Determination of the Velocity of Fragments Produced from Exploding Firework Maroon Shells

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ABSTRACT

This paper describes a method for determining the velocity of fragments produced when firework maroon shells explode. Fragment velocities for shells fired in free air and in steel mortar tubes (causing them to rupture) are reported. The maximum velocity of plastic shell casing fragments that was recorded (964 m/s) was substantially higher than that measured for steel mortar fragments (512 m/s). The magnitude of the velocities measured indicates the potential hazard associated with these fragments and the need to consider methods of reducing such hazards.

Keywords: mortar, firework, shell, maroon, steel, velocity, fragment, salute, report, exploding, explosion

Introduction

After an accident in 1988, at the Glasgow Garden Festival as a result of which a firework display operator had to have his leg amputated[1] and a member of the general public was seriously injured,[2] the UK Health and Safety Executive examined the extent of current knowledge relating to the safe use of mortar tubes. Little published material was available at that time and therefore a programme of research was initiated to provide information on the fragmentation characteristics of different mortar tube types and the effectiveness of mitigation measures such as mortar tube burial and sandbagging. The need for the work was reinforced by subsequent accidents in Japan[1] and reports of prematurely exploding shells from the USA in 1992,[3] 1994,[4] and 1995.[5] It is envisaged that safety-related information of this type could form an important input to the development of guidance for firework display operators.

A survey of factors relating to the use of mortars at firework displays[6] provided information on the types of shells and mortar tubes commonly used in the UK. This enabled an experimental programme to be designed to investigate the fragmentation behaviour of a range of steel mortar tubes when various types of firework shells were exploded in them.

An important measure of fragment hazard is the velocity with which fragments are projected. This paper reports on the range of initial projectile velocities likely to be encountered when firework shells explode prematurely, shattering the surrounding mortar tube. The possible safety implications of the results are also briefly discussed. Maroon shells, also known as salutes or aerial reports, were used in all the tests. Future analyses of fragment velocities in conjunction with fragment dimensions, mass, and trajectory will enable flight distances for fragments to be estimated.[7]

Experimental

Time, mass and linear distance measurements recorded during this work can be traced to National Standards.

Experiments were undertaken in a Blast Cell that had wooden walls lined with plastic sheeting. This allowed low kinetic energy fragments to cut or mark the plastic sheet and enabled high kinetic energy fragments to penetrate into the wooden lining. The system has been described more fully in previous work.[8]

Seamless and spiral-wound steel tubes with 3 mm thick steel baseplates were used for 75 mm calibre mortars. Spiral-wound tubes with 6 mm thick baseplates were used for 152 mm calibre mortars. Baseplates were fitted inside the tube wall and continuously welded into place using a Metal Inert Gas (MIG) welding technique. Seamless tubes complied with British Standard 6323 Pt4 CFS 3BK. Spiral-wound tubes were formed from a mild steel strip using a four-ply lockseam. All the tube types were available from general engineering companies.

The shells used were 70 mm diameter cylindrical and 150 mm diameter spherical shells for use in 75 and 152 mm calibre mortar tubes, respectively. The 70 mm diameter shells contained 120 g of flash composition; the 150 mm diameter shells contained 400 g of a similar composition.

Three types of test were performed:

1) Explosion of maroon shell charges, which had been removed from their shell casings, in thin-walled, spiral-wound steel mortar tubes (<2.00 mm wall thickness). The removal of the shell casing meant that only steel mortar tube fragment velocities were measured. This simulated the effects of a maroon shell exploding prematurely in a steel mortar tube.

2) Explosion of maroon shells in thick-walled steel tubes (>2.6 mm wall thickness) to measure the velocity of fragments of plastic shell casing produced when the mortar splits open but does not produce many steel fragments.

3) Explosion of maroon shells in free air to measure the velocity of plastic shell casing fragments that had not been affected by the presence of a mortar tube.

Experiments involving the fragmentation of steel mortar tubes by exploding firework maroon shells in them would expose velocity measuring equipment to a hostile environment. As a consequence, the velocity measuring system was designed to be inexpensive and disposable. Wooden frames with wire screens on the front and back faces were used (Figure 1). The wire screens were made using 0.315±0.004 mm diameter insulated copper wire that was connected through an electronic circuit to an oscilloscope, which recorded the time that the front and back screens were broken (Figure 2). Four frames were arranged in a square with the mortar tube positioned at the centre. The distance from the mortar tube to each frame was 450 mm for 75 mm calibre tubes and 1000 mm for 152 mm calibre tubes. These distances were sufficient to prevent the wire screens from being broken by the blast wave when maroon charges in plastic

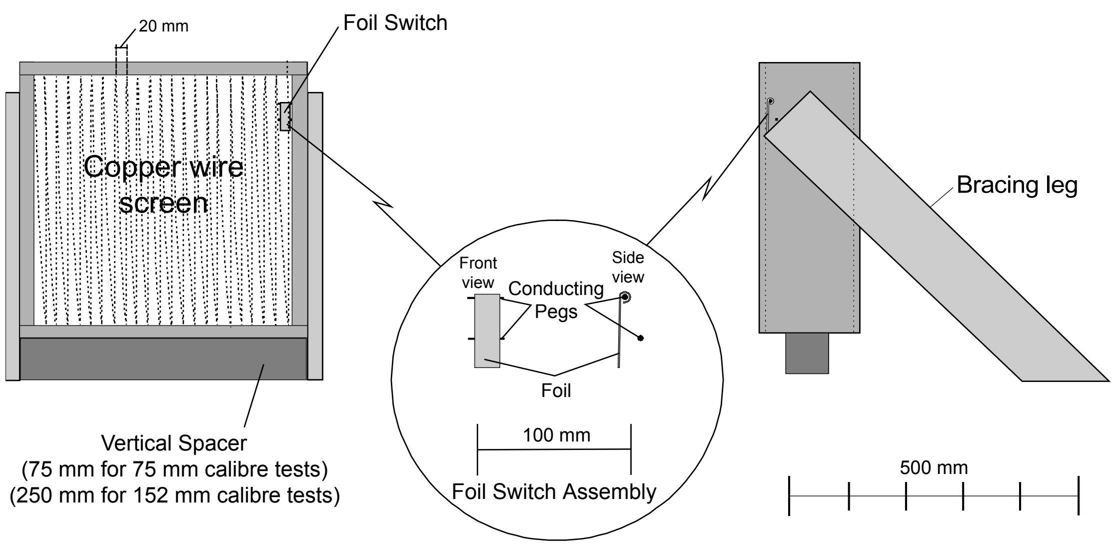

Figure 1. Diagram of wooden frames used to measure the velocity of projectiles generated from prematurely exploding firework maroon shells.

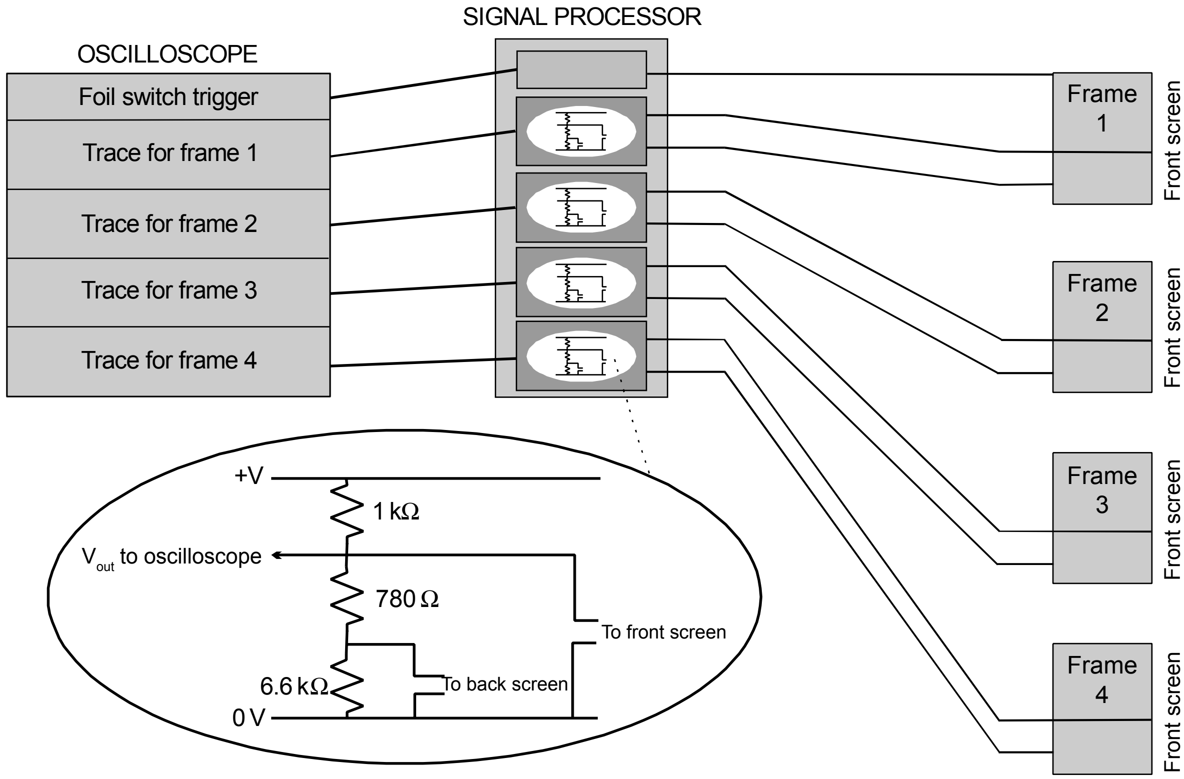

Figure 2. Schematic diagram of the fragment velocity data recording system.

bags were exploded. One of the four screens had a foil switch located directly behind the front screen (Figure 1). This made a circuit as the blast wave passed and activated the oscilloscope recording system to all four frames. A 10% pre-trigger setting was used. A voltage change occurred when a wire screen was broken, and therefore, in those cases in which both the front and back screens of a frame were broken by a projectile, the time interval between the events could be measured. Since the distance between screens on a frame was 150 mm, it was possible to calculate the average velocity of a projectile over this distance from the measured time interval.

Velocity verification experiments, which compared the wire screen system with a more accurate high speed photographic system, showed that the calculated wire screen velocity values were likely to be accurate to ±10%.[9]

Mortar fragment velocity experiments were carried out as indicated in Table 1.

In tests designed to measure the velocity of fragments from steel mortar tubes (test type 1), the explosive charge was removed from its shell casing and placed in a plastic bag. This prevented plastic shell fragments from interfering with steel fragment velocity measurements. Preliminary experiments had shown that removal of the charge from its casing reduced fragment numbers by up to 10% for 75 mm calibre thin-walled (1.65 mm wall thickness) mortar tubes and by 37% for 152 mm calibre (2 mm wall thickness) mortar tubes.

In tests using thicker walled (2.65 mm) seamless tubes (test type 2) that did not produce many steel fragments, the shell, including the plastic shell casing were exploded to study the velocity of the plastic fragments that passed through splits in the mortar tube.

Shell explosions carried out in free air, without a mortar tube present (test type 3), simulated the effect of a maroon shell lifting out of the mortar tube and bursting directly above it as it ascended (a ‘low-burst’ or ‘muzzle break’). This provided velocity data on the plastic fragments produced.

Table 1. Summary of Fragment Velocity Experiments.

Shell Height (mm)	Distance from Frames to Explosion Point (mm)	Mortar Calibre (mm)	Shell Description	Tube Description (Type/ wall thickness in mm)
300	450	75	Maroon main charge removed from shell casing	Spiral wound/ 1.65
				Seamless/ 1.63
			Maroon main charge in shell casing	Seamless/ 2.65
		N/A	Maroon main charge in shell casing	N/A
500	1000	152	Maroon main charge removed from shell casing	Spiral wound/ 2.00
		N/A	Maroon main charge in shell casing	N/A

Note: N/A refers to experiments in free air.

This provided velocity data on the plastic fragments produced.

Wherever possible, measured velocities were associated with individually identified fragments. This was done by inspecting the walls directly behind the wooden frames to locate fragments that had penetrated into the wooden lining of the Blast Cell. The line of flight of the fragments was projected back to the explosion point to see if the break points on the wire screens could be linked to specific fragments. Where fragments had not penetrated into the wood, those fragments on the floor in the vicinity of the impact point were inspected to see if any could be matched with the impression or cut made in the plastic liner. In cases where more than one fragment could be attributed to a specific velocity measurement, all the masses of likely fragments were recorded.

Experiments where the shell was exploded in free air generated a large number of very small plastic shell casing fragments. It was not possible to match an individual fragment with the velocity measurement; therefore fragments were not weighed.

Results

A typical oscilloscope trace produced from steel mortar tube fragments is reproduced in Figure 3. It shows four traces corresponding to the four frames used for the test and the typical step profile produced as the front and back wires on a frame are broken in sequence. Fragments passed through frames 1, 2 and 3 while the wires on frame 4 remained intact.

Velocity and mass measurements for steel mortar fragments are summarised in Table 2. These show that for the 75 mm calibre spiral-wound and seamless tubes, the maximum velocity recorded was 450 metres per second (m/s) and the minimum velocities were 54 and 19 m/s, respectively. The calculated mean velocities of fragments from these tubes were similar (i.e., 230 and 250 m/s, respectively). Fragments from the 152 mm calibre spiral-wound mortar tubes that could be confidently associated with a measured velocity, or where the mass difference between two possible fragments for a given measured velocity was small, gave a velocity range of 147–512 m/s and a mean velocity of 310 m/s.

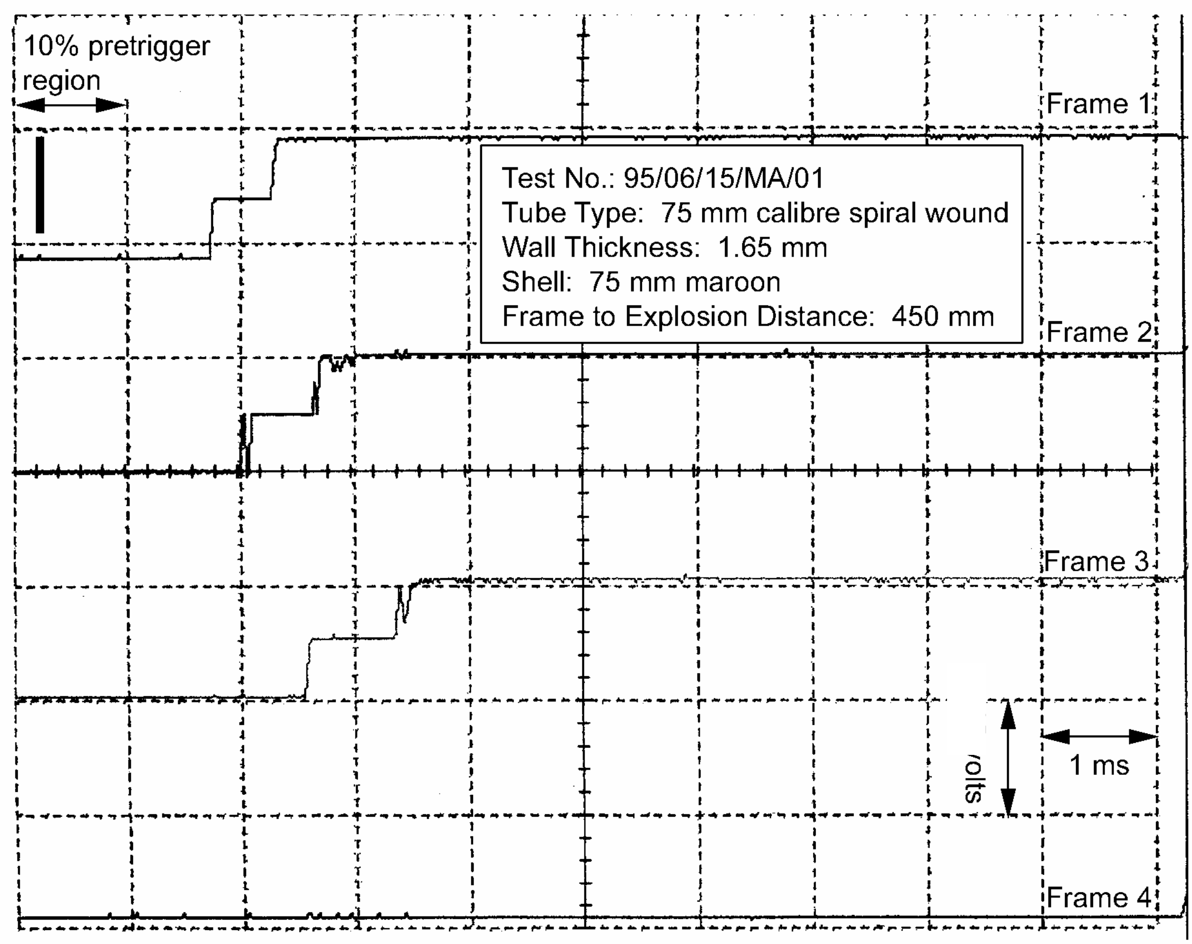

Figure 3. Oscilloscope traces showing the step voltages typical of those generated by fragments when a maroon shell main charge is exploded in a steel tube.

Examination of the relationship between mass and velocity for the steel fragments produced in the tests showed that there was a wide variation in fragment mass for a similar velocity. For example, during tests using seamless 75 mm calibre tubes, three fragments were recorded with a velocity of 450 m/s and masses in the range 0.6–41.0 g. No clear trends could be detected between fragment mass and velocity for the 75 or 152 mm calibre tube tests.

Results for the velocities of plastic shell casings are shown in Table 3. They show that plastic casing fragments ejected from ruptured 75 mm, 2.65 mm wall-thickness mortars, had velocities in the range 135–540 m/s with a mean velocity of 310 m/s. The mass range of the fragments (0.7–7.1 g) was substantially lower than that recorded for steel fragments.

Plastic shell casing fragments from maroon shells suspended between the wooden frames with no mortar tube present showed that the velocities obtained were significantly higher than the velocities recorded for plastic fragments ejected from within ruptured mortar tubes. A maximum velocity of 900 m/s was recorded for shells normally fired from 75 mm mortar tubes and the corresponding maximum velocity from shells normally fired from 152 mm calibre tubes was 964 m/s. Association of individual fragments with the velocities recorded was precluded because of the large number of small fragments produced.

Table 2. Velocity and Mass Measurements for Mortar Tube Fragments Produced Using Maroon Main Charges Removed from their Shell Casings.

Mortar Calibre (mm)	Distance from Frames to Mortar Tube (mm)	Tube Description (Type/ Wall thickness)	Fragment Mass (g)	Velocity (m/s)
75	450	Spiral wound/ 1.65 mm	30.7	450
			—	113
			—	54
			194.9 or 96.8	61
			3.7	318
			16.2	93
			24.2	386
			32.4	386
			28.6	225
			6.1	270
			18.6	193
			—	246
		Seamless/ 1.63 mm	69.5	225
			45.1	19
			0.6	450
			38.2 or 41.0	450
			3.1	108
			2.0 or 2.8	450
			51.7	208
			16.5	135
			20.3	235
			3.8 or 9.8	415
			22.7	270
			407.9	44
152	1000	Spiral wound/ 2.0 mm	56.0	386
			—	338
			85.0	245
			191.0	180
			70.5 or 36.5	304
			262.4	371
			52.1 or 54.5	512
			110.6 or 111.9	325
			141.5	253
			—	264
			72.5 or 68.7	147
			78.9	410
			107.5 or 56.0	256

Discussion

An inexpensive and easy to manufacture means of measuring steel fragment velocities was developed. It can be modified to provide velocity data on fragments from plastic shell casings that are ejected from thicker walled tubes (2.65 mm) that split but do not produce many mortar fragments. It can also measure the velocity of plastic shell casing fragments produced when shells explode in free air. The reduction in the number of fragments generated when the maroon explosive charge is exploded

Table 3. Velocity and Mass Measurements for Plastic Shell Casing Fragments Produced from Maroon Main Charges.

Shell Diameter (mm)	Distance from Frames to Explosion Point (mm)	Test Description	Fragment Mass (g)	Fragment Velocity (m/s)
70	450	Shell fired in seamless, 2.65 mm wall thickness, 75 mm calibre tube, causing rupture of the tube but little fragmentation	0.8 or 0.7	216
			1.0	135
			1.10	540
			2.0	415
			1.0	245
			1.60	235
			7.10	360
			—	300
		Shell fired while suspended 300 mm above floor between frames	—	771
			—	900
			—	900
			—	900
			—	711
			—	900
			—	900
			—	750
150	1000	Shell fired while suspended 500 mm above floor between frames	—	794
			—	844
			—	964
			—	587

without its shell casing suggests that the rate of energy release is less than for the cased equivalent and that the fragment velocities measured are likely to be a conservative estimate.

This study has suggested three categories of fragments that would correspond to hazards that may pose different risks to firework operators and spectators when shells explode prematurely. These are:

1) Fragments produced from the mortar tube that can have a large mass (407.9 g has been recorded in this study) and velocities in the range 19 to 450 m/s. This means that their kinetic energy is high in comparison with shell plastic case fragments. Such fragments could travel large distances and would pose a hazard to firework operators and spectators.

2) Plastic shell casing fragments that emanate from splits in a rupturing mortar tube. These fragments have velocities similar to mortar fragments but are of significantly lower mass (approx. 1–7 g) and have a correspondingly reduced kinetic energy. The low density of these fragments suggests that air drag would prevent them from travelling far, suggesting that the primary threat is to the firework operator.

3) Plastic shell casing fragments produced in free air, which are small and have low mass, but have high velocity in comparison to category 2. These fragments have high kinetic energy that may have the potential to cause injury. Ballistic properties are likely to be similar to category 2 resulting in hazards primarily to the firework operator when a shell bursts low.

The velocity data generated do not represent the maximum velocity of the fastest fragment produced during a test. By its design, the system samples an area of the expanding projectile cloud and therefore provides a range of maximum velocities for projectiles that are travelling in a direction that will result in their passing through the wire screens.

The velocities of the steel mortar fragments cover a wide range (19–512 m/s), which suggests that a number of factors could affect the velocity of fragments as they leave the explosion point. Factors that could be important are:

1) Fragment mass, which will vary and will affect fragment inertia. More massive fragments will require more acceleration energy, which will mean that their resultant velocity is less than lighter fragments.

2) Fragment shape, which will affect air drag coefficients. This will affect the rate at which the fragment is decelerated.

3) The perimeter of the fragment (i.e., the fracture surface). The larger the perimeter is the more energy will be needed to break the fragment from the main body of the mortar tube, and therefore the less energy there will be to accelerate the fragment.

4) The original location of the fragment. Some fragments are produced from areas adjacent to the explosion point while others are produced from areas farther away. This will lead to different amounts of energy being transferred to the fragments.

The velocity of plastic fragments generated from shells exploded in mortar tubes was substantially less than similar fragments generated by shells exploded in free air. This is likely to be due to the mortar tube interfering with the flight of the shell case fragments. The faster plastic fragments will catch up with the mortar tube as it ruptures and collisions will occur. Therefore, it is unlikely that plastic fragments in a mortar tube will attain their full velocity unless their trajectory is along the major axis of the mortar tube (i.e., nearly vertical). The plastic fragments produced were of low mass and had directional trajectories due to the limited number of splits produced in the mortar tube. This type of fragment is considered to be of importance when assessing the safety of firework operators because they might be close to the launch tube when shells are being fired.

Velocities of fragments produced from 152 mm calibre mortars and from plastic fragments from shells of this size exploded in free air were measured at approximately twice the distance from the explosion point as fragment velocities for the equivalent 75 mm calibre tests. This suggests that the velocities for 152 mm calibre tube tests may have been higher had it been possible to take measurements at the same distance from the explosion point as the 75 mm calibre tests. Tests at closer distances were not possible because the frames were destroyed by the explosion before meaningful velocity data could be recorded.

Conclusions

The main conclusions from this study are:

1) The wire screen system for measuring fragment velocity provides data that are likely to be accurate to within ±10%. This is adequate for estimating flight distances in future work, provided that fragment trajectory, mass and air drag are also known.

2) The use of maroon main charges removed from their shell casings marginally reduces the number of fragments produced from thin-walled mortar tubes. This effect becomes more pronounced as mortar calibres increase, indicating that fragment velocities could be conservative estimates.

3) The measured velocities for the fragments generated by this study indicate that some of the types of projectiles produced as a result of the premature explosion of firework shells in or close to mortars will have substantial kinetic energy.

4) Data generated by this series of experiments will be useful in helping to assess the hazard posed by different types of fragments at various distances from the explosion point assuming that no mitigation methods are used.

Acknowledgements

The author would like to thank Dr. R. K. Wharton, Head of Explosives Section, Health and Safety Laboratory and Dr. A. W. Train of the Explosives Inspectorate of the Health and Safety Executive for guidance during the course of the work; Mr. S. A. Formby and Mr. I. M. Howard of the Health and Safety Laboratory for experimental assistance; and the Health and Safety Executive for financial support of the project.

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