The Hazards Posed by Fragments from Rupturing Steel Fireworks Mortar Tubes — Predictions from a Computer Model —

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ABSTRACT

Fragments with masses of up to 100 g and velocities of up to 510 m/s can be produced from spiral-wound mild steel mortar tubes when firework maroon shells of diameters up to 150 mm are exploded in them. External ballistics calculations indicate that such fragments could travel up to 165±60 m, and possibly 30% further if ricochets on a concrete surface take place. Calculations indicate that these fragments possess sufficient kinetic energy density to penetrate the skin of spectators on landing. In addition, large slow–moving fragments of up to 7 kg are also produced and these could inflict blunt trauma injuries on operators.

Keywords: firework, mortar tube, safety, fragment, steel velocity, projection, injury, shell

Introduction

A firework accident in which a mortar shell exploded prematurely in its steel mortar tube resulted in the display operator having to have his leg amputated and members of the public being injured.[1] As a result, the UK Health and Safety Executive instigated a research programme into hazards associated with firework mortars.[2] A summary of this work was presented at the 4th International Symposium on Fireworks.[3] The need for the work was reinforced by subsequent mortar-related accidents which led to fatalities[4] and serious injuries[5–7]

At public firework displays, it is not uncommon for firework mortar tubes to be used without a means of mitigating the hazards from fragmentation of the mortar tube if a shell explodes prematurely in it.[8] Large numbers of fragments can be generated, particularly when maroon or large calibre cylindrical effect multi-break shells are used.[9] Some of the fragments are small and have high velocities, while others, which are produced from areas of the mortar tube away from the explosion point, are large (up to 7 kg) and relatively slow-moving. Plastic fragments from shell casings could also pose a hazard when shells are propelled out of the mortar tube but explode at low altitude (a ‘low-burst’), or when a shell explodes prematurely in a mortar tube that does not fragment but ruptures, producing splits in its side that allow the plastic fragments to escape.

There was a need to estimate how far such fragments could travel and the types of injury they could inflict, so that estimates of hazard ranges could be made. Another factor to be considered was the possibility of fragments ricocheting off hard surfaces, and thus increasing the hazard range. Velocity and mass data for steel mortar and plastic shell case fragments (which allow such an analysis to be carried out) have been previously reported[10].

In the UK professional firework operators are covered by the Health and Safety at Work, etc.

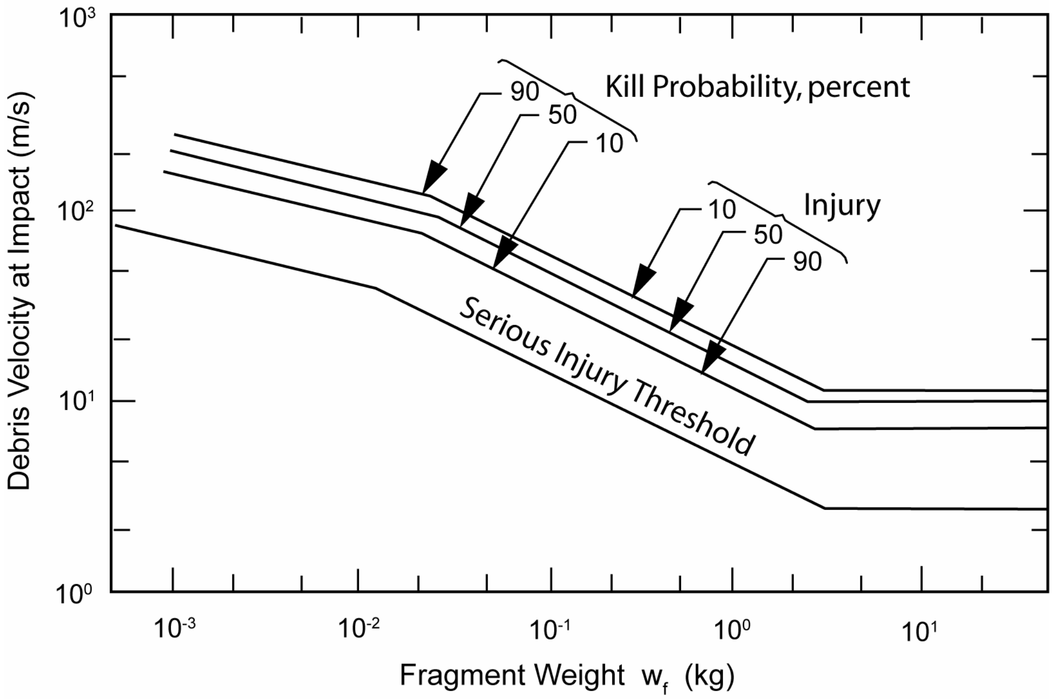

Figure 1: Effect of non-penetrating fragment impact on the human body (Abdomen and limbs)[12]
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Act, 1974. This places duties on operators who are employers to ensure, as far as is reasonably practicable, the health and safety of their employees at work and that of other people, including the public, who may be affected by their operations. Similar duties are placed on self-employed operators in respect of the health and safety of themselves and other people.

Possible injuries to spectators and operators can come from penetrating wounds, where the energy density of the fragment exceeds a threshold value, or from blunt trauma (where large non-penetrating projectiles impact with the surface of the body and impart their energy to it causing internal injuries), which is governed by the total kinetic energy of the fragment hitting the body.

The threshold energy densities required to penetrate various parts of the body[11] range from 0.06 J/mm^2 for the eye, 0.1 J/mm^2 for skin and 0.19 J/mm^2 for bone. Threshold energy density is defined as the kinetic energy of the penetrating fragment divided by the cross-sectional area of the penetrating edge of the fragment in the direction of motion. Thus a 40 g fragment with a penetrating edge of 1.6 mm × 0.1 mm (estimated to be equivalent to the sharp corner of a mortar tube fragment), will only need to be travelling at 0.9 m/s to break the skin.

Blunt trauma can range from bruising to death. Figure 1[12] shows that for a 100 g fragment, there is a 90% probability of death at a velocity of 100 m/s and that the onset of serious injury is at a velocity of 10 m/s. These values are all within the range of velocities measured for fragments from bursting steel mortar tubes,[10] suggesting a risk of injuries from blunt trauma, as well as from penetrating fragments.

Fragment ricochets will occur when there is insufficient vertical velocity to penetrate the ground. The possibility of ricochets will be higher when the ground is hard (e.g., concrete, rather than soil), and when the velocity vector has a small angle to the horizontal. Thus fragments that are fired near to the horizontal are most likely to ricochet. When assessing separation distances, consideration should therefore be given to the effects of ricochets, especially if displays are conducted on hard surfaces.

The aim of this work is to present computer model estimates for the likely flight distances of

Table 1: Calculated Projected Distance Against Frontal Area for 200 g Steel Fragment Travelling at 400 m/s.

	Drag Coefficient (C_d)	Presented frontal area (mm^2)	Equivalent calibre (mm)	Optimum elevation of fragment trajectory (degrees)	Maximum horizontal distance if exploded at ground level (m)
Maximum area	0.9	15400	140	22	85.40
Mean area		7880	100	23	151
Minimum area		204	16	35	2670
No drag	0	—	—	45	16000

fragments formed when maroon shells explode in free air (simulating a 'low-burst') and when they explode within, and fragment, steel mortar tubes. The data will be a parameter used to establish the separation distances required to protect both operators and spectators from penetrating and blunt trauma injuries.

Ballistics Calculations

The results obtained from the calculations performed during this study are based on the output from a computer model that requires specific data inputs. To satisfy these requirements a number of assumptions have been made regarding the behaviour of fragments during flight, and no experimental work has been performed to validate the model used. Therefore, the findings presented in this paper should only be considered as indicators of what is likely to happen when firework shells explode in steel mortar tubes or directly above them. Experimental work will be necessary to validate the model before the calculated flight distances can be verified.

The majority of calculations assumed that the fragment impact site was at the same height as the explosion site. A small sample of calculations assumed that the impact site was lower than the explosion site to simulate displays fired from buildings or bridges. These indicated that high velocity fragments at elevations of up to 50 m do not significantly affect projected distances (<10% increase in distance), and it was concluded that elevation of the explosion position in relation to the impact point was not a critical factor when considering separation distances.

To calculate the external ballistic behaviour of fragments it was assumed that they were square in section with a thickness equal to the wall thickness of the mortar tube from which the fragment was formed (i.e., 1.65 mm and 2 mm for 75 mm and 152 mm calibre steel tubes, respectively).

Using literature values for fragment mass (200 g)[13] and velocity (400 m/s),[14] it is possible to calculate projection distances of 2700 m, 85 m and 150 m for the fragment depending on whether it is presenting its minimum, maximum or mean frontal area to the direction of flight. See Table 1. The value obtained using the mean frontal area (150 m) is appropriate to those circumstances when the fragment is tumbling in flight and is in line with experimentally measured distances (120 m) reported in the literature for metal fragments.[15] These results, together with a report that "all orientations of bomb fragments are equi-probable",[16] indicate that it is reasonable to assume that fragments are aerodynamically unstable and tumble in flight.

The forces acting on the fragment will be gravity, drag, which will be a function of the shape of the fragment, its velocity and its cross-sectional area, and lift, which will be a function of the same variables as drag.

From the literature it has been reported that:

1) In velocity trials,[10] steel mortar fragments of up to 100 g mass can travel at initial velocities of up to 512 m/s. However, the one large fragment recorded (408 g) had a much

lower velocity (44 m/s) which suggests that ballistics calculations of large fragments at high velocities would be inappropriate,

2) In fragmentation trials,[9] the maximum mass of a fragment that had sufficient energy to penetrate into the wooden fragment-capture system was 533.5 g,

3) Initial trajectory data indicate that 72% of steel fragments have initial trajectories of ±15° from the horizontal with <10% having trajectories >45°.[9]

4) Drag coefficients (C_d) for tumbling fragments are likely to be 0.91±0.27,[16] which suggests that an average value of 0.9 should be used. In order to show the effect of reducing drag coefficients, a value of 0.6 was also used in our calculations.

5) Assuming that fragments tumble, a mean frontal area can be set equal to $S/4$, where S = fragment surface area.[16] The mean lift for a tumbling fragment can be assumed to be zero provided that the rotational speed is much less than the translational speed.

Using these assumptions, the parameters used to calculate steel fragment flight distances were as shown in Table 2.

Table 2: Fragment Parameters Used in Ballistics Calculations.

Drag coefficient (C_d)	Velocity (m/s)	Mass (g)	Trajectory (degrees)
0.6	19	4.9	0
0.9	246	30.3	5
	450	118.6	10
		533.5	15
			25
			45

Equations covering the movement of projectiles have been incorporated into many computer programs that can calculate the distance travelled by the projectile as a function of its mass, launch angle and launch velocity. The model used for this work[17] is due to be issued through the NATO Range Safety Working Party (NRSWP).

The effect of ricochets was calculated from a knowledge of the coefficient of restitution, e,[18] which was measured experimentally for concrete by carrying out drop tests with steel balls. These experiments generated a value of 0.56. For a projectile hitting the ground with horizontal velocity and vertical velocity (upward velocities being taken as positive), the ricochet velocity is given by:

$$\text{Horizontal velocity} = v_x$$

$$\text{Vertical velocity} = e v_y$$

$$\text{Trajectory angle} = \tan^{-1}\left(\frac{e v_y}{v_x}\right)$$

Thus, for successive ricochets, the resultant velocity will reduce and the trajectory will move closer to the horizontal.

Velocity trials[10] showed that plastic shell fragments of up to 7.1 g with velocities of 540 m/s were generated in mortar tubes that ruptured but did not fragment, and that smaller fragments with velocities of up to 964 m/s were generated from shell explosions in free air. These data were used to estimate the distances that such fragments could travel.

Analysis and Discussion of Results

Ballistics calculations indicated that maximum projected distances occurred when fast moving fragments had an initial trajectory of approximately 25°. Table 3 shows the projected distances that steel fragments could fly as a function of fragment mass and velocity (C_d=0.9 and 0.6). The data suggest that the distances that fragments will fly will increase with fragment mass and velocity, but that in the typical ranges of mass and velocity for the lighter fragments, the distance is not very sensitive to variations in either mass or velocity. However, in all cases, the distances travelled are well in excess of 50 m, a minimum separation distance commonly given in guidance material.[19–22] Thus, when staging firework displays, it is unlikely that an adequate separation distance could be provided at venues such as football grounds to allow the safe use of steel mortar tubes that are not surrounded by some form of

Table 3: Maximum Projected Distances for Tumbling Steel Fragments As a Function of Fragment Mass, Velocity and Drag Coefficient (Trajectory Angle 25°).

Fragment initial velocity (m/s)	Tube diameter (mm)	Fragment mass (g)	Mean Presented frontal area (mm^2)	Projected distance (m)		Projected distance after 2 ricochets on concrete (m)	
				C_d=0.6	C_d=0.9	C_d=0.6	C_d=0.9
246	75	4.9	221	175	126	225	160
		30.3	1250	188	135	242	172
		118.6	4730	193	139	248	177
	152	533.5	17300	228	165	297	212
450	75	4.9	221	204	145	252	178
		30.3	1250	221	157	272	193
		118.6	4730	227	162	279	198
	152	533.5	17300	n/a	n/a	n/a	n/a

fragment mitigation system. Results for a drag coefficient of 0.6 show the same relationship between distance travelled and fragment mass and velocity as for a value of 0.9, but the distance travelled is greater as a consequence of the reduced drag of the fragment.

Calculations using the minimum projected area, a mode of travel similar to that of a discus, suggest maximum projected distances of 1470 m, or 2000 m after two ricochets, for a 30.3 g fragment with initial velocity of 450 m/s. However, given the irregular shape of tube fragments, it is unlikely that they would fly in this fashion.

In addition to the distance travelled by fragments, their effect on the body must be considered. Table 4 summarises the velocity and energy density data that corresponds to the ballistics data given in Table 3. The energy density of the fragments on landing will range from 5.0 J/mm^2 for a 4.9 g fragment travelling at an initial velocity of 246 m/s to 151 J/mm^2 for a 118.6 g fragment with initial velocity of 450 m/s (assuming C_d = 0.9). Even after two ricochets, energy densities are only reduced to 1.88 J/mm^2 in the former case and 48.1 J/mm^2 in the latter. These values are all substantially greater than the 0.1 J/mm^2 required to cut skin,[11] indicating that unacceptable injury would be inflicted if the bare skin of a spectator were to be hit by a steel fragment.

In connection with blunt trauma injuries, the key factor is the total kinetic energy of the fragment. Table 5 lists the velocity required to exceed the serious injury threshold and the 50% kill probability threshold (Figure 1) for fragments of masses of 4.9–533.5 g. At a velocity of 246 m/s it can be seen that fragments in the mass range indicated will have sufficient kinetic energy to cause serious injury and exceed the 50% kill probability. At the point of first impact with the ground, total kinetic energies will be reduced but the serious injury threshold will still be exceeded for the 118.6 g and 533.5 g fragments and the 50% kill probability will be exceeded for all velocities of the 533.5 g fragment. The greatest risk of blunt trauma injury would be to an operator who fired shells in a display using flame ignition assuming the tube to be completely without any form of mitigation. Such an operator might be very close to a mortar tube at the time of its disintegration. Measurement of fragment velocities[10] has shown that very few fragments of mass greater than 100 g have initial velocities of greater than 100 m/s, and thus the risk of serious blunt trauma injury to spectators, standing at the distances of 50–100 m from the mortar tube recommended by current codes of practice, will be lower.

Table 4: Velocity and Kinetic Energy Densities for Tumbling Steel Fragments As a Function of Fragment Mass and Velocity (Drag Coefficient 0.9, Trajectory Angle 25°).

Fragment initial velocity (m/s)	Tube diameter (mm)	Fragment mass (g)	Presented frontal area (mm^2)	Initial energy density (J/mm^2)	Velocity after 1st flight (m/s)	Kinetic energy density after 1st flight (J/mm^2)	Velocity after 2 ricochets (m/s)	Kinetic energy density after 2 ricochets (J/mm^2)
246	75	4.9	221	925	0.8	5	0.3	1.88
		30.3	1250	5730	5.6	35	1.8	11.3
		118.6	4730	22400	22.8	143	7.2	45
	152	533.5	17300	101000	125	781	38.9	243
450	75	4.9	221	3100	0.9	5.63	0.3	1.88
		30.3	1250	19200	6	37.5	1.9	11.9
		118.6	4730	75100	24.2	151	7.7	48.1
	152	533.5	17300	n/a	n/a	n/a	n/a	n/a

It should be noted that even if the steel mortar tube is fully protected by burial or being surrounded by sandbags, there will still need to be a separation distance between tube and spectators. This will reduce the likelihood of plastic fragments from the firework shell or debris from burning stars from reaching spectators if the shell explodes above the mortar tube but at a low altitude (a 'low–burst'). Plastic fragments are likely to travel up to 40 m with an energy density just sufficient to damage the eye,[9] while the radius of the star debris is likely to be around 70 m for a 152 mm diameter mortar tube, since the burst diameter of star shells that fit that tube has been estimated to be 130 m by Shimizu[23](Figure 2).

Overall, it appears that in order to prevent fragments generated from unmitigated firework mortar tubes from injuring spectators, extremely large separation distances would have to be implemented. Such precautions would not protect firework operators when they have to work within the separation distance between the mortar tubes and the spectators. Clearly, the implementation of such large separation distances would preclude the use of many of the venues currently used for firework displays.

A better approach for operators and spectators would be to protect steel mortar tubes. This would enable the minimum separation distance to be reduced and provide some protection to operators. A minimum separation distance will still be necessary to protect spectators from plastic fragments from firework shells and from burning debris from stars.

Table 5: Blunt Trauma Injury to the Body by Projectiles as a Function of Mass and Velocity.

Fragment mass (g)	Fragment velocity to exceed the serious injury threshold (m/s)	Fragment velocity to exceed the 50% kill probability (m/s)
4.9	52	109
30.3	26	85
118.6	11	34
533.5	3	11

Conclusions

This paper has indicated that:

1) For shells of up to 150 mm diameter, steel mortar tube fragments of up to 100 g mass are likely to travel up to 165±60 m.

2) Ricochets, which will tend to occur on concrete surfaces, can increase the distance traveled by fragments from steel mortar tubes by up to 30%. Ricochets will present a significant additional hazard on concrete surfaces, and a negligible hazard on grass, except when it is compacted and dry.

3) The risks to spectators from mortar tube fragments are likely to be from penetrative injuries. Calculations indicate that at the current minimum recommended separation distances all fragments that are not hindered by a mitigation system will have sufficient kinetic energy density to puncture bare skin.

4) Hazards to operators can come from both penetrative and blunt trauma injuries.

It is suggested that the following steps should be considered to reduce the hazard to spectators and display operators:

1) Steel mortar tubes should have some form of mitigation system in place to retain any fragments produced as a result of a shell exploding in the tube.

2) Remote firing of mortars should be encouraged because operators can then fire the display from a sheltered position, or from a position outside the separation distance between the mortar tubes and the spectators.

3) Even when there is a mitigation system around the tube, appropriate separation distances are required between mortars and spectators to protect them from shell fragments and debris from burning stars. This varies with the size and type of shell being fired (Figure 2) and is approximately 70 m for a 150 mm diameter shell.

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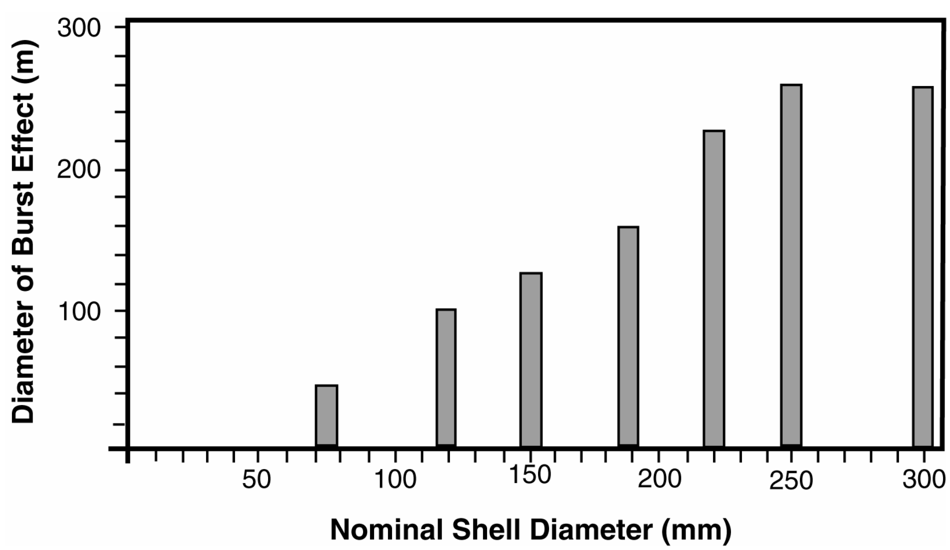

Figure 2: Shell burst diameter as a function of star shell diameter (Data from Shimizu).[23]

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