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The Peterborough Explosion

A report of the investigation by the Health and Safety Executive into the explosion of a vehicle carrying explosives at Fengate Industrial Estate, Peterborough on 22 March 1989

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Summary

1 At 09.45 on 22 March 1989 a vehicle carrying approximately 800 kg of mixed explosives exploded at the premises of Vibroplant Ltd on the Fengate Industrial Estate, Peterborough. The explosion caused the death of a fireman and injuries to at least 107 other people, 84 of whom received hospital treatment. Two of the injured were admitted to intensive care.

2 The vehicle was a standard commercial model specially modified to carry explosives, operated by Nobels Explosives Company (NEC), a subsidiary of ICI. It had entered the Vibroplant yard, in order to turn round off the road, when a minor explosion occurred inside the load compartment, causing a fire. The fire brigade was called and took up position. The fire increased and after approximately 12 minutes the entire load, apart from a small number of detonators, detonated en masse.

3 The vehicle did not carry any external placarding to tell emergency services that it contained explosives, but this did not contravene the legislation in force at the time. The fire brigade was told that the vehicle was carrying commercial explosives before firemen arrived on the scene.

4 The investigation has concluded that the source of the fire and hence the cause of the explosion that followed was a box of Cerium fusehead combs destined for a local fireworks manufacturer. The combs were in unauthorised and unsafe packages.

5 On 11 April 1990 the company was fined £250 000 at Peterborough Crown Court after admitting failure to meet the duty of care for persons not in its employment set out in Section 3(1) of the Health and Safety at Work etc Act 1974, in particular for the fireman who was killed.

6 Three months after the incident the Road Transport (Carriage of Explosives) Regulations 1989 came into force. These Regulations, which had been in train well before the date of the explosion, require placarding, better training of vehicle crews and safer segregation of explosives in the vehicle compartment. These factors would not have prevented the incident, but might have ensured the provision of better information to the emergency services.

7 The report contains recommendations on the systems that should be developed to ensure the safe carriage of explosives by road, and comments on aspects of regulatory control.

Description of site

8 The yard of Vibroplant Ltd, Fengate, Peterborough, where the explosion occurred, is on the outer edge of an industrial estate mainly comprising small to medium size commercial and industrial properties, on the south east side of the town. The area is shown in Figure 1.

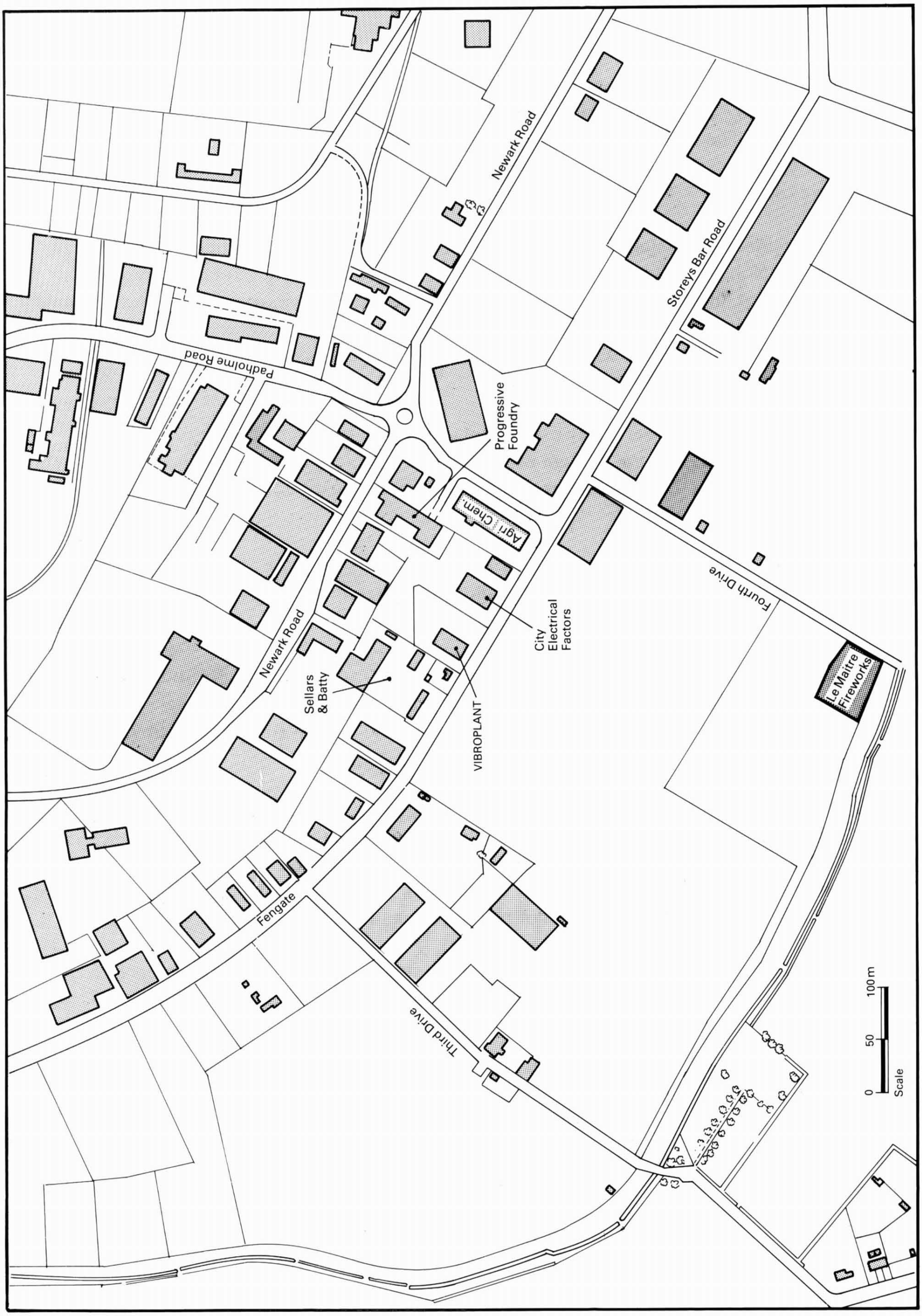


Figure 1 Plan of area around Vibroplant, Peterborough

9 The Vibroplant business is contract hire of plant and equipment for civil engineering work and has no connection with the explosives industry. It was a matter of chance that the explosives vehicle missed its way while heading for the nearby Le Maitre Fireworks Factory and used the yard as a turning place.

10 The aerial photographs in Figures 2 and 3 show the Vibroplant yard some time before, and after, the incident. The entrance to the yard is set back and separated from the road by a pavement and grass verge some 24 m wide: the yard is about 90 x 60 m, bounded on the south side by a 2 m high, 22.5 cm brick wall, and on the other sides by a chain link fence. There is a car park along the boundary wall. A wide range of contractors' plant, including portacabins, was parked around the yard perimeter, with room in the middle for manoeuvre. The yard's surface was of asphalt over hard core. There was a `sleeping policeman' speed ramp just inside the main gate.

11 At the time of the incident there were 19 people working in the Vibroplant premises, including factory and office staff. The premises immediately adjoining were City Electrical Factors Limited, with 20 employees, Sellers and Batty (Peterborough) Ltd, motor vehicle repairers and dealers, with 40 employees, and a small builder's yard.

Description of vehicle

12 The vehicle was a Ford D series 11.5 tonne box van, registration number MSO 233W, owned and operated by Nobels Explosives Company Ltd, a subsidiary of ICI. A photograph of the type is shown in Figure 4. It was one of a fleet of vehicles, specially modified to carry up to 5 tonnes of explosives in order to comply with legal requirements concerning the carriage of explosives, the Order of Secretary of State No 11 dated 1924, made under the Explosives Act 1875 and as amended from time to time.

13 The van had a sheet aluminium box load compartment with a rear roller shutter door, separated from the cab by a fire-resistant screen. The vehicle was marked with a black ICI logo on the side of the load compartment, but it had no other means of external identification apart from an emergency telephone number on the cab side. The vehicle was crewed by a driver and an attendant who had been employed by NEC for 13 months and 11 years respectively.

Explosives contents

14 At the time of the incident the vehicle contained:

High explosive
- Powergel 800, 150 kg in 6 x 25 kg cases
- Powergel E800, 500 kg in 20 x 25 kg cases
- Magna Primers 56 kg
- Ammon-Gelit 75 kg

Detonators
- No 8 Star, 500 in number
- Magnadet, 250 in number

Fuseheads
- Vulcan, 10 000 in 1 box
- Cerium, uncut combs, 2400 in 3 boxes

15 The high explosives and detonators were typical of those used in quarrying and other blasting work. Powergels are relatively insensitive and are initiated by a detonator, normally with a primer (booster) such as Magna Primer or other more sensitive high explosive such as Ammon Gelit. The detonators are sensitive initiating explosives and are electrically fired. Fuseheads are a type of small electrical igniter. They look rather like matches and are mainly used to provide the ignition in detonators. They have been used for several years at Le Maitre Fireworks Factory as igniters for pyrotechnic devices. There were two types on the vehicle: Vulcan, which were supplied as individual (cut) fuseheads, and Cerium, which were supplied uncut on combs with 20 fuseheads per comb. They are shown in Figure 5.

16 All the explosives were produced by NEC either at their Ardeer works in Ayrshire or Roburite works in Lancashire, except for the Ammon Gelit which was produced by Dynamit Nobel of the Federal German Republic.

Events leading to the explosion

The journey

17 The vehicle was loaded by the driver and his attendant at the NEC Fisherwick Depot, Lichfield, Staffs, at approximately 06.00 on the day of the incident. The load included two consignments of blasting explosives to be delivered on route to Peterborough, the fuseheads for Le Maitre, and a further consignment of high explosives for a destination beyond Peterborough. The first two deliveries were made at 07.15 and 08.00. It would be normal practice to rearrange the load as deliveries were made, and this was done at the second stop, before the vehicle departed for Peterborough. The new arrangement of the load is shown in Figure 6.

18 The drive to Peterborough seems to have been uneventful. The route ran south of Leicester on the

Figure 2 Aerial photograph of area before explosion (*Photograph reproduced by kind permission of Skyviews and General Ltd*)

Figure 3 Aerial photograph of area after explosion (*Photograph reproduced by kind permission of Peterborough Evening Telegraph*)

Figure 4 Vehicle of the type involved in the explosion

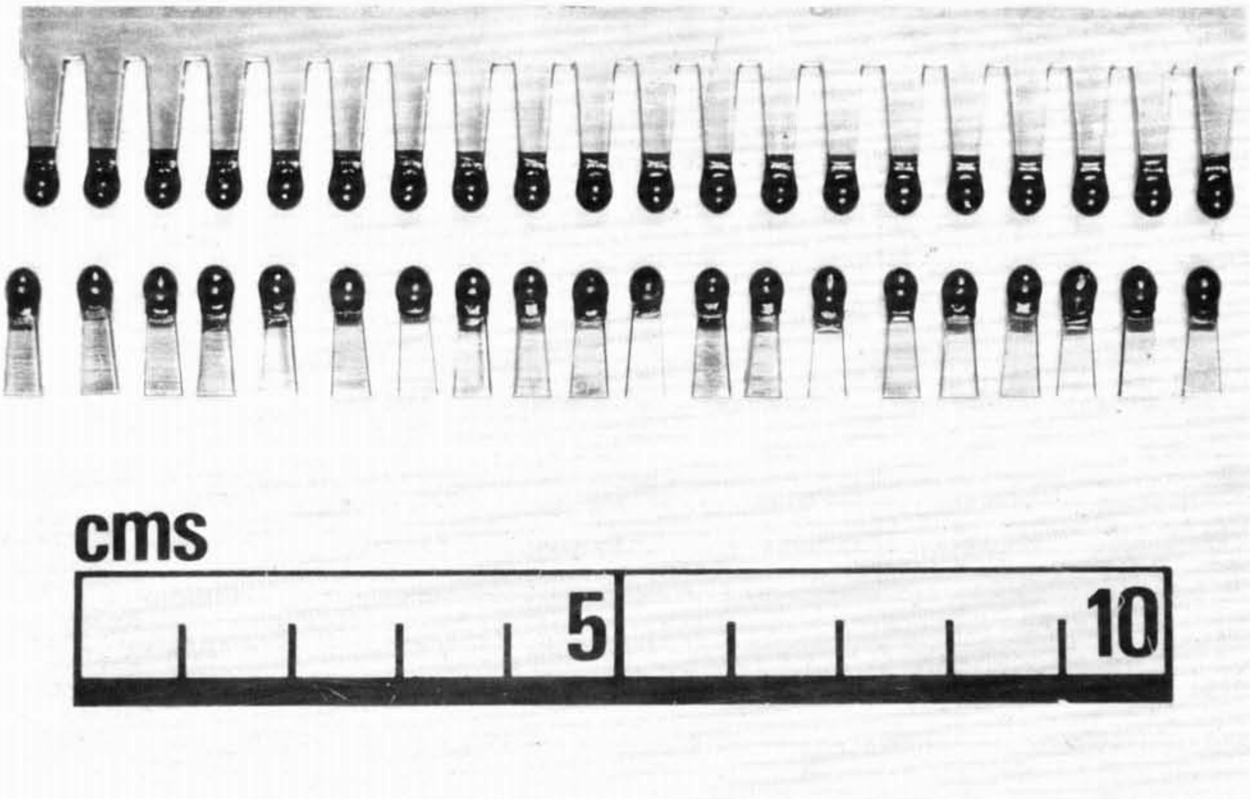
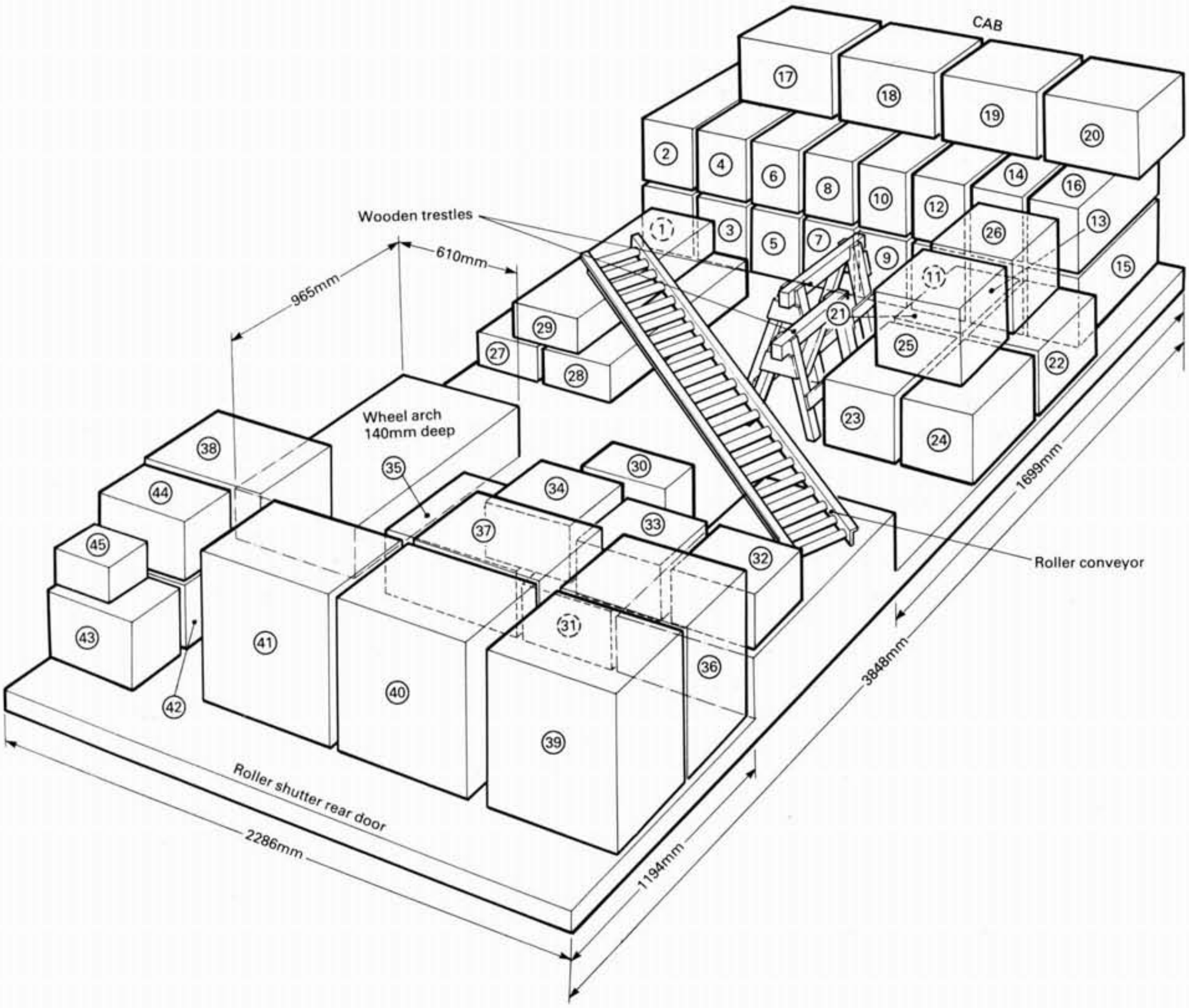


Figure 5 Cerium fusehead comb (above) and (below) cut fuseheads



NUMBER	QTY	CONTENTS
1 to 20	20	Fibreboard boxes of Powergel E 800 (25kg each) (495mm × 268mm × 268mm)
21 to 26	6	Fibreboard boxes of Powergel 800 (25kg each) (440mm × 357mm × 270mm)
27 to 29	3	Fibreboard boxes of Ammon Gelit (25kg each) (735mm × 255mm × 133mm)
30 to 34	5	Fibreboard boxes of Magna Primers (385mm × 385mm × 172mm)
35	1	Fibreboard box of wire (non explosive) (559mm × 381mm × 203mm)
36 to 41	6	Plywood boxes for transporting detonators (521mm × 432mm × 457mm) 36-38 Empty at time of incident 39-41 Containing Electric Detonators
42 to 44	3	Wooden boxes of Cerium Fuse-Head Combs (400mm × 240mm × 240mm) Each containing 2 tinned steel boxes
45	1	Wooden box of Vulcan Fuse Heads (260mm × 190mm × 140mm) Containing 10 tinned steel boxes

Figure 6 Layout of vehicle load

B4114, then along the A47 to the outskirts of Peterborough. The vehicle entered the Fengate Industrial Estate along the outer ring road (Figure 7). It was heading for the Le Maitre Fireworks Factory, Fourth Drove, on the Fengate Industrial Estate but missed the left hand turning. The driver decided to continue along Fengate and turned right into Vibroplant's yard to turn around. The precise time of entry into the yard is not known but was probably shortly after 09.30 am.

Fire and explosions

19 As the vehicle entered the yard it passed over a concrete speed ramp (or 'sleeping policeman'), whereupon there was a minor explosion inside the load compartment which blew the rear roller shutter door outwards. The attendant was aware of a flash on entering the yard and informed the driver. As the driver continued in a right hand circle around the yard he noticed, in his rear view mirror, blue smoke behind the lorry. He stopped the vehicle near the middle of the yard facing the exit. Both the driver and his attendant went to the rear to investigate.

20 The roller shutter door was hanging out of its guides on the passenger side and only partially in the guides on the driver's side. The door was secure at the top and locked at the bottom. Smoke and flames were coming from inside through the gaps at the side of the door, but no fire was seen outside the compartment.

21 The men decided not to fight the fire but to alert people in Vibroplant and get them to contact the emergency services. Men working in the yard were told that there was a fire and that the vehicle contained commercial explosives. One of the workers made a 999 call from the workshop at 09.36 but mistakenly referred to a tanker being on fire. The driver warned the receptionist who made a second call at 09.39 which clearly referred to explosives being on board. After warning the people in Vibroplant the driver and his attendant went along Fengate in opposite directions to stop traffic and warn people to evacuate the area.

22 According to statements from witnesses, the fire produced only a small amount of black smoke initially. As it progressed, however, minor detonations or 'pops' were heard, which increased in frequency. Many witnesses reported that at one stage during the fire the roller door fell or slumped down. As the fire progressed further thick yellow smoke was observed and immediately before the explosion witnesses saw the vehicle side start to bulge. The vehicle exploded at approximately 09.45.

Emergency services action

23 The first 999 telephone call was relayed by the control room to a rescue vehicle (Alpha 145) and a fire tender (Alpha 143) which were re-routed to the premises. A second tender (Alpha 163) was mobilised from its base fire station. The second emergency telephone call was also relayed to the mobile units and was received by the rescue vehicle as it reached the Vibroplant yard at 09.41. On arriving at the yard, the Leading Fireman with the rescue vehicle was told by a member of the NEC crew that the burning vehicle contained detonators. The Leading Fireman sent a message to the fire control confirming that the vehicle contained explosives and that they were detonating. The rescue vehicle was parked behind a brick perimeter wall for safety and the crew fulfilled a support role and helped in the evacuation of surrounding buildings. The two fire tenders arrived at the premises at 09.43 and 09.44. Prior to their arrival at the Vibroplant premises the crews of both tenders had received radio messages confirming that the vehicle contained industrial explosives. They were also given this information by the Leading Fireman from Alpha 145 when they reached the scene of the accident.

24 The first priority was the evacuation of personnel in surrounding buildings. It was decided that water should be turned on the burning vehicle to give more time for evacuation. The crew of fire tender Alpha 163, which was parked outside the entrance to the yard, ran a hose along the base of the perimeter wall, using the wall as protection from the burning vehicle on the other side, towards the yard. The crew of the other tender (Alpha 143) intended to drive to the back of the site and play water on the vehicle from that direction. Fireman Humphries (Alpha 163) and another fireman took the two man branch (nozzle) beyond the edge of the wall some 15 metres from the burning vehicle and stood ready to receive water. At that moment (09.45) the vehicle exploded. Fireman Humphries was struck in the head by shrapnel and died shortly afterwards. Nearly all members of both fire crews were injured to varying degrees.

25 Within minutes after the explosion police, ambulance and fire services were in attendance and treated the situation as a major disaster. The original fire crews were withdrawn by the fire brigade and replaced by other crews. There was a conference of police, fire and ambulance officers to assess the situation, likelihood of danger and casualties. The police set up a command post and cordoned off the area encompassing Newark Road, Boongate and Padholme Road.

Injury damage and other effects

26 At least 107 people were injured in the explosion, of whom 84 received hospital treatment and 2 were admitted to intensive care. One of these had extensive burns to the face and body, the other had fractured ribs

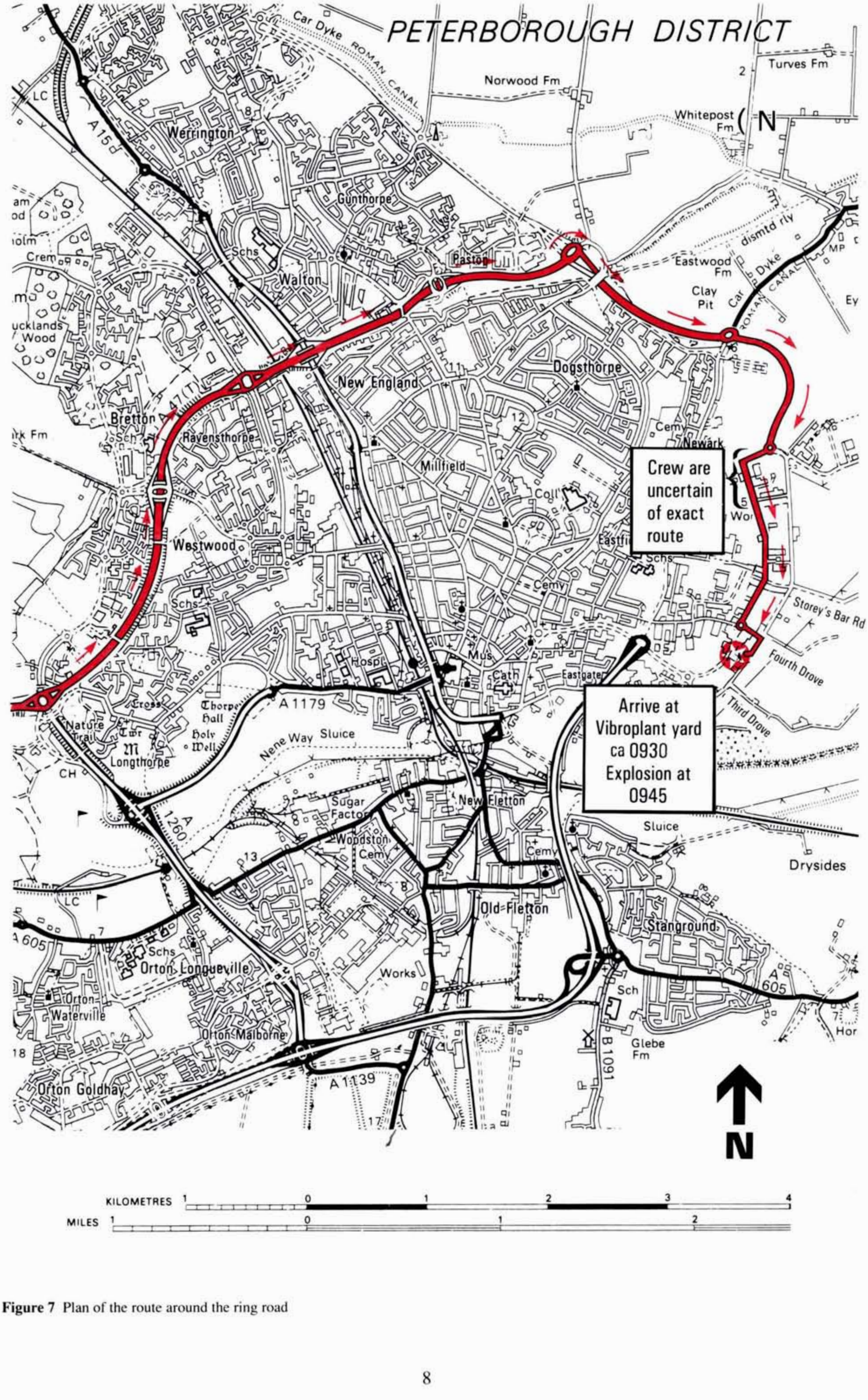


Figure 7 Plan of the route around the ring road

and scapula, a deflated right lung and lacerations.

27 The fireman killed in the incident was struck in the forehead by a piece of shrapnel which entered his brain. He also suffered severe burns. His partner, and another fireman who was standing slightly to their rear, received burns and damaged eardrums. Nearly all the other members of the fire service suffered burns, head, ear and eye injuries from blast, noise and flying debris, and severe shock. Some were rendered temporarily unconscious and nearly all were knocked over by the blast itself. A man who was in a building approximately 150 metres away was injured by a space heating unit which fell from the ceiling.

28 People who were outdoors and close to the explosion received perforated ear drums, cuts and bruises from flying debris and were thrown to the ground. Most of the injuries to those indoors were caused by flying glass. The delay between the start of the incident and the actual explosion gave workers time to go to their office windows to watch what was happening. Other indoor injuries were caused by collapsing ceilings.

29 The epicentre of the explosion was marked by a depression 46 cm deep and 7 m across in the tarmac surface of the yard. Structural damage to the two buildings on either side of the explosion was considerable and the Vibroplant building to the south west had later to be demolished. About 150 buildings further afield received significant damage with large doors blown in, metal cladding damaged or removed, asbestos roofs collapsed, window frames blown in and extensive window damage. About 130 cars were also damaged to varying degrees - around 60 beyond repair, 13 badly, 51 slightly and the remainder superficially. Figure 3 shows the scene after the explosion.

30 A more detailed assessment of the injuries and blast damage is given in the Appendix. Summaries of both damage and injuries versus distance are given in Tables 3 and 4. The observed distances corresponding to defined effects are compared with those predicted for 800 kg of TNT. The studies suggest that the violence of the explosion was equivalent to about 800 kg of TNT.

HSE investigations

31 The work of HSE was led by the Explosives Unit of Technology Division supported by of the Factory Inspectorate, Field Consultant Groups and the Research and Laboratory Services Division. This coordinated approach proved invaluable in the initial stages, when reports of the incident were received in different offices and gave conflicting information, and then later as teams were formed to follow separate strands of the overall investigation.

32 HM Factory Inspectors from the local area office in Luton were first on the scene and took initial responsibility for HSE. They rapidly drew in colleagues from the Field Consultant Group to give specialist construction engineering advice on site clearance and demolition work necessary to make the area safe. In parallel, the area was checked to ensure no residual explosives remained. A sector ground search was carried out by the Army Bomb Squad and police teams supported by NEC staff and by HM Inspectors of Explosives as they arrived on site from HSE Merseyside.

33 Once the site was secure, attention turned to more detailed assessment of the injuries and other damage caused by the blast; an extensive survey of remaining structures and searches for vehicle fragments were completed. Eye witnesses were interviewed, and statements taken earlier by the police were handed to HSE. NEC were requested to locate and hold in storage all remaining explosives from the batches involved in the incident and not to distribute them until further notice.

34 A considerable amount of eye witness evidence was obtained which enabled HSE to piece together the likely sequence of events. Statements obtained from the driver and passenger of a van which was travelling immediately behind the explosives vehicle along Fengate and followed it into the Vibroplant yard were particularly significant. These witnesses saw nothing untoward before the vehicle entered the yard; however, a minor explosion occurred as it passed over the speed ramp causing the roller shutter door to be lifted up and blown out slightly. The lower near side of the door swung out first indicating that the first explosion occurred at the rear of the van on the near side floor. These statements corroborated those of the driver and attendant on the timing of the explosion.

35 Information was obtained from the driver and attendant about the loading arrangement using similar packages and a similar vehicle in practical tests at the NEC depot at Fisherwick. It was established that the vehicle was loaded as shown in Figure 6, with blasting (high) explosives at the front of the compartment, primers in the middle, and detonators and fuseheads at the rear close to the shutter door. The fuseheads were at the nearside of the compartment.

36 Several visits were made to the NEC factories at Roburite, Lancashire and Ardeer, Ayrshire, where the explosives were made. Information was obtained on the specific explosives substances involved, the specification and quality control, and the method of packing. Compliance with legal requirements relating to the authorisation, packing and labelling of explosives was assessed.

37 Le Maitre Fireworks provided further information on the supply of fuseheads. Prior to 1980 only cut fuseheads had been supplied. Deliveries of uncut fusehead combs then commenced, initially packed in wooden boxes. The wooden boxes were replaced by tinned boxes in October 1985. Samples of those fusehead combs and of the tin boxes in which they had been supplied by NEC were taken for examination.

38 Representative samples of all the explosives present on the vehicle were examined at HSE's research facilities at Buxton. The work included:

(a) checks on the thermal stability and sensitiveness to ignition and assessment against accepted criteria;

(b) checks on the suitability against authorised requirements of the packages and packaging materials for the purposes of carriage by road;

(c) vibration tests to simulate the likely conditions inside the vehicle during a typical journey and including such jolts as might be caused by a speed ramp;

(d) tests on the possible communication of explosion between various explosives as packed and the effects caused by placing them in turn in a bonfire or by dropping them from different heights.

Results of tests

39 All of the high explosives and detonators behaved quite normally in the tests carried out. Their packagings fully met the requirements laid down. Examination of production records revealed no anomalies. All were found to be safe to transport.

Communication testing of detonators

40 Communication tests were carried out on both types of detonator as packed for transport to examine the effect of initiating a single one among a larger quantity. The No 8 Star failed to produce a mass explosion, with only a minority of the detonators initiating. The damage to the transport box was generally limited to the displacement or removal of one side. Similar tests on the Magna gave a much greater degree of communication between detonators with more severe damage to the transport box. The main effect was a scattering of live detonators outside the box.

Examination of fuseheads

41 The *Vulcan fuseheads* met the required specification and their packagings, although not quite as had been authorised, met the objective to contain the effects of any internal ignition in all tests carried out. No ignitions were produced in drops up to 3 m. 1000 fuseheads were packed into appropriately sized good quality tinned metal boxes, two bundles of five boxes each well wrapped in paper were then placed with wood shavings into an outer wooden transit case and the lid screwed in place.

42 The *Cerium fusehead combs*, however, were found to be packed in unauthorised and unsafe packagings. Samples of the tinned metal box containers taken from Ardeer were found to contain rust on the inner surfaces and holes in the corner. Samples from Le Maitre contained debris and loose composition which probably accumulated during transport from Ardeer. A total of 400 combs were packed in four layers with pressboard between into a tinned metal box. Two boxes each containing the equivalent of 8000 individual fuseheads were then packed with wood shavings in an outer wooden transit case. Gaps within the tins were filled with paper, a sheet of cardboard placed on top, and the lids taped into position. Further commentary on compliance with legal requirements is given in paragraphs 57 to 61.

43 Cerium fusehead composition was examined and found to be sensitive to impact and extremely sensitive to friction. Mixtures with small quantities of rust (1%) were found to be ten times more sensitive to impact than composition alone. No friction test was carried out on the mixture containing rust, but the rust particles would have been expected to increase the sensitiveness even further.

44 All trials on packages of uncut combs were carried out at the premises of NEC to avoid their transport in that form, and HSE is grateful for their collaboration. Packages were subjected to dropping from various heights, and to internal ignition both in the open and on board a representative explosives vehicle. When dropped from a height of 1.2 m they exploded in some tests but not in others. Internal ignition trials on the vehicle produced the effect of blowing out the roller door, but not detaching it, when one box was ignited. The effect observed was similar to that described by witnesses at Peterborough. When two boxes were ignited the explosion completely detached the door. In both cases the explosion caused a fire in the cargo compartment.

Other tests

45 Laboratory vibration tests were carried out to simulate the effects of movements in transport. When a tinned box of Cerium combs was tested it was found that some of the fuseheads suffered damage causing loose composition to collect at the bottom of the box.

46 Measurements were carried out to establish the

accelerations likely to have been experienced by the boxes when they passed over the speed ramp. The highest peak acceleration measured was only some 10% of that produced in a 1.2 m drop test, the minimum to produce an ignition of the package, indicating that some other effect or condition had to be present to cause an ignition of the combs. However the packages used in the drop tests were clean and the contents had not been subject to transport vibrations. As reported in paragraph 43, the presence of rust increased impact sensitiveness by a factor of 10.

47 As an aid to the loading and unloading of the vehicle a roller conveyor was carried loose in the cargo hold with the explosives. Tests were carried out to determine whether any impact that could have been produced by the roller conveyor might have caused an ignition. Simulation spigot drop tests on the Ammon-Gelit produced no ignitions, indicating that this mechanism was unlikely.

Cause of the fire and explosions

Initial minor explosion

48 The evidence clearly shows that the incident began with a minor explosion inside the load compartment. This was followed by a fire which increased steadily for about 12 minutes and then the bulk of the cargo detonated.

49 The most likely explanation for the initial minor explosion was an ignition within one of the boxes of Cerium fusehead combs. It was probably initiated by friction between the metal of the box and rust sensitised composition. The evidence for this is summarised as follows:

(a) good eye witness accounts indicated that the source of the ignition was low down at the rear near-side, confirmed by the driver to be where the boxes of fuseheads were located;

(b) tinned boxes used for Cerium fuseheads were discovered at the manufacturers which contained rust and holes, and at the Le Maitre factory which contained loose composition;

(c) laboratory tests showed that fusehead composition is extremely sensitive to friction and impact and that this sensitiveness is enhanced by even a small quantity of rust;

(d) simulation tests showed that the vibration of packed Cerium combs, as might be experienced during transport, could lead to the damage of the fuseheads and the consequential accumulation of loose explosive composition within the tinned box;

(e) the behaviour of the combs on ignition was similar to that observed at Peterborough, ie they produced a flash which blew out and damaged the rear door of the vehicle;

(f) the acceleration forces the packages experienced, when passing over the ramp, were assessed as being sufficient to ignite fusehead composition when sensitised by rust;

(g) the holes may have contributed to the ignition by allowing fuseheads or pieces of fusehead debris to become trapped in them, producing the risk of ignition by nipping.

50 The other types of explosive were examined as possible sources of ignition and none was found to have the sensitiveness to impact or friction to cause it to ignite when the vehicle passed over the ramp, nor was anything untoward found in their packaging or manufacture. Furthermore their behaviour on ignition did not reflect what actually happened: detonators would explode in small numbers or detonate en masse with a louder, more `brissant', shattering effect; Ammon-Gelit and Magna primers if so ignited would burn or mass detonate; the Powergels are relatively insensitive and do not burn readily. It was concluded that they were not the source of the initial explosion.

Mass detonation

51 In the ignition trials it was shown that one box of Cerium combs produced a fireball approximately 2.5 m in diameter and lasting 0.3 seconds. The fireball and the burning debris thrown out would be likely to start fires at various positions inside the compartment. Various popping noises were heard by witnesses which were probably the ignitions of detonators.

52 Once the fire started in the load compartment the eventual detonation could have occurred in either of two ways:

(a) the Ammon-Gelit or Magna primers could have burned with increasing intensity until a transition from deflagration to detonation occurred. A detonation of the Magna primers or Ammon-Gelit would be sufficient to communicate instantly to the main load of Powergel;

(b) the scattering and subsequent functioning of detonators, blown from their packages onto the high explosives whose packaging had been consumed by fire, could have caused initiation.

53 It cannot be stated conclusively which of the two

mechanisms occurred. Trials carried out support the theory that detonation was caused by detonators, scattered largely unexploded from their transport box. The high explosives failed to detonate in bonfire tests.

Legal considerations

Transport

54 At the time of the accident the legal provisions governing the transport of commercial explosives by road were contained in the Order of Secretary of State No 11 (OSS11). These were due to be replaced by new provisions and indeed the Road Traffic (Carriage of Explosives) Regulations 1989 came into force on 3 July 1989, except for the training provision which came into force 6 months later. The OSS11 Bye-laws required that mechanically driven vehicles complied with conditions approved by the Secretary of State which were published by HSE as document LP64.

55 Although the OSS11 provisions allowed the use of the vehicle involved in the explosion to carry the types and quantities of explosives which were on board, there were aspects of non-compliance. Bye-law 2(c) in particular required detonators to be stowed as far away from other explosives as reasonably practicable, and that was not the case, as might be seen from Figure 6. According to evidence from the driver, the arrangement complied with the Bye-law at the beginning of the journey, but the load was rearranged after the second stop.

56 Much was said in the public debate that followed the incident about the lack of placarding on the vehicle to indicate the explosives it carried and about the balance that might need to be drawn between safety and security demands. Placarding was not a requirement at the time but was included in the new Regulations.

Packing

57 The requirements for the packing of explosives are contained in The Packing of Explosives for Conveyance Rules 1949. Three rules are of significance to this incident - Numbers 5, 6 and 10(d).

58 Rules 5 and 6, which apply to all explosives, require that the interior of every outer and inner package should be clean and free from grit (No 5), and that iron or steel should not be used unless it is so covered as to prevent it being or becoming exposed (No 6). As described in paragraph 42, tinned boxes used for the Cerium combs were found to be rusted and to contain debris.

59 Rule No 10(d) applies specifically to fuseheads classified as Class 6 Division 2, such as those involved in the explosion. It stipulates that the packing method shall comply with the requirements of a government inspector. The Vulcan type was found not to be packed strictly in compliance with the relevant special packing authority but met its objectives in that the packaging contained the effects of internal ignition. The Cerium type was not packed in accordance with the existing authority and no alternative had been sought or issued.

60 The authorised method limits the number of fuseheads in an inner tinned box to either 500 or 1000, depending on the type of fusehead. Each inner box is packed into an intermediate box with, in the case of Cerium, cushioning separators. A number of such combinations up to a maximum of 25 000 or 50 000 fuseheads, depending on the type, are then placed in an outer tin-lined wooden box.

61 The Cerium type of fusehead, as attached to the uncut combs involved in the incident, should have been packed in that way with no more than 500 in each inner box. But 400 combs, each with 20 fuseheads (ie 8000 in total), had been packed into each inner tin, which then needed to be much larger than those authorised. Two of the boxes were then placed in no more than an unlined wooden box. The packages were not only technically illegal but also highly dangerous in that:

(a) the combs were relatively loosely packed, which allowed the shedding of highly sensitive composition in transport;

(b) the boxes contained rust, composition debris and holes which significantly increased the sensitiveness to and likelihood of ignition;

(c) ignition of the excessive quantity of fuseheads produced an instantaneous explosion and a significant fireball effect.

Authorisation

62 Before they can be transported, explosives must be authorised for general sale either by a licence to manufacture or an importation licence. A list of all explosives so authorised is published annually by HM Chief Inspector of Explosives. Each item is separately described, and the descriptions are issued to the applicant company. All the explosives involved in the incident were checked for compliance with the authorised description and were found to meet the requirements, except for the fusehead combs. A description had been issued for fuseheads but this was for individual items, not when on combs. If inspectors in the Explosives Unit had received a request from the company for authorisation of such combs, they would have enquired as to the packaging method to verify that it complied with Rule 10(d) of the Packing of Explosives for Conveyance Rules 1949.

General duties

63 The general provisions of the Health and Safety at Work etc Act 1974 (HSWA) also applied in addition to the more specific requirements just detailed. Section 3 HSWA places duties on employers to conduct their undertakings so as to, as far as is reasonably practicable, not expose those not in their employment to risk to their health and safety. The transport of unauthorised explosives which as packed were liable to be susceptible to ignition and explosion was in breach of that duty. Section 2 concerning systems of work to protect employees also applies in respect of the driver and the mate, placing duties in respect of training and instruction. Nobels Explosives Company was charged with and pleaded guilty to a breach of Section 3 HSWA at Peterborough Crown Court on 11 April 1990 and was fined £250 000.

64 The training of drivers was found to be insufficient and to lack any formal structure. They were given a handbook containing instructions and merely taken through them briefly by the depot manager, after which they simply worked with an experienced person. There was no assessment of competency or of knowledge and understanding of risks involved, nor any monitoring and review of individual training requirements. The company, however, did undertake routine housekeeping inspections and depot tours, and set standards of loading storage and stacking.

Management organisation

65 The company organisation and systems of work were examined in an attempt to discover how the failures described above had come about. The joint managing directors and members of senior and middle management were interviewed. There had been several changes in systems of control and personnel since October 1985 when the fusehead combs were first packed and transported in tinned boxes. The management structure was a complex matrix system in which managers had both functional and business responsibilities covering separate areas of work.

66 A Design Representative and Packaging Adviser were responsible for packing requirements. However, they checked new products and amendments to existing ones when they occurred, but did not review those introduced in previous years, such as fusehead combs. No clear explanation was given for the use of unapproved packages for fusehead combs, the method appeared to have by-passed any assessment for compliance with requirements.

67 The safety department was primarily concerned with manufacture, ie plant and processes, and had little involvement in product development and design, including correctness for transport. There was no clear managerial responsibility for safety in either of these functions.

68 No written specification for fusehead comb packages existed, nor were there any written operating instructions on the method of packing. No inspection of the containers for suitability for use in transport, against laid down rules, was carried out.

Fire services

69 In one of the strands of the overall investigation, factory inspectors concentrated on the response of the emergency services, particularly the degree to which the Fire Brigade fulfilled its duties as an employer under the Health and Safety at Work etc Act 1974, with regard to the safety of its employees. During the course of the enquiry each of the firemen was interviewed individually, as were the senior firemen involved in training programme development and implementation. In addition both station and individual training records and procedures were examined. The results of these enquiries were related directly to the type of action taken by the Brigade and the degree to which it was applied.

70 Each brigade is responsible for conducting its firefighting and for training its own firemen on the basis of information and advice provided by the Home Office. The principal guidance on firefighting techniques available to the Brigade was the *Manual of Firemanship, Part 6C, Practical Firemanship - III*, which contains sections on dealing with explosives fires during transit. The manual was published by HMSO in 1962, with a second edition in 1971. The whole of the manual is currently undergoing progressive revision by the Home Office. This manual is supplemented by Fire Service Circulars, 'Dear Chief Officer Letters', and other information issued by the Home Departments. The guidance in the manual recognises "that in no circumstances can firefighting among explosives be carried out in accordance with the practices and techniques adopted for ordinary risks". It states, however, that "success in fighting fires involving explosives is largely dependent on action being taken before the fire can develop and the availability of copious water supplies" and, for explosives in transit "When the type of explosive combined with an early arrival at the scene of the outbreak make it practicable, a quick and resolute attack on the fire is the best means of averting all danger.......". The guidance clearly envisages that such an attack can be made by firefighting with water and the action of the brigade in attempting to apply a water jet to the vehicle followed that concept.

71 The guidance in the Manual is based on the premise that use of copious amounts of water may control the fire. Water controls fire by excluding oxygen and by its cooling effect. Explosives, by their nature, supply their own combustion oxygen, and any cooling effect that might be achieved to the explosives will be extremely limited when dealing with a transport incident because the weather resistance of the vehicle and the packaging will prevent the water reaching the explosives themselves. That is not to say that the use of firefighting methods for vehicles carrying explosives is wrong in principle. It may prevent a fire on the vehicle itself reaching the explosives cargo, but it introduces an added difficulty to the very rapid decision the officer-in-charge must make as to what he should do.

72 Standards of Brigade training and efficiency are independently and routinely scrutinised by HM Inspectors of Fire Service. All the crews involved had received training in the nature and problems of explosives based on Part 6, chapter 45, section 2, 9C of the manual of *Fire fighting involving explosives in transit*. At each individual station the training is carried out by a Leading Fireman or Sub-Officer and is repeated periodically. One crew had received such instruction only one week before the explosion. Practical knowledge of service explosives had been obtained by one crew during a visit to a Ministry of Defence bomb store. Training appeared to have been restricted to theoretical applications and no practical exercises on fighting explosives fires on road vehicles had ever been attempted. Clearly there would be considerable difficulties in doing so.

73 The timescale for action by the Brigade was extremely short. The total time from the arrival of the rescue vehicle crew (originally despatched on the basis of incorrect information) to the explosion was only 5 minutes. The appliances equipped to fight the fire were on site for only 1 to 2 minutes respectively before the explosion occurred. The action taken was prompt and consistent with the guidance and training they had received. The service managed to achieve much success in alerting and evacuating members of the public. However, for the reasons given in paragraph 71 above, the action taken to attempt to play water on the vehicle was misconceived.

74 The accident demonstrates that there may be incidents involving explosives when all the attention of the emergency services and vehicle crew should be given to evacuation and reduction in numbers exposed to risk. There appears to be a need to review and revise the guidance given to emergency services. Guidance to vehicle crews on the action to take in the event of a fire is given in the Approved Code of Practice to the 1989 Regulations and this advocates that a distinction should be made between fires not involving the load and those that do and the different action required. The HSE view is that when a fire involves the explosives load or is imminently threatening it, every possible effort should be given to the evacuation of the area and only where this is for some reason clearly not possible, and where the rapid application of water would have a good chance in the circumstances of preventing an explosion, should an attack by firefighters be attempted.

The new regulations

75 The 1989 Regulations are far more comprehensive than the provisions of OSS No 11. They are supported by an Approved Code of Practice and Guidance. While the root cause of the incident lay with incorrect packaging, a matter for separate legislation, it is worthwhile to consider the effect the new regulations would have in such a situation. The more relevant factors are:-

- placarding
- training and provision of information
- carriage of mixed loads
- fire resistance of vehicle
- manning.

Placarding

76 The vehicle was not placarded but the firemen at the scene of the accident, including the fatally injured officer, were made aware that explosives were on board. They were informed both by the fire station by radio, and by the vehicle crew on arrival at the scene. The 1989 Regulations require that vehicles carry an orange rectangular placard front and rear to signify the carriage of dangerous goods, and orange diamonds on each side indicating the hazard classification of the explosives carried.

77 The placarding is aimed towards the emergency services rather than the public, though it should be clear that explosives are present. Nevertheless the difficulties encountered in the evacuation of the public at Peterborough should be further considered in a review of placarding standards, and especially in relation to the large distances over which the public need to be cleared in an emergency. At Peterborough, many members of the public moved forward to get a better view of the burning vehicle, some placed themselves at even greater risk by standing on cars. One suggestion is for vehicles to carry portable warnings which can be quickly set up in an emergency showing the need to keep clear, for example 'EXPLOSIVES INCIDENT - CLEAR THE AREA'.

Training and provision of information

78 The 1989 Regulations and Code of Practice require formal training to be given to crews. An

important aspect is effective communication with the emergency services on the nature of the danger involved. There was evidence that the information passed to the fire service could have been clearer and passed more quickly. There is a need for operators to ensure that in addition to fulfilling the legal obligation to carry information on emergency action and to keep it readily available, crews are trained so that information is supplied to the emergency services quickly, clearly and accurately. This is necessary to enable a professional judgement to be made on the correct action to be taken in the short time available.

Mixed loads

79 The earlier provisions for the segregation of incompatible explosives have been strengthened in the 1989 Regulations. Operators are now forbidden to carry different kinds of explosive together unless they adopt effective measures to ensure that the carriage of the mixed load is no more dangerous than carriage of the same amounts of the separate types alone. In practical terms, this means that trials may well be necessary to resolve any doubts about the effects of an accident, including the effects of a fire likely to degrade protective packagings.

80 But the Regulations make a number of exceptions from that general provision, and the potential need to carry out further trials, when for example such segregation appears unnecessary on safety grounds. The exceptions are specified by reference to classification codes which denote the way different explosives behave in a fire - whether they detonate violently, throw out high speed fragments, create a more severe fire hazard or have a limited, even insignificant, effect - and which also denote other features relevant to the compatibility of explosives, one with another. Those exceptions should now be reconsidered in the light of the findings following the incident, ie the possibility that degradation of packagings may introduce a further factor not taken into account in classification tests, allowing rapid generation of fire as then observed.

Fire resistance of the vehicle

81 Because the fire started in the load compartment it by-passed any fire resistance provided by the vehicle, and there was only a relatively short period before the main explosion occurred. Standards for the fire resistance and construction of vehicles are laid down in the Approved Code of Practice to the 1989 Regulations, and are subject to review by HSE. Additional guidance was circulated to industry in September 1989. The Peterborough explosion was not the prime cause of this review although cognizance of its effects will be taken.

Manning

82 Regulation 11 requires that explosives are carried safely and securely , and among the advice set out in the Approved Code of Practice is the requirement that the driver should be accompanied by another person while the vehicle is in motion (double manning). During an incident such as that at Peterborough, the crew of the vehicle should if they are able carry out a number of actions such as obtaining help, stopping traffic, warning the public and, in some circumstances, fighting the fire. It would not be possible for a single crew member to take all these actions within the short time available: there are therefore clear benefits in maintaining double manning. The response of a crew in obtaining help in an emergency would probably be helped by the provision of a radio telephone or other immediate means of communication; this should, however, be an additional facility and not an alternative to double manning, the more especially because of the recognised variability of performance of radio communication across the country. In the incident at Peterborough both members of the crew made valuable and separate contributions to warning members of the public of the fire and the dangers involved, more than could have been achieved by one person alone.

Packaging Regulations

83 New regulations concerning the packaging of explosives are in preparation and planned for implementation in 1992. These will specify requirements for the use of compatible packaging materials and for packages to meet specific performance criteria. The packing methods laid down in the United Nations Recommendations for the Transport of Dangerous Goods will form the basis for the regulations and there will be a formal certifying body for packaging. It must be emphasised, however, that the existing packing rules clearly specify the method and types of packaging that should have been used and if these requirements had been met, it is very unlikely that the Peterborough explosion would have occurred. The rapid spread of the fire was assisted by the presence of flammable packagings. It should therefore be considered whether the new regulations should require the use of the fire-resistant packaging. This consideration should be taken together with a review of the suitability of other systems, to reduce the spread of fire within the load compartment.

Conclusions

84 The sequence of events began when a minor explosion inside the vehicle started a fire. After an estimated 12 minutes the main bulk of the cargo, blasting explosives, detonated.

85 The initial minor explosion was probably caused by ignition of Cerium fusehead combs when the vehicle jolted over a speed control ramp. The likely mechanism was impact or friction of fusehead debris or loose composition against the metal box packaging. The fusehead explosive composition was probably sensitised by the presence of rust.

86 The ignition occurred because Cerium fusehead combs were carried in unauthorised and unsafe packages. Excessive quantities in each package produced the scale of effect.

87 There was no proper system to check that all explosives had the appropriate packing authorities and that containers were maintained in a safe condition.

88 The mechanism for the detonation of the whole cargo cannot be firmly established. It was most likely to have been caused by detonators scattered about during the fire, although it may have been induced through fire engulfment alone.

89 The fire services arrived at the scene of the vehicle fire promptly. Prior to the explosion they were aware of the presence in the vehicle of commercial explosives, even though the vehicle was not placarded outside. The information was communicated to them by the crew of the vehicle and also by their vehicle radio. The action taken by the crew members was both courageous and consistent with the training and guidance they had received.

Recommendations

90 Operators and consignors should develop systems to ensure that **all** activities relating to the carriage of explosives are safe. Such systems must of necessity cover a wide number of elements and it is appropriate to indicate here the main features.

(a) Care must be taken to ensure that all explosives have been properly classified and labelled in accordance with the Classification and Labelling of Explosives Regulations 1983. The classification of explosives is dependant on the packaging used and the management systems must ensure that all explosives are packed in the manner so classified.

(b) The Packing of Explosives for Conveyance Rules 1949 state the legal requirements for packaging and it is the responsibility of companies to ensure that packages are designed and materials of construction selected to ensure compliance with these requirements.

(c) When laying down procedures for checking the suitability of materials used in explosives products attention should be paid to packaging components as well as explosive substances or articles. Safety and quality systems should cover not only new or modified products but also a periodic review of established ones.

(d) Safe systems of work should apply equally to product safety and manufacturing safety in order to comply with all HSWA requirements, notably sections 2, 3 and 6. Safety departments should have an input into all areas in which such duties are placed on the company.

(e) Operators should ensure that the training of all their drivers and attendants in accord with the Road Traffic (Carriage of Explosives) Regulations 1989 is kept under review and brought up to date whenever circumstances change - for example when new products are to be carried, or changes are made to packing methods. The general training required by crews to allow them to comply with their duties under the Regulations, whether provided 'in house' or by external training companies, must be supplemented by training on the specific products to be carried and the particular measures to be adopted when mixing loads. The responsibilities of the driver, including those for loading and unloading, should be clearly defined by the operator.

(f) All movements of explosives should be pre-planned with clear instructions issued concerning the loading and layout of the vehicle and the emergency information to be carried. Procedures should be available to verify that only explosives which have been properly packaged, classified and authorised are carried.

(g) Before carrying explosives of different compatibility groups together, in particular detonators, operators should take effective measures to comply with the legal requirement that there should be no increased risk. Such measures should ensure that the different types are prevented from coming into contact with one another when their packaging is degraded whether through partial explosion of the contents or fire. Since the most likely means of detonators coming into contact with the rest of the load is by scattering, the simple approach of segregation by open space is unlikely to succeed. Operators will need to consider alternative measures such as fire-resistant overpacking or mesh barriers to prevent the effects of the detonators initiating, or thrown detonators reaching, the rest of the load.

91 The acceptability of carriage of mixed loads of detonators with other explosives should be reviewed, by HSE, depending on the progress in developing effective measures to prevent increased danger as in recommendation 90(g).

92 The feasibility of additional placarding or other warning devices to heighten the perception of the public of the hazard of explosives vehicles should be considered by HSE in consultation with other relevant government departments and the explosives industry.

93 The provision for double manning of vehicles while in motion, recommended in paragraph 22 of the Approved Code of Practice to Regulation 11 of the 1989 Regulations, should be retained in any future proposals for amendment.

94 Consideration should be given by HSE to the deletion of paragraph 4(b)(iii) of Schedule 3 of the Road Traffic (Carriage of Explosives) Regulations 1989 so that articles of hazard code 1.4G may be carried with substances of compatibility group D only if effective measures are taken to ensure that the carriage of such mixed loads does not lead to increased danger. Further consideration should be given to how this would affect other permitted mixed loads.

95 Systems to prevent the spread of fire within the vehicle load compartments should be studied by industry and their suitability for use in explosives transport assessed. This would include both active and passive systems such as fire-resistant packaging material, physical resistant barriers and detection and extinguishing methods.

96 The guidance given to emergency services should be reviewed to provide improved information and instructions on how to deal with emergencies involving explosives vehicles. This has commenced through the normal liaison routes in HSE and should continue on a periodic basis to ensure guidance is in step with developments in the explosives industry.

97 Evidence from the pathologist at the inquest on John Philip Humphries and from individual fire crew members described how certain items of personal protective equipment had sustained damage in the blast incident. The Coroner himself raised the question of the lack of a visor to Fireman Humphries' helmet and the possibility that one might have saved his life. The integrity and suitability of the basic cloth uniform became an issue, as did the suitability of the PVC type waterproof leggings ('wet legs') which melted onto some injured crew members following the blast. Reference was made to the specification to which protective clothing was manufactured and the particular point was made that these specifications were being revised by the Home Office.

98 How information should be used by the fire service is a matter for the service itself to determine. However it is recommended that the written instructions carried by the transport vehicle crew should include information to enable the emergency services to make the difficult judgements in priorities between evacuation and fire fighting, and on precautions to be taken concerning blast protection. The matters raised in this and the previous paragraph have been drawn to the attention of HM Chief Inspector of Fire Services via the normal routes in HSE.

Appendix : Report on blast damage and injuries

Damage caused by explosion

1 Figures 2 and 3 show aerial photographs of the Vibroplant yard some time before the explosion, and the general area after the explosion. The epicentre of the explosion is marked by a depression (46 cm deep and 3.5 m radius) in the tarmac surface of the yard. The floor of the explosives vehicle was about 1 metre off the ground.

2 Approximately 130 cars were damaged to varying degrees: about 60 were beyond repair, 13 were badly damaged, 51 were slightly damaged, and the rest were superficially damaged (Figure 8). Blast damage to the two buildings on either side of the explosion, occupied by Vibroplant and City Electrical Factors, was considerable - see Figures 9 and 10.

3 It is common to relate structural damage simply to blast overpressure, as shown in Table 1, when attempting either to predict the damage likely to be caused by an accidental explosion or, in any post accident investigation of an explosion, to estimate the quantity of explosives involved. This, however, ignores the considerable effects of impulse, ie the duration of the positive phase of the blast wave, in relation to the quantity involved. A compilation of blast overpressure/damage criteria which includes an impulse factor is given at Table 2.

4 Window damage was extensive, reaching as far as the Flag Fen archaeological site some 1260 m away. The flimsy wooden structure at that location flexed so much in the pressure wave that the twisting motion almost certainly caused the window damage and not the blast wave directly.

5 In general, the steel and concrete framed buildings withstood the effects of the blast very well, and much better than would have been expected for conventional brick built housing. Furthermore, due to their ability to flex, the steel framed buildings performed better than those with concrete frames.

6 A summary of damage versus distance is given in Table 3. Column [4] of Table 3 lists the distances at which the various levels of damage occurred. Column [6] gives the corresponding overpressures predicted from 800 kg of TNT. Column [5] lists the distances (using information from Table 2 and other sources) at which these levels of damage might be expected to occur.

Blast damage discussion

7 This incident has presented a unique opportunity to study the effects of a relatively small quantity of commercial blasting explosive upon a modern industrial estate. By comparing actual damage with what would have been predicted for this situation it is possible to confirm or refine as appropriate, damage/injury prediction techniques.

8 Tables 1 and 2 show that many of the blast damage 'markers' are construction elements of traditional British brick built houses. Most of the premises in the area were not houses, however, but steel clad and/or brick fronted, steel and concrete framed buildings. Opportunities therefore for comparisons between what damage would have been expected from an explosion of 800 kg of high explosive, and what can be found here, are limited. On the other hand, information on 'new' industrial markers is provided.

9 Window damage was very variable and greater than might have been predicted. This was mainly because most of the buildings in the area were capable of flexing. Some windows dropped out of their frames intact, not breaking even on impact with the ground. Variations also arose from the different sizes and thicknesses of glass and their construction. The size of many of the buildings gave a fundamental problem in specifying window damage in relation to the distance of the buildings from the epicentre of the explosion. This will clearly introduce increasing inaccuracy with increasing length of building. On this same point, a particular record of percentage window damage for a long face of a building which is in line with the direction of travel of the blast wave is again subject to much error due to the considerable variation in overpressure effect along its length.

10 Fragments were thrown over a very large area - see Figure 11. The prime requirement in this instance was to collect all pyrotechnic items from the surrounding area. Recognisable pieces of the vehicle (except for the many small pieces of aluminium from the body of the vehicle) were also collected. The extremity of fragment throw could not be accurately determined, but within the licensed fireworks site, some 380-400 m away, a number of small items in the weight range 100-3000 g were found. A number of cars were allegedly damaged by falling gravel up to 470 m away.

Injuries

11 The number of persons injured was well in excess of 100. Of these 84 were admitted to hospital: 2 to intensive care, 12 as in-patients with other blast related injuries (head, spine, eardrums) and the remainder with superficial injuries (cuts, shock).

Figure 8 Cars damaged in the explosion (*Photograph reproduced by kind permission of Peterborough Evening Telegraph*)

Figure 9 Blast damage to the Vibroplant building (*Photograph reproduced by kind permission of Peterborough Evening Telegraph*)

Figure 10 Blast damage to City Electrical Factors building (*Photograph reproduced by kind permission of Peterborough Evening Telegraph*)

12 The fireman who died in the incident was standing about 15 metres from the centre of the explosion and was hit in the head by a fragment. Of those seriously injured, one was a fireman who had been standing close to the man who died, the other was in a building approx 150 metres away, and was injured when a space heating unit fell from the ceiling.

13 A summary of injury versus distance is given in Table 4. Column [4] of Table 4 lists the distances at which the various levels of injury occurred. Column [6] gives the corresponding overpressures predicted from 800 kg of TNT. Column [5] lists the distances (on the basis of information from Table 2 and other sources) at which these levels of injury might be expected to occur.

Discussion of injuries

14 Existing models for predicting the consequences of explosions have been developed by analysis of information from a number of sources, including World War II bomb data, in which the greatest number of serious injuries and fatalities to people indoors were caused by partial or complete demolition of the houses; people were crushed and asphyxiated by falling debris and dust. In this incident there were no instances of complete building collapse and consequently no related serious crushing injuries. Any housing as close to the explosion as the Vibroplant and City Electrical Factors buildings would have been expected to suffer considerable damage, with corresponding numbers of serious injuries/fatalities (for 800 kg TNT radii of A and B damages respectively are 22.1 and 32.2 m, see Table 2). The two closest `industrial' buildings survived well in comparison.

15 In the period between the onset of fire and the explosion, numbers of people congregated outside near to the van (see Figure 12), and indoors against windows which overlooked the Vibroplant yard. Many of those outdoors were blown off their feet (Figure 13), sustaining hearing damage (Figure 14) or injuries by fragments. Those indoors received serious cuts from flying glass, injuries from falling, or from collapsing ceilings and associated debris. Most of the people who were kept in hospital had suffered cuts. It might have been expected that the delay between the onset of the fire and the final explosion would have given people the chance to move well away from the area. This did not happen.

16 The 1875 Explosives Act requires that any place where explosives are manufactured or kept should be licensed. The Explosives Inspectorate administers that Act on behalf of HSE. The Inspectorate also licenses ports handling explosives under the Dangerous Substances in Harbour Areas Regulations. In both of these activities explosion consequence models are used

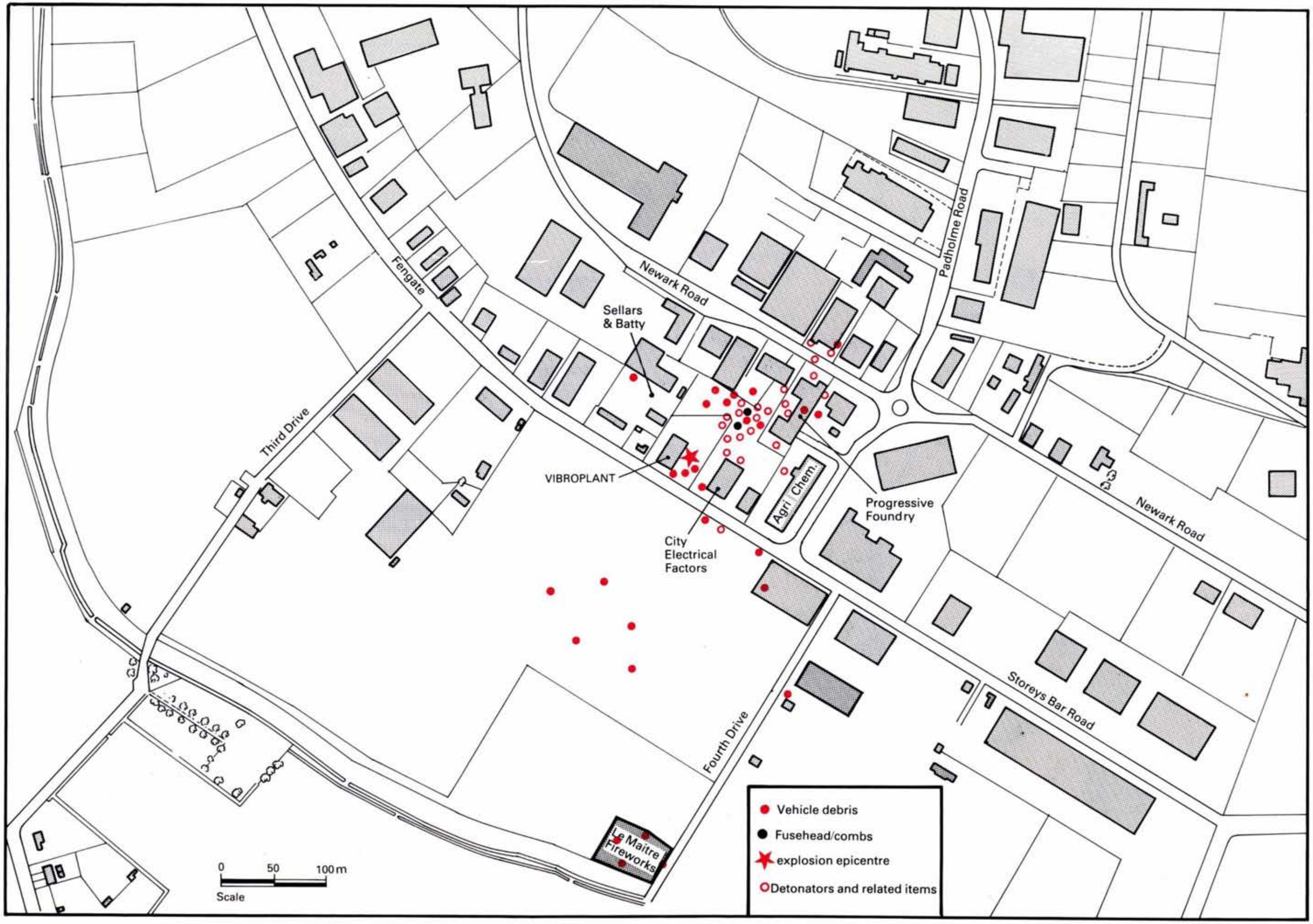


Figure 11 Debris plan

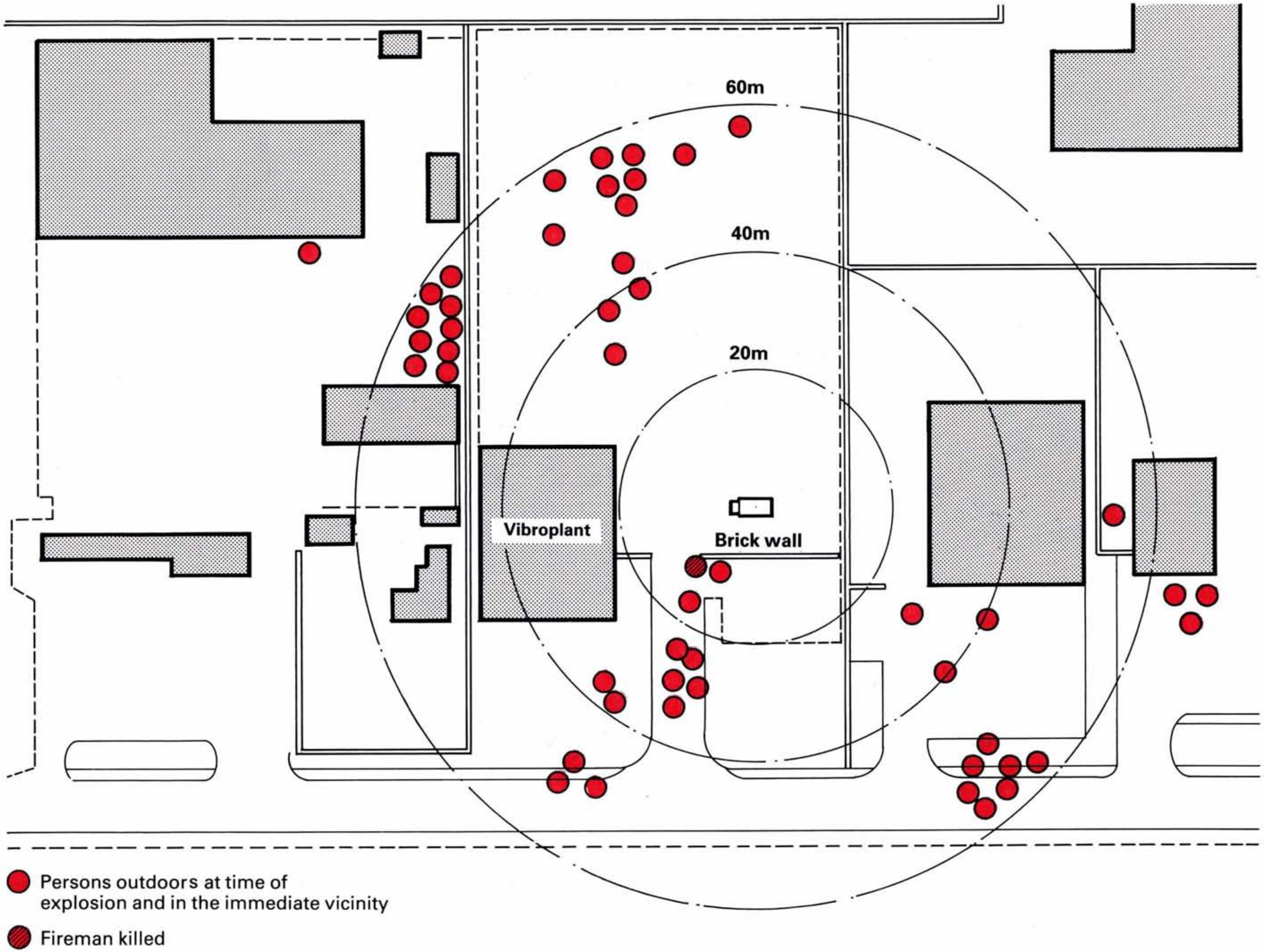


Figure 12 Plan showing people outdoors at time of explosion

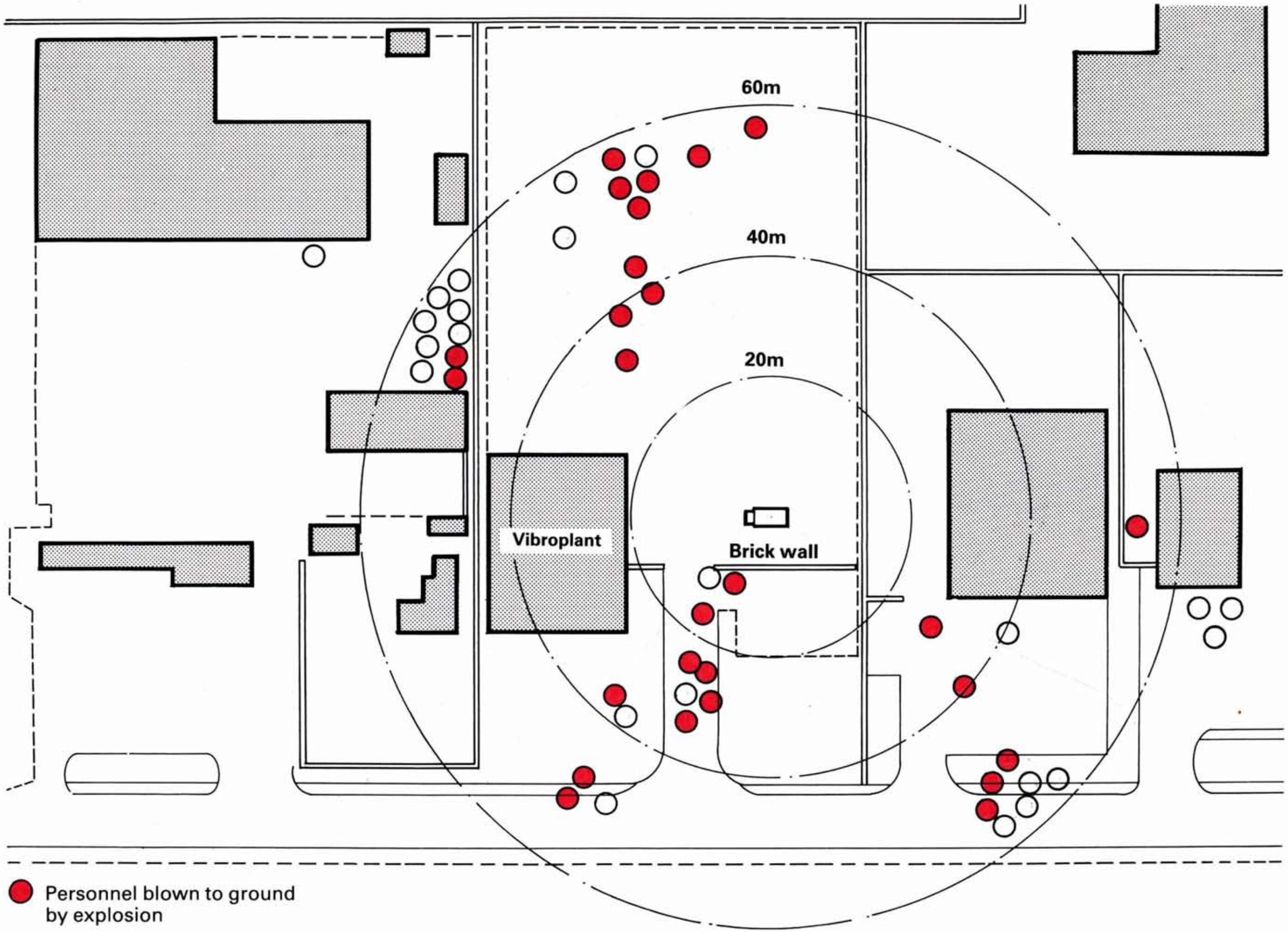


Figure 13 Plan showing people blown to ground

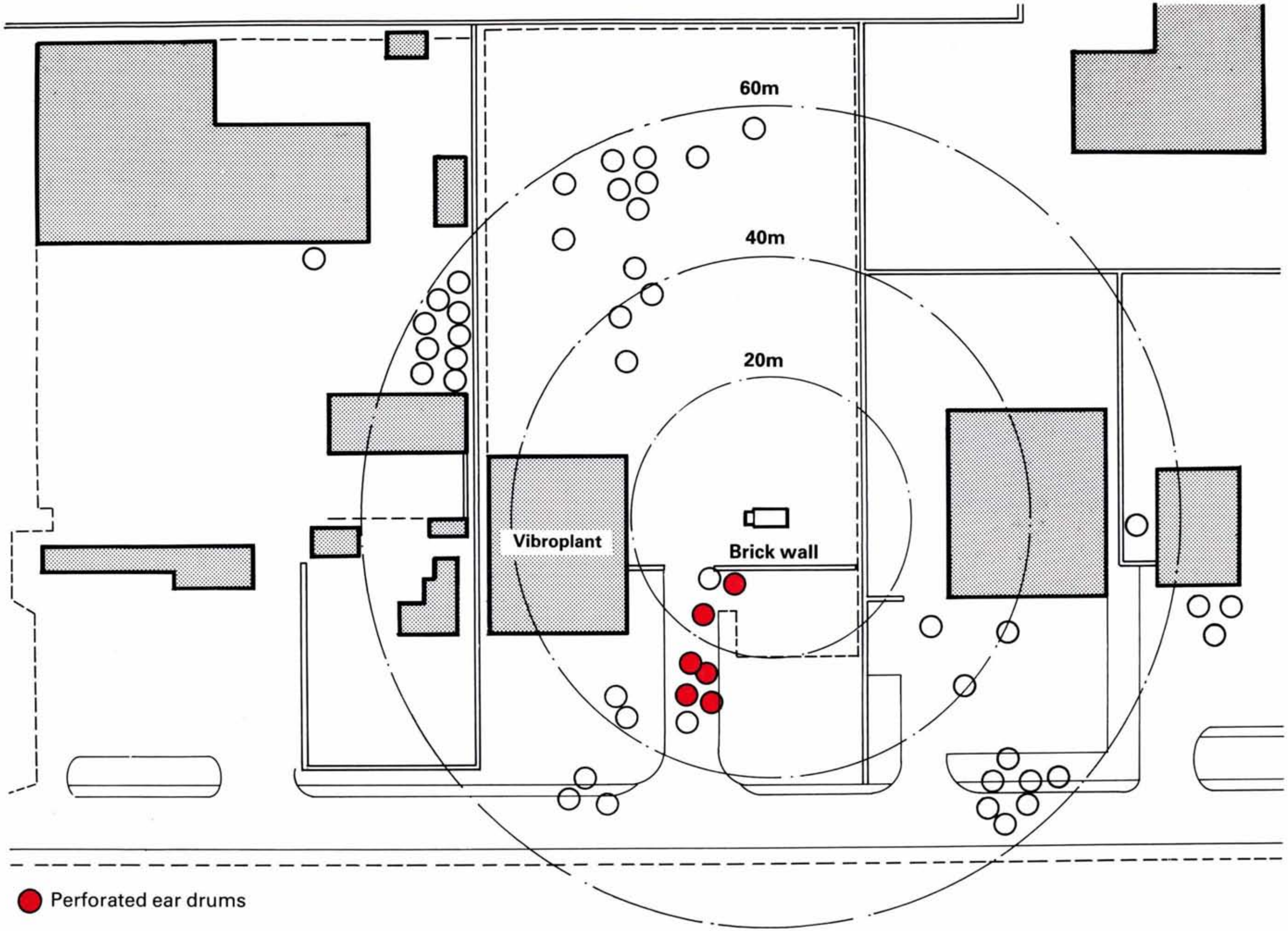


Figure 14 Plan showing people with perforated ear drums

to set safety distances appropriate to the quantity of explosives involved. Applying such models to the situation at Peterborough allows a comparison of actual against predicted numbers of fatalities and injuries. For people indoors the models currently used were found to be conservative. This is partially due to the nature of construction of the nearby buildings. Even so this is reassuring. For people outdoors the blast induced injuries were generally in line with predictions. With regard to the outdoor fragmentation effects, however, existing explosion consequence modelling is most probably the least developed. This is due to a number of factors, not least of which are the wide range of explosives available and the paucity of fragmentation information particularly from explosives transport incidents.

Conclusions

(a) Overall, the blast damage appears to be consistent with a high order detonation of approximately 800 kg of high explosives.

(b) A pre-warning of the fire before the explosion, coupled with the problems in evacuation of the area, caused people to congregate both in the open, close to the vehicle, and inside buildings adjacent to glazing. This resulted in many injuries from flying glass, fragments, and damaged eardrums.

(c) Many steel and concrete framed buildings withstood the effects of the explosion very well. The steel framed buildings, being able to flex, performed better than the concrete framed buildings. The same explosion in the centre of an housing estate would have been expected to produce more fatalities and serious injuries.

(d) Information gathered in this incident on the explosion effects of a fairly small quantity of commercial blasting explosive upon a modern industrial estate is very valuable and can be used for refinement, as necessary, of HSE's damage assessment techniques.

(e) Application of existing explosion consequence models (as used in HSE statutory licensing activities) to the situation here would have predicted more fatalities and serious injuries than actually occurred.

Table 1 Damage produced by blast

Pressure	*Damage*
psig	
0.02	Annoying noise (137 dB), if of low frequency (10-15) (cps)
0.03	Occasional breaking of large glass windows already under strain
0.04	Loud noise (143 dB). Sonic boom glass failure
0.1	Breakage of windows, small, under strain
0.15	Typical pressure for glass failure
0.3	'Safe Distance' (probability 0.95 no serious damage beyond this value)
0.3	Missile limit
0.3	Some damage to house ceilings; 10% window glass broken
0.4	Limited minor structural damage
0.5-1.0	Large and small windows usually shattered, occasional damage to window frames
0.7	Minor damage to house structures
1.0	Partial demolition of house, made uninhabitable
1-2	Corrugated asbestos shattered
1-2	Corrugated steel or aluminium panels, fastenings fail, followed by buckling. Wood panels (standard housing) fastenings fail, panels blown in
1.3	Steel frame of clad building slightly distorted
2	Partial collapse of walls and roofs of houses
2-3	Concrete or cinder block walls, not reinforced, shattered
2.3	Lower limit of serious structural damage
2.5	50% destruction of brickwork of house
3	Heavy (3000 lb) machines in industrial building suffered little damage
3	Steel frame building distorted and pulled away from foundations

Pressure	*Damage*
3-4	Frame loss, self-framing steel panel building demolished
3-4	Rupture of oil storage tanks
4	Cladding of light industrial buildings ruptured
5	Wooden utilities poles (telegraph etc) snapped
5	Tall hydraulic press (wt 40 000 lb) in building slightly damaged
5-7	Nearly complete destruction of houses
7	Loaded train wagons overturned
7-8	Brick panels, 8-12 in thick, not reinforced, fail by shearing or flexure
9	Loaded train box-cars completely demolished
10	Probable total destruction of buildings
10	Heavy (7000 lb) machine tools moved and badly damaged
10	Very heavy (12 000 lb) machine tools survived
300	Limit of crater lip

Table 2 Effect of explosives quantity on failure criteria

Structural element	*Failure mode*	*Approximate peak side on over-pressure in psi (kPa x 1.45 x 10^{-4}) at which failure occurs*		
		1 Te	10 Tes	100 Tes
Window panes	5% broken	.15	.1	.1
	50% broken	.36	.24	.21
	90% broken	.9	.6	.54
Houses	Tiles displaced	.64	.42	.38
	Doors & window frames may be blown in	1.3	.86	.77
	Category D damage	.71	.44	.42
	Category Ca damage	1.8	1.15	1.10
	Category Cb damage	4.0	2.4	2.3
	Category B damage	11.5	5.2	5.0
	Category A damage	26.5	11.5	11.0
Telegraph poles	Snapped	52	26	24
Large trees	Destroyed	57	26	24
Primary missiles	Limit of travel	.20	.14	.12
Rail wagons	Limit of derailment	26.5	11.5	11.0
	Bodywork crushed	20	8.7	8.4
	Damaged but easily repairable	11.5	5.7	5.5
	Superficial damage	4.6	2.6	2.5
Railway line	Limit of destruction	205	97	93

Note: All distances (overpressures) are measured to the furthest point of the structure from the explosion source.

A Damage Houses completely demolished, ie with over 75% of the external brickwork demolished.

B Damage Houses so badly damaged that they are beyond repair and must be demolished when opportunity arises. Property is included in this category if 50-75% of the external brickwork is destroyed, or in the case of less severe destruction, the remaining walls have gaping cracks rendering them unsafe.

Cb Damage Houses which are rendered uninhabitable by serious damage, and need repairs so extensive that they must be postponed until after the war. Examples of damage resulting in such conditions include partial or total collapse of roof structure, partial demolition of one or two external walls up to 25% of the whole, and severe damage to load bearing partitions necessitating demolition and replacement.

Ca Damage Houses that are rendered uninhabitable, but can be repaired reasonably quickly under war-time conditions, the damage sustained not exceeding minor structural damage, and partitions and joinery wrenched from fixings.

D Damage Houses requiring repairs to remedy serious inconveniences, but remaining inhabitable. Houses in this category may have sustained damage to ceilings and tilings, battens and roof coverings, and minor fragmentation effects on walls and window glazing. Cases in which the only damage amounts to broken glass in less than 10% of the windows are not included.

Table 3 Blast damage

			Distance: m		*Over pressure:*
		Damage/Other	*Observed*	*Expected*	*psi*
[1]	[2]	[3]	[4]	[5]	[6]
(a)	Clean area	Area of yard near to explosion cleared of cars etc	14	n.a	78
(b)	Fireball	Vehicles set on fire, and fireman was engulfed in flames	18	17.5	44
(c)	Frames	Serious damage to concrete frames of building	110		1.7
		Steel frame moved	120		1.5
(d)	Walls	Cavity brick/block walls of steel framed building belonging to Vibro-plant and City Electrical Factors, totally destroyed	30	< 35	14
		Next nearest facing wall damaged only along top edge where meets with steel roof beams	70	n.a	3.2
		Metal cladding; fastenings, fail, and followed by buckling	115	63-113	1.6
(e)	Roofs	Metal roof cladding on steel frames removed.	30	n.a	14
		Asbestos cement type roof panels badly damaged/removed	90	70-110	2.2
		GRP roof lights all destroyed	140	n.a	1.25
(f)	Windows	Windows were broken as far out as the Flag Fen archaeological site. The flimsy wooden structure there (at ca 1260 m) flexed considerably causing the distant damage.	1260	n.a	0.06
		90% window damage (small, single-glazed and well retained units)	ca.225	182	0.69
		50% window damage	ca.360	360	0.37
		5% window damage	ca.580	695	0.19
		Damage to window frames	160	110-195	1.06

Table 4 Blast injuries

		Damage/Other	Distance m Observed	Expected	Over Pressure: psi
[1]	[2]	[3]	[4]	[5]	[6]
(a)	Burns	Fireman engulfed in flames at	18	17.5	44
		Fireman slight burns at	25	n.a	21
(b)	Perforated eardrums	100% within a distance of	28	n.a	17
		50% at a distance of	30	29	15
		Furthest reported instance	45	54	6.6
(c)	Fragments	Serious injuries experienced up to this distance (excluding flying glass injuries).	40	*	
(d)	Blown off feet	Persons outdoors blown over up to	70	93	3.2
		50% " " " " " "	55	45	4.7
(e)	Cuts from glass	Cuts to all persons indoors	0-50	n.a	>5.5
		Cuts to many	70-100	n.a	3.2-1.9
		Cuts to few	100-150	n.a	1.9-1.15
		Furthest instance of cuts	ca. 200	n.a	0.80

* Clearly there was potential for more injuries much further out - see Figure 11.

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