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Physical and Chemical Evidence Remaining After the Explosion of Large Improvised Bombs. Part 2: Firings of Calcium Ammonium Nitrate/Sugar Mixtures*

REFERENCE: Cullum H, Lowe A, Marshall M, Hubbard P. Physical and chemical evidence remaining after the explosion of large improvised bombs. Part 2: Firings of calcium ammonium nitrate/sugar mixtures. J Forensic Sci 2000;45(2):333–348.

ABSTRACT: Six test firings of large improvised explosive devices were carried out. The principal objectives of the firings were to measure the physical effects of the explosions upon representative objects placed nearby and to recover any chemical traces deposited on these objects. The results are intended for use as an aid in determining the approximate size and type of an explosive employed in terrorist attacks. Three 454 kg charges of a mixture of calcium ammonium nitrate (CAN) fertilizer and sugar, and three 2268 kg charges of a similar mixture, all confined in cylindrical steel containers were fired. Each charge was surrounded by 19 road signs mounted on posts and four vehicles, to act as witness materials. The analysis of aqueous swab extracts taken from the witness materials after firing showed the recovery of nitrate, ammonium and low levels of glucose. No sucrose was detected. Nitrate was usually recovered in greater quantities than ammonium and recovery generally decreased with increasing distance from the charges in any given direction. Quantities recovered from objects placed at the same distance in different directions varied considerably. Patterns of physical damage to the witness materials could be discerned according to their distance from the charge and the size of the charge. The velocities of detonation and air blast effects were measured.

KEYWORDS: forensic science, explosives, homemade explosives, improvised explosive devices, witness materials, fertilizer, calcium ammonium nitrate, sugar, chemical residue, physical damage, velocity of detonation, charge density

A major forensic task following the detonation of a terrorist bomb is to identify the nature, type and approximate size of the explosive charge. This includes the interpretation of both physical and chemical evidence. The general nature of the explosive can be identified from physical evidence such as the degree of shattering close to the seat of the explosion while chemical traces recovered from nearby debris allow more precise identification. The interpretation of such physical evidence following very large terrorist bombings is severely constrained by the lack of practical experience of such explosives on a large scale. Four sets of trials were performed over four years. Each set of trials examined the characteristics of improvised mixtures of ammonium nitrate containing fertilizer and confectioner's sugar (AN/S), although firings of other compositions such as ammonium nitrate/fuel oil (ANFO) and trinitrotoluene (TNT) were also carried out. This paper describes results obtained from the second in the series of trials. The experimental methods used are described in a companion paper in this publication(1). Large explosive charges similar in size and composition to those recently employed by the Provisional IRA were prepared. Each charge consisted of a mixture of calcium ammonium nitrate fertilizer and confectioner's sugar confined in a steel container. Charges were surrounded by vehicles and road signs, representative of those witness pieces from which forensic evidence may be recovered in real cases. The physical and chemical signatures produced from these firings are reported and in conjunction with information gathered during the three associated trials may be of value in determining the approximate size and type of an explosive employed in a terrorist attack.

Materials, Preparation and Procedures

Test Site Location

All firings were performed at the High Performance Magazine (HPM) Site, New Mexico Institute of Mining and Technology (NMT), Socorro, NM. This site has an altitude of approximately 1900 m above sea level.

Preparation of the Charges

The explosive was prepared from calcium ammonium nitrate fertilizer and confectioner's sugar. Three smaller charges (454 kg CAN/S) were loaded into open-top cylindrical steel vessels (965 mm diameter by 965 mm high by 3.2 mm wall thickness) 38 × 38 × 1/8 in.). Three larger charges (2268 kg CAN/S) were loaded into similar but larger vessels (1520 mm diameter by 1520 mm high (60 × 60 in.). The vessels were prepared before loading with the fertilizer/sugar mixture for measuring the velocity of detonation (VOD). Six piezoelectric pins were placed vertically at the base of the charge and four were placed radially at the top of the charge. After

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loading and transportation of the charge to the firing site, the vessel was placed on top of a 760 mm (30 in.) steel frame to simulate the height in the back of a vehicle. A suitable booster was positioned in the charge to ensure complete detonation and the charges initiated electrically. Figure 1 shows the position of the VOD pins and booster. Signal cables to the VOD pins were buried in trenches below ground to minimize potential fragment damage and loss of data.

In the interest of public safety certain details of the preparation of the explosive mixture have been omitted. Bona fide requests for details will be honored if received in writing by the corresponding author.

Firing Sequence

A test charge of inert material was fired prior to firing the CAN/S charges to determine the blast pressure effects of the booster and to check the response of the instrumentation. A steel drum 673 mm high, 1249 mm in circumference was filled with sand up to a depth of 379 mm. The booster was inserted into the top of the sand and initiated electrically. The CAN/S charges were then mixed and fired in the order shown in Table 1.

Preparation of Sampling Materials

Cotton wool swabs were prepared by extraction with deionized water and acetone and dried under vacuum. Five swabs from each batch of 200 were then quality assured by extraction with

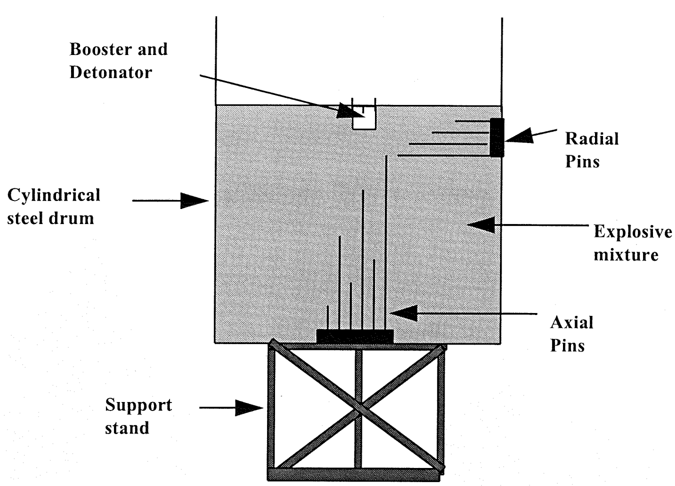

FIG. 1—*Diagram of charge.*

TABLE 1—*Mixing/firing order of CAN/S charges.*

Order of Mixing	Order of Firing (Test Number)	Quantity of CAN/S in Charge (kg)
1	1 (Day 3)	454
2	2 (Day 4)	454
3	4 (Day 8)	2268
4	3 (Day 7)	2268
5	5 (Day 9)	454
6	6 (Day 10)	2268

two aliquots of UHQ water. The combined extracts were analyzed by ion chromatography (1). No ammonium or sugars were detected on the swabs. Nitrate contamination was found to be less than 1 μg per swab. Kits were then prepared containing the materials that would be used to sample the road signs and areas from the vehicles after firing. The kits were packaged in individual sealed plastic containers. The whole process was carried out in a dedicated trace explosives laboratory which is regularly sampled to ensure the absence of conventional organic explosives traces. Although this sampling does not include screening for ammonium, nitrate or sucrose, this laboratory is subject to a strict cleaning regime and is necessarily the cleanest laboratory at our facility.

The contents of each kit were:

4 gloves (bagged)
5 glass vials (10.5 mL, snap top, bagged)
5 swabs (in vials)
5 pairs of forceps
1 large paper towel
1 pen
6 labels

Two kits from the batch of 52 were selected for quality assurance. All items from each kit and the inside of the plastic container holding the items were sampled using UHQ water-moistened swabs and one pair of forceps from the same kit. An area of a bench in the laboratory was cleaned and covered with fresh glazed paper. The lid of the first kit was removed and one pair of gloves from that kit was put on. The contents of the kit were placed onto the glazed paper. One vial containing a swab was opened and 6 mL of UHQ water was added. The lid of the vial was replaced and this sample was retained as a swab/solvent/vial control. A second vial was opened and 6 mL of UHQ water was added to the swab inside. The swab was clamped between one pair of forceps and gently squeezed against the inside of the vial to remove excess water. The swab was used to sample the entire surface of the gloves being worn and the second pair of gloves from the kit. The swab was returned to the vial to be remoistened when necessary. After sampling had been completed, the swab was returned to the vial and the lid was replaced. A similar procedure was used to sample the remaining items in the kit and the container. The second kit was sampled in a similar manner.

Each swab was extracted separately as follows: The swab was compressed a number of times using a clean Pasteur pipette and the water removed to a clean vial using the same pipette. A further 4 mL of UHQ water was added to the swab and again the swab was compressed a number of times before removing the water to the clean vial. This combined extract was analyzed by ion chromatography (1). All kit components were found to be essentially free of ammonium and sugar. The swab of the forceps from one kit showed that approximately 3 μg of nitrate was present. Other materials which would come into contact with the witness materials were also quality assured to ensure they were essentially free of ammonium, nitrate and sugar. These materials included the polyethylene bags used to seal the clean road signs and transport the used road signs from the test site after firing and the clips used to fix the signs to their posts. A4 card frames (usually used as frames for overheads) were also quality assured since these were used as templates to mark specific sampling areas on vehicles. All were found to be free of the relevant species except the fixing clips from which a low level of nitrate was recovered.

Preparation of the Witness Materials

The witness materials used were aluminum road signs (British design and manufacture) and family-sized sedan cars (American design). The road signs were 46 cm × 30 cm × 0.27 cm thick aluminum with a class 2 PVC reflective face, gray back and horizontal fixing runners and were supplied with posts and attachment clips. These road signs and posts are typical of those that can be found on many streets in the U.K. The two runners fixed to the back of each road sign make them more robust than the U.S.-designed road sign used during the previous trials (1).

One hundred eighty road signs were purchased directly from the manufacturer and were thoroughly washed with deionized water, allowed to dry and sealed first individually in a polyethylene bag and then further in a nylon bag. One in twenty signs was selected for quality assurance. These signs were sampled using UHQ water-moistened cotton wool swabs as previously described. The swab was compressed in a clean vial using a Pasteur pipette and the water transferred to a separate clean vial. The swab was extracted with a further aliquot of deionized water, the extracts combined and analyzed by ion chromatography. All were found to be essentially free of ammonium, nitrate and sugar.

Vehicles were purchased locally near the test site and prepared on the test site immediately prior to firing. The use of vehicles typically driven in Britain was impractical and prohibitively expensive when considering the cost of shipping them to the U.S. Each vehicle was washed with deionized water and an area marked out on each front door (using A4 card frames) from which control samples were taken using the prepared kits described above and sampling procedures outlined below.

Preparation of the Site and Arrangement of Witness Materials

The sign posts (which were stronger than those used during the previous trials) were secured with the base approximately 60 cm beneath the ground and the soil above was tamped down to give extra support. Small holes were made in the back of the polyethylene bags containing each road sign to allow fixing to the posts. The signs were fixed with their lower edges approximately 1.8 m above the ground. Soil samples were taken from the site.

The saloon cars were positioned on the site using forklift trucks. The charge was transported to the site under a thick polyethylene cover to minimize escape of any fertilizer or sugar particles. The ullage was measured to enable a rough density calculation and the booster was carefully placed inside the charge after which the vehicles were prepared as described above. The polyethylene bags were removed from the road signs by personnel wearing clean disposable paper oversuits and gloves, the detonator was put in position and the charge was fired. Video tape recording and high-speed cine film of the explosions from several angles were taken.

Procedure after Firing

After firing, the damage to the vehicles and signposts was carefully described, photographed and video taped. Residues were recovered from the marked, controlled areas on the vehicles immediately following the firing using the prepared sampling kits. Personnel carrying out the sampling wore clean disposable paper oversuits and did not visit the site where the charge preparation was carried out on that day or wear clothes previously worn at that site which had not been thoroughly washed. These precautions were enforced to minimize the possibility of inadvertent contamination of the surfaces by the sampler. The kit was opened and a pair of disposable gloves put on. Approximately 1 to 2 mL of deionized water was added to a 10.5 mL glass vial containing a cotton wool swab. The swab was clamped into a clean pair of disposable forceps and excess water was removed from the swab by squeezing it against the inside of the vial. The swab was then used to systematically wipe the marked area on the vehicle. The swab was returned to the vial for remoistening when necessary and retained in the vial once the required area had been covered. The vial was capped, labeled and returned to the plastic container. The next sample was taken in a similar manner using a clean swab, vial and forceps. Once all of the samples had been completed and a sample of the water and a clean swab placed in a separate vial as a kit control, the vials were placed back in the container, it was sealed and returned to the laboratory. At the laboratory each swab was extracted with approximately 5 mL of deionized water and the volume of eluate extracted was made up to 10 mL in a volumetric flask for analysis.

The road signs were carefully removed from the posts and sealed in clean prelabeled self-seal polyethylene bags. The personnel again wore clean disposable paper suits and disposable gloves and touched only the minimum surface area of the road signs. They also must not have visited the mixing site that day. Road signs that had been blown from their posts were sealed in polyethylene bags and retained for damage reports only. Fragmented pieces of road signs were collected and retained, some of which could not be assigned to the post from which they had originated. Residue was recovered from the road signs in the laboratory using the prepared sampling kits. Each road sign in its polyethylene bag was placed flat on a clean surface covered with fresh glazed paper. The polyethylene bag was opened at the top and the side seams were slit open with a clean scalpel. The bag was then carefully opened out. The exposed surface of the road sign and the area of polyethylene bag previously in contact with that surface were sampled using a clean swab wetted with deionized water as described above. After completion of the sample, the road sign was turned over and placed on top of the area of the polyethylene bag included in the previous sample. The opposite face of the road sign and the corresponding area of polyethylene bag were then swabbed as a separate sample. The residue was then extracted from each swab separately by elution with 5 mL of deionized water and the eluate was made up to 10 mL with deionized water in a volumetric flask prior to analysis. The areas sampled from each sign were consistent throughout the six firings and were approximately 30 cm × 45 cm (all of the front) and 23 cm × 40 cm (all of the back excluding the runners). When swabbing the back of the road sign care was taken not to swab the runners as they had been in contact with the fixing clips which were found to have a low level of nitrate contamination when quality assured. Some road signs that were closest to the charge were destroyed during the firing and thus no swabs could be taken. Signs which had been blown from their posts and fallen on the ground were also not swabbed due to the potential risk of contamination by the

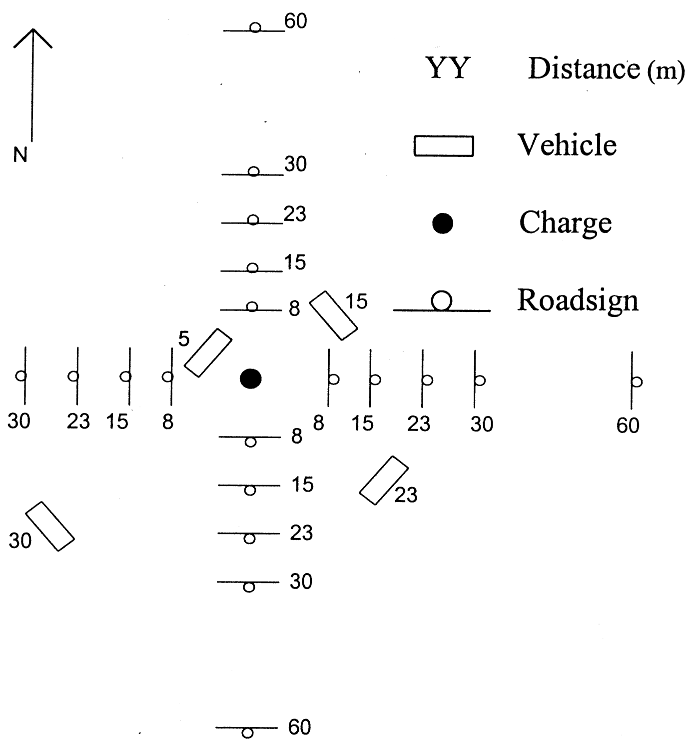

FIG. 2—*Site plan for all 454 kg firings and 1st 2268 kg firing.*

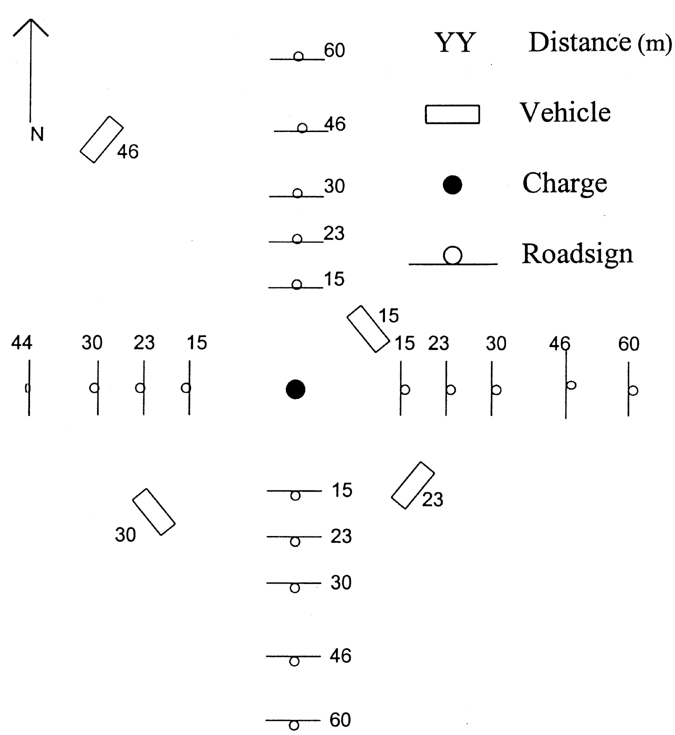

FIG. 3—*Site plan for 2nd and 3rd 2268 kg firings.*

soil. These signs were labeled and retained for physical damage reports only.

After collection of materials, samples and information was complete, vehicles and debris were removed and the soil smoothed out in preparation for firing the next charge. The signposts farther away from the charge were usually intact and were retained. Damaged or missing ones were replaced.

Alteration of Site Layout

Shown in Figs. 2 and 3 are the site plans for the 1st, 2nd, 3rd, and 5th firings and the 4th and 6th firings. Larger numbers of witness materials were destroyed than had been expected during the first firing of a 2268 kg charge. The layout was altered before firing the last two 2268 kg charges, moving some witness pieces further away in order that a greater number were left preserved for residue recovery after firing.

Results and Discussion

Road signs and vehicles placed closest to each charge were destroyed during each firing. Results of the chemical analysis of residues recovered from the intact road signs still attached to their posts are shown in Figs. 4–15. Road signs that had fallen to the ground, even if still attached to their posts, were deemed not suitable for residue recovery due to the possibility of contamination from the soil. Quantities of residue recovered from intact vehicles are shown in Tables 2 and 3. Three swab samples taken from vehicles before firing showed low levels of nitrate, less than 10 μg. No data for the recovery of sucrose are displayed as none were detected in any sample. Glucose was detected in some samples, figures for the recovery are listed in Table 4. No glucose was detected in any control swabs.

Analysis of residue deposited on the surfaces of the road signs shows a greater recovery of nitrate than ammonium and no detectable recovery of sucrose. Recovery generally decreased with increasing distance in any given direction but quantities recovered at the same distance in different directions were not comparable, indicating the influence of some directional factor. The first firing of a 454 kg charge shows a greater recovery from the back of the road signs than from the front.

Nitrate was recovered in greater quantities than ammonium and the relationship between the two was not stoichiometric. The recovery of nitrate from the vehicles after the first 454 kg firing shows an unexpected pattern in that quantities increased with increasing distance from the charge. Residue recovery from samples taken from the side of the vehicles facing away from the charge was generally lower and the pattern less predictable than for samples taken from the side facing the charge.

No glucose was detected in any samples taken from the road signs for the 2268 kg firings. Analysis of samples obtained after the 454 kg firings showed that higher quantities of glucose were recovered from the backs of the road signs than from the fronts. Larger quantities of glucose were recovered from the vehicle swabs, the greatest quantities being recovered from the side of the vehicle facing the charge prior to firing. Recovery of glucose from the vehicles was significantly lower in the 2268 kg firings. Variations in the quantity recovered in relation to direction were also noted for the road signs. Analysis of the confectioner's sugar used in the charge mixture showed the presence of sucrose only (a small quantity of anti-caking agent is also present).

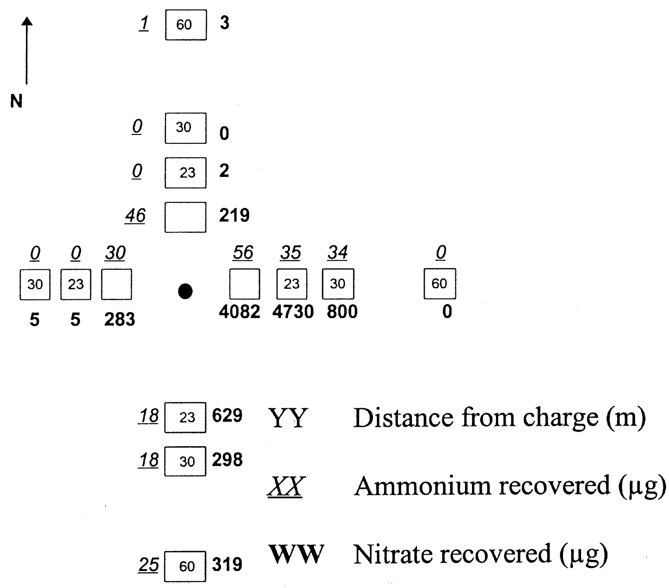

FIG. 4—*Recovery of residues from the front of road signs—Test 1 (454 kg).*

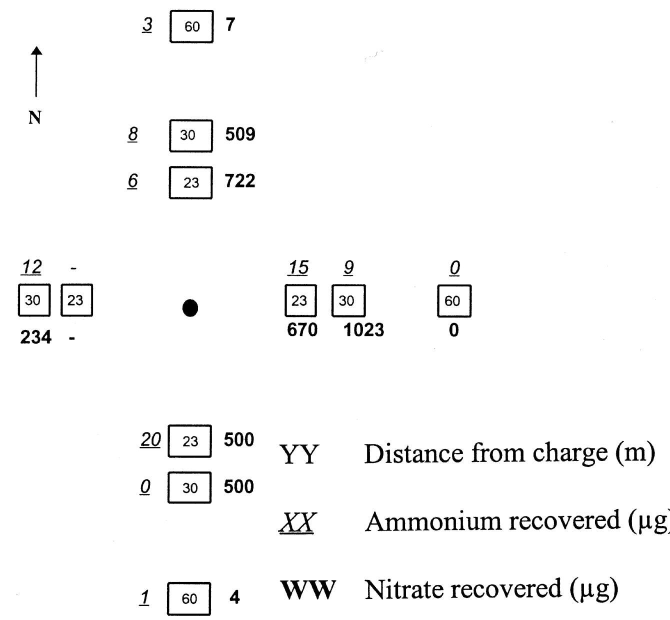

FIG. 6—*Recovery of residue from front of road signs—Test 3 (2268 kg).*

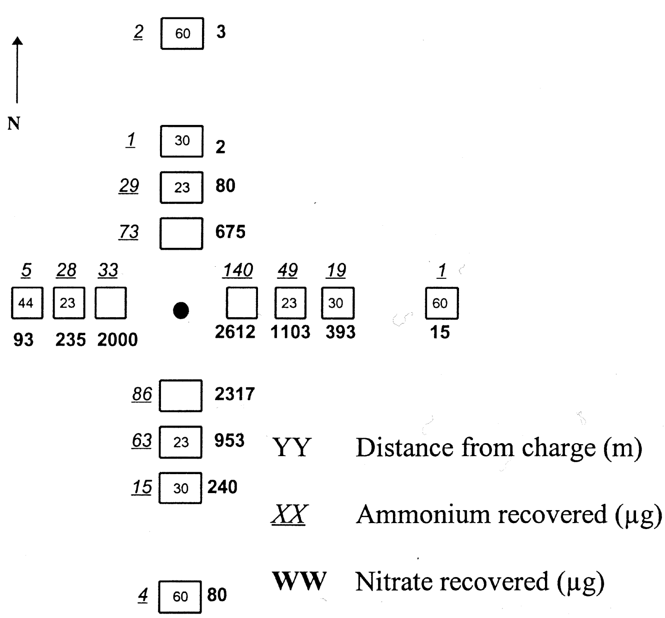

FIG. 5—*Recovery of residue from front of road signs—Test 2 (454 kg).*

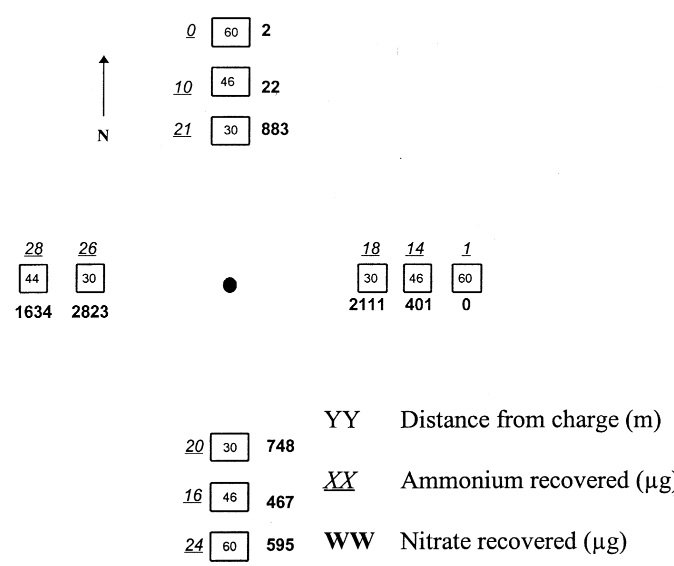

FIG. 7—*Recovery of residue from front of road signs—Test 4 (2268 kg).*

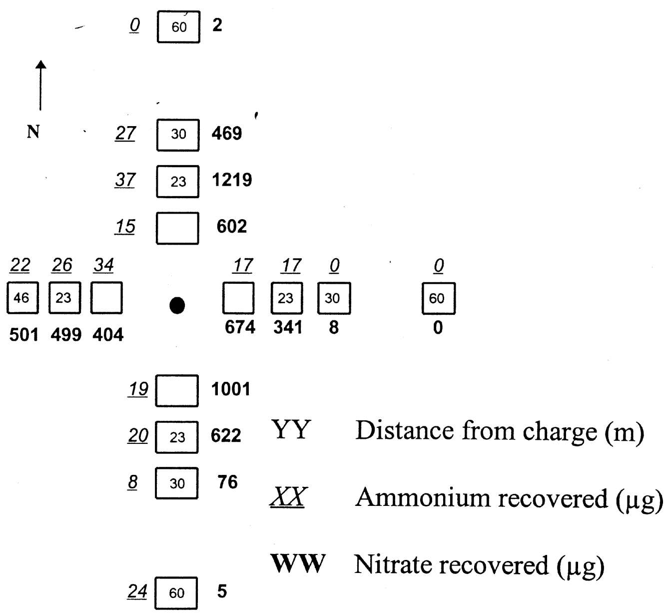

FIG. 8—*Recovery of residue from front of road signs—Test 5 (454 kg).*

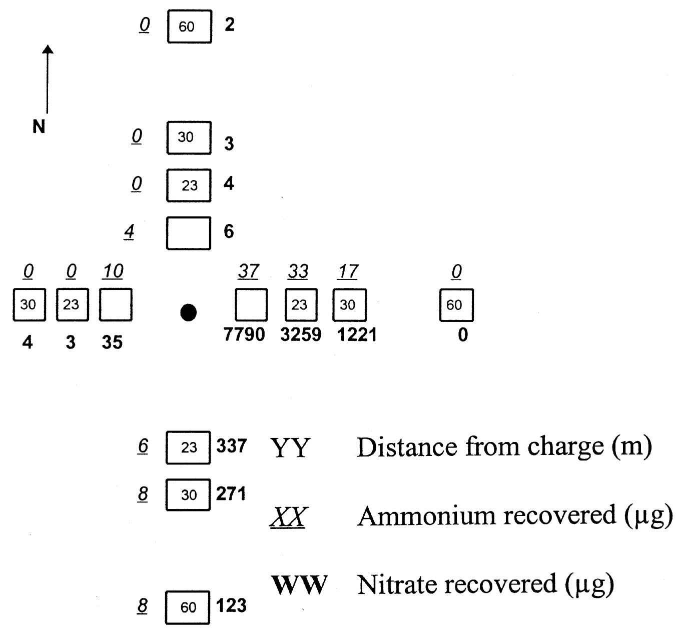

FIG. 10—*Recovery of residue from back of road signs—Test 1 (454 kg).*

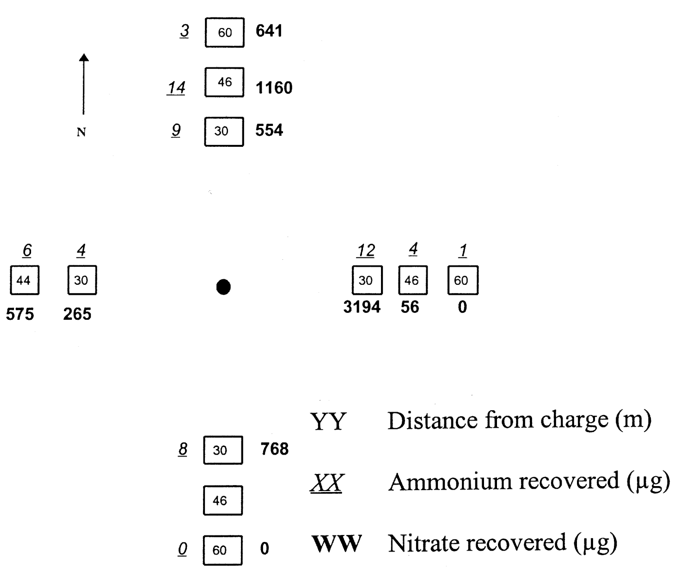

FIG. 9—*Recovery of residue from front of road signs—Test 6 (2268 kg).*

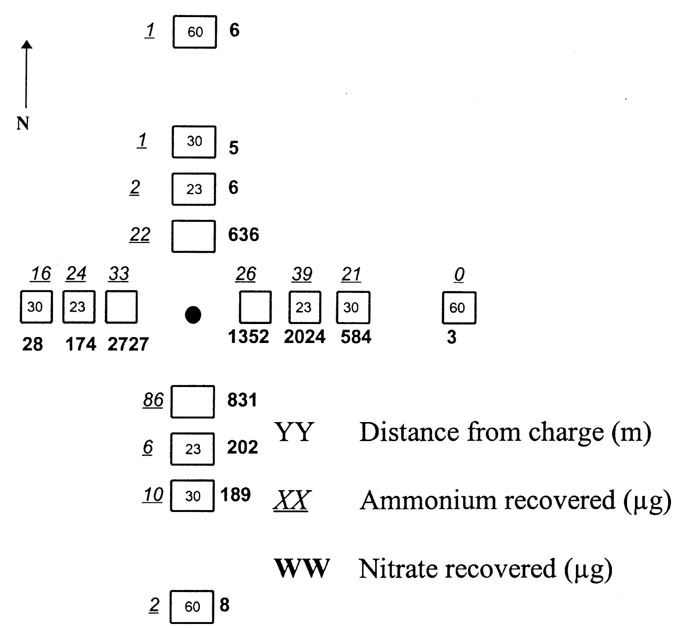

FIG. 11—*Recovery of residue from back of road signs—Test 2 (454 kg).*

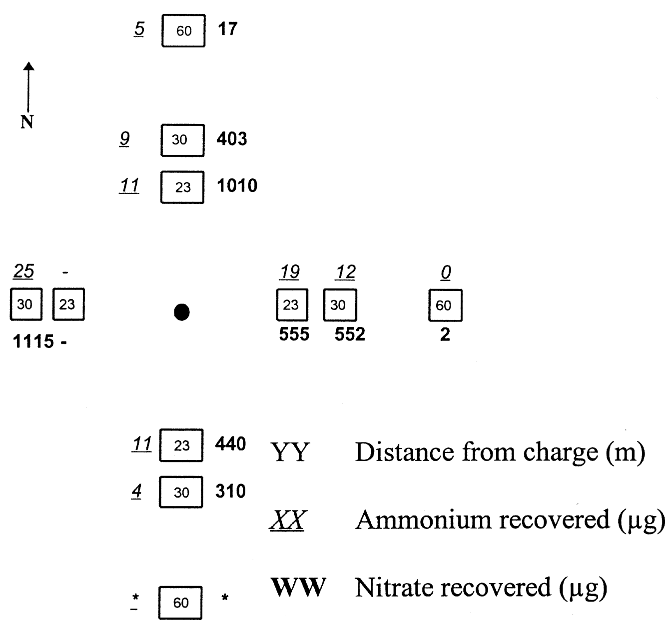

FIG. 12—*Recovery of residue from back of road signs—Test 3 (2268 kg).*

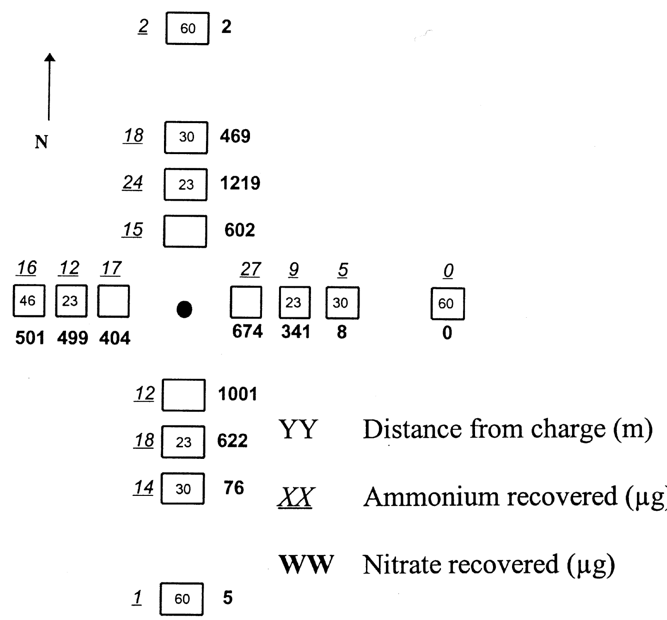

FIG. 14—*Recovery of residue from back of road signs—Test 5 (454 kg).*

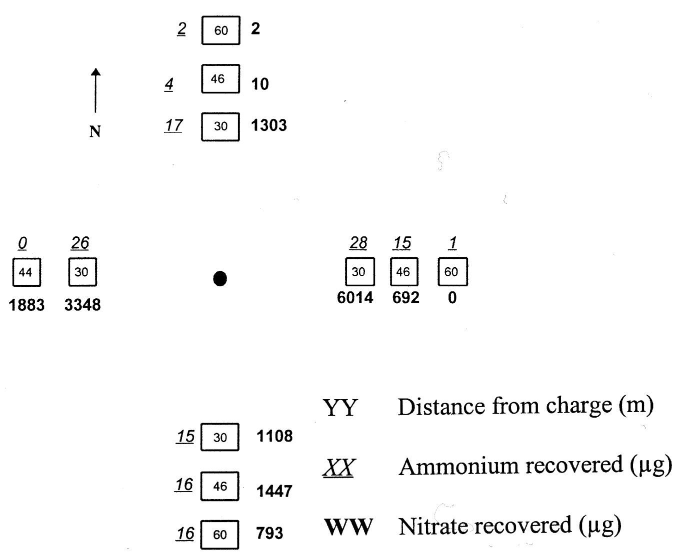

FIG. 13—*Recovery of residue from back of road signs—Test 4 (2268 kg).*

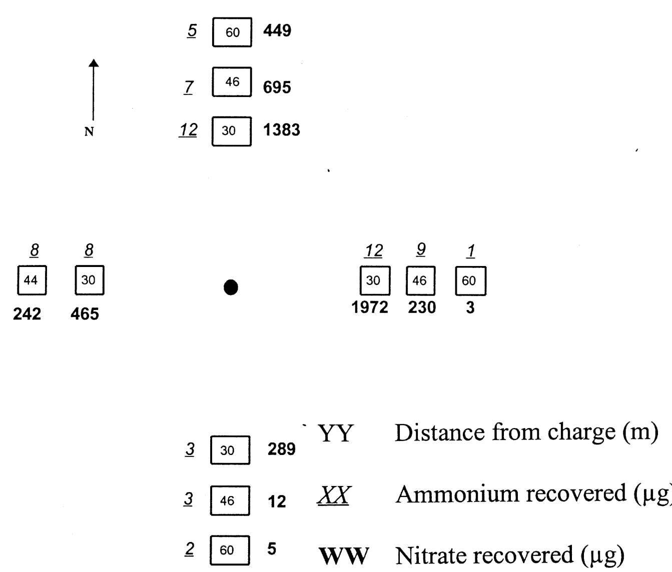

FIG. 15—*Recovery of residue from back of road signs—Test 6 (2268 kg).*

TABLE 2—*Recovery of ammonium and nitrate from vehicles after 454 kg firings.*

Distance of Vehicle from Charge (m)	Ammonium Recovered (μg)						Nitrate Recovered (μg)					
	Test 1		Test 2		Test 5		Test 1		Test 2		Test 5	
	Side facing charge	Side away from charge	Side facing charge	Side away from charge	Side facing charge	Side away from charge	Side facing charge	Side away from charge	Side facing charge	Side away from charge	Side facing charge	Side away from charge
5	*	*	*	*	*	*	*	*	*	*	*	*
15	45	47	326	0	157	22	0	618[7]	10750	470	4814	0[3]
23	69	38	169	39	51	19	2218	787[5]	4678	729	763	257
30	98	0	39	0	23	0	0	0	1616	199	636	0

Figures in brackets denote quantities detected on any positive control swabs taken before firing—all others are zero.
* Vehicle destroyed.

TABLE 3—*Recovery of ammonium and nitrate from vehicles after 2268 kg firings.*

Distance of Vehicle from Charge (m)	Ammonium Recovered (μg)						Nitrate Recovered (μg)					
	Test 3		Test 4		Test 6		Test 3		Test 4		Test 6	
	Side facing charge	Side away from charge	Side facing charge	Side away from charge	Side facing charge	Side away from charge	Side facing charge	Side away from charge	Side facing charge	Side away from charge	Side facing charge	Side away from charge
5	*	*	†	†	†	†	*	*	†	†	†	†
15	*	*	*	40	*	*	*	*	*	611	*	*
23	32	32	107	0	0	0	0	1027	4980	0	175	62
30	22	22	87	12	21	0	867	254	2958	188	319	0
46	†	†	57	0	6	7	†	†	1105	553	253	147

* Vehicle destroyed.
† No vehicle in this position.

Soil Sample Analysis

Soil samples were taken from the test site at the beginning of the two-week period and prior to each individual firing. Samples were extracted with UHQ water and the extracts analyzed by ion chromatography (1). Results of the analyses are shown in Table 5. These results show that contamination of the soil with nitrate and ammonium occurred during the duration of the series of firings.

Charge Density

The ullage of each charge was measured just prior to firing and the charge density calculated from this. The time of storage of the charge after its preparation was complete was also estimated. These figures are shown in Table 6. It can be seen that in this time scale of a few days the storage time has no appreciable effect on the density of the charge.

Meteorological Data

Details of the weather at the test site were recorded using a portable weather monitor immediately prior to firing each charge. Data recorded are listed in Table 7. There was no rainfall during the two-week period. The wind direction recorded by the weather station was not always the same as the direction traveled by the dust cloud generated during the explosion, as seen on the video recordings. This is not unexpected since air currents vary with height. However, the predominant direction of the dust cloud may have some bearing on the deposition of the residues. Wind direction is given as the direction which the wind is coming from. The highest constant wind speed for the 454 kg firings was recorded prior to the first firing. This is the firing that showed the most pronounced variation in residue recovery with direction, the wind direction being northerly and the greatest quantity of residue recovered from the easterly road signs. The third 2268 kg firing shows similar results for a "gusty" wind.

Blast Pressure Measurements

Nine pressure gages were located at ground level at distances of 15, 30, 46, and 60 m from the charge for each firing. From day 7 onwards, two pencil gages were added at 30 m SE and SW of the charges, approximately 1 m above ground

TABLE 4—*Glucose recovery.*

Type of Witness Material	Day/Size of Charge (kg)	Distance from Charge (m)	Direction	Quantity of Glucose Recovered (μg) Front	Back
Road sign	Test 1/454	15	East	20	25
Road sign	Test 1/454	23	East	15	22
Road sign	Test 1/454	30	East	0	5
Road sign	Test 2/454	15	South	5	6
Road sign	Test 2/454	15	East	7	11
Road sign	Test 2/454	15	West	0	8
Road sign	Test 2/454	23	East	0	11
Road sign	Test 2/454	23	West	0	8
Road sign	Test 4/2268	30	East	0	11
Road sign	Test 4/2268	30	West	0	6
Road sign	Test 5/454	15	South	9	0
Road sign	Test 5/454	15	West	0	12
Road sign	Test 5/454	23	North	10	5
Vehicle	Test 1/454	15	North East	104	50
Vehicle	Test 1/454	23	South East	20	10
Vehicle	Test 1/454	30	South West	86	6
Vehicle	Test 2/454	15	North East	92	86
Vehicle	Test 2/454	23	South East	25	0
Vehicle	Test 2/454	30	South West	17	6
Vehicle	Test 3/2268	23	South East	4	0
Vehicle	Test 4/2268	23	South East	8	8
Vehicle	Test 4/2268	30	South West	5	0
Vehicle	Test 5/454	15	North East	54	44
Vehicle	Test 5/454	23	South East	9	0
Vehicle	Test 5/454	30	South West	0	14

TABLE 5—*Soil sample analyses.*

Sample	Day	Nitrate (μg/g)	Ammonium (μg/g)	Sucrose (μg/g)
Ground zero	1	4	0	0
A	1	11	0	0
B	1	4	0	0
C	1	6	0	0
D	1	6	0	0
E	1	15	0	0
F	3	0	1	0
G	3	392	46	0
H	4	12	0	0
I	4	16	4	0
J	7	679	84	0
K	7	126	11	0
L	8	38	31	0
M	8	106	22	0
N	9	557	78	0
O	9	562	0	0
P	10	147	0	0
Q	10	342	37	0
Water control—extraction	…	0	0	0

TABLE 6—*Charge density.*

Day of Firing/ Test Number	Charge Size (kg)	Approx. Time in Storage After Preparation (hr)	Ullage (m)	Density (kg m^{-3})
3—Test 1	454	24	0.367	1043.48
4—Test 2	454	24	0.387	1080.57
7—Test 3	2268	24	0.267	1004.41
8—Test 4	2268	96	0.318	1045.87
9—Test 5	454	24	0.356	1023.11
10—Test 6	2268	36	0.279	1012.88

TABLE 7—*Meteorological data.*

Test	Charge Size (kg)	Barometric Pressure (mbar)	Temp. (°C)	Relative Humidity (%)	Wind speed (km/hr)	Wind Direction (weather station)	Wind Direction (video tape)
1	454	818.8	15.0	14	16	N	NE
2	454	818.4	16.4	18	2	ENE	N
3	2268	820.0	24.0	…	0–4	NNE	SE
4	454	824.3	24.9	12	0–2	…	E
5	2268	824.6	29.5	16	0–2	NNW	SE
6	2268	820.7	25.2	15	8–20	SE	SE

with a fragment protector (50 mm diameter) positioned 2440 mm in front, between the charge and the gage. During the first set of trials (1), a significant quantity of data were lost because signal cables were damaged by high velocity fragments from the charge. The positive impulse and maximum pressure readings are listed in Tables 8 and 9. The figures are not corrected for height above sea level.

There are three main measurable characteristics for an explosive mixture: velocity of detonation, positive impulse and peak pressure. Positive impulse is a measurement which is known in

TABLE 8—*Positive impulse.*

Gage No.	Distance from Charge (m)	Positive Impulse (Pa·s) Test 1 (454 kg)	Test 2 (454 kg)	Test 3 (2268 kg)	Test 4 (2268 kg)	Test 5 (454 kg)	Test 6 (2268 kg)
1	15 N	582.8	668.1	1695.4	*	367.8	*
2	15 E	491.1	521.6	1357.9	912.2	285.6	*
5	15 S	553.6	568.5	*	1408.4	391.3	*
9	15 W	558.5	506.5	*	968.5	214.5	588.9
3	30 E	295.4	119.7	*	665.4	232.2	861.3
6	30 S	265.4	272.0	805.7	671.7	278.3	806.6
4	46 E	125.8	191.8	554.7	415.5	92.7	550.1
7	46 S	160.3	185.5	508.5	513.0	164.0	493.0
8	60 S	80.3	114.5	303.3	421.8	238.5	404.3
10**	30/46 SE	†	†	348.7	*	81.8	272.7
11**	30/46 SW	†	†	*	375.5	117.5	396.4

* No results obtained.
** Pencil gage.
† Not used.

TABLE 9—*Maximum pressure.*

Gage No.	Distance from Charge (m)	Maximum Pressure (kPa) Test 1 (454 kg)	Test 2 (454 kg)	Test 3 (2268 kg)	Test 4 (2268 kg)	Test 5 (454 kg)	Test 6 (2268 kg)
1	15 N	216.9	205.9	679.5	*	189.4	*
2	15 E	348.1	157.5	580.1	794.2	140.9	*
5	15 S	165.7	184.8	*	637.2	109.6	*
9	15 W	179.4	172.2	*	315.8	160.8	330.1
3	30 E	35.0	17.6	*	102.3	45.2	140.1
6	30 S	44.2	34.6	138.4	119.8	37.8	136.6
4	46 E	14.9	14.7	37.0	36.7	15.3	56.4
7	46 S	21.6	21.6	47.6	62.8	17.3	46.0
8	60 S	10.6	12.8	34.2	32.5	20.5	30.2
10**	30/46 SE	†	†	108.9	*	13.2	35.6
11**	30/46 SW	†	†	*	39.6	18.5	43.5

* No results obtained.
** Pencil gages.
† Not used.
NOTE: 1 kPa = 0.45 psi.

the literature for a number of types of explosive composition. If particular compositions have similar positive impulse values then it can be said that they would have similar effects on their surroundings when detonated in similar quantities. The figures have been included to enable a rough comparison if less well-documented explosive compositions are thought to have caused an explosion.

Velocity of Detonation Measurements

Six piezoelectric pins were placed vertically at the base of the charge and four were placed radially at the top of the charge to measure the velocity of detonation. The mean velocity of detonation for each firing is shown in Table 10.

TABLE 10—*Mean velocity of detonation.*

Mean Velocity of Detonation (m/s) Test 1 (454 kg)	Test 2 (454 kg)	Test 3 (2268 kg)	Test 4 (2268 kg)	Test 5 (454 kg)	Test 6 (2268 kg)
3240	3160	3320	3200	3070	3240

Physical Damage to Road Signs

The blast wave caused the road signs in close proximity to the explosion to fold back around their posts. Significant fragmentation damage caused by projectiles from the charge

TABLE 11—*Damage to road signs after the 454 kg firings.*

Distance from Charge (m)	Damage	Category
8	Generally bent/folded in half around the post	ii
	Not much fragment damage	
15	Crumpled/slightly bent	iii
	Minor fragment damage	
23	Flat, few fragment holes	iv
30	Flat, no damage	iv
60	Flat, no damage	iv

TABLE 12—*Damage to road signs after the first 2268 kg firing (Test 3).*

Distance from Charge (m)	Damage	Category
8	Fragmented/mangled	i
15	Generally bent/folded in half around the post	ii
	Large pieces missing, severe fragment damage	
23	Slight bends, considerable fragment damage	iii
30	Almost flat, minor fragment damage	iv
60	Flat, very minor fragment damage	iv

TABLE 13—*Damage to road signs after the second and third 2268 kg firings (Tests 4 and 6).*

Distance from Charge (m)	Damage	Category
15	Generally bent/folded in half around the post	ii
	Large pieces missing, severe fragment damage	
23	Slight bends, considerable fragment damage	iii
30	Almost flat, minor fragment damage	iv
46/(44W)	Flat, very minor fragment damage	iv
60	Flat, very minor fragment damage	iv

container and steel stand was also evident on closer signs. The damage to each road sign was assessed and categorized as follows:

(i) Fragmented/mangled, large pieces missing.
(ii) Severely bent/twisted, fragment damage.
(iii) Slight bends/considerable fragment damage.
(iv) Flat, minor or no fragment damage.

Categorization of road signs from the firings is given in Tables 11–13. Figure 16 shows a typical category "i" road sign while Fig.

FIG. 16—*Road sign showing typical damage at 8 m from 2268 kg charge.*

FIG. 17—*Road sign showing typical damage at 15 m from 2268 kg charge.*

17 shows a typical category "ii" road sign removed from its post by the force of the explosion.

Physical Damage to Sign Posts

Observations were recorded concerning the physical effects of each explosion on the signposts. It must be remembered that the bases of the posts were not secured as firmly in the ground as they would be on a roadside and to do so would be prohibitively expensive and time consuming. Nevertheless, the observations made may still be useful in some contexts. A summary of the effects noted is given in Table 14.

Physical Damage to Vehicles

Although the vehicles used during the firings are not all of the same type (make, model, etc.) the damage can be documented by summarizing the effect on features of each vehicle which are common to all vehicles, for example, windscreens, wing mirrors, tires, bonnet, roof, and headlamps. Summaries of the damage caused to the vehicles by the two sizes of charge are given in Tables 15 and 16. Figure 18 shows a Toyota Celica that had been positioned approximately 15 m from a 5000 lb (2268 kg) charge. Figure 19 shows the less severe damage caused to a Dodge placed 30 m from a 5000 lb charge.

Crater Dimensions

The width and depth of the crater formed were measured; dimensions are listed in Table 17. It should be noted that the craters were measured in sandy soil that had been repeatedly subjected to explosions and then filled in; therefore, the dimensions are not expected to be representative of real-life situations.

Discussion

Road signs and vehicles both proved to be useful materials for the recovery of the post-blast explosion residues.

There was no detectable recovery of sucrose from any of the witness pieces or the soil after firing. Glucose was detected in small quantities on some road signs and at more significant levels on some vehicles. No glucose residue was detected

TABLE 14—*Summary of physical effects on signposts.*

Size of Charge (kg)	Distance of Signpost from Charge (m)	Effect on Signpost
454	8	Pole either sheared close to ground level or uprooted and located at distances varying between "close to original position" and 55 m from charge position. Large fragment holes evident and some posts bent or nearly cut through, probably due to fragment strikes.
454	15	Poles were pushed over in the ground to angles of between 12 and 42°. Posts not bent although one was nearly cut through by a fragment strike.
454	23	Poles all unbent, some upright, others bent to angle of between 2 and 5°.
454	30	Majority of poles upright, one pushed to angle of 2°.
454	60	All poles upright.
2268	8	Some posts not found, one sheared at ground level.
2268	15	Most poles uprooted, located at distances varying between 23 and 55 m (pole at 55 m may have been originally located at 23 m, both posts were uprooted during one particular firing, located at 40 and 55 m, distinguishing between the two was not possible). One post was cut by a fragment and the portion remaining in the ground pushed to an angle of 30°.
2268	23	Most poles uprooted, located at distances of between 24 and 180 m (see above). One post pushed to an angle of 42°, not bent.
2268	30	Most posts pushed over to angle of between 9 and 31°. One post cut approximately halfway down by fragment, portion remaining in the ground pushed over to an angle of 27°.
2268	46	Majority remained upright, one pushed over to an angle of 2°.
2268	60	All remained upright.

on the road signs after the 2268 kg firings and low levels were detected on the vehicles compared to levels detected after the 454 kg firings.

Nitrate was usually recovered from witness pieces in greater quantities than ammonium but there was no consistent stoichiometric relationship between the two. This is at least in part due to the use of single-point calibration for quantitation, and for ammonium the ion chromatography detector response is known to be nonlinear; therefore, the true recovery for larger quantities of ammonium would be underestimated. Since during the explosion ammonium is oxidized to a mixture of nitrogen and nitrogen oxides, the recovery of an excess of nitrate over ammonium is to be expected.

Residue recovery generally decreased with increasing distance from the charge. Quantities of residue recovered from similar witness pieces at similar distances from the charge during one individual firing were not usually comparable, indicating the influence of some directional factor affecting the deposition of residue. This factor could be environmental, or perhaps due to some unintentional asymmetry in the charge.

Areas sampled on the road signs were approximately twice that sampled on the vehicles; however, residue recovery from the vehicles was generally greater than that recovered from the road signs. This may be related to the fact that samples were taken from the vehicles at the site shortly after firing the charges, but samples from the road signs were taken (some weeks) later at the laboratory. Alternatively it may be that the surface of a road sign is not as favorable as vehicle surfaces for residue recovery. Areas sampled on the vehicles were much closer to the ground than the road signs and the air currents around the two types of witness pieces will also differ due to the difference in size of the witness pieces.

Residue recovery from witness pieces closest to the charges during firing was not possible due to the high level of damage incurred.

TABLE 15—*Summary of damage to vehicles after the 454 kg firings.*

Feature	Distance from Charge (m)			
	5	15	23	30
Windscreen	Not found	Completely shattered	Shattered with glass remaining in frame	
Side windows	Not found	Shattered	Shattered with possibly one intact one side facing away from charge	
Rear windscreen	Not found	Shattered	Shattered	Possibly intact
Bonnet	Not found	Indentations, raised on side facing the charge		
Side body panels	Not found	Severely dented	Minor dents	Negligible indentations
Roof	Not found	Dented and raised on side facing the charge	Intact	
Wheels	Not found	Wheels generally intact with tires deflated on side facing the charge, possibly one or more tires intact on side facing away from the charge		
Front headlamps	Not found	Shattered	Intact	
Rear headlamps	Not found	Shattered	Intact	
Orientation of vehicle	Not found	Generally upright	Upright	Upright
Comments	Vehicle completely destroyed, only chassis remaining	Severe fragment damage	Minor fragment damage	Body shell intact and undistorted

TABLE 16—*Summary of damage to vehicles for the 2268 kg firings.*

Feature	Distance from Charge (m) 5	15	23	30	46
Windscreen	Not found	Not found	Shattered	Shattered with glass remaining in frame	
Side windows	Not found	Not found	Shattered		
Rear windscreen	Not found	Not found	Shattered		
Bonnet	Not found	Not found	Severely mangled		
Side body panels	Not found	Not found	Severely disrupted	Dented	Slightly dented
Roof	Not found	Not found	Disrupted	Dented	Minimal change
Wheels	Not found	Not found	Wheels generally intact with tires deflated on side facing the charge, possibly one or more tires intact on side facing away from charge		
Front headlamps	Not found	Not found	Shattered	Intact	
Rear headlamps	Not found	Not found	Shattered	Intact	
Orientation	Not found	Not found	Flipped upside down	Upright	Upright
Comments	Completely destroyed	Bodyshell remaining as tangle of metal	Bodyshell intact but severely distorted	Bodyshell intact, moderate fragment damage	Minor fragment damage

FIG. 18—*Damaged Toyota Celica positioned 15 m from 2268 kg charge.*

FIG. 19—*Damaged Dodge positioned 30 m from 2268 kg charge.*

TABLE 17—*Crater dimensions.*

Charge Size (kg)	Average Depth of Crater (cm)	Average Diameter of Crater (m)
454	54	2.0
2268	92	3.5

Contamination of the soil with ammonium and nitrate occurred to some extent during the series of trials. Therefore, the decision not to sample road signs that had fallen to the ground was a prudent one.

Road signs closest to the charges folded around the signposts but did not show much fragment damage. Signs slightly farther away did not fold around the posts but exhibited a much greater degree of fragment damage. The signs positioned farthest away appeared undamaged.

It had been anticipated prior to the firings that the angle of bend of the signs may be representative of the blast pressure. The horizontal reinforcing bars fixed on the reverse of the British road signs minimized the angle of bend of all but the closest road signs, thus preventing the acquisition of any meaningful measurements. The U.S. road signs used in the previous trial (1), which had no horizontal reinforcing bars, were found to bend in a more regular and systematic fashion.

Improvements Made Since the First Trials (1) and Recommendations for Further Trials

Burying the cables in trenches enabled the collection of more data since fragment damage to cables was minimized. This should be continued in further trials.

British road signs were found to be ideal for residue collection partly due to the more robust signposts which support them.

The orientation of the vehicles could be altered, since in this and the previous set of trials (1) the vehicles were placed side-on to the charge.

Monitoring the weather conditions was introduced and found to be useful to some degree. However, the wind direction recorded by the weather station did not always reflect the direction traveled by the dust cloud. Observation of the direction of travel of the dust cloud should be recorded.

Monitoring of the soil for contamination showed that contamination occurred to some degree. This should be continued and the effect of wind speed and direction on the deposition of residues should be examined if possible.

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