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Physical and chemical evidence remaining after the explosion of large improvised bombs

1. Preparation of charges and firings for the fourth trials 20/10/97 - 31/10/97

DERA/CES/FEL/CR9802

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Executive Summary

Following detonation of a terrorist bomb one main task is to identify the explosive charge type and its approximate size. Physical evidence can be obtained after the blast from, for example, the degree of shattering or bending of various materials near to the seat of the explosion. Similarly chemical traces recovered from nearby debris and witness pieces can provide an identification of the explosive type and composition.

In collaboration with the FBI, nine firings were performed in October 1997 comprising two 50 kg calcium ammonium nitrate/icing sugar (CAN/S) test charges, two 1000 kg ammonium nitrate/fuel oil (ANFO) charges, three 1000 kg CAN/S charges, one 1000 kg TNT charge and one 1000 kg C4 charge. Four of the charges, both 50 kg test firings and two of the 1000 kg CAN/S firings, were detonated using a tube booster broadly similar to those used by PIRA. The remaining charges were initiated with C4 boosters.

Each 1000 kg charge was contained within a wooden box, placed inside a large transit van. The charge-containing van was surrounded by four motor cars, eight UK roadsigns, six US roadsigns, two PVC plates and a number of small aluminium, steel and copper witness pieces. Additionally, three simulated Time and Power Units (TPUs) and a large battery were positioned in various places in the van.

This report describes the preparation and firing of the charges, the preparation and collection of the witness pieces and the velocity of detonation and blast pressure data.

List of contents

1. Introduction

1.1 This report has been prepared by the Forensic Explosives Laboratory (FEL) for the Home Office Police Department Science and Technology Group under contract reference 38G1W.

1.2 Following detonation of a terrorist bomb one main task is to identify the explosive charge type and its approximate size. Physical evidence can be obtained after the blast from, for example, the degree of shattering or bending of various materials near to the seat of the explosion. Similarly chemical traces recovered from nearby debris and witness pieces can provide an identification of the explosive type and composition.

1.3 In order to increase our knowledge of the effects of a large explosion on the surrounding area, and aid its subsequent identification, four sets of trials have been carried out at the New Mexico Institute of Mining and Technology (NMT) in the USA. This project follows three previous sets of trials; the first in November/December 1994[1-3], the second in October 1995[4-6] and the third in June 1996[7-9]. In collaboration with the FBI, nine firings were performed in October 1997 comprising two 50 kg calcium ammonium nitrate/icing sugar (CAN/S) test charges, two 1000 kg ammonium nitrate/fuel oil (ANFO) charges, three 1000 kg CAN/S charges, one 1000 kg TNT charge and one 1000 kg C4 charge.

1.4 Each 1000 kg charge was contained within a wooden box, placed inside a large transit van. The charge-containing van was surrounded by four motor cars, eight UK roadsigns, six US roadsigns, two PVC plates and a number of small aluminium, steel and copper witness pieces. Additionally, three simulated Time and Power Units (TPUs) and a large battery were positioned in various places in the van.

1.5 Four of the charges, both 50 kg test firings and two of the 1000 kg CAN/S firings, were detonated using a tube booster similar to those used by PIRA. The remaining charges were initiated with C4 boosters.

1.6 This report describes the preparation and firing of the charges, the preparation and collection of the witness pieces and the velocity of detonation and blast pressure data. Results of the chemical analysis of the witness pieces are given in a second report[10], whilst post blast evidence is detailed in a third report[11]. A detailed report on the velocity of detonation and blast pressures recorded by NMT has been prepared.[12]

2. Experimental

2.1 Test Site Location

2.1.1 Firings were performed in the USA at the High Performance Magazine (HPM) Site, NMT, Socorro, New Mexico 87801. Grinding and mixing of the fertiliser-based explosives and loading of the TNT flake was carried out at the Torres Site, NMT.

2.2 Calcium Ammonium Nitrate/Sugar (CAN/S) Firings

2.2.1 **Grinding:** The calcium ammonium nitrate, containing 21% calcium magnesium carbonate (dolomite), was manufactured by Irish Fertiliser Industries (IFI), Warrington Place, Dublin, and supplied in prill form in 50 kg bags. Material manufactured in 1997 was used for all the CAN/S shots except the first 1000 kg with the booster tube where 1995 material was used. The CAN was ground prior to mixing with the icing sugar using three coffee grinders with the product being directed into a 45 gallon drum lined with polythene. The particle size of the ground CAN was checked frequently by sieve analysis, using a portable sieve shaker and six brass sieves of 1000, 500, 250, 125, 63 and <63 µm mesh sizes.

2.2.2 **Mixing:** The ground CAN was scooped into a tray where it was re-powdered by hand before being weighed out into an Odjob mixing barrel using a Mettler electronic top pan weighing balance. The icing sugar was manufactured by the Imperial Sugar Company, Imperial Holly Corporation, Sugarland, Texas 77478 in 22.6 kg bags and similarly weighed out. For each 1000 kg CAN/S charge, 71.5 Odjobs each containing 12.83 kg ground CAN and 1.17 kg icing sugar were first rotated within an electronic rolling device before being emptied into the wooden charge box. The composition of the mixture was an 11:1 ratio by weight of CAN to sugar.

2.2.3 **Booster tubes:** The booster tubes were fabricated from steel tubes of 80 cm length by 6.35 cm outer diameter and 0.5 cm thickness, shown in Figure 1. Holes were drilled along the length of the tube at 10.0 cm intervals, then the whole tube was wrapped with Duck tape to cover the holes, but leaving the ends open. A length of detonating cord (2.13 m for the 1000 kg charges, 1.83 m for the 50 kg test charges) of 200 grains per foot (42.5 gm^{-1}) was knotted at one end with the remaining length running through the steel tube (Figure 2). One end of the tube was sealed with Duck tape with the knot remaining visible outside. The tube was filled with the CAN/S mixture through the open end and tapped against a wooden table at regular intervals to ensure even packing (Figure 3). The finished tube is shown in Figure 4. The amount of CAN/S mixture in the tube was weighed by difference and found to be 1.65 kg.

2.2.4 **1000 kg Charges:** The first 1000 kg CAN/S charge was loaded into an approximately 1.1 m^3 wooden box (with lid) with the exact dimensions given in Figure 5. The charge ullage was 25.4 cm, giving a bulk density of 1000 kgm^{-3}. The 2.27 kg C4 booster was placed in a coffee can (19.37 cm height by 16.83 cm diameter) so that the top of the C4 was level with the surface of the charge. The C4 ullage was 12.07 cm. The detonator used for all charges initiated by a C4 booster was an RP83 (Exploding Bridge Wire) placed directly into the centre of the C4. Once the charge was loaded into the van the distance measured between the charge base (taken as the underside of the van) and the ground was 55 cm.

2.2.5 The second and third 1000 kg CAN/S charges were also loaded into identical wooden boxes (Figure 6). On half-filling the box, a booster tube was laid horizontally across the middle of the box on wooden brackets (Figure 7) and the extra length of detonating cord was fed out through a hole in the side of the box. The box was then completely filled to respective ullages of 25.5 cm and 26.2 cm, and bulk densities of 1001 kgm^{-3} and 1003 kgm^{-3} for each charge. With the charges loaded within the vans, the distances measured between the charge bases and the ground were 56 cm and 59 cm respectively.

2.2.6 **50 kg Charges:** The test charges consisted of an aluminium drum, 65.4 cm height by 38.7 cm diameter by approximately 0.3 cm wall thickness, with a booster tube placed vertically in the middle, surrounded with 50 kg of the CAN/S mixture. The ullage of the improvised explosive mixture was 20.4 cm for the first charge and 24.5 cm for the second charge. The charge was placed on a wooden stand at a height of 76.2 cm from the ground, as shown in Figure 8.

2.3 Ammonium Nitrate/Fuel Oil (ANFO) Firings

2.3.1 Ammonium nitrate prills (34.5%, El Dorado Chemical Company, Missouri, USA) were mixed, using the Odjob mixing barrels, with diesel oil in a 94:6 weight ratio. The wooden box was sealed with a large polythene sheet before being filled with the ANFO mixture. The charge ullages were measured at the firing site as 36.2 cm and 37.8 cm respectively, giving bulk densities of 1143 kgm^{-3} and 1167 kgm^{-3}. These charges were each boosted with 2.27 kg C4, again level with the surface of the charge, with booster ullages of 12.1 cm and 12.4 cm respectively. The distances measured between the charge base and the ground were 41 cm and 61 cm for each charge. Figure 9 shows the charge loaded into the van.

2.4 2,4,6-Trinitrotoluene (TNT) Firing

2.4.1 Flake TNT was packed into one of the wooden charge boxes (Figure 10) and had to be allowed to settle before the full 1000 kg could be accommodated. The charge ullage was 6.7 cm, giving a density of 822 kgm^{-3}. The booster was again 2.27 kg C4 with an ullage of 12.4 cm. The distance between the charge base and the ground was found to be 56.0 cm.

2.5 C4 Firing

2.5.1 The batch number of the C4 used was C403-R5054 and the lot number was HDC95J428-004. This malleable white compound was packed by hand in 60 kg blocks into the wooden charge box. The width of the wooden charge box was modified from 107.63 cm to 71 cm to enclose a smaller area for the denser plastic explosive (Figure 11). The ullage was measured to be 26.2 cm, giving a bulk density of 1519 kgm^{-3}. The RP83 detonator was positioned directly into the main C4 charge. The distance measured between the charge base and the ground was 48 cm.

2.6 Velocity of Detonation (VOD) Pins

2.6.1 The VOD measurements were recorded using piezoelectric pins (Dynasen Inc., Model CA-1135). The 10 axial pins were positioned vertically in the centre of the base of the wooden charge box for all the 1000 kg firings initiated using a C4 booster (Figures 12-14). The 1000 kg charges initiated by booster tubes had two sets of six radial pins positioned horizontally and 38 cm from the base of the wooden box, as detailed in Figures 15-17. The first (middle) set was positioned midway along the booster tube whilst the second (end) set was positioned at the end of the booster tube. A further pin, the fiducial pin, was positioned next to the booster tube and used as a time reference. The 50 kg test charges did not contain any VOD pins.

2.7 Mixing and Firing Sequence

2.7.1 The charges were mixed in the following sequence:

21.10.97	1000 kg CAN/S (C4 booster)
22.10.97	2 x 50 kg CAN/S (tube booster)
	1000 kg CAN/S (tube booster)
23.10.97	1000 kg CAN/S (tube booster)
24.10.97	2 x 1000 kg ANFO (C4 booster)

2.7.2 The charges were fired in the following sequence:

24.10.97	Firing Nos 1 & 2	2 x 50 kg CAN/S test/calibration
27.10.97	Firing No 3	1000 kg CAN/S (C4 booster)
28.10.97	Firing No 4	1000 kg ANFO (C4 booster)
	Firing No 5	1000 kg TNT (C4 booster)
29.10.97	Firing No 6	1000 kg ANFO (C4 booster)
30.10.97	Firing No 7	1000 kg CAN/S (tube booster)
	Firing No 8	1000 kg CAN/S (tube booster)
31.10.97	Firing No 9	1000 kg C4

2.8 Witness Materials

2.8.1 **Type of Witness Materials Used:** Motor cars, roadsigns, PVC pieces, various small metal plates, simulated TPUs and batteries were used as witness pieces for firings 3-9. The motor cars, mostly medium sized saloon cars, were placed side on to the charge at distances of 10 m, 20 m, 30 m and 40 m. The relative positions of the motor cars and the other witness pieces are detailed in Figure 18. The metal witness materials were collected after the explosion for Scanning Electron Microscope (SEM) analysis under another Home Office project. Soil samples from four positions around the charge zero were collected before and after each 1000 kg firing to be analysed for background target analytes relevant to each firing.

2.8.2 **Description and Location of Roadsigns:** The UK roadsigns were aluminium rectangles (45 cm by 30 cm by 0.3 cm thickness) with a class 2 PVC reflective face, grey or aluminium back with two fixing rails, and were supplied with posts and attachment clips by PR Signs, 2A Valley Industries, Hadlow Road, Tonbridge, Kent. The signs were mounted on hollow coated steel posts (3.7 m length), of which 0.6 m was placed within a slightly larger diameter metal tube that had been previously set into concrete within barrels and buried in the ground (Figure 19). The signs were mounted in a landscape fashion, facing the charge, with the lower edge of the sign 1.8 m above the ground surface. One sign was mounted per post and eight signs and posts were used per firing: two in the south-west (SW) direction, two in the north-west (NW) direction, two in the north-east (NE) direction and two in the south-east (SE) direction. For each pair of signs, the first was set at 15 m from the charge and the second directly behind it at 30 m from the charge. The US signs were also aluminium (31 cm by 46 cm by 0.17 cm thickness) and were mounted on channelled steel posts (3 m length) which were set up similarly to the UK posts. The signs were set onto the posts in a portrait fashion, again 1.8 m above the ground. Six US signs and posts were used per firing: two in the NW position, two in the NE position and two in the SE position. These signs were set next to the UK signs, again at 15 m and 30 m respectively.

2.8.3 **Description and Location of PVC pieces:** Two pieces of white PVC (42 cm high by 18 cm wide by 0.75 cm thickness) were mounted in a portrait fashion on metal stakes positioned at 10 m NW and 10 m NE for firing no 3, 10 m NW and 17 m N for firing no 4, 10 m and 23.5 m N for firing no 5 and 40 m and 50 m N (approximately 1 m apart) for firing nos 6-9.

2.8.4 **Description and Location of Metal Plates:** Three sets of metal witness pieces were set out on metal stakes on the north side of the charge at distances of 10m NW, and 5 m and 10 m NE. Each of the 10 m sets consisted of a length of copper tube (6 cm length, 0.5 cm diameter), an aluminium plate (80 cm^2) and a steel plate (110 cm^2). The 5 m set had an additional copper plate (80 cm^2) included. Figure 20 shows one of the 10 m sets of metal witness pieces alongside a piece of PVC.

2.8.5 **Description and Location of TPUs and batteries:** Two types of simulated TPUs were made up at FEL with one type ("Memopark TPU") containing one Memopark timer and a second type ("Diehl TPU") incorporating both Diehl and Memopark timers. Batteries and wiring were also added for authenticity (Figures 21 and 22). The units were then sprayed a variety of different colours; yellow, red, green and blue so that a different colour a second type ("Diehl TPU") incorporating both Diehl and Memopark timers. Batteries and wiring were also added for authenticity (Figures 21 and 22). The units were then sprayed a variety of different colours; yellow, red, green and blue so that a different colour combination of three TPUs could be used in each firing to enable easier identification of any fragments found after the explosion. In each charge-containing van, a Diehl TPU and a 6 V zinc carbon battery were positioned on the front passenger seat and two Memopark TPUs were placed in the cargo hold next to the charge and taped to the wooden box itself.

2.8.6 **Preparation of the Roadsigns:** Before transportation to the United States, 46 UK roadsigns for the inorganic firings were washed and rinsed with deionised water and allowed to air dry before being double wrapped in clean nylon bags. Three signs were removed and quality assured. Two batches of eight UK roadsigns for the organic firings were transferred into the Trace Laboratory where they were washed with a weak solution of detergent and deionised water, thoroughly rinsed with deionised water then with absolute ethanol. The signs were laid out on clean glazed paper and allowed to air dry before each batch of eight was quality assured. These signs were then double wrapped in clean nylon bags. Once at the HPM site, the appropriate signs for the particular firing (inorganic or organic) were mounted onto the posts with the nylon bags intact except for a slit along the fixing rails. These bags were removed immediately prior to the firing and the reverse of the sign was marked with the date, firing no, direction and distance. The US signs were fixed into position and, prior to firing, the NW and NE pairs were washed with a weak solution of water and detergent. They were then rinsed well with deionised water (provided by NMT) and the front face of each sign was swabbed using the appropriate water or ethanol-based kit to provide control samples. Only the four NW and NE US signs were used for residue recovery. The two SE US signs were used for damage analysis only.

2.8.7 **Preparation of the Motor Cars:** The target vehicles were marked with their position and distance from the charge in black permanent pen. An A4 sized area was marked out on the driver and front passenger side doors and windows (four samples per car) by drawing round an A4 card frame. Prior to firing the doors and windows were washed with a weak solution of detergent and water, rinsed with deionised water and allowed to dry briefly before the control swabs were taken from the A4 areas.

2.8.8 **Preparation of the Other Witness Materials:** The fourteen PVC pieces were washed and quality assured in the Trace Laboratory in a manner identical to that described for the UK roadsigns used for the organic firings. They were then double wrapped in two nylon bags. Two holes were drilled through the nylon bags in the top and the bottom of each PVC piece to allow a cable tie to be inserted top and bottom. Each PVC piece was then attached to a metal stake in a portrait position using the cable ties. The nylon bags were removed, and the date, firing no and distance written on the back, just prior to firing.

2.8.10 **Collection of witness material:** After firing, the roadsigns were swabbed to recover residues, their damage was assessed and they were removed from the posts and carefully stacked inside heavy duty plastic bags. The bend angles of the posts were measured at the scene, whereas the signs were measured on a level concrete surface outside the bunker. Roadsigns that had fallen off their posts were not swabbed. Swabs were taken from the previously marked areas on the motor cars. The PVC pieces that were still attached to the metal stakes were swabbed then all pieces were bagged for analysis back at FEL. The metal samples remaining were either removed from their posts or picked up from the ground, bagged and labelled for analysis back at FEL.

2.9 Measurement of Blast Pressure

2.9.1 Pressure gauges were provided by both NMT and DERA and were set out south of the charge as shown in Figure 18. NMT set up ten air gauges (PCB type pressure transducers, Piezoelectronics Inc., US) located in pairs at 20, 40, 60, 80 and 100 m, and six ground gauges located individually at 10, 20, 40, 60, 80 and 100 m. DERA (ESC) used fifteen air gauges (B12 pressure transducers, EME UK Ltd, Sidcup, Kent) with seven set on a south-west axis at 20, 30, 40, 50, 60, 70 and 80 m, and a further eight set on a south-east axis at 20, 30, 40, 50, 60, 70, 80 and 90 m. Fragment poles (5 cm diameter) were set on each of these axes, 10 m from the charge, to protect the air gauges from flying debris. All the signal cables to the gauges were buried in trenches to avoid damage.

2.10 Video and Photographic Recording

2.10.1 **Pre-firing:** Photos and video recordings were taken of all four vehicles, the van inside and out, the charge before loading, whilst being loaded in and once in place, the TPUs and batteries in position, the signposts, metal and PVC witness pieces from ground zero, an overview of the whole pad from the west hill and a continuous shot of the explosion from the bunker.

2.10.2 **During Firing:** One high speed cine camera was based on the west hill (Hicam 3000 frames per second, 20 mm lens@f/4) and another was based at the north site (Hicam 3000 frames per second, 25 mm lens@f/2.8).

2.10.3 **Post-firing:** Photos and video recordings were taken of an overview from the west hill, the crater, the remaining cars, van or damaged remains, the individual signs and posts, and the remaining metal and PVC witness pieces.

2.11 Meteorological Data

2.11.1 Temperature, barometric pressure, relative humidity, wind speed and direction were recorded at the test site using NMT apparatus prior to each firing.

3. Results and Discussion

3.1 **Particle size distribution of the CAN after grinding:** The coffee grinders used to grind the CAN gave an acceptable particle size distribution. The results of the sieve analyses are given in Tables 1-3 and Figure 23.

3.2 **Preparation of the charges:** The CAN/S charges were ground and mixed in three half days, using five or six personnel. The ANFO charges were mixed in two hours, using four personnel.

3.3 **Charge Density:** The charge density was determined from the volume of the wooden box and the ullage of the charge itself. The calculated values are given in Table 4. The density calculated for the flake TNT was lower than the density usually obtained for cast TNT.

3.4 **Meteorological data:** Data taken just prior to each firing is listed in Table 5. Windy weather was encountered for most of the firings, particularly for firings 7 and 8.

3.5 **VOD Measurements:** Details of the measurements are given in Tables 6-9. Figures 24 and 25 plot the velocity of detonation against the distance of the pins from the booster. The VOD results for the conventionally boosted charges are simpler to interpret since the time of arrival pins are located perpendicular to the oncoming detonation front. In the case of the tubular boosted shots, the detonation front reaches the pins at an undetermined angle and the velocity calculations are more complex.

3.5.1 The observed mean detonation velocity of 8.01 mm/µs for the C4 charge (at a density of 1519 kgm^{-3}) was slightly higher than the reported values.[12] This may have been due to the point initiation of the charge by the detonator creating a changing detonation front which gave very high velocities at the shorter run distances. The mean velocity for the TNT charge was low, as expected, due to the lower density of TNT flake compared to cast TNT. The density of the flake was calculated to be 822 kgm^{-3}, giving a mean velocity of 4385 mm/µs which corresponded well to the literature value[13] of 4400 mm/µs for a density of 810 kgm^{-3}.

3.5.2 The velocities observed for the two ANFO shots, 3.47 and 3.53 mm/µs respectively, showed good reproducibility despite the slight differences in density and were comparable to values observed in previous tests.[7] The mean velocity of the C4-boosted CAN/S shot (3.46 mm/µs) was also similar to previous tests.

3.5.3 The VOD results for the two tubular boosted CAN/S shots illustrated a slightly different and more complicated process. The values given in Table 8 have been calculated from the original data recorded to take into account the angle of the detonation front.[12] As noted from Figure 25, a low velocity shock front originated at the booster surface, then accelerated as a curved front, thereby reaching the time of arrival pins at correspondingly higher angles with respect to the booster axis. This process indicates that the tube boosters do not provide a prompt shock initiation of the main explosive charge.

3.6 **Pressure Gauge measurements:** Tables 10-12 give the maximum pressure (kPa) and the positive impulse (Pa/s) for both the 50 kg and 1000 kg firings. These figures were corrected to standard temperature and pressure.

3.6.1 Maximum pressure is the maximum valid pressure reading within the trace obtained by the instrumentation for the blast wave. It can be concurrent with the peak pressure (the first peak reading obtained) or can occur later than the peak in the form of a secondary shock. The positive impulse is the integral of the positive pressure of the blast wave expressed as a function of time. Figures 26 to 34 are logarithmic plots of the maximum pressure against the distance of the gauge from the charge and illustrate the way in which the pressure decreases with distance. Further details on the pressure gauge measurements can be found in reference 12.

3.6.2 The plots consist of both NMT and DERA gauge data and contain variations of between 2% and 20% (with one or two exceptions) between the British and US instrumentation. These differences could be due to a number of reasons: variations in the placement of the gauges, particularly the height, the types of gauges employed with their respective response characteristics, and the calibration of those gauges. NMT employed both ground and air gauges. Each air gauge was shaped like a pencil and pointed towards the charge, whereas the DERA air gauges were shaped like a discus with the edge facing the charge, creating different aerodynamic effects. The topography of the ground could also cause non-uniformity in the pressure wave. However, both types of gauges exhibit less variation and become more accurate at greater distances from the charge due to the reduced speed of the shock front.

4. Conclusions

4.1 The grinding and mixing of the charges was carried out quickly and efficiently.

4.2 Comprehensive VOD and blast pressure data was collected for all firings.

4.3 The simulated tube boosters resulted in full detonation of the both the 50 kg test charges and the two 1000 kg CAN/S charges and has provided valuable data for this type of initiation system.

4.4 A van was used to contain the charge to provide a more realistic effect of fragment damage on the witness pieces provided.

4.5 Time and Power Units of differing colours were positioned in various locations in the charge-containing van so that any post-explosion fragments could be located and collected to give examples of the size and type of debris that could be expected to be found after detonation of a bomb of this size.

4.6 US and British signs and posts were positioned at locations 15 m and 30 m south-west, north-west, north-east and south-east of the charge to be used for chemical residue recovery and damage assessment. The sign posts were set into concrete bases, as recommended from previous trials.

5. Recommendations

5.1 Similar particle size distributions should be used in the next trials to ensure uniformity of charges.

5.2 More experiments should be conducted with the use of the simulated tube boosters to investigate their uses with a variety of different charges.

5.3 A greater number of VOD pins set at shorter intervals should be used in any further velocity measurements of the tubular booster systems, in order to obtain a more detailed description of the detonation wavefront propagation.

5. References

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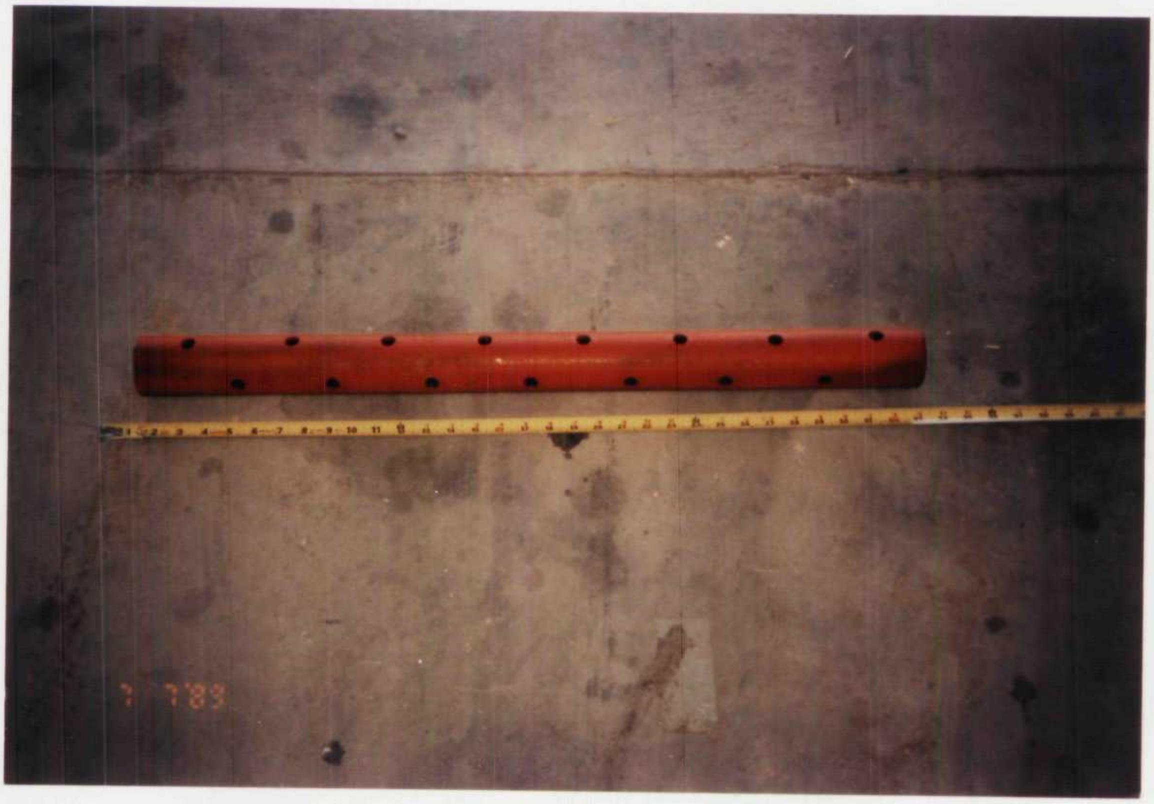

Figure 1. Steel tube used for tube boosters

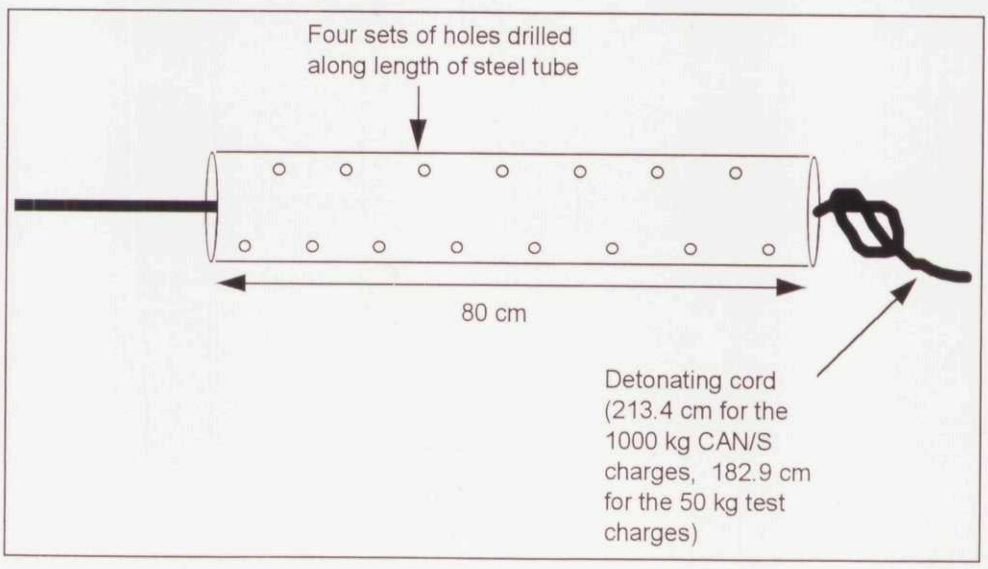

Figure 2. Diagram of simulated booster tube

Figure 3. Filling the booster tube with CAN/S

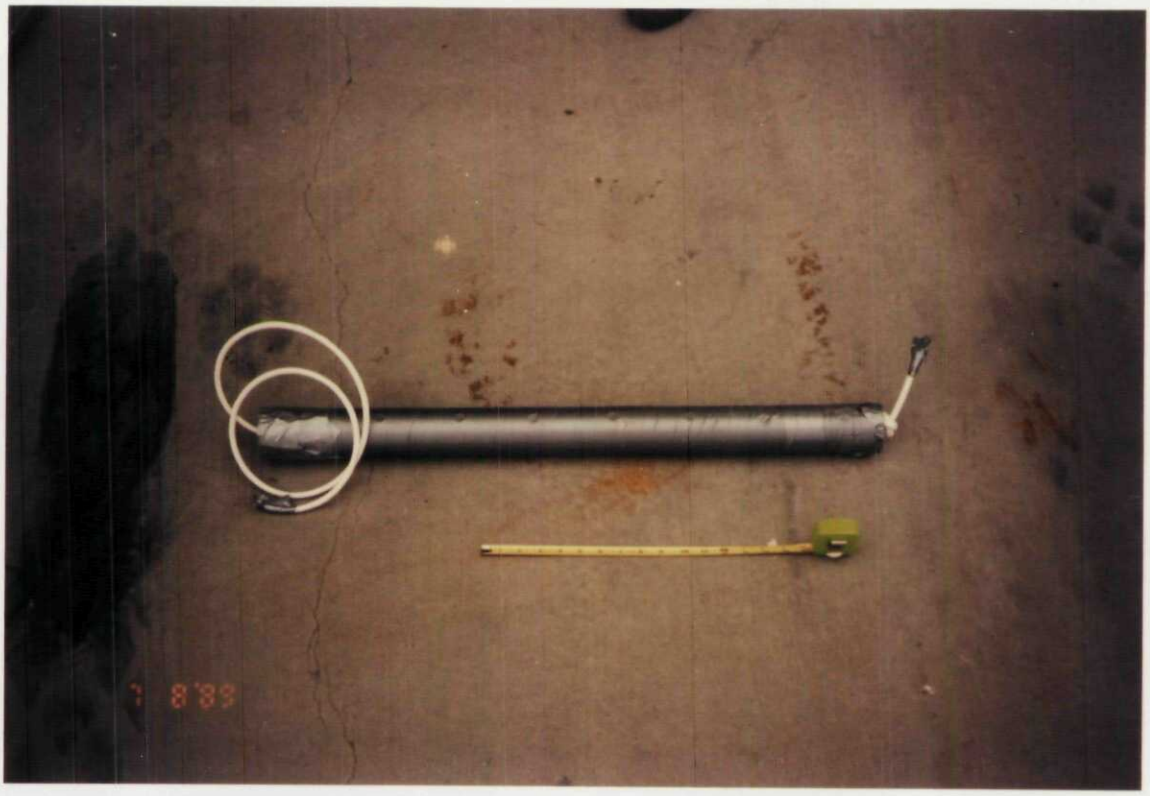

Figure 4. Filled booster tube ready for position within the charge box

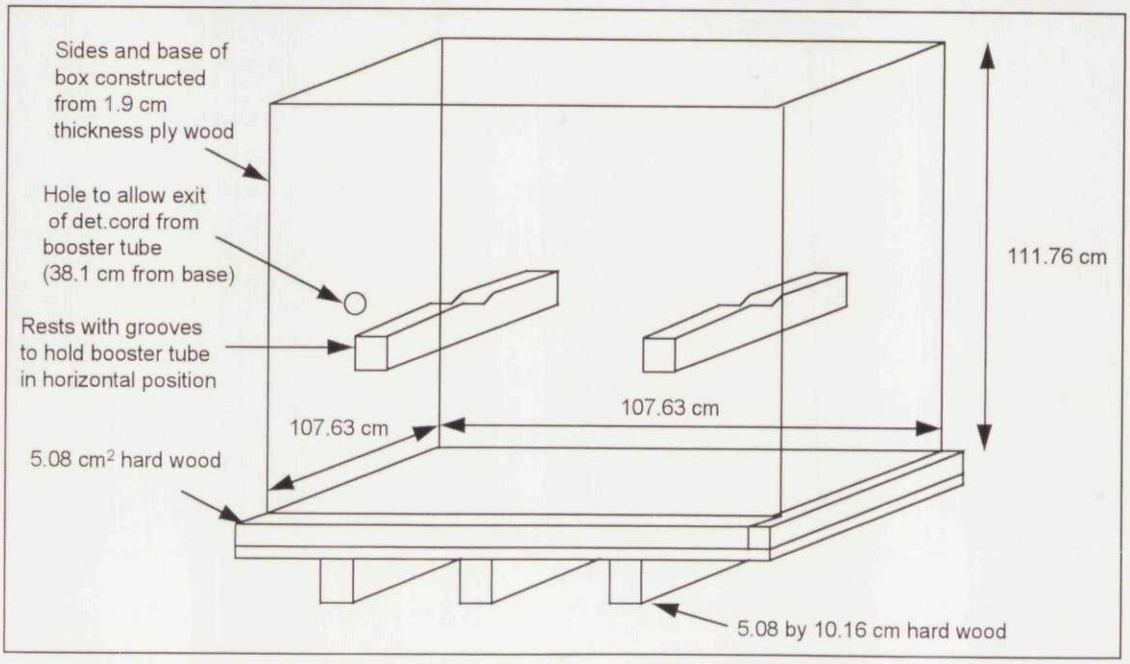

Figure 5. Diagram to show dimensions of wooden charge-containing box and position of booster tube

Figure 6. Wooden charge box filled with 1000 kg CAN/S

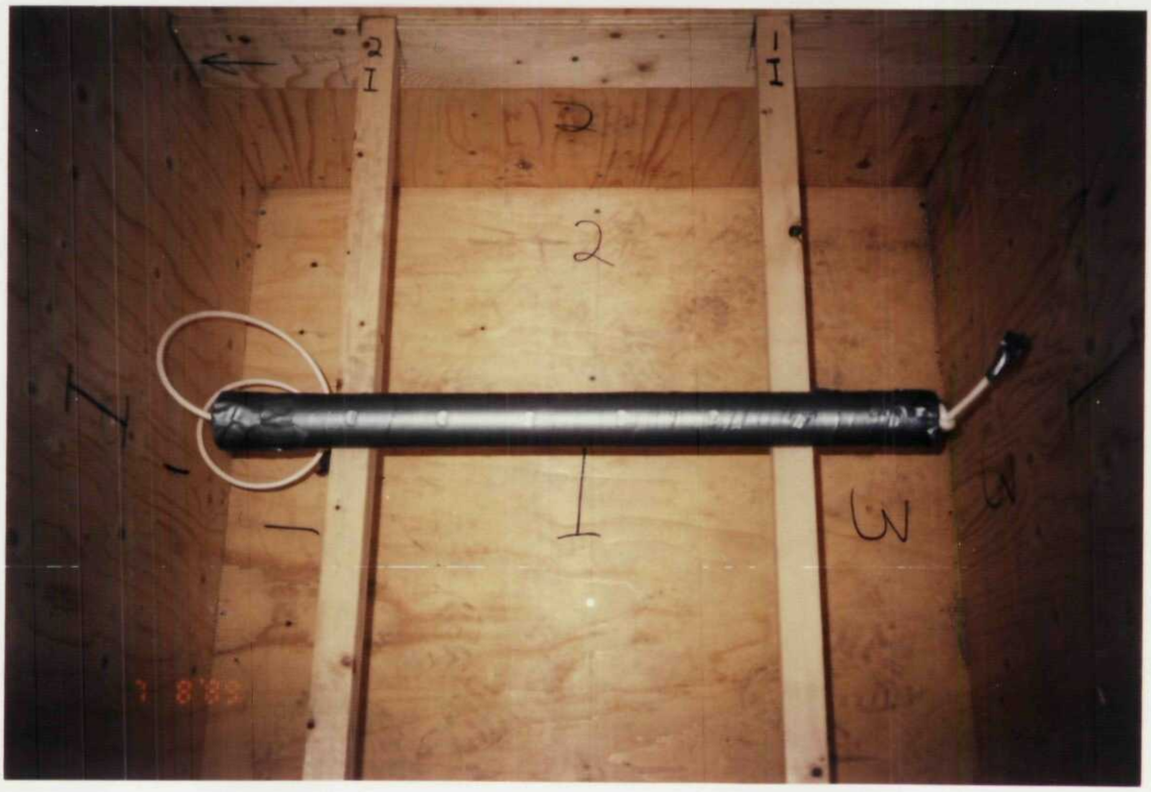

Figure 7. Booster tube in position within wooden box

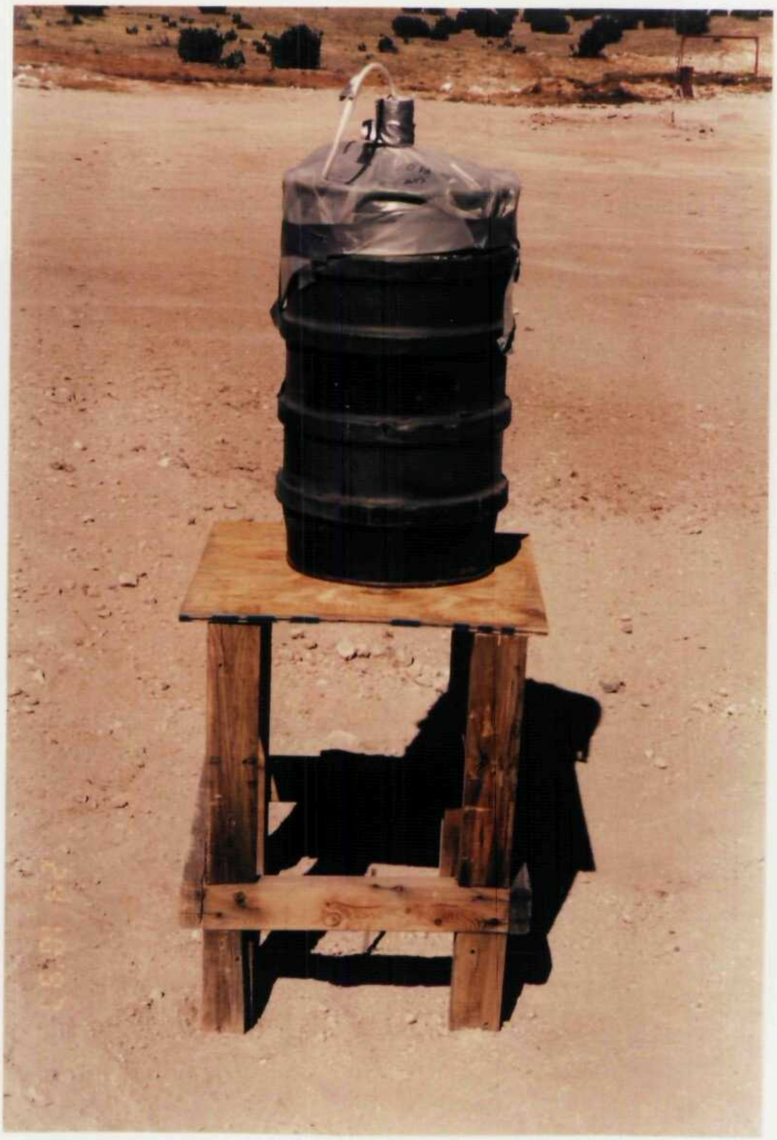

Figure 8. 50 kg CAN/S calibration charge with booster tube set vertically

Figure 9. 1000 kg ANFO charge showing position of wooden box in cargo hold of van

Figure 10. 1000 kg flake TNT charge showing C4 booster

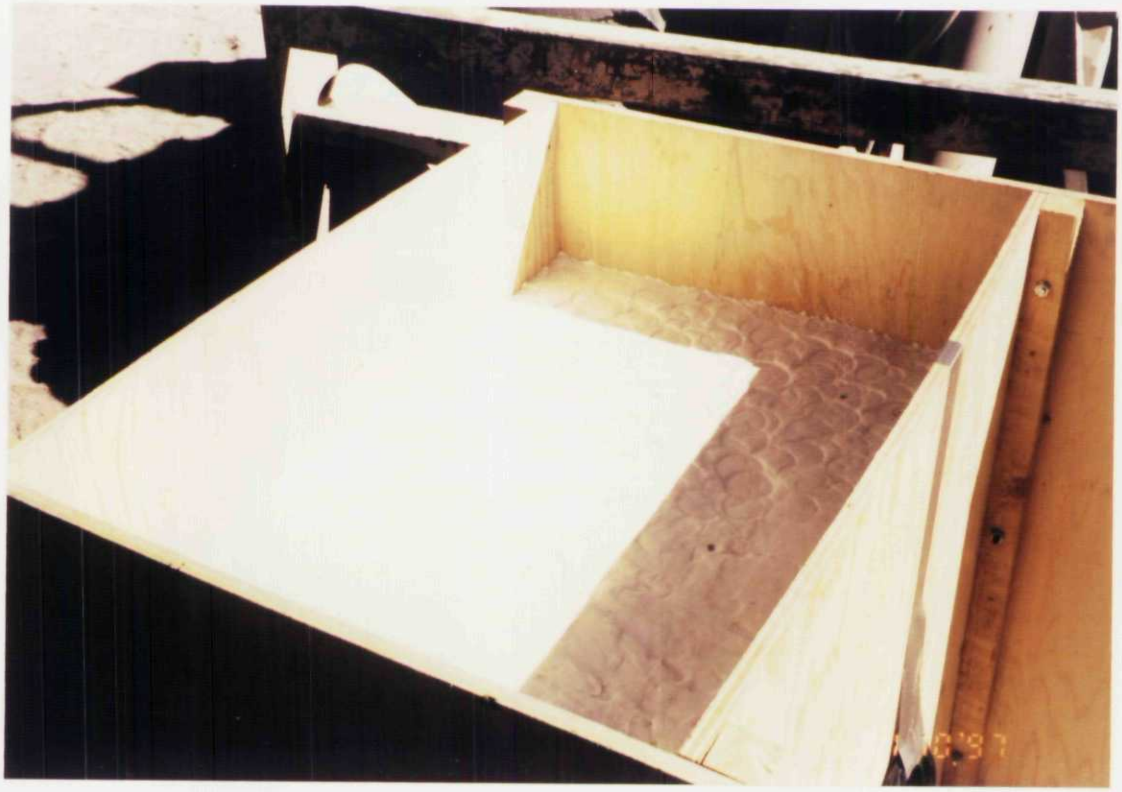

Figure 11. 1000 kg C4 charge within modified wooden box

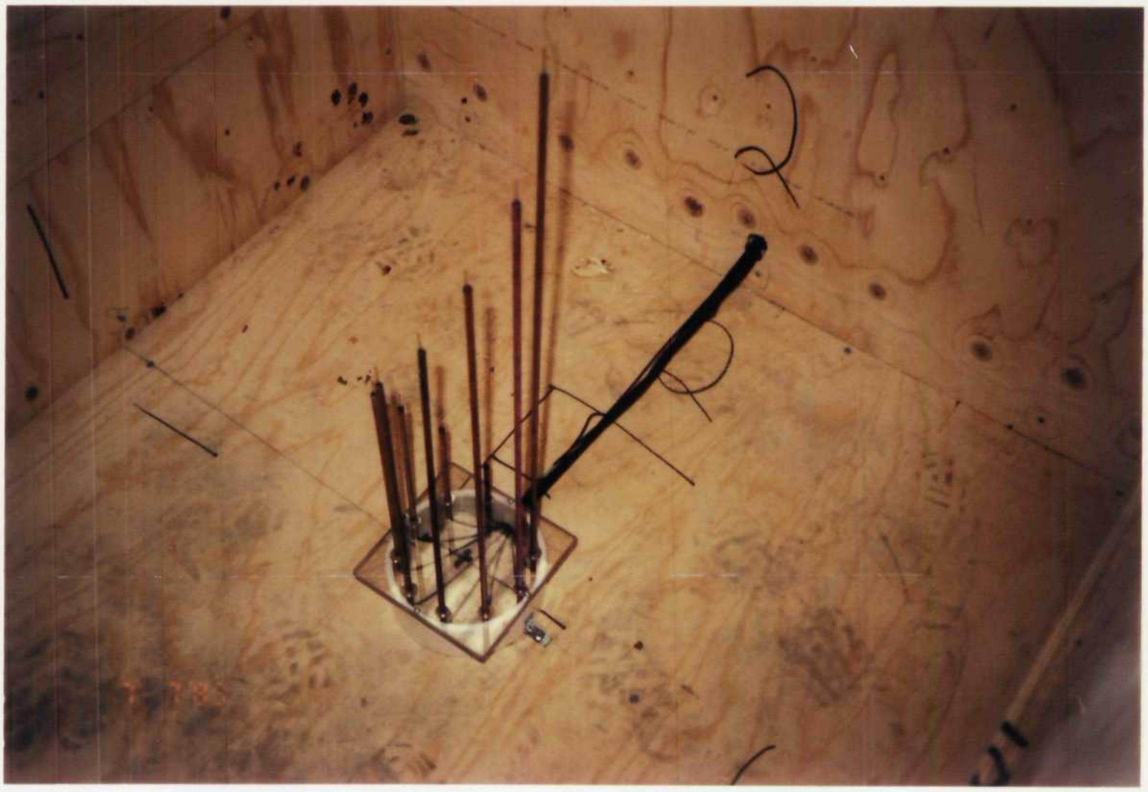

Figure 12. Position of axial VOD pins for charges with a C4 booster

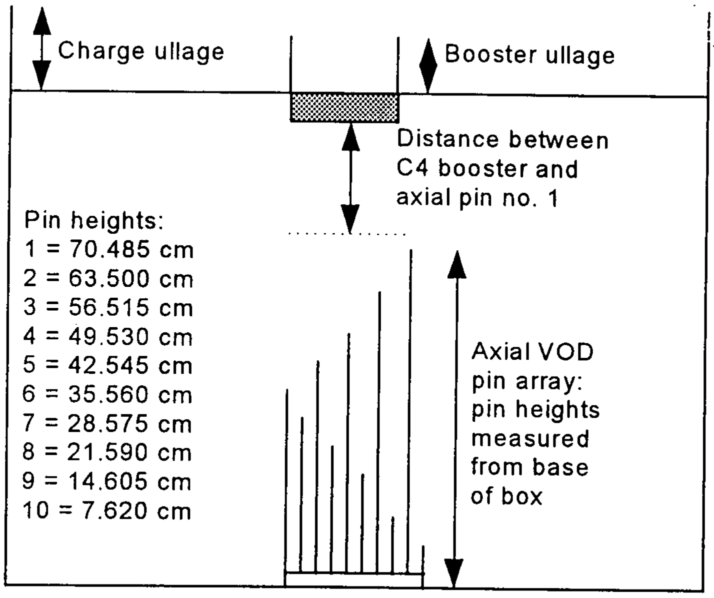

Figure 13. Side view of wooden box showing position of axial VOD pins and C4 booster

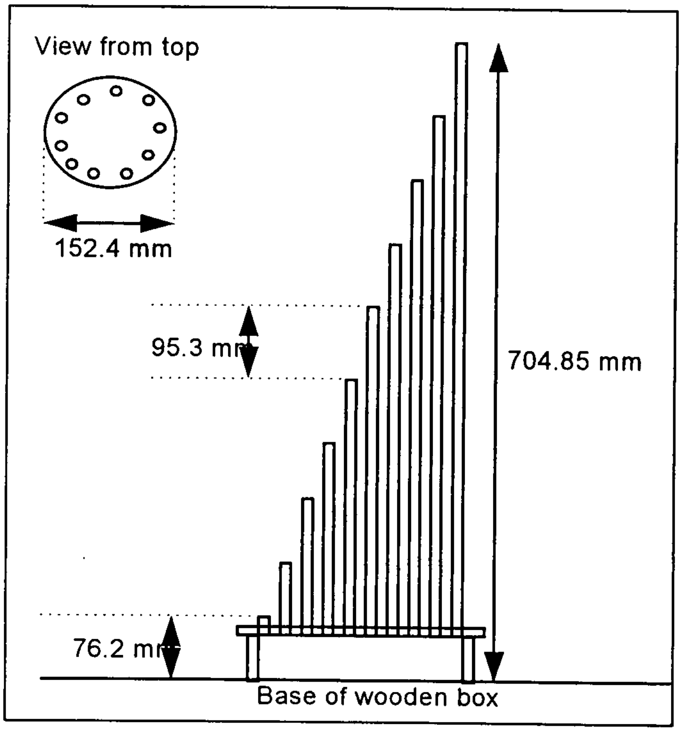

Figure 14. Dimensions of axial VOD pins

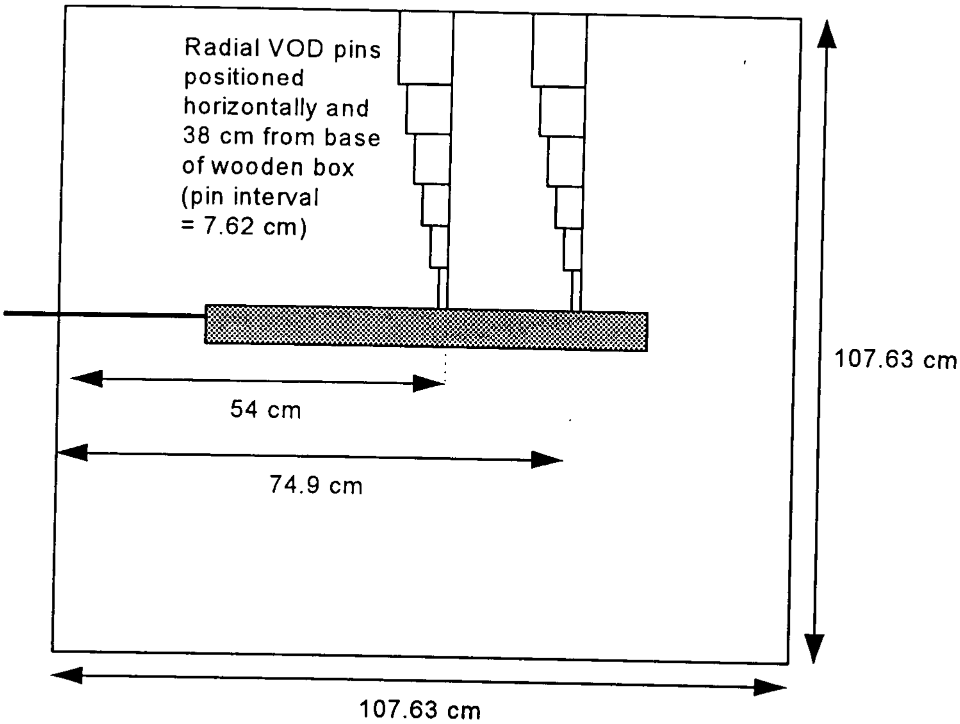

Figure 15. View from above wooden box showing position of radial VOD pins and booster tube

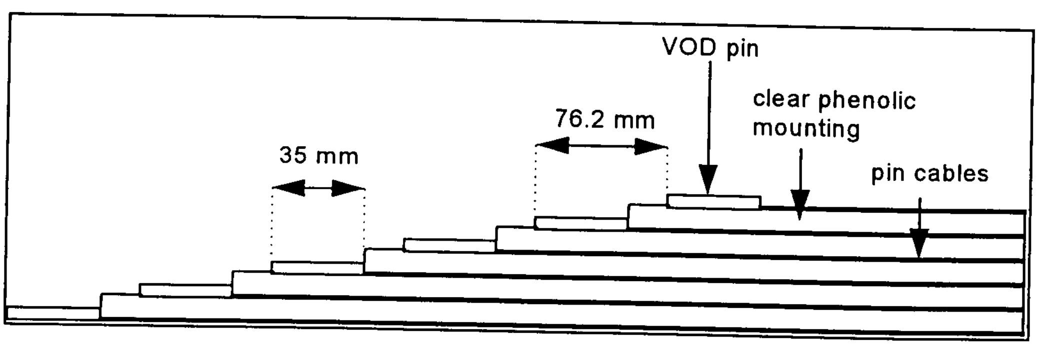

Figure 16. Diagram to show dimensions of the radial VOD pins

Figure 17. Position of radial VOD pins in relation to the booster tube

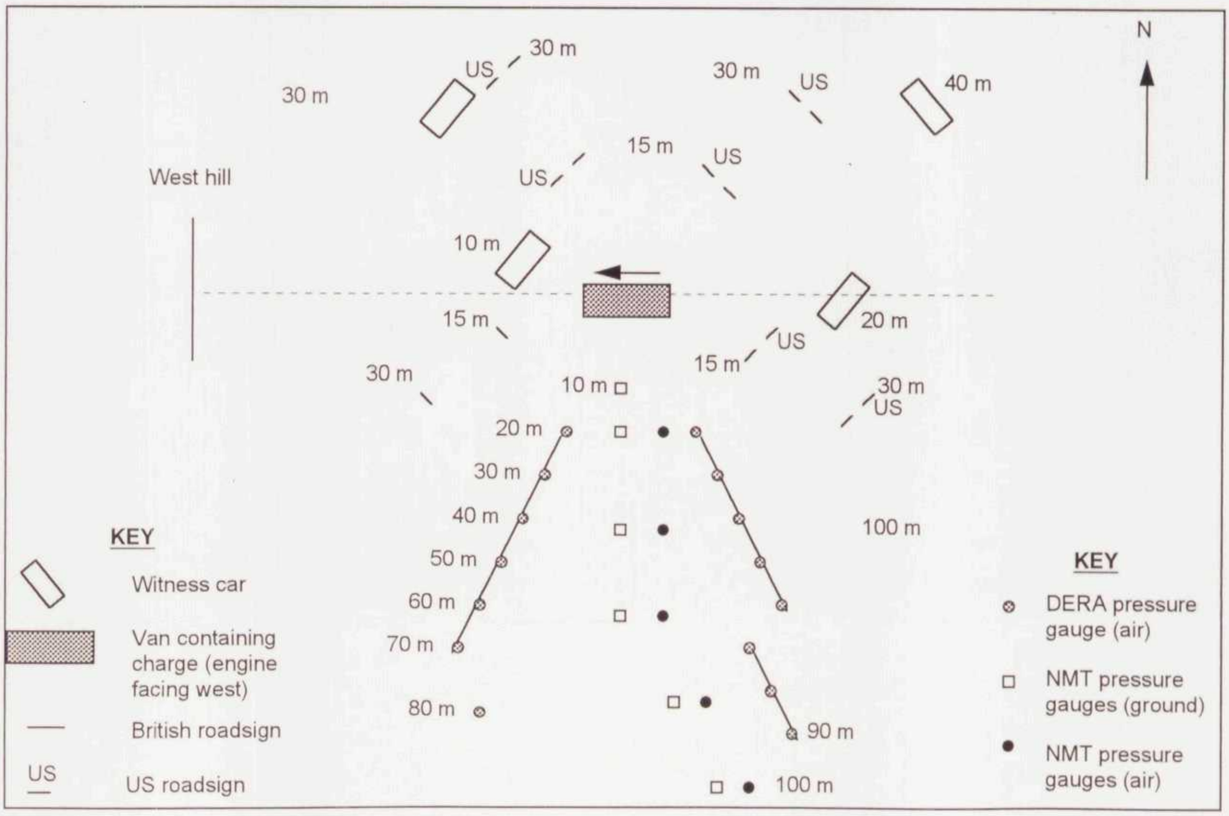

Figure 18. Schematic layout of firing site

Figure 19. Buried concrete drums provide support for sign posts

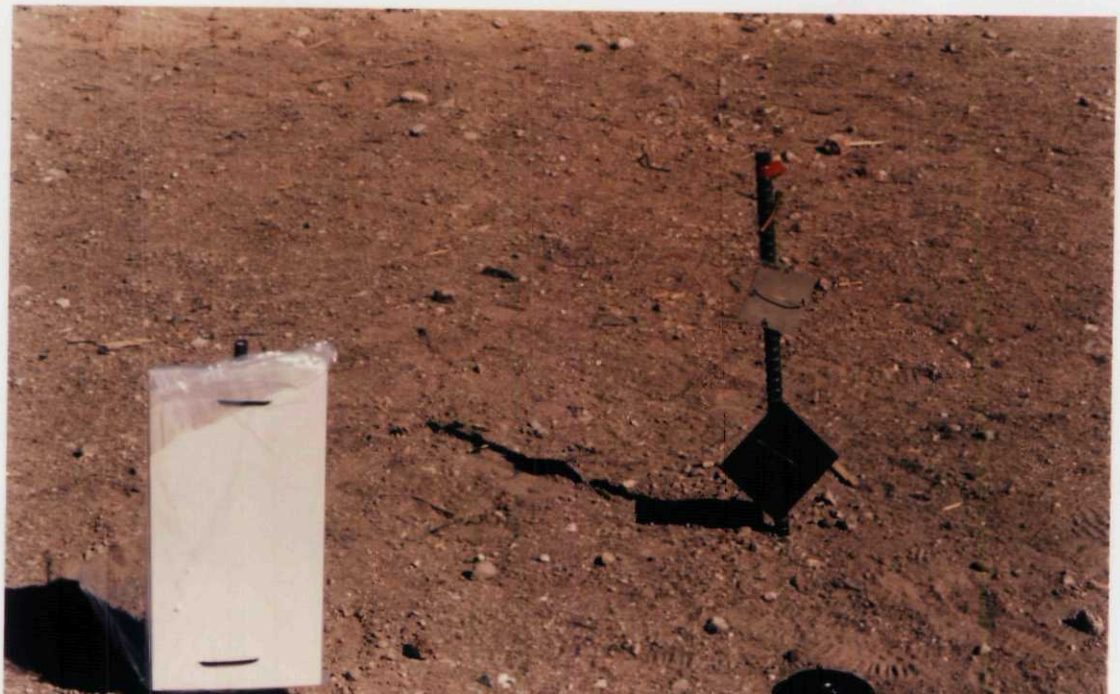

Figure 20. PVC and metal witness pieces

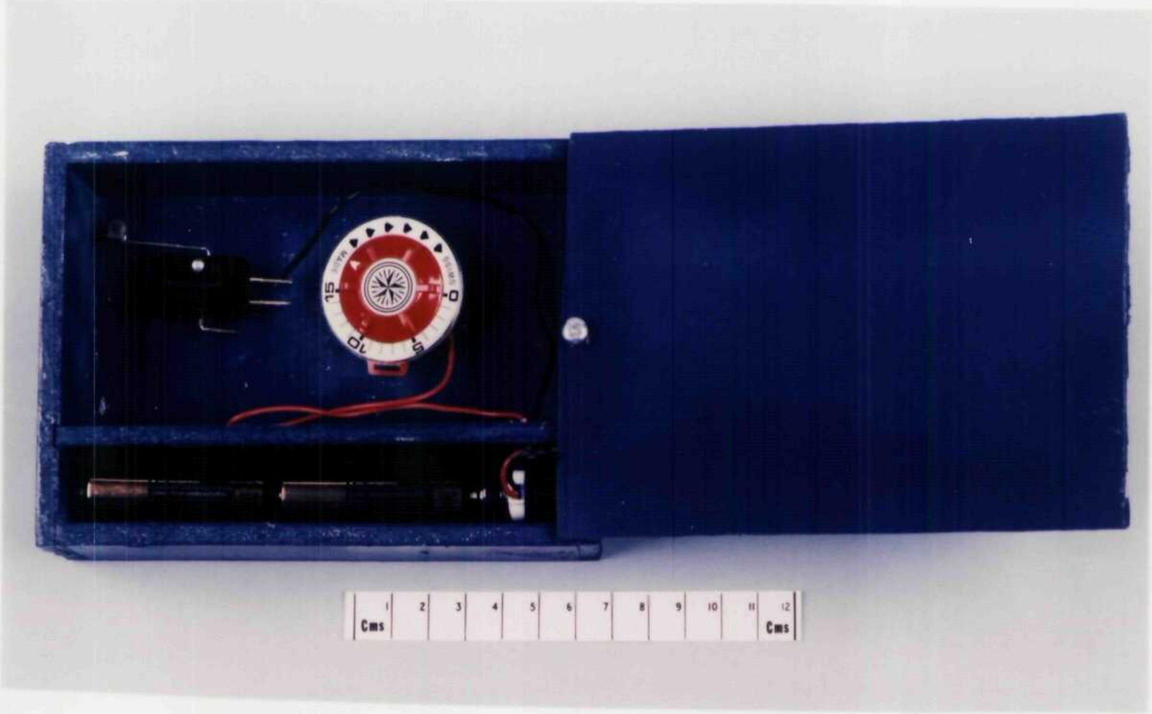

Figure 21. TPU containing Memopark timer

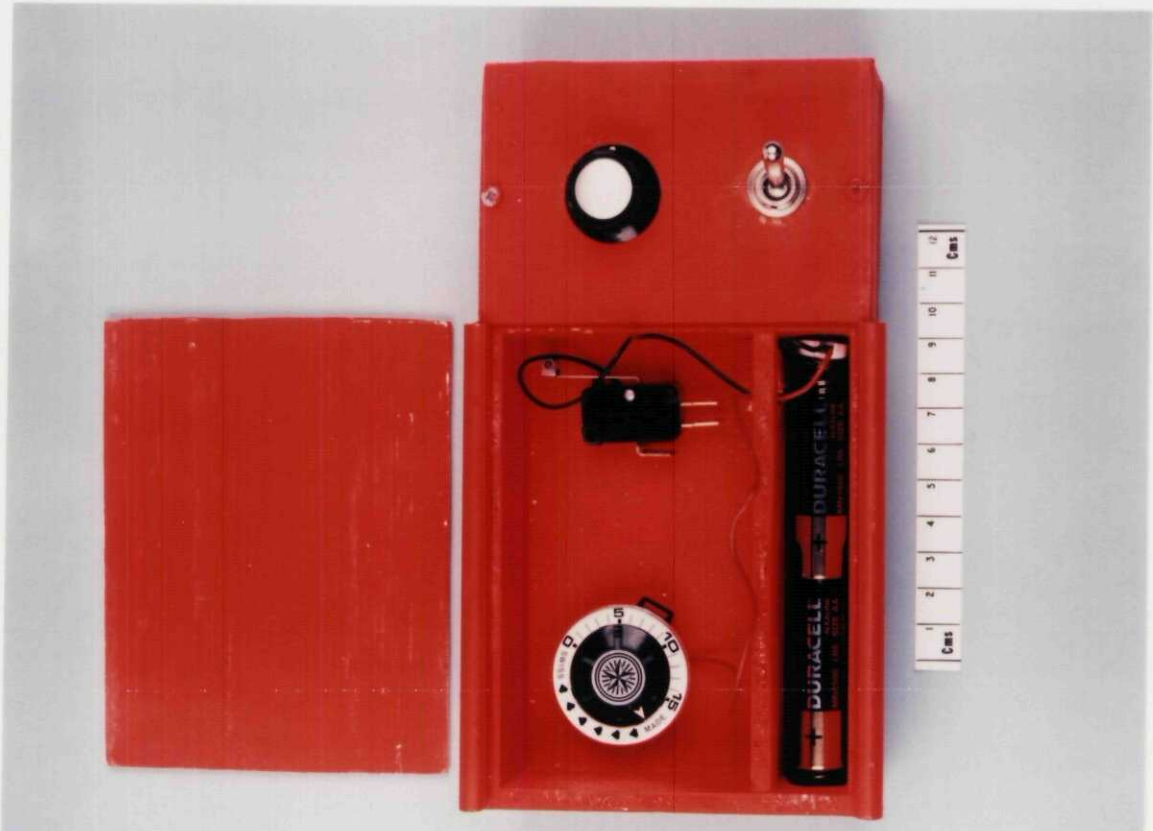

Figure 22. TPU containing Memopark and Diehl timer

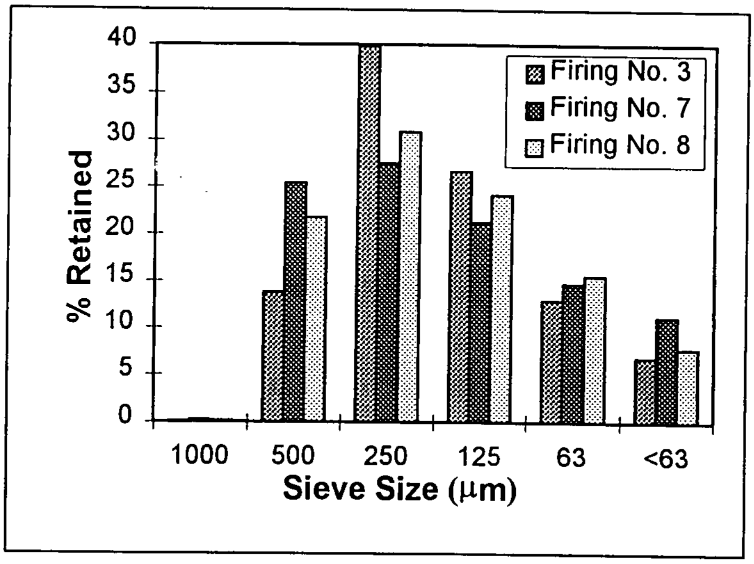

Figure 23. Particle size analysis of CAN/S mixtures (% retained given as an average of two analyses)

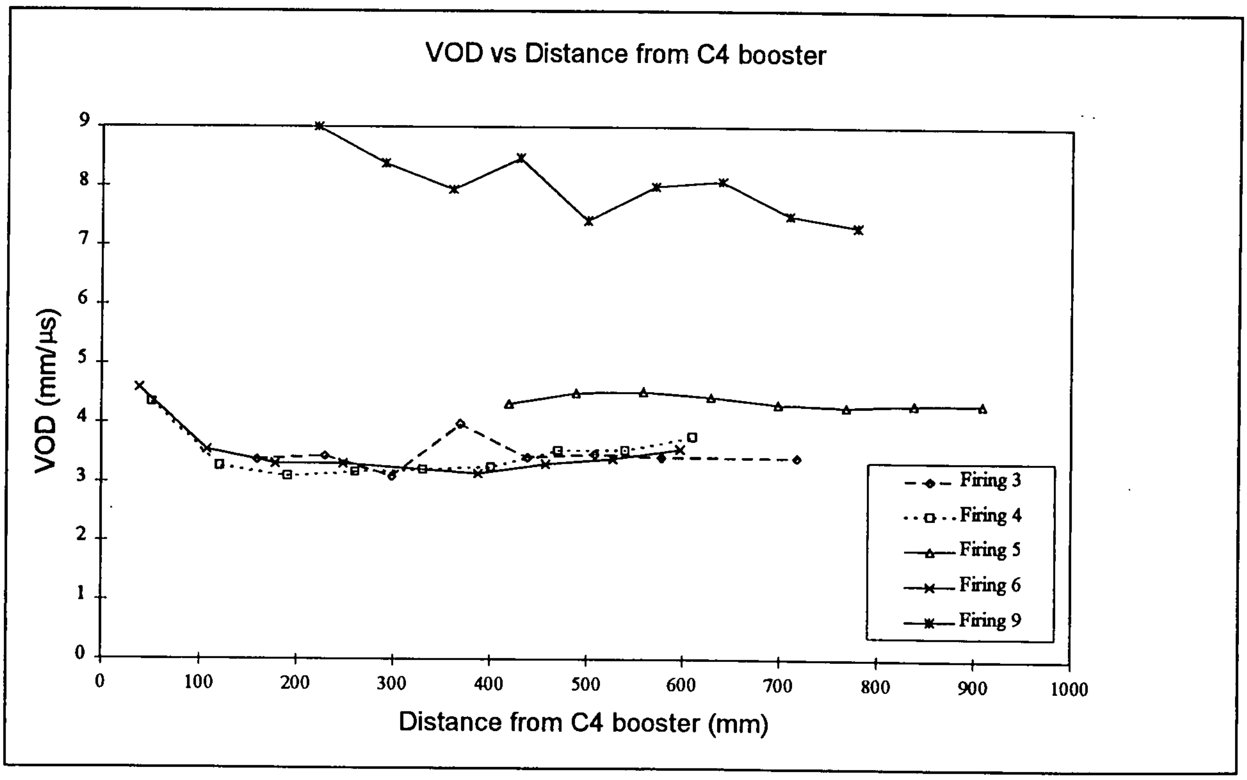

Figure 24. Graph showing the relationship between velocity of detonation and distance of the axial pins from the C4 booster

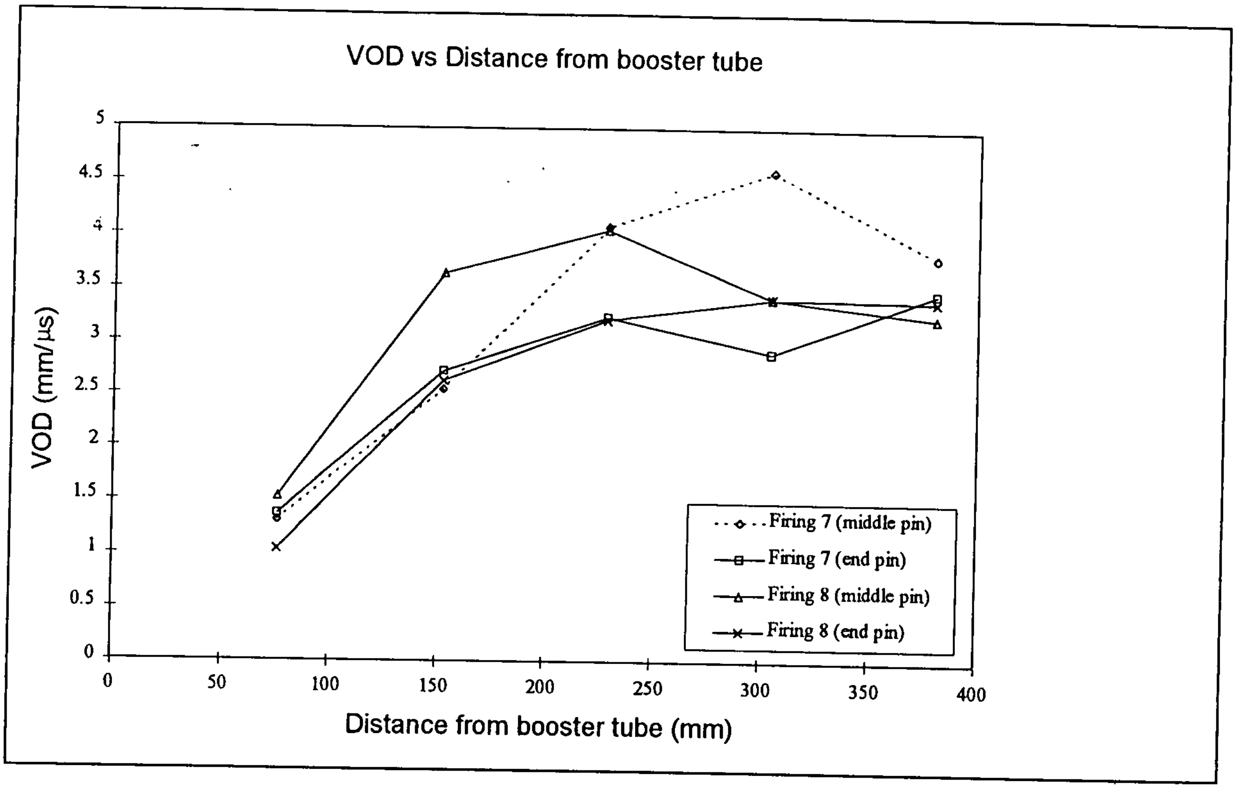

Figure 25. Graph showing the relationship between velocity of detonation and distance of the radial pins from the booster tube

Sieve Size (μm)	Firing Numbers 1 - 3	
	Sample taken at beginning of grinding (% retained)	Sample taken at end of grinding (% retained)
1000	0	0.12
500	10.35	17.21
250	40.36	39.37
125	27.70	25.57
63	13.42	12.27
<63	8.18	5.46

Table 1. Particle size distributions for firing numbers 1 - 3

Sieve Size (μm)	Firing Number 7	
	Sample taken at beginning of grinding (% retained)	Sample taken at end of grinding (% retained)
1000	0.09	0.26
500	16.26	34.51
250	29.97	25.04
125	29.24	13.11
63	14.14	15.13
<63	10.30	11.88

Table 2. Particle size distributions for firing number 7

Sieve Size (μm)	Firing Number 8	
	Sample taken at beginning of grinding (% retained)	Sample taken at end of grinding (% retained)
1000	0.059	0.27
500	20.86	22.61
250	33.95	27.58
125	18.83	29.41
63	16.76	14.13
<63	9.546	5.99

Table 3. Particle size distributions for firing number 8

Firing Number	Charge	Ullage (cm)	Explosive Volume (m^3)	Charge Density (kgm^{-3})
3	1000 kg CAN/S	25.4	1.000	1000
4	1000 kg ANFO	36.2	0.875	1142
5	1000 kg TNT	6.7	1.217	822
6	1000 kg ANFO	37.8	0.857	1167
7	1000 kg CAN/S	25.5	0.999	1001
8	1000 kg CAN/S	25.7	0.997	1003
9	1000 kg C4	26.2	0.917	1519

Table 4. Charge density values

Firing Number	Date	Pressure (mbar)	Temp. (°C)	Relative humidity (%)	Wind speed (m/s)	Wind direction
1	24/10/97	796.3	14.6	27	3.1	SE
2	24/10/97	793.3	16.6	25	5.4	N
3	27/10/97	807.7	13.1	27	5.4	SSE
4	28/10/97	807.5	13.8	20	4.5	N
5	28/10/97	806.3	17.4	22	2.7	N
6	29/10/97	809.7	15.7	27	0.4	NE
7	30/10/97	809.4	15.5	22	6.3	N
8	30/10/97	808.0	18.3	19	4.9	N
9	31/10/97	806.4	22.8	13	3.1	NNW

Table 5. Meteorological data for each firing

AXIAL PIN NO.	FIRING NO. 3		FIRING NO. 4		FIRING NO. 5	
	Distance from C4 booster (mm)	VOD (mm/μs)	Distance from C4 booster (mm)	VOD (mm/μs)	Distance from C4 booster (mm)	VOD (mm/μs)
1	39.3	-	-18.8	-	279.3	-
2	159.1	3.38	51.1	4.35	349.1	-
3	229.0	3.45	121.0	3.27	419.0	4.32
4	298.8	3.10	190.8	3.10	488.8	4.51
5	368.7	3.99	260.7	3.17	558.7	4.54
6	438.5	3.42	330.5	3.21	628.5	4.44
7	508.4	3.48	400.4	3.26	698.4	4.32
8	578.2	3.43	470.2	3.54	768.2	4.28
9	648.1	-	540.1	3.55	838.1	4.33
10	717.9	3.42	609.9	3.78	907.9	4.33

- not measured, pin did not function

Table 6. Details of distances from bottom of C4 booster to axial pins and corresponding velocity of detonation values

AXIAL PIN NO.	FIRING NO. 6		FIRING NO. 9	
	Distance from C4 booster (mm)	VOD (mm/μs)	Distance from C4 booster (mm)	VOD (mm/μs)
1	-31.8	-	150.8	-
2	38.1	4.59	220.6	8.99
3	108.0	3.56	290.5	8.38
4	177.8	3.31	360.3	7.94
5	247.7	3.31	430.2	8.47
6	317.5	-	500.0	7.42
7	387.4	3.15	569.9	8.00
8	457.2	3.31	639.7	8.08
9	527.1	3.40	709.6	7.50
10	596.9	3.57	779.4	7.31

- not measured, did not function

Table 7. Details of distances from bottom of C4 booster to axial pins and corresponding velocity of detonation values

RADIAL PIN INTERVAL	FIRING NO. 7		FIRING NO. 8	
	Distance from tube booster (mm)	VOD (mm/μs)	Distance from tube booster (mm)	VOD (mm/μs)
Middle pin 1-2	76.2	1.31	76.2	1.53
2-3	152.4	2.55	152.4	3.64
3-4	228.6	4.08	228.6	4.05
4-5	304.8	4.61	304.8	3.42
5-6	381	3.81	381	3.24
End pin 1-2	76.2	1.37	76.2	1.04
2-3	152.4	2.72	152.4	2.63
3-4	228.6	3.24	228.6	3.21
4-5	304.8	2.90	304.8	3.42
5-6	381	3.47	381	3.40

Table 8. Details of distances from tube booster to radial pins and corresponding calculated velocity of detonation values[12]

FIRING NO.	CHARGE	MEAN VOD (mm/μs)
3	1000 kg CAN/S	3.46
4	1000 kg ANFO	3.47
5	1000 kg TNT	4.39
6	1000 kg ANFO	3.53
7	1000 kg CAN/S + tube booster	3.01
8	1000 kg CAN/S+ tube booster	2.96
9	1000 kg C4	8.01

Table 9. Mean velocity of detonation for each charge

Gauge No.	Distance from charge (m)	Maximum Pressure (kPa)*		Positive Impulse (Pa/s)*	
		Firing No. 1	Firing No. 2	Firing No. 1	Firing No. 2
DERA					
1	20.28	28.6281	29.9348	111.11	108.955
2	30.91	17.3914	16.8431	76.6798	76.3485
3	39.95	10.4049	11.1683	54.0206	54.2863
4	49.93	7.89684	9.2276	45.9064	46.194
5	59.92	6.51197	6.93499	39.9298	39.8639
6	69.91	4.52921	5.33149	30.7395	31.1462
7	82.63	3.7074	4.28615	25.9581	26.1113
8	19.58	30.6947	33.5852	117.476	115.82
9	29.67	18.0895	21.935	76.1224	75.3803
10	39.61	10.3634	9.98904	53.0316	52.1817
11	49.58	7.61742	8.33396	45.8298	45.791
12	59.70	5.73814	5.79435	37.3597	36.8895
13	69.84	5.09279	5.22242	32.868	31.7349
14	79.82	3.822	3.7051	28.5603	27.8799
15	89.81	3.41683	3.41584	23.6713	23.5003
NMT					
1 G	10.15	114.776	118.584	244.782	230.635
2 G	20.09	23.2383	28.7272	66.3347	78.4439
3 G	40.04	13.01	154.564	67.4678	541.877
4 G	60.10	6.29241	10.6909	31.6982	41.1929
5 G	79.62	4.03191	3.98285	31.1491	30.299
6 G	99.80	2.90266	2.5314	25.0858	22.1134
7 A	19.96	28.4764	30.4631	128.252	121.08
8 A	19.96	20.6539	-	115.588	-
9 A	39.93	-	-	-	-
10 A	39.93	7.67525	7.9755	54.5957	49.0274
11 A	59.87	5.68154	4.61046	35.8519	37.1549
12 A	59.87	6.64391	6.63414	43.1954	36.8967
13 A	79.80	3.94425	4.05706	26.0418	29.7508
14 A	79.80	3.99255	3.94108	28.7688	29.2953
15 A	99.84	-	-	-	-
16 A	99.84	2.97588	2.62233	23.0836	22.7453

*Corrected to standard temperature and pressure
G = ground gauge, A = air gauge
- not measured, gauge did not function

Table 10. Maximum pressures and positive impulses obtained for each of the gauges for the 50 kg charges

Gauge No.	Distance from charge (m)	Maximum Pressure (kPa)*						
		Firing No 3	Firing No 4	Firing No 5	Firing No 6	Firing No 7	Firing No 8	Firing No 9
DERA 1	20.28	246.346	296.909	-	376.951	387.167	283.443	795.691
2	30.91	103.018	133.093	161.461	94.475	93.234	114.587	286.775
3	39.95	55.798	60.269	70.720	51.473	54.264	66.494	103.447
4	49.93	36.642	39.517	38.563	33.520	34.702	40.056	72.833
5	59.92	24.893	23.805	29.774	22.843	25.579	29.545	39.252
6	69.91	17.779	18.467	24.927	18.974	19.259	22.507	29.719
7	82.63	14.020	14.479	17.324	13.847	15.415	16.611	20.588
8	19.58	233.044	326.409	-	254.218	259.820	294.546	424.063
9	29.67	-	-	118.813	-	97.939	113.300	184.456
10	39.61	55.849	69.910	87.168	59.508	55.076	60.157	111.761
11	49.58	37.042	48.348	58.570	44.403	41.351	43.355	64.503
12	59.70	27.369	35.208	41.132	30.433	30.025	29.462	41.833
13	69.84	21.566	26.976	32.271	22.373	21.698	22.344	31.407
14	79.82	18.903	23.640	25.969	18.399	18.947	22.188	24.783
15	89.81	14.295	17.878	19.551	15.139	13.966	20.492	18.524
NMT 1 G	10.15	1677.90	1696.85	-	-	1346.71	1402.58	-
2 G	20.09	344.378	363.414	597.550	466.916	510.749	319.032	722.167
3 G	40.04	64.374	73.106	96.588	-0.2751	85.586	91.928	109.537
4 G	60.10	32.010	33.978	42.301	32.034	38.843	36.841	59.094
5 G	79.62	16.658	24.049	25.872	19.762	25.404	21.732	37.498
6 G	99.80	13.500	19.756	23.667	14.609	17.876	19.371	22.382
7 A	19.96	255.467	274.692	-	346.536	503.637	295.614	-
8 A	19.96	265.799	278.264	-	293.528	504.214	344.331	-
9 A	39.93	-	-	-	-	-	-	-
10 A	39.93	56.874	60.865	64.067	62.936	52.152	51.226	114.225
11 A	59.87	28.790	34.056	32.089	28.483	29.055	28.415	50.494
12 A	59.87	-	-	-	22.167	26.215	25.259	48.038
13 A	79.80	17.305	23.684	25.943	17.776	18.968	18.209	25.643
14 A	79.80	17.163	21.067	23.316	16.102	16.656	17.145	24.774
15 A	99.84	12.517	14.866	17.734	12.088	13.424	13.073	16.445
16 A	99.84	12.235	13.437	16.926	11.857	12.101	12.365	15.022

*Corrected to standard temperature and pressure
G = ground gauge, A = air gauge
- not measured, gauge did not function

Table 11. Maximum pressures obtained for each of the gauges for the 1000 kg charges

		Positive Impulse (Pa/s)*						
Gauge No.	Distance from charge (m)	Firing No 3	Firing No 4	Firing No 5	Firing No 6	Firing No 7	Firing No 8	Firing No 9
DERA 1	20.28	788.350	991.137	-	736.246	790.179	947.365	1128.83
2	30.91	563.633	587.276	715.874	600.742	544.621	597.077	1006.75
3	39.95	411.495	411.575	512.944	453.777	406.063	434.984	656.285
4	49.93	342.816	366.421	380.910	378.806	336.144	359.807	511.458
5	59.92	278.378	289.129	335.603	301.843	268.119	283.445	390.496
6	69.91	232.805	254.409	353.263	256.464	229.848	242.168	337.712
7	82.63	204.633	227.484	304.310	219.811	198.440	212.145	278.974
8	19.58	731.499	912.517	-	908.624	777.592	964.680	592.827
9	29.67	-	-	702.771	-	583.389	600.570	901.732
10	39.61	453.236	508.398	669.243	483.365	427.655	440.504	801.097
11	49.58	351.245	431.831	525.062	410.835	365.846	374.211	649.667
12	59.70	308.894	362.739	461.880	340.679	308.446	314.392	536.826
13	69.84	266.806	293.410	385.583	288.177	267.044	273.935	417.422
14	79.82	234.053	268.726	339.862	244.636	224.437	224.493	372.353
15	89.81	197.046	227.464	290.589	206.438	190.381	199.635	315.274
NMT 1 G	10.15	1822.85	1727.35	-	-	1233.37	1554.12	-
2 G	20.09	1021.53	1506.09	1833.65	1120.55	1241.78	842.667	1497.37
3 G	40.04	447.297	430.077	492.393	-	476.674	424.201	687.765
4 G	60.10	321.553	321.037	350.591	333.042	343.388	322.720	410.822
5 G	79.62	244.268	266.864	337.188	289.055	260.198	247.929	411.287
6 G	99.80	177.756	242.324	358.467	242.523	178.487	252.738	262.964
7 A	19.96	969.363	849.831	-	1109.70	941.754	1066.41	-
8 A	19.96	1012.79	1116.53	-	1294.70	987.148	1104.69	-
9 A	39.93	-	-	-	-	-	-	-
10 A	39.93	431.793	507.526	566.998	400.093	358.347	359.851	691.528
11 A	59.87	333.421	384.876	428.003	322.603	326.867	320.183	456.887
12 A	59.87	-	-	-	29.601	268.621	303.206	415.587
13 A	79.80	219.804	291.204	342.828	248.835	225.784	252.670	332.482
14 A	79.80	237.716	262.948	316.654	220.382	209.139	234.496	312.077
15 A	99.83	192.039	199.311	272.504	192.228	179.234	192.947	285.357
16 A	99.83	183.581	169.404	267.188	188.360	164.834	178.460	245.170

*Corrected to standard temperature and pressure
G = ground gauge, A = air gauge
- not measured, gauge did not function

Table 12. Positive impulses obtained for each of the gauges for the 1000 kg charges

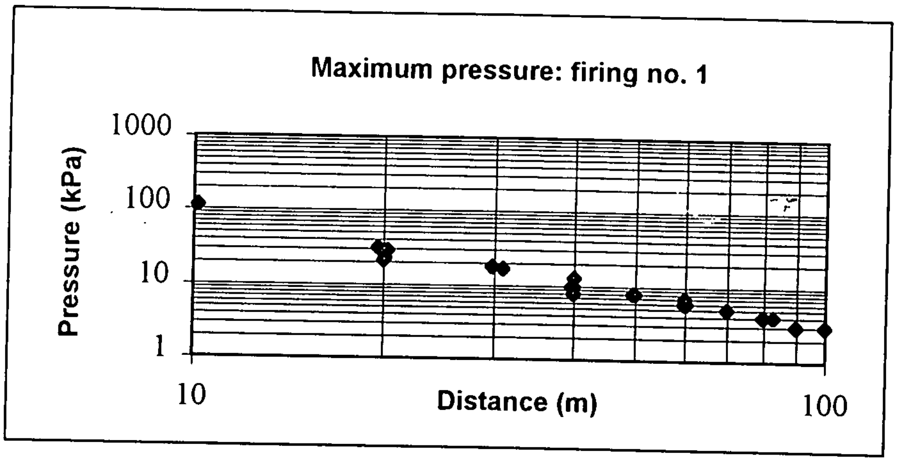

Figure 26. Graph showing the relationship between maximum pressure and distance for firing 1

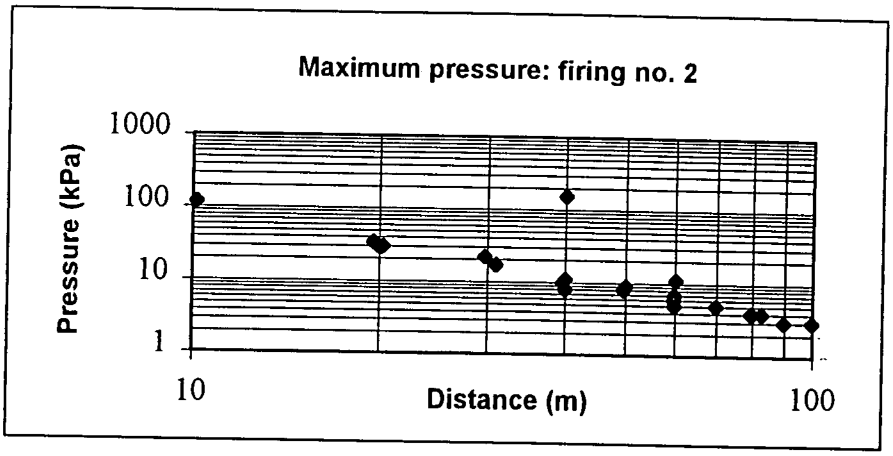

Figure 27. Graph showing the relationship between maximum pressure and distance for firing 2

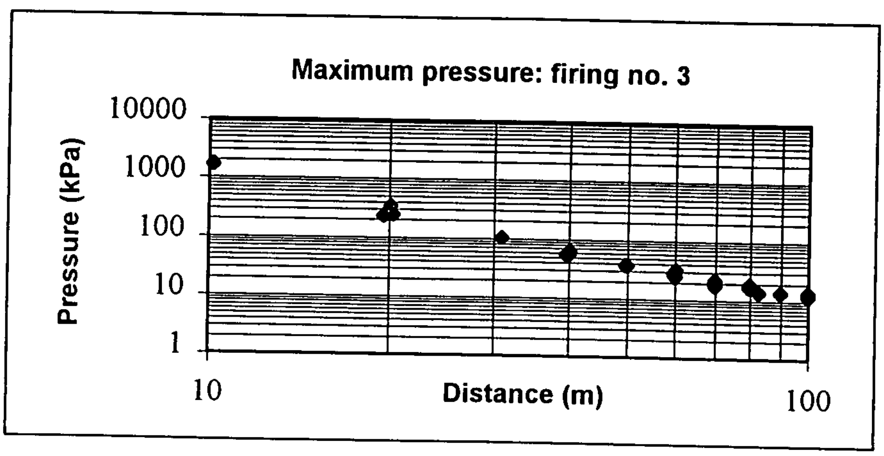

Figure 28. Graph showing the relationship between maximum pressure and distance for firing 3

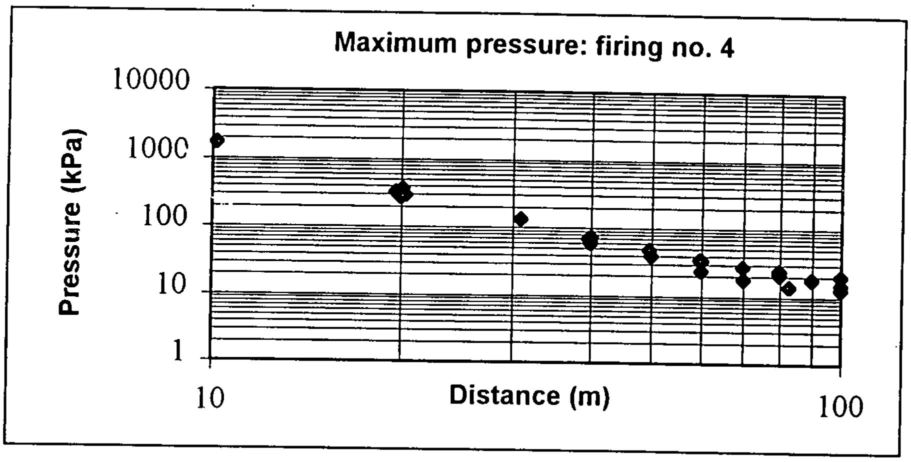

Figure 29. Graph showing the relationship between maximum pressure and distance for firing 4

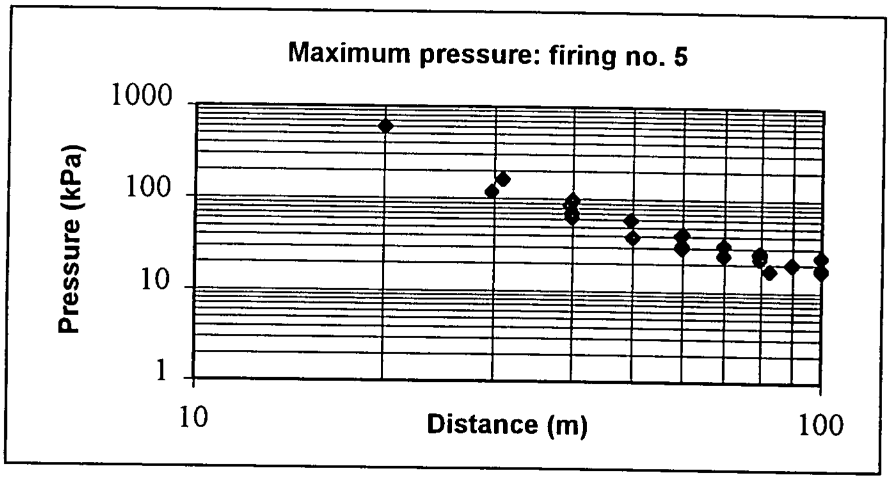

Figure 30. Graph showing the relationship between maximum pressure and distance for firing 5

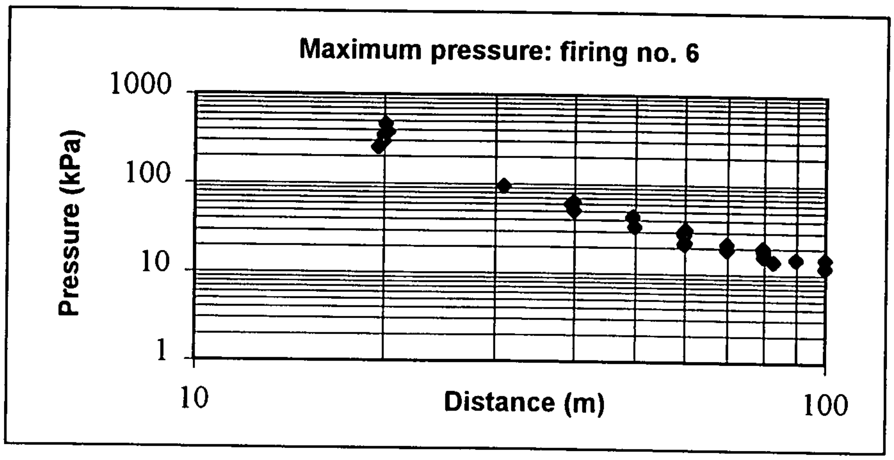

Figure 31. Graph showing the relationship between maximum pressure and distance for firing 6

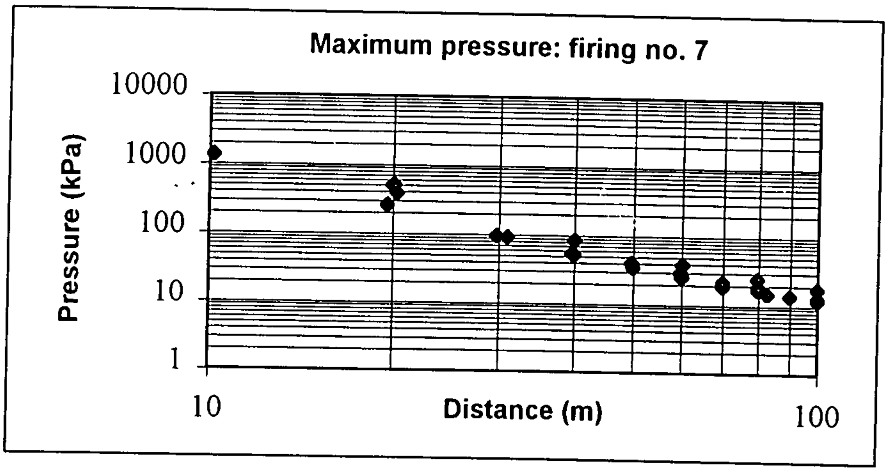

Figure 32. Graph showing the relationship between maximum pressure and distance for firing 7

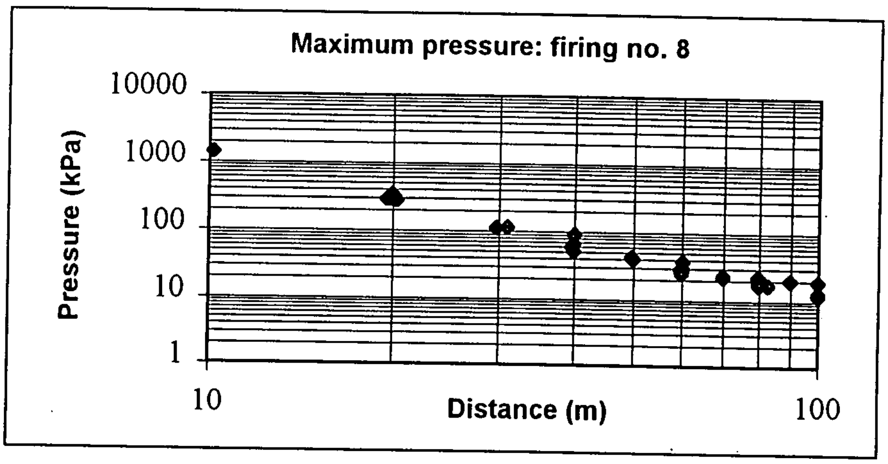

Figure 33. Graph showing the relationship between maximum pressure and distance for firing 8

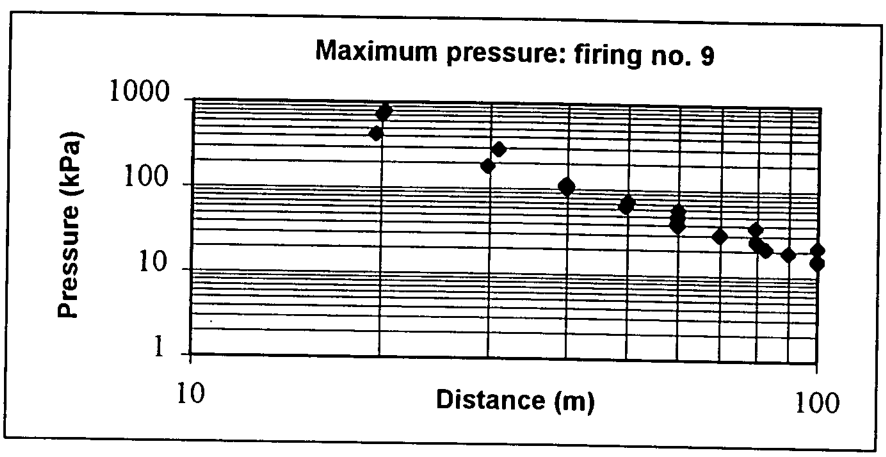

Figure 34. Graph showing the relationship between maximum pressure and distance for firing 9

REPORT DOCUMENTATION PAGE

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10a. Abstract

Following detonation of a terrorist bomb one main task is to identify the explosive charge type and its approximate size. Physical evidence can be obtained after the blast from, for example, the degree of shattering or bending of various materials near to the seat of the explosion. Similarly chemical traces recovered from nearby debris and witness pieces can provide an identification of the explosive type and composition. In collaboration with the FBI, nine firings were performed in October 1997 comprising two 50 kg calcium ammonium nitrate/icing sugar (CAN/S) test charges, two 1000 kg ammonium nitrate/fuel oil (ANFO) charges, three 1000 kg CAN/S charges, one 1000 kg TNT charge and one 1000 kg C4 charge. Four of the charges, both 50 kg test firings and two of the 1000 kg CAN/S firings, were detonated using a tube booster broadly similar to those used by PIRA. The remaining charges were initiated with C4 boosters. Each 1000 kg charge was contained within a wooden box, placed inside a large transit van. The charge-containing van was surrounded by four motor cars, eight UK roadsigns, six US roadsigns, two PVC plates and a number of small aluminium, steel and copper witness pieces. Additionally, three simulated Time and Power Units (TPUs) and a large battery were positioned in various places in the van. This report describes the preparation and firing of the charges, the preparation and collection of the witness pieces and the velocity of detonation and blast pressure data.

10b. Abstract classification
UNCLASSIFIED