One important aspect of the incident was that a severe explosion took place, which would not have been envisaged in any major hazard assessment of the oil storage depot before the incident. Paragraph 35 of the first progress report[1] states:

> 'Work is continuing to find out the exact nature and composition of the flammable mixture and to determine the precise mechanism which led to such a violent explosion. This includes establishing the nature and composition of the fuel from which the mixture was formed. Priority is being given to this work so that HSE's advice to local planning authorities about developments adjacent to Buncefield and other fuel storage sites can be reviewed and, if necessary, amended.'

4 Initial work investigating the causes of the vapour cloud formation and the subsequent explosion has been carried out by HSL. However, in paragraph 77 of the initial report,[4] the Board states that:

> 'Further work is needed to research the actual mechanism for generating the unexpectedly high explosion over-pressures seen at Buncefield. This is a matter of keen international interest, and participation from a broad range of experts, as well as the industry, is essential to ensure the transparency and credibility of any research programme. The Board will consider further recommendations about the nature and scope of such work.'

5 This proposal for such work has been prepared in response to the goals identified by the Board in its reports.

Scope of work

6 The proposed programme has two phases although the actual number will depend on the outcome of each stage of the programme. The two phases are outlined in Table 1.

Table 1 Outline of programme

Phase	*Title*	*Scope of work*
1	Initial assessment	Define what is known about the vapour dispersion and explosion at Buncefield, what can be explained by current understanding and what gaps in knowledge there are. If possible, interim guidance would be provided to industry and regulators on the basis of this analysis. Develop a full proposal for Phase 2.
2	Research to fill gaps	Conduct experimental and/or theoretical research to fill any gaps identified in Phase 1 and develop a generic solution to vapour cloud explosion modelling. This work would be directly related to the conditions pertaining to Buncefield and would aim to provide updated guidance to industry/ regulators based on the conclusions of the research.

7 It is recommended that funding for the first phase of this project is sought from industry. At this stage, Phase 2 can be described only in broad terms and cannot be costed in a realistic manner. However, a budget price is provided in paragraph 30. This approach has the advantage that work can be initiated in the short term that will:

- provide a definitive record of the characteristics of the Buncefield incident relevant to the formation and dispersion of the vapour and to the explosion, including the distribution of damage to nearby items and structures;
- where possible, provide industry and the regulator with guidance for the operation of oil fuel storage sites based on this record of information and current knowledge of vapour cloud formation, dispersion and explosions;
- define the research that would be required in Phase 2 to confirm in further detail the explosion mechanism involved in the Buncefield incident and to provide improved guidance for both oil storage facilities and facilities storing other flammable liquids.

8 It is recognised that this proposal potentially involves a substantial research activity with the final guidance likely to take upwards of three years. Given the international relevance of the guidance to be provided from the investigations and the potential impact on industry, this approach is believed to be justified and consistent with the Board's intention as stated in paragraph 84 of the initial report:

> 'The Board intends to address these issues in more detail, but not before seeing the preliminary conclusions of HSE's review. A measured approach is justified since the likelihood of a similar explosion remains low, and should be made lower still by a programme of actions designed to increase the reliability of primary containment. In our view, the importance of reaching conclusions that are considered, costed, and sustainable greatly outweighs any benefit that might be derived from coming to summary judgements.'

Phase 1 – Initial assessment

9 The initial assessment will have six main activities:

- review of apparently similar or relevant incidents;
- detailed review of data from the incident that are associated with the formation and dispersion of the vapour, the generation of the vapour cloud, and the subsequent ignition and explosion behaviour;
- assessment of potential scenarios for the explosion by comparison with observations from the incident;
- identification of gaps in information or understanding;
- formulation of interim guidance if possible;
- formulation of the Phase 2 research programme.

10 Further details of the activities are given in paragraphs 11–21.

Review of data

11 Information obtained from the investigations carried out by the MIIB, the Advisory Group and HSL will be collated and critically reviewed by a technical committee. The review will examine information related to:

- the discharge of unleaded gasoline from the tank and its evaporation;
- the development of the vapour cloud and its composition;
- the topography of the area in which the vapour cloud developed;
- potential ignition sources;
- the nature and extent of the damage caused by the explosion;
- the initial assessment and experimental work carried out by HSL;

and any other relevant information from other sources that is made available to the project. At the same time, the quality, reliability and value of the forensic evidence will be reviewed.

12 The objective of this activity is for the Technical Committee to have as detailed an understanding as possible of the conditions at the time of the explosion and of the forensic evidence left by the explosion (eg the pattern of damage to structures).

Assessment of scenarios

13 Given the current understanding of vapour cloud dispersion and explosions, potential scenarios will be identified that could lead to the generation of a severe explosion. This will include means of pressure generation that are not normally considered for this type of event. The scenarios will be tested against the understanding gained from the above review of data to determine if they could be consistent with the sequence of events and forensic evidence.

14 Two mechanisms for the generation of significant blast pressures that will be specifically included in this assessment are:

- a deflagration involving flame acceleration within a congested region. It is recognised at this stage that it is unlikely that on-site congestion, such as from pipework, would have been sufficient to provide significant flame acceleration, and the assessment will therefore focus on off-site features, including areas of vegetation and trees; and

- ignition within a confined volume resulting in the venting of a high velocity flame from the confined volume, which initiates a deflagration to detonation transition. Such a detonation might be able to propagate through at least part of the vapour cloud, generating high local pressures.

15 The possibility of pressure generation mechanisms not normally associated with this type of environment will also be considered. These include, for example, shock wave interaction with the flame front and pressures generated by a rapid change in phase, which could occur if any liquid droplets in the cloud were exposed to thermal radiation generated from combustion of part of the vapour cloud.

16 It is likely that this assessment will refer to previous experimental research and may involve modelling some aspects of the incident using existing dispersion and explosion models.

17 Based on the assessment of the scenarios, the panel will identify the gaps in understanding or information that need to be filled to explain the severity of the explosion in the Buncefield incident.

Interim guidance

18 On the basis of the assessment of the potential scenarios, it should be possible to prepare an interim review of guidance for operators of oil storage facilities, specifically in relation to the explosion issue. This guidance, which will also be of interest to regulators in the UK and overseas, will refer to the likely causes of the Buncefield explosion and highlight any actions operators or local planning authorities may need to take, including additional assessment or changes to facilities. It will also aim to provide important guidance for regulatory inspections.

Phase 2 proposal

19 The gaps in information or understanding identified during the assessment of potential scenarios will be used to prepare a proposal for Phase 2, if required.

20 Phase 2 would continue to address the Buncefield incident and therefore also be relevant to comparable facilities. The interim guidance provided in Phase 1 would be updated in the light of the results of the further research.

Deliverables

21 The deliverables from Phase 1 will be:

- report that provides:
  - a review of past incidents considered to be similar to Buncefield;
  - a record of information relevant to the formation and dispersion of vapour at Buncefield;
  - a record and critical review of the forensic evidence relevant to the explosion at the Buncefield site;

- identification of potential scenarios and mechanisms that could have led to the generation of a severe explosion at Buncefield;
- determination of scenarios consistent with the forensic evidence;
- a list of the gaps that need to be filled in our understanding and in the information needed to establish the cause of the severe explosion;

▼ interim guidance for operators of storage facilities, if possible; and

▼ a detailed proposal for Phase 2.

Phase 2 – Research to fill gaps

22 Phase 2 is likely to involve experimental research combined with modelling studies but it is possible that a need for more fundamental research will be identified. The experimental work is likely to involve both laboratory and large-scale experiments. Large-scale experiments would be necessary as the physics of explosions are scale dependent. Laboratory experiments can, however, provide fundamental data that underpin the understanding and modelling of the large-scale phenomena.

23 As stated above, Phase 2 would allow an update to the interim guidance issued following Phase 1. This would provide definitive recommendations on measures that could be justified to prevent a recurrence of the type of explosion that occurred at Buncefield.

Project delivery

Project management

23 The project will be overseen by a steering committee, which will comprise representatives of the stakeholders including: industry sponsors, the regulator, other potentially interested parties, industrial organisations and co-opted relevant specialists. The steering committee will be responsible for defining and monitoring the overarching aims of the project and ensuring its successful completion. It will review and provide comment on reports drafted by the technical committee and will provide authorisation for the publication of any reports.

24 Project management will be provided by a nominated project manager, who will co-ordinate the activities associated with the project and be responsible for providing a record of meetings and activities. It is recommended that for Phase 1, the project manager will be a member of the technical committee.

25 The main activities of the project will be carried out through the technical committee, which will comprise experts from industry, government and academia. The project structure is illustrated in Figure 2.

26 It will be the responsibility of the project manager to facilitate the technical discussions, and to compile the input from different members of the technical committee and form them into a single coherent and agreed report. It is suggested that this report should contain recommendations regarding the structure and management of Phase 2 of the project.

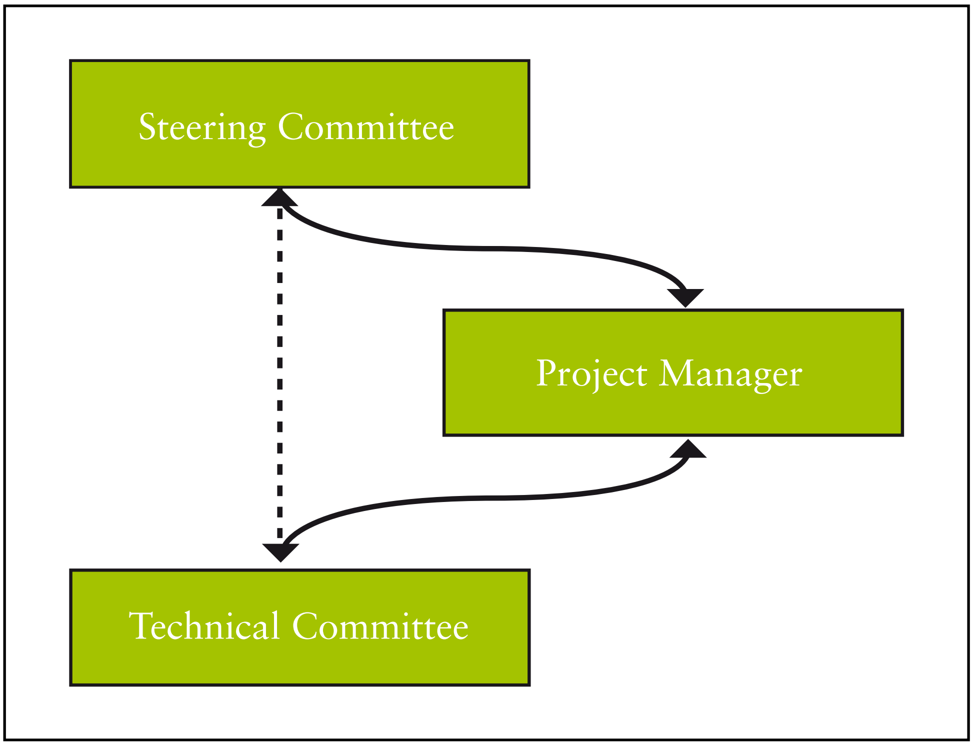

Figure 2 Project structure

Schedule

27 It is anticipated that the draft of the main Phase 1 report would be completed within a period of up to nine months and will include any industry guidance that can be provided at this stage.

28 The Phase 2 proposal will be produced within this period. The scope of work described in Phase 2 will be based on the gaps in our knowledge and understanding identified in Phase 1.

Commercial

Project cost

29 It is estimated that the price for conducting the Phase 1 study will be no more than £200 000. To ensure that Phase 1 can be initiated and completed without avoidable delay, it is suggested that the sponsor group should be limited to between five and ten members.

30 At this stage it is not possible to cost Phase 2, but as it is likely to involve large-scale experiments, it is anticipated that the budget for the programme of work will be in excess of £1 million. It may be appropriate to widen the sponsor group for this Phase to reduce the cost to individual members.

Terms and conditions

31 This proposal is subject to agreement on terms and conditions. Once interested parties have been identified, draft contractual terms and conditions will be distributed for comment.

Appendix 3

Map of the Buncefield depot and a selection of relevant photographs indicative of the damage

Figure 3 Pre-incident layout of Buncefield depot and immediate surroundings

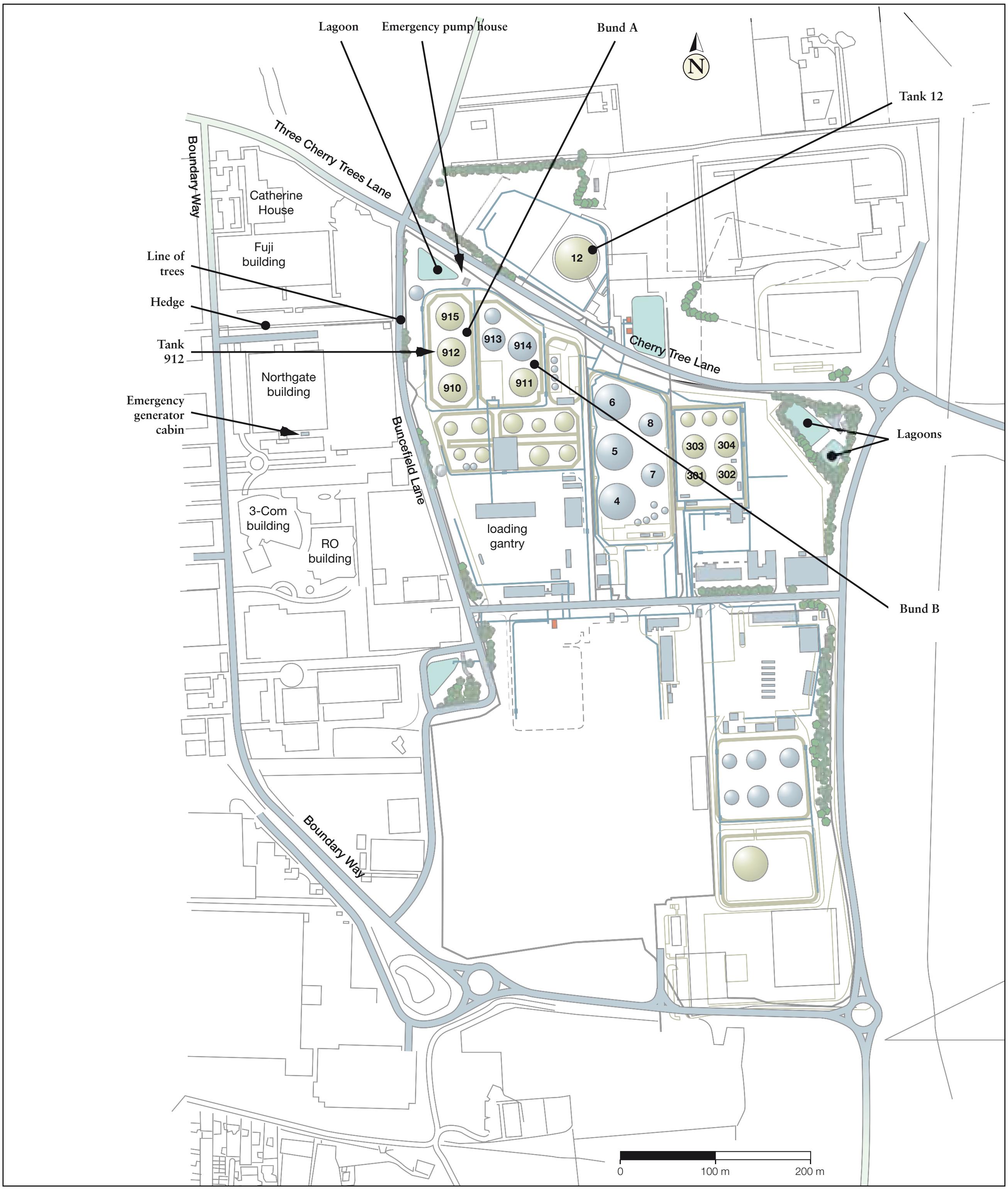

Figure 4 Fuji building looking north-west from the boundary with the Hertfordshire Oil Storage Ltd (HOSL) site

Figure 5 North side of the Northgate building

Figure 6 Looking east from the edge of the HOSL West site into the British Pipeline Agency Ltd site (Tank 4 on the left of the picture). The white tanks in the background are on the HOSL East site

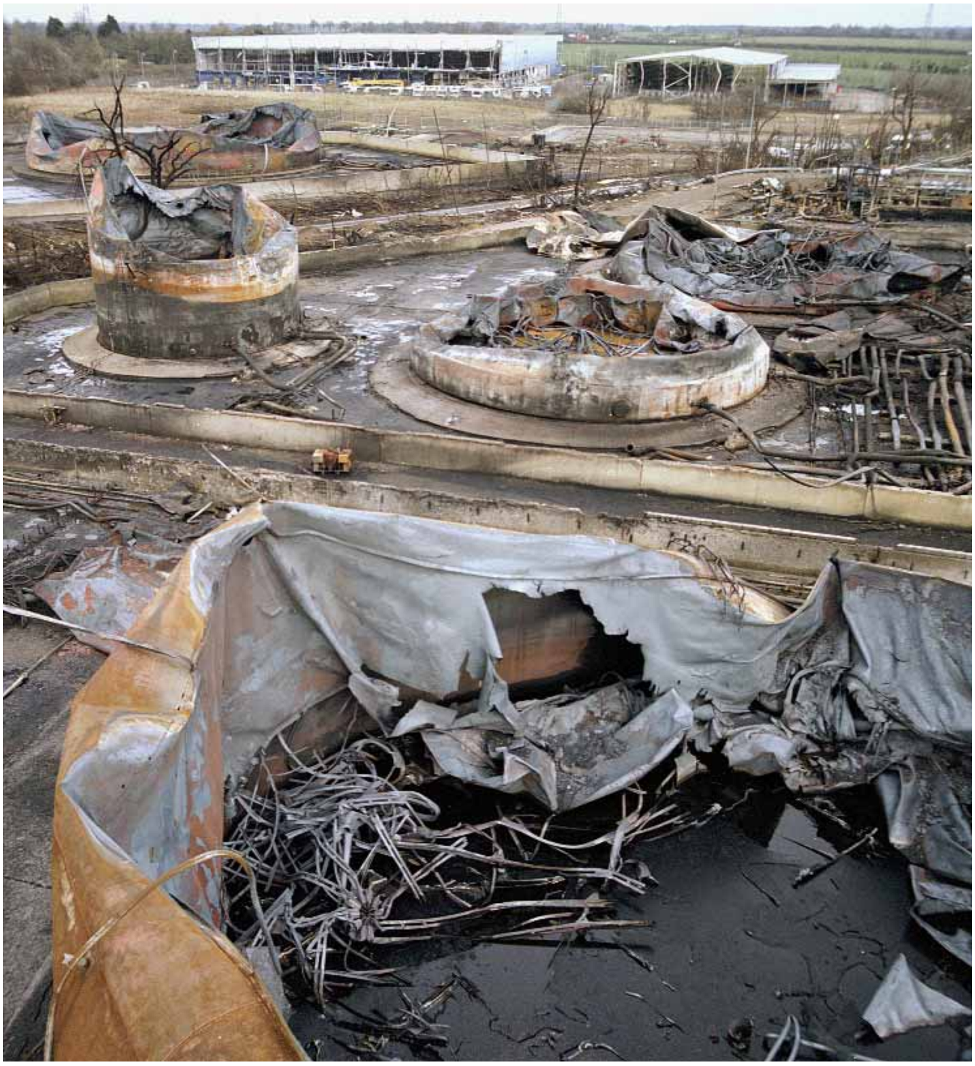

Figure 7 Looking east across the top of Tank 912. Tank 12 is in the background, across Cherry Tree Lane

Figure 8 Looking west into Northgate building car park, from the position of Tank 912 (HOSL West)

Figure 9 View into Tank 912

Figure 10 Looking south-west towards the Northgate building from Tank 915 (HOSL West)

Figure 11 View of the north side of the Northgate building, between the Northgate and Fuji buildings

Figure 12 View looking north towards the Northgate and Fuji buildings, with the Buncefield depot just off picture on the right. The emergency generator cabin is highlighted

Photograph courtesy of Hertfordshire Constabulary

Figure 13 Emergency pump house on the HOSL West site, from its north-east corner

Figure 14 HOSL West emergency pump house from the south-west side. The line of trees behind marks Cherry Tree Lane

Figure 15 Steel post in the west car park of the Northgate building. The post shows abrasion marks on its south face

Figure 16 View south along Buncefield Lane, showing sooting of lower parts of telegraph poles and trees

Figure 17 Abrasions to the base of a tree in the Northgate building west car park, viewed from the south

Figure 18 Damaged car in RO building car park (car facing south)

Figure 19 Cars on Three Cherry Trees Lane (near Catherine House)

Figure 20 Damaged cars at the south-west of the Northgate building car park; Boundary Way is in the background. The picture also shows blast damage to the north-west corner of the 3-Com building

Figure 21 Emergency generator cabin, close to the south-east corner of the Northgate building, viewed from the north east. The north-east segment of the damaged 3-Com building is shown to the left of the picture

Figure 22 Damaged car located at the south end of the Fuji building car park, adjacent to the hedge with the Northgate building car park

Appendix 4

Membership of the Advisory Group

- Professor Dougal Drysdale, University of Edinburgh (member, Major Incident Investigation Board)
- Professor Derek Bradley, University of Leeds
- Professor Geoffrey Chamberlain, Shell Global Solutions
- Dr Laurence Cusco, Health and Safety Laboratory
- Mike Johnson, Advantica
- Professor Hans Michels, Imperial College, London
- Professor Vincent Tam, BP Exploration

References

1 *The Buncefield Investigation: Progress report* Buncefield Major Incident Investigation Board 21 February 2006

2 *The Buncefield Investigation: Second progress report* Buncefield Major Incident Investigation Board 11 April 2006

3 *The Buncefield Investigation: Third progress report* Buncefield Major Incident Investigation Board 9 May 2006

4 *Initial Report to the Health and Safety Commission and the Environment Agency of the investigation into the explosions and fires at the Buncefield oil storage and transfer depot, Hemel Hempstead, on 11 December 2005* Buncefield Major Incident Investigation Board 13 July 2006

5 *Recommendations on the design and operation of fuel storage sites* Buncefield Major Incident Investigation Board March 2007

Buncefield Major Incident Investigation Board reports are available at:
www.buncefield investigation.gov.uk

Buncefield Major Incident Investigation Board
Marlowe Room, Rose Court, 2 Southwark Bridge, London SE1 9HS
Tel: 0207 717 6909 Fax: 0207 717 6082

Printed 08/07 C12

recycle

When you have finished with