Reasons for Fuse Failure and Drift Distance of Spherical Fireworks Shells

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ABSTRACT

This work investigates the reasons for the ignition-failure of spherical (round) shells. It further statistically assesses the probability that the resulting blind (dud) shells will fall within a certain range from the launch point.

Keywords: fuse failure, shell drift, Magnus effect, interior ballistics, exterior ballistics, shell ballistics, blind shell, dud shell

Introduction

Prompted by an accident at a public fireworks display in 1997, German regulators have stepped up efforts to re-examine safety distances for viewers at public displays. The BAM (Federal Institute for Material Research and Testing) performed research to establish an overall model of interior- and flight-ballistics of spherical (round) firework shells.[1]

In support of this regulatory effort, representatives of the professional pyrotechnics association conducted their own research program on safety distances. The German Professional Pyrotechnic Association (VDBF)[2] allocated the necessary funds to perform statistical research on drift distances of 4-, 5- and 6-inch (100-, 125-, and 150-mm) fireworks shells.

The main intention of the VDBF was to provide statistical data on shell drift, using parameters that should match—as close as possible—the conditions of firework displays. Contrary to the existing safety distance table, which was formed with practical experience, this review provided scientific data to assess the risks of blind (dud) shells. The experimental drift distance data were used to establish a statistical model of probability of impact distance for three shell sizes. Nonlinear functions of probability were found to match the given conditions best. A new distance table was created—based on those data—using the shell diameter as the basic parameter.

The results of both the BAM research program and this work led to a fundamental change in the safety distance table for display shells in Germany. The safety distances now used are equivalent to the National Fire Protection Association *Code for Fireworks Displays* (NFPA 1123).[3a]

The other fundamental topic of research was to find out why when fireworks shells are fired that sometimes they do not ignite and subsequently fall to earth as blind shells. This study starts with interior ballistics of fireworks shells (within the mortar), investigating the reasons for time fuse failure and some countermeasures. The main part details the flight (exterior) ballistics and statistic evaluation of drift distance. Impact ballistics for blind shells in our tests are also given.

Interior Ballistics: Reasons for Fuse Failure

The first reason for fuse failure is fire transfer failure due to systematic material deficiencies (SMD) such as insufficient priming of the fuse. This may lead to a critical temperature drop as soon as the shell clears the hot exhaust plume from the mortar. Another example of SMD would be the incorporation of inert material into the fuse, which will cause instant cessation of the ignition sequence. A third important SMD is crumbling of the surface of the prime composition on the fuse during mortar passage.

The other potential cause for fuse failure in an otherwise perfect shell is the shearing off of the fuse from rotation of the shell inside the

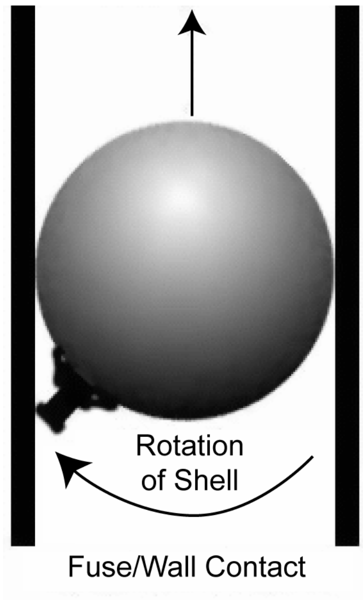

Figure 1. Sketch indicating fuse contact, rotation and direction of shell in mortar.

mortar and energetic fuse to mortar contact. (See Figure 1.)

Upon inspection, the outer part of the time fuse is usually found to be dislocated. The inner powder core inside the shell casing is still intact. When samples of this remaining powder core were ignited with an electric match, the fuse functioned normally from that point onward.

In our tests we used a plastic heat shield to cover the end of the time fuses that protrude from the shell. The exact preparation of the heat shield is described below under "Experimental Setup". The destructive effect was found to be dependent on the shell size, based on the damage the head shields sustained:

- None of the heat shields of the 4-inch (100-mm) shells were damaged; all shells came down as expected.
- None of the heat shields of the 5-inch (125-mm) shells were damaged sufficiently that the fuse ignited. Slight scratches (0.1–0.2-mm deep) were barely noticeable in only 10% of all recovered shells; the other 90% of the heat shields were completely intact.
- On the other hand, over 17% of the 6-inch (150-mm) shells used in the tests ignited in spite of a well prepared heat shield over the fuse. This value is consistent with earlier tests by Kosanke.[4] The heat shield was rubbed off during passage through the mortar, because the shell rotated in a way that the shield and fuse came in contact with the mortar wall. The fuses recovered from the exploded shells had the heat shield missing or destroyed.
- Approximately 20% of all recovered 6-inch (150-mm) shells were found to have parallel scratches in the outer plastic layer. Those scratches were up to 1-mm deep. It is assumed that the asymmetrically placed lift charge rotated the shell enough to bring the fuse into contact with the mortar wall.

Table 1. Energetic Wall Contacts.

Shell Diameter (in.)	Shell Diameter (mm)	Energetic Wall Contacts	Failure Rate for Single-Fused Shells(a)
4	100	0/55 (0%)	0.1%
5	125	5/45 (≈11%)	
6	150	14/40 (≈35%)	

(a) Approximately, based on experience.

As a hypothesis, we propose that the increased torque of the larger shells is responsible for the damage to the heat shield. The scratches in the heat shields were on one side and parallel. Single sideward rotation seems the most likely explanation for the observed marks. Otherwise, irregularities in the marks or multiple marks would be inevitable. The orientation of the moving shell seems to be constant after the fuse hits the mortar wall.

Comparing the high rate of energetic fuse to mortar contact in the test shells (Table 1) with the good reliability of fireworks shells in general, shows that fuse to mortar interactions rarely cause fuse failure.

This choking-off mechanism explains the majority of fireworks shells fuse failures and is consistent with the physical appearance (ruptured and destroyed fuse) of recovered blind shells from fireworks displays.

Countermeasures, Multiple Fusing and Contact Stop

Multiple Fusing

To reduce the stress of impact between fuse and mortar wall, double fusing is recommended. This decreases the angle of rotation of the shell so that the fuse will contact the mortar wall at 20 to 30° rather than 40 to 50° as in the case of single fusing. See Figure 2. Due to the resulting shortened accelerating time, the imparted energy is lowered to 50–60% in all possible impacts. This reduces the impact force between the fuse and the mortar wall.

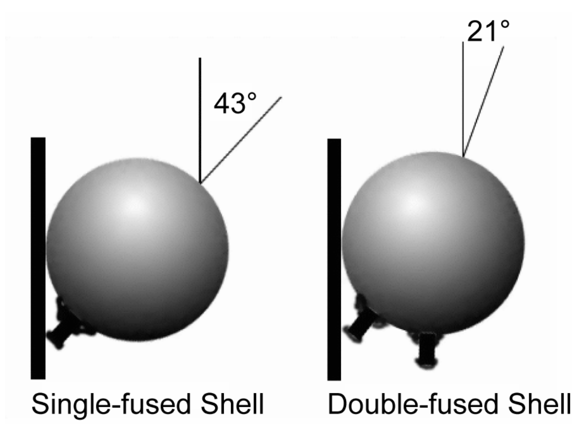

Figure 2. Angle of rotation for fuse contact with mortar wall for single-and double-fused shells.

If one fuse is approaching the mortar wall, the other fuse will be centered. Should the angle of rotation be vertical to the line between the two fuses, it may cause both fuses to contact the mortar wall at the same time. The angle of rotation is still somewhat smaller than that of single-fused shells, and the fuses each receive only half of the impact energy. Still, this might be enough to dislocate both fuses.

Contact Stop

An effective way of preventing fuse contact with the mortar wall is to attach a ring around the fuse, which keeps the fuse away from the mortar wall. The best way is a non-detaching lift charge with a downward facing pressure disc. See Figure 3. German shell maker ZINK® and other producers use such a system in combination with detaching quick match for optimum ballistics and spolette fusing.

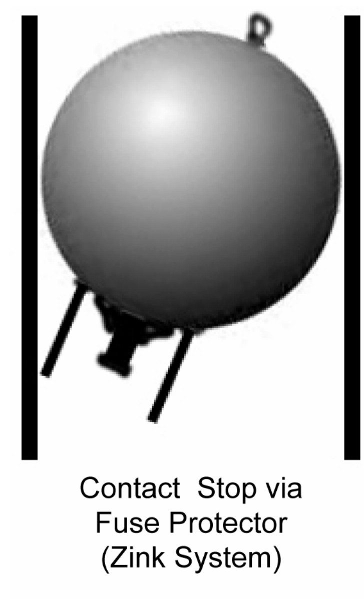

Figure 3. Example of how a ring around the fuse prevents it from contacting the mortar wall.

Comets or other attachments on the top of the shell (see Figure 4) may effectively prevent rotation of the shell. Under no circumstances can the shell rotate into a position where a fuse would touch the mortar wall. Comets not only prevent physical contact, but they also center the shell's fuse. By entering the fast gas flow near the walls, the shell is subject to restoring forces just like in the example described under stabilizing interior ballistic factors below. Considering the flimsy comet configuration in some commercial oriental shells, the restoring forces may not be very great. Unfortunately, the muzzle ballistics of comet shells are more irregular than that of smooth ball shells, see below.

Stabilizing Interior Ballistic Factors

It has to be stated that the quick match seems to play a role in this process as well. The quick match tends to centre the shell as soon as a stable gas flow is established. The latter happens because the gas flow is much faster near the mortar wall and the quick match is moved out of the peripheral area. See Figure 5. The same

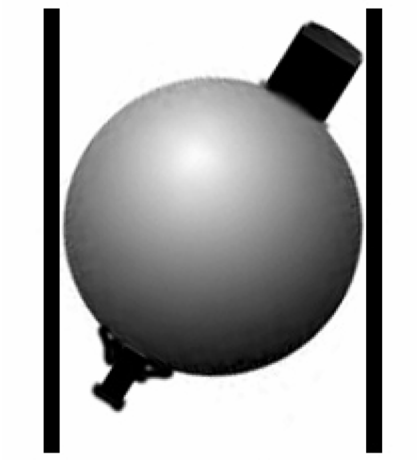

Figure 4. Example of a comet preventing the fuse from contacting the mortar wall.

scheme applies for other extensions placed on top of a round shell, like comets, etc. While these restoring forces are independent of the shell size, the angular momentum of a shell increases with radius. Therefore the quick match-stabilizing effect decreases with shell size. Since the heat shields of all shell sizes were made the same, this is another factor that explains the damage to the heat shield in the larger shells.

In conclusion, it has to be stated that the conditions for ignition are better with larger shells. The pressure in the mortar increases with shell size (e.g., by a factor of 1.5–2 when comparing 6-inch with 4-inch shell data), and the temperature during the lift process increases as well. This can be easily concluded from basic thermodynamics. Also, the shell remains in the mortar longer, which means better chances for ignition or even re-ignition—if the fuse has been quenched.

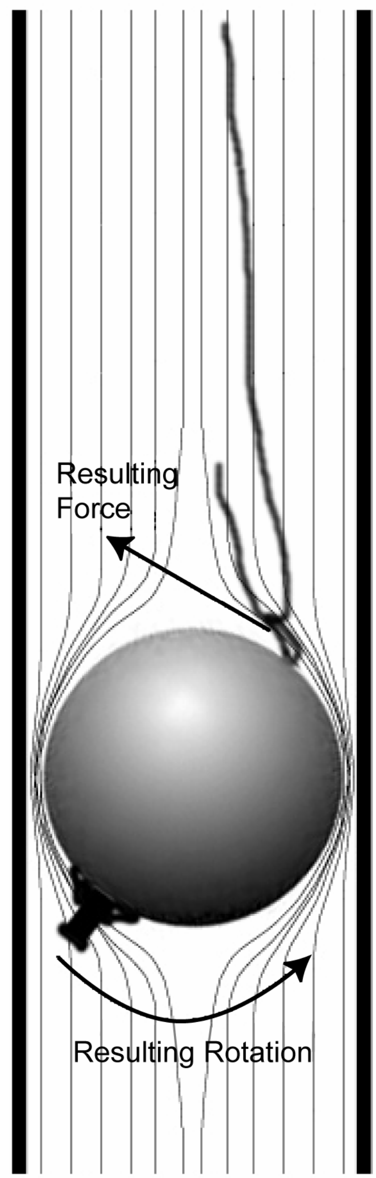

Figure 5. Influence of quick match.

Ballistics: The Deviation of the Ideal Trajectory and Statistical Investigation

Muzzle Ballistics

There are several forces affecting the shell when it exits the mortar that explain shell drift more appropriately than irregular mortar setup, wind drift and Magnus effect.

Irregular Mortar Clearance

When the shell leaves the mortar off-center, the gas flow on the side of major clearance pushes the exiting projectile sideways in the opposite direction. See Figure 6. This sideways push is more pronounced because of friction between the shell or its extensions (e.g., fuse, lift pocket, quick match) and the mortar wall in the upper regions of the mortar.

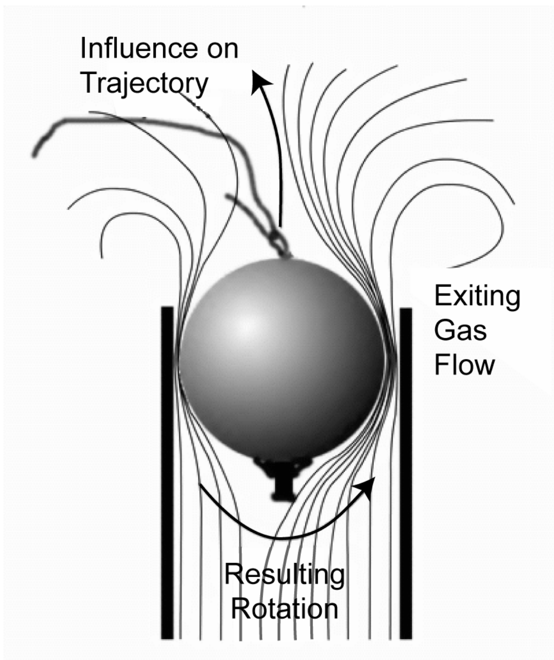

Figure 6. Demonstration of sideways push when the shell leaves the mortar off center.

Asymmetrical Frontal Air Flow

As soon as the shell leaves the mortar, the flow of the lift gases from the "rear" ceases within a small fraction of a second. The shell is now influenced by the frontal air flow. Since the shell is in an unbalanced aerodynamic position with regard to the new environment, asymmetrical extensions—like rising effects or remains of the quick match—cause forces that move the shell sideways and make it spin. The extension, which is pictured as a comet attachment in Figure 7, may also be the wadded remains of the quick match.

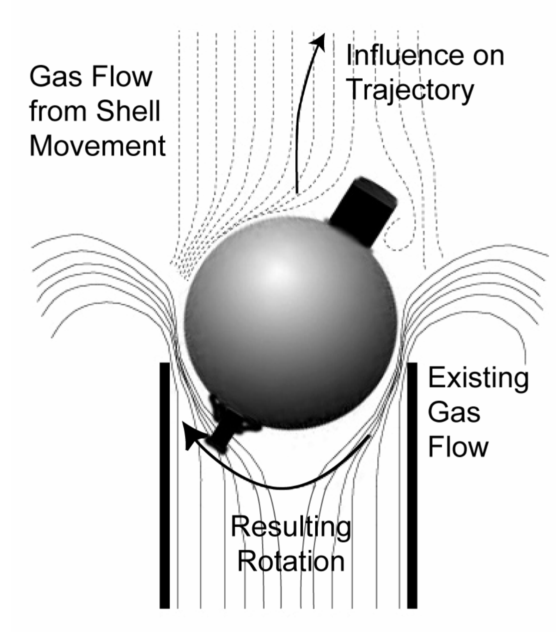

Figure 7. Asymmetrical frontal air flow.

Quick Match Effects

The quick match can cause two other important disturbances in muzzle ballistics, whether or not it is fastened to the mortar.

In the first case the mechanical sling-shot effect diverts the projectile from its course and induces a rotation. As the quick match is ripped away from the mortar rack that was holding it, the resulting rotation might cause a Magnus effect of sorts. This effect depends on how much of the quick match remains in the fuse loop. If a sufficient length remains, the rotation could pull the shell in the opposite direction of the sling-shot effect while the shell is ascending. See Figure 8.

Even an unfastened quick match may cause a slight slingshot effect if it is propelled sideways out of the mortar before the shell exits. In this case the force results from the mass momentum of the quick match and its aerodynamic drag. Letting the quick match hang loose out of the mortar will also risk dragging chained shells out of the next mortar. See Figure 9.

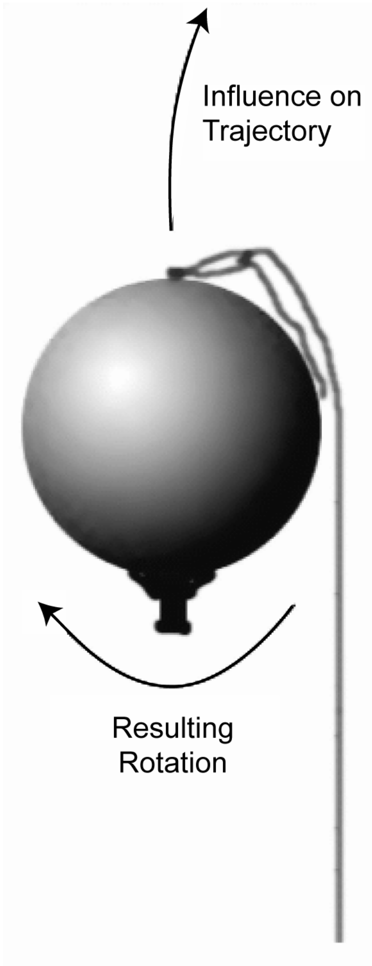

Figure 8. Slingshot effect with a fastened quick match shell leader.

The behavior of the quick match depends on its type, and the stability and size of the fuse loop. Because of the large number of different types of oriental shells, numerical simulations have only limited value. Further, the combination of the aerodynamic effects on the shell as described above is dependent on so many parameters and their correct logical combination that a "true" numerical model for "all" shells is nearly impossible. Nevertheless, numerical calculations are possible for certain types of shells when taking the statistical drag coefficient into account. But this factor can only arise from experimental testing.

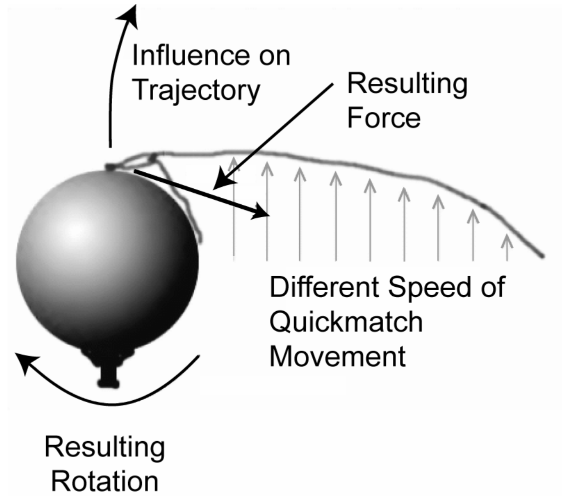

Figure 9. Slingshot effect with an unfastened quick match shell leader.

Flight Ballistics

General Ballistics of Round Shells

The density and muzzle speed of round shells are roughly independent of the shell size. The density is ~0.8 ± 0.1 g/cm^3 for most display shells, and the average muzzle speed is between 120 and 140 m/s. The shell apex height depends principally on its surface area to mass ratio. While the mass of a shell rises as the third order with its radius, the surface area rises only as the second order. The surface area to mass ratio rises linearly with shell size and so do the flight time and apex height. The approximate flight time is given in equation (1), which is valid for shells three-inch diameter and above and is a good fit to Shimizu's data[5] and our results:

Total ground to ground flight time [s]
≈ *Shell diameter* [in.] + 6 (1)

Numerical modeling

A numeric model of a shell's flight was established before the tests. This model takes shell size, diameter, mass and muzzle velocity into account and calculates the trajectory depending on the mortar angle, side wind, air density and Magnus effects. The program is a step routine that solves the movement equations with a 0.1 ms time-step during the flight. It starts with a certain initial state, integrates all affecting forces for the period of the next tenth millisecond and subtracts the result from the ground state, which gets the shell to a new state of time, place, velocity, direction and spin.

To calibrate this routine, shell apex heights were measured during a number of different long test series. The first method used shells with comets during ordinary firework displays, which were filmed from a greater distance. Rectangular landmarks (flares) on the ground were used as scale with the same parallax as the ascending shell. Shimizu's Tiger Tail comets were manufactured for these measurements, since the glowing charcoal particles were carried nearly uniformly by the wind. The long hang-time of the particles allows measuring the wind velocity depending on the height and the shell's behavior in the wind. This behavior was taken into account in the numerical model of the shell flight.

In the second approach a video camera was set up exactly vertical on the ground near the mortar setup. The film was digitized and the time difference of burst flash and burst report were recorded and used to calculate the burst height with an accuracy of 10 m in a series of several hundred shells per size. With regard to the firework shells the following were found:

a) They explode at or near the zenith of their flight.

b) The apex was found to be up to 25% lower than expected by the numerical model. The model used an average muzzle velocity of 130 m/s and the drag coefficient of a sphere depending on the speed (0.4–0.5).

c) The apex height varied up to ± 30% for shells of identical interior ballistics.

The tests revealed information about the appearance of a blind shell, especially that the quick match remains in the fuse loop after firing and that parts of the lift charge bag remain attached to the shell. [In over 80% of all shells portions of quick match (pieces at least 15 to 25 cm in length) remained in the fuse loop, see below]. This has an important influence on the drag coefficient. New numerical models now take this factor into account.

The variation of the apex height is caused by the quick match factor as well as by variation in the amount of lift powder. It seems that some Far East manufacturers measure the lift amount by volume and not by weight. Discrepancies up to 15% were found in general for the shells used in our tests. One four-inch shell was obviously double-charged with 72 g of lift powder compared to 40 ± 6 g for the other shells of that series. The quality of the lift powder, especially the moisture content, also varied. Apart from that, the results are consistent with the data of many Asian manufacturers.

There are three main influences on a shell's trajectory: (1) the angle of the launch caused by mortar setup and muzzle ballistics, (2) wind drift, and (3) Magnus effects. These are discussed in detail below.

1) *Launch Angle*: An intended launch angle adjusted by the mortar setup may be altered by the muzzle ballistics described above that adds an irregular angular momentum. Figure 10 shows the numeric simulations of trajectories of 4-inch (100-mm) round shells without any muzzle disturbances. The average shell weight is one pound (454 g), and the average muzzle velocity is 140 m/s. This is a rather heavy shell with a density of 0.9 g/cm^3 and a relatively high muzzle velocity. The angle of launch starts at 1° and increases in 5° increments up to 46°.

The horizontal distance at apex height (the normal burst point) increases effectively up to a launch angle of 25°. Angling the mortars further mainly lowers the burst height but does not substantially increase the horizontal distance. This is true for all sizes of round shells and important for the artistic design of fireworks shows.

The drift distance (horizontal displacement) for 1° angled shots increases from 25 m for 4-inch (100-mm) shells to 45 m for 12-inch (305-mm) shells at muzzle velocities of 130 m/s. One degree is considered the practical limit when using a water level to set up the mortars. It explains a large fraction of the average shell drift, especially if wooden mortar racks are used in chains. In this case the recoil of the first shot might influence the whole construction, especially in fast fired salvos when the battery tends to swing up.

2) *Wind Effect*: Wind is the most common influence on the trajectory and cannot be prevented. While being a small effect under normal circumstances, its influence can be severe

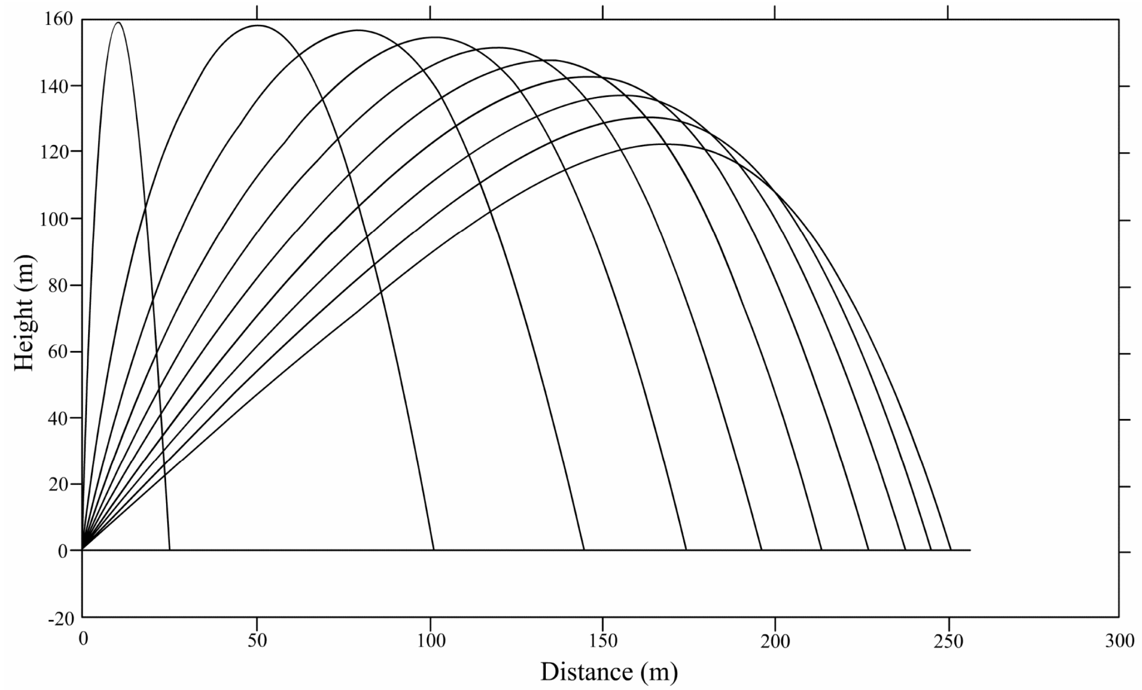

Figure 10. Effect on horizontal displacement distance for 4-inch (100-mm) round shells, as the mortar is angled from 1 to 46° in 5° increments.

in stormy conditions, making any display impossible. The reason for this is that the influence on the shell's drift rises as the second order with wind velocity. Wind drift of a shell is nearly independent of its diameter. Larger shells do not drift as much as smaller ones. This is caused by their greater surface-to-mass ratio, or in other words: larger shells remain in the air longer but are far less influenced by the wind. Stated another way—the same effect that makes a larger shell ascend higher explains its lower susceptibility to wind drift. The problem is to find a corresponding angle for each caliber to balance out the wind effect since smaller shells have to be more angled against the wind than larger ones. Figure 11 shows the numeric simulations of trajectories of 4-inch (100-mm) round shells, weighting 454 g, and shot at a muzzle velocity of 140 m/s. The wind velocity starts at 1 m/s and rises in 1 m/s increments up to 10 m/s. Based on the information in Figure 11, a wind drift of about 55 m occurs at 10 m/s wind velocity. To offset this amount of drift, one would need to angle the 4-inch (100-mm) mortars 3° against the wind as can be estimated from Figure 10.

A 12-inch (305-mm) shell of the same density and muzzle velocity would rise to 325 m and have a wind drift of about 40 m at a wind velocity of 10 m/s. That is equivalent to an angled shot of 1° for that size of mortar.

It should be kept in mind that measuring the wind velocity at ground level does not necessary give precise results for the average wind velocity during the flight. The difference between ground level wind and the wind at higher altitude increases with increasing wind velocity.

3) *Magnus Effects*: As a rotating shell moves through the air, the interaction of the side circling "against" the wind versus the side circling "with" the wind makes the shell move sideways toward the side circling "against" the wind. The Magnus effect only works for laminar (i.e., nonturbulent) flows. These are not the conditions for a shell immediately after leaving the muzzle, where mostly turbulent flows predominate. In broader understanding, the Magnus effect describes the transfer of rotational and vertical energy into linear movement in a horizontal direction, even under turbulent conditions and for non-round bodies. In the case of a round shell with extensions like fuse, quick match or

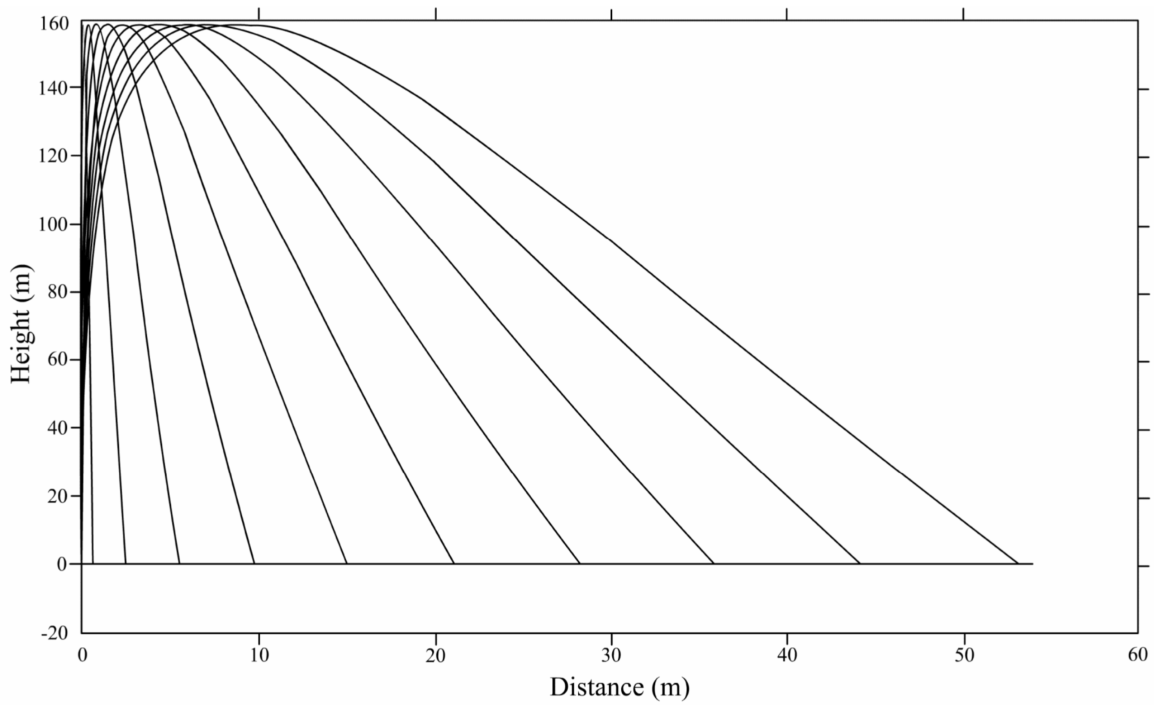

Figure 11. Effect of wind on 4-inch (100-mm) shells as the wind increases from 1 to 10 m/s in 1 m/s increments.

comets, these extensions can interact with the airflow like a paddle, causing turbulence. Additionally, the rotation of the shell decreases rapidly under these conditions. Exact modeling would be quite complicated under these circumstances. The Magnus effect and its turbulent analogies are responsible only for a fraction of the shell's deviation from its ideal trajectory as can be seen in Figure 12.

The time fuse of a normal fireworks shell prevents its free rotation in the mortar. Assuming the shell rotates 36° during the mortar passage of 10 ms duration at constant acceleration and the rotation is not stopped or slowed by the fuse contacting the mortar wall, we get a maximum rotating frequency of 10 Hz at a typical muzzle velocity of 130 m/s. The model used to calculate Figure 12 used the same parameters as for Figure 10 but with a slightly higher muzzle velocity.

The drift distance for a 1° angled shot with Magnus effect added to the direction of the angle is 42 m. Without the Magnus effect, it would have been only 25 m. (See Figure 10.) Earlier test series of 4-inch (100-mm) shells under windless conditions resulted in maximum drift distances of 64 m. So it can be seen that even slightly irregular angled mortars and Magnus effect together cannot fully explain the drift distances.

Research on 6-inch (150-mm) shells done by the BAM, showed rotations of up to 50 turns per second (50 Hz) for shells without extensions, rotating free in the mortar. In those tests the lift pressure was found to be significantly lower than in normal behavior, indicating that irregular gas flows may transfer a lot of energy (up to one third of the total energy) into rotation. That resulted in long drift distances by energy transformation from rotational and vertical energy to transversal energy by Magnus effects.[4]

The Magnus effect of a fast spinning spherical shell on the flight ballistics can be seen in Figure 13. The same parameters as in Figure 12 were used to calculate Figure 13, but the rotation was 80 turns/s (80 Hz). The drift distance for a 1° angled shot with this Magnus effect added to the direction of the shot would be approximately 120 m. Compared to a possible drift of 42 m for normal 4-inch fireworks shells (rotating at 10 Hz), this is quite enormous. Obviously, the prevention of free rotation of the shell in the mortar is one key to improving the

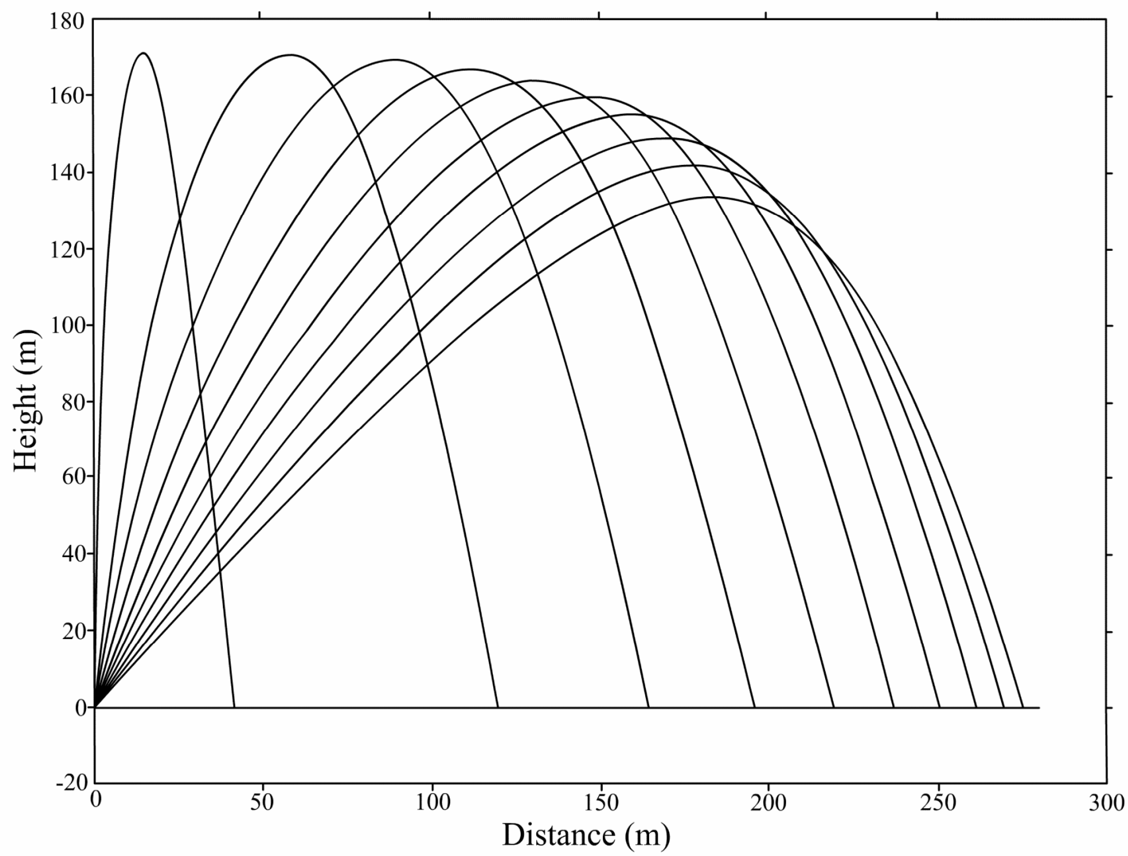

Figure 12. Magnus effect on the drift distance for 4-inch (100-mm) shells, assuming a 10 Hz Magnus influence on angled shots at 5° increments, from 1 to 46°.

safety at firework displays. This is possible by using a fit of 1/8-inch (3-mm) for the shell in the mortar as recommended in the National Fire Protection Association *Code for Fireworks Displays* (NFPA 1123).[3b]

When a shell fits loosely inside the mortar, the fuse is more likely to be damaged if the shell starts to rotate in the mortar during the launch process. This may result in multiple energetic fuse-to-mortar contacts. Additionally, the fast spinning shell will induce a strong Magnus effect on the trajectory. There seems to be a higher risk of creating blind shells in combination with long drift distances when using overly large inner mortar diameters.

Experimental Setup

Shells

The shells used in our tests were a representative range of display shells, mainly radially symmetric peony and chrysanthemum shells, as well as a few dozen asymmetrically charged Crisscross shells. The latter contained 25 to 30 small bombettes in an orderless mix with burst charge and were used to investigate the effects of charge symmetry on rotation and drift effects.

The shells were prepared as follows:

- The first step was to cut off the paper bag or cardboard cylinder containing the lift charge along the line where the container is attached to the shell. Then the primed end(s) of the time fuses were cut off and covered with a 1.5-mm thick layer of carbon-fiber reinforced epoxy-resin. This layer

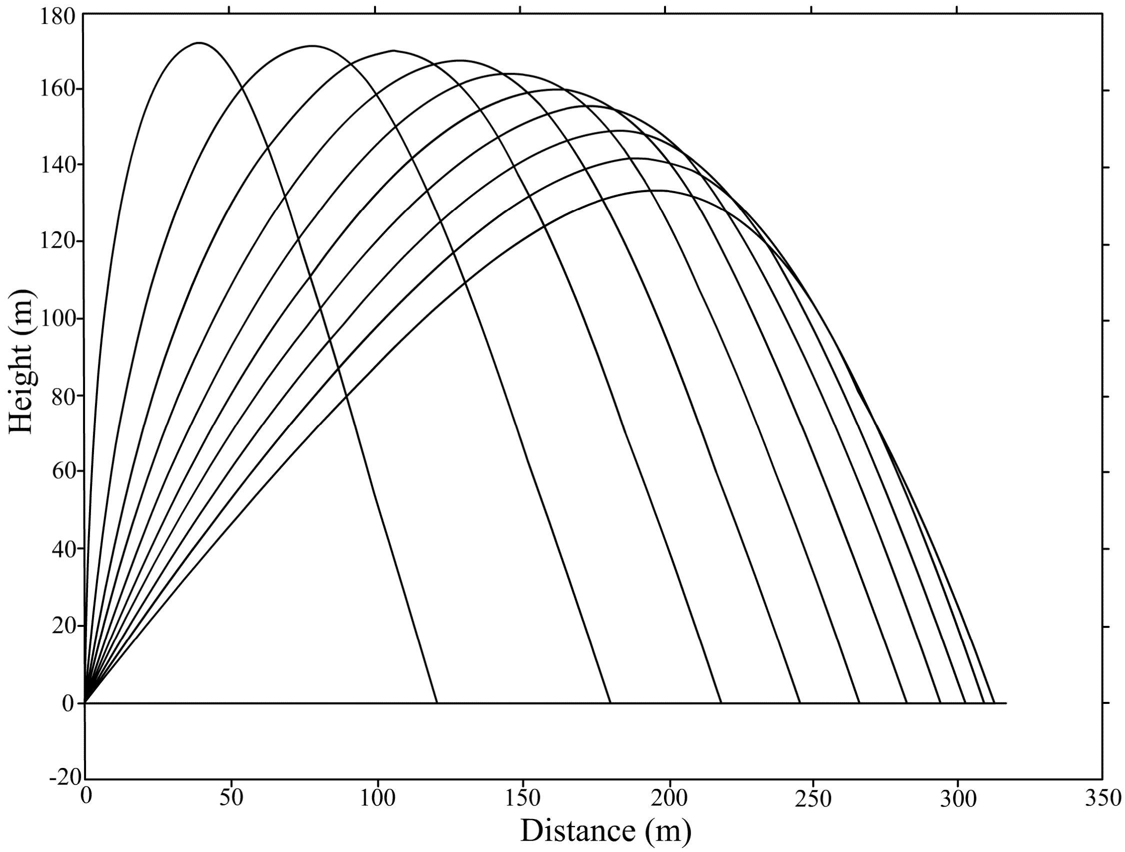

Figure 13. Magnus effect on the drift distance for 4-inch (100-mm) shells, assuming an 80 Hz Magnus influence on angled shots at 5° increments from 1 to 46°.

served as thermal insulation. To adjust the viscosity of the epoxy resin either 5 to 10 percent by weight of charcoal was added, or charcoal was used instead of the carbon fibers in the epoxy resin.

- After this layer cured, a second layer of 0.5-mm thickness was applied with a brush. This layer contained epoxy resin with a 5% load of flitter aluminum to reflect the IR-radiation of the lift charge and to protect the fuse against the hot dross of the charge.
- Before reattaching the lift charge with duct tape—to reestablish the original shell and lift charge configuration as close as possible—the shell was sprayed with yellow paint to improve visibility. In contrast to tests on 6-inch (150-mm) shells performed by the BAM[1] as described above, the test shells maintained their original inner and outer configuration, apart from the thin inert layers on their fuses.

We found the quality of the 6-inch (150-mm) shells to be superior to the smaller shells. The fuses were tightly wound with string, which provided more structural integrity to help prevent the fuses from being bent over during mortar passage.

Mortar Racks

The setup closely resembled the current practice. Standard Chinese fiberglass mortars were used. The fiberglass mortars were supported in wooden racks and secured with wedges. The mortar racks were set up vertically, checked with a water level, and connected with wooden boards nailed to the front sides of all racks.

The mortars were slightly deformed by the pressure of the wedges. This was tolerated because mortars become a bit irregular after some use.

Mortar Dimensions

The mortar dimensions are summarized in Table 2.

Table 2. Mortar Dimensions

Nominal Diameter		Inner Diameter	Length
(in.)	(mm)	(mm)	(mm)
4	100	102	600
5	125	125	750
6	150	152	900

Experimental Procedure

The tests were performed under official supervision of the “Staatliches Amt für Arbeitsschutz” (roughly equivalent to the BATF) by the companies Ingmanns & Schmiedeknecht Pyrotechnik and Speer Pyrotechnik on a suitable ground in Loevenich near Aachen, Germany.

The shells were loaded into the mortar racks and chained with delay fuse by taping the bare ends of the quick match against the delay fuse with masking tape. The delay fuse was not fixed to the mortar racks to let the quick match fly freely with the shell. The delay fuse used was yellow WASAG® time fuse, which burns at approximately 23 s/m or 44 mm/s. After igniting the delay fuse, we watched the test from a distance of 150 m. After firing a salvo, the shells were located, and the distance from the blind shell to the launch point was determined using a Bushnell Laser meter (accuracy ± 1 m). The direction of drift was estimated in 5° increments by choosing “West” as the meridian and increasing clockwise.

Results

5-inch (125-mm) Shells

The shells for these tests were supplied by PyroArt, Berlin. Forty-five shells were fired; the average drift distance was found to be 45.8 m with a standard deviation of 23.6 m. The minimum drift was 4 m, and the maximum drift was 101 m. Four shells drifted further than the safety distance of 75 m, recommended by German law. This represents a probability of 8.7%. All impacts were within the 70 feet-per-shell-inch (22 m/25 mm) recommendation of NFPA 1123.

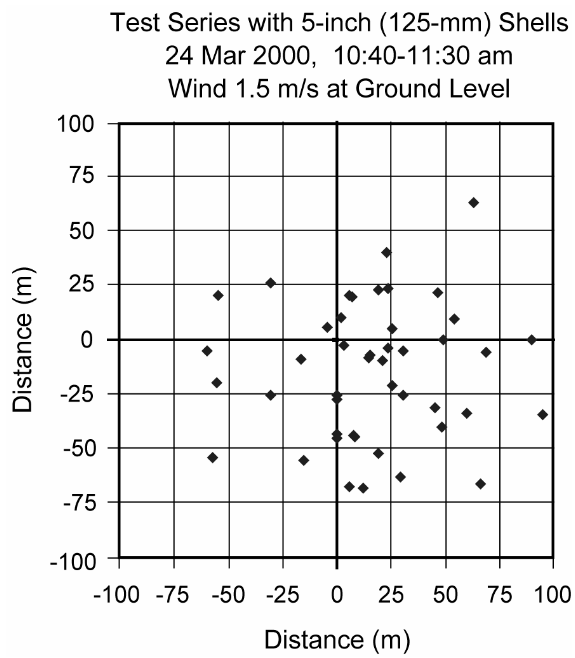

Figure 14. Impact diagram for 5-inch (120-mm) shells.

As one can see from Figure 14, the distribution of the shells’ impact points were irregular, which could be caused by the wind or a very slight slope of the ground that falls in that direction. Perhaps the mortar angle was too small to be measured by the water level.

Impact Ballistics

Six shells landed on asphalt paving. All of them broke upon impact. None ignited on impact. The 39 remaining shells hit the ground; 4 broke upon impact. Similarly, there were no ignitions on impact. This turned out to be an important result of the tests, namely, there is not much chance for ignition upon impact with 5-inch (125-mm) star shells.

Approximately 20% of the shell casings were deformed severely by the impact and showed an axis ratio of 1.10–1.25 to 1. The rest of the shells were deformed only very slightly. Twenty-nine shells had at least 20 cm of quick match still attached.

It was found that the impact with the slightly muddy and unbroken ground caused them to penetrate to a depth of 5 to 7 cm.

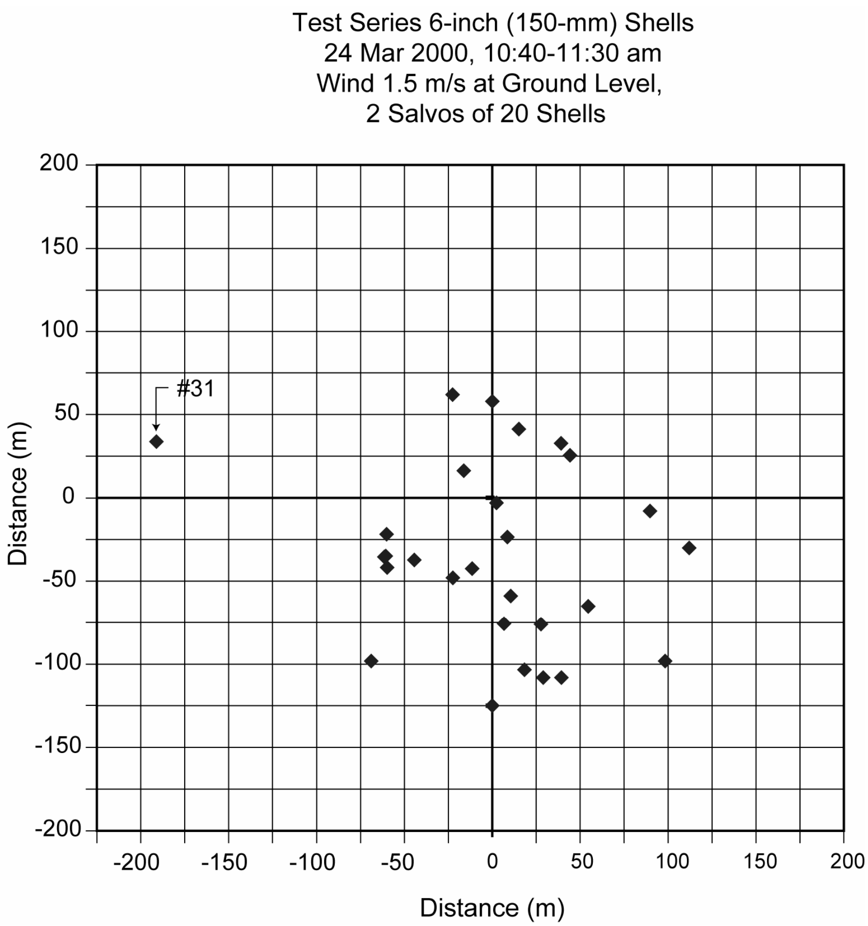

Figure 15. Impact distribution for 6-inch (150-mm) shells. The location of shell 31 is noted.

6-inch (150-mm) Shells

All shells for these tests were supplied by PyroArt, Berlin. Forty shells were shot in two salvos of 20 shells each. The minimum drift was 3 m, and the maximum drift was 160 m. The average drift distance was 78.5 m with a standard deviation of 33.3 m. Most of the larger drift distances were recorded in the second salvo. This appears to be an effect of the first salvo on the mortar setup. It is believed that the mortars were slightly angled out of their vertical position, because the mortar racks were not re-leveled after the first salvo. After the second salvo, the mortars were found to deviate up to 3° from the vertical. With the NFPA safety distance of 70 feet-per-inch of shell diameter, about 10% of all blind shells would leave the safety zone. Shell 31 shows another important result (see location of shell 31 in Figure 15). One mortar had not been secured in all directions because of a missing wedge. During the first salvo another wedge came off, which resulted in the mortar standing loose in the rack. The extreme drift distance of 194 m shows the importance of the stability to the mortar setup and should clearly indicate the need to secure the mortars tightly.

Impact Ballistics

Although the primed ends of the fuses were cut off and the ends of all fuses were completely covered with the same type of heat shield as the 5-inch shells [0.5 mm of flitter-aluminum-loaded (8 wt. %) epoxy cover over 1.5 mm carbon-fiber-reinforced epoxy resin], 7 shells exploded at the apex of their flight. This was explained above. This proves the reliability of ignition because under these circumstances no ignition was expected to occur. All shells were double fused.

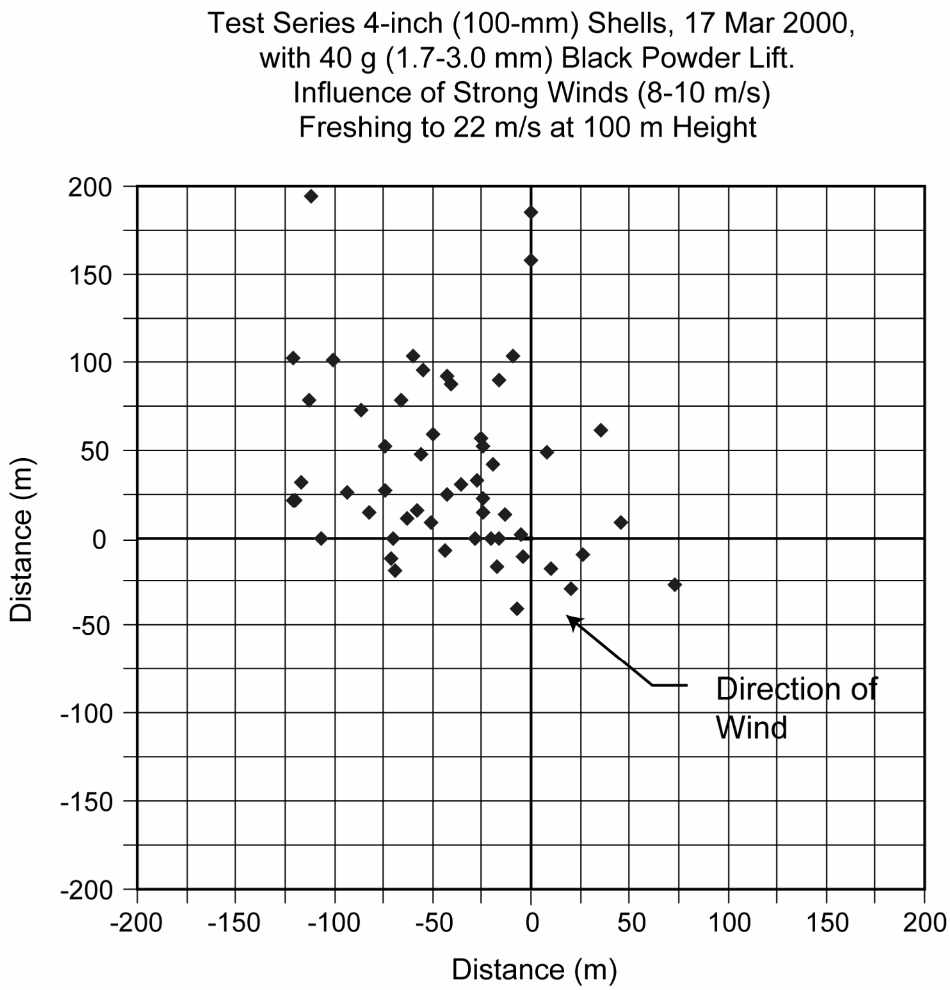

Figure 16. Impact distribution for 4-inch (100-mm) shells at wind velocities from 8 to 22 m/s.

The remaining 33 shells landed on the ground as expected. All were severely deformed from the impact, 21 shells cracked open and spilled part of their contents. This is explained by the smaller ratio between wall thickness and weight compared to smaller shells. The 6-inch (150-mm) shells in this investigation had a wall thickness of 8 mm as compared with 5-inch (125-mm) shells with a wall thickness of 7–7.5 mm and 4-inch (100-mm) shells with 6.5–7 mm wall thickness. The impact velocity rises with the shell size as well, adding some energy. With regard to the shell diameter, this influence is not as important as the mass, which is increasing as the cube of the diameter.

Four of the 6-inch (150-mm) shells ignited and burned upon impact. The result of the ignition was quite moderate and could by no means be compared with the normal burst. The burning debris was thrown less than 2 m from the point of impact. In no instance was a report produced, the sound was more a strong hiss from the burst charge and burning stars. Vegetation beyond 50 cm was not damaged. No crater was formed.

Reasons for Ignition of Larger Shells upon Impact

The remains of the shell cases were quite deformed near the fuse loop, the direction the shell was facing when it hit the ground. The cracks that spread radially from the point of the fuse loop were scorched more than the other edges of shell pieces. It was concluded that the cracks already existed at the time of ignition. It may be possible that glowing parts of the quick match might have ignited the contents of the shell. Parts of quick match were discovered in the fuse loops in all cases. This is consistent with the content's moderate burning. The shells which "ignited" upon impact went 4 to 5 cm into the ground, non-"igniting" shells went 5 to 10 cm into the ground. With an estimated impact velocity of 70 m/s the ignition delay calculates to 1–2 ms before the case bursts. Even in the case of internal ignition, the pressure could not rise to critical values in this short time. So the danger of shock waves, burning stars and debris thrown over long distances is quite low. That risk should be considered primarily as a potential problem in the fallout area with regard to fire protection.

4-inch (100-mm) Shell Influence of Wind Drift (Shells in Storm)

All shells for this test were supplied by Weco. On a stormy day with wind velocities of 8 to 10 m/s at ground level and up to 22 m/s at 100 m height, 55 4-inch (100-mm) shells were shot. The average shell drift distance was 71.5 m; the minimum drift was 3 m, and the maximum drift was 224 m. The latter was reached by a shell with 72 g of lift powder of 0.8–1.25 mm grain size, which is quite unusual for that size of shell. Also the mortar was angled at 10° toward the "north" on the map. Other shells had approximately 40 g of lift charge of 1.68–3.2 mm grain size. Also, the whole length of the quick match remained within the fuse loop, which surely raised the drag-coefficient. The increased drag-coefficient lowers the apex height but does not decrease the flight time very much since the shell also falls slower. Thus, the drift distance caused by the wind is increased due to a higher drag coefficient.

Although any display would have been cancelled under these conditions (small unsecured items were literally blown away), we support the BAM proposal of a wind limit of 5 m/s for standard safety distances and accordingly greater distances for higher wind velocities.

It is known that the wind blows erratically even at high average velocities, making angling difficult since angled shots during periods with no wind would result in long drift distances.

Evaluation

Evaluation of Apex Height versus Drift Distance

As can be seen in Table 3, our results indicate that the apex height in meters, multiplied by a factor of 0.8, gives the maximum drift distance in meters.

The old German standard did not take shell size into account. This was changed after the BAM investigations and this report. Further it can be seen that multiplying the burst height by 0.8 results in the US 70 feet-per-shell-inch safety distance recommendation of NFPA 1123.

It has to be kept in mind that safety distances are only one possible way to prevent accidents and that equivalent technical means (redundant or spolette fusing) should always be taken into account when considering the safety distance.

Worst Case Statistical Evaluation

Despite performing a limited number of experiments, the results support the dependence of shell drift distance on shell diameter. The fact that no greater drift occurred during the limited number of test shots does not exclude the possibility that greater drifts may be possible. Therefore the drift distance results were put into a statistical model for closer investigation. It was found that the functions of impact probability versus drift distance shown in Figure 17 correlate best with the raw data without a preset upper range limit. The probability of impact above the maximum ballistic trajectory has to be zero. The upper, nonlinear part of the function, which is influenced by the few shells with high drift distances, comes close to the point to a good degree, with an error of 0.001% for the 5-inch (125-mm) shells (see bracketed value in Table 4) and 0.1% for the 6-inch (150-mm) shells (see bracketed value in Table 5). This worst case scenario considers that the shell may even be subject to a ballistic trajectory by a combination of muzzle- and flight-ballistic effects. In reality this is extremely unlikely but shall be the basis for further assumptions. From Figure 17 one can see that a 5-inch (125-mm) shell has an 88% chance to land within a radius of 75 m (old German standard) and a 96% chance to land within 105 m (new German standard). A 6-inch shell has a 57% chance to land within a

Table 3. Shell Data and Safety Distances According to Diameter.

Nom. Inner Mortar Diam. (in.)	2	2.5	3	4	5	6	8	10	12	16
Nom. Inner Mortar Diam. (mm)	50	65	75	100	125	150	205	255	305	405
Ave. Quick Match Length (cm)	50	60	75	90	110	122	140	170	170	220
Ave. Shell Diameter (in.)	2	2-1/3	2-5/6	3-3/4	4-2/3	6	7-1/2	9-5/6	11-3/5	15-5/9
Ave. Shell Diameter (mm)	52	59	72	95	119	150	190	250	295	395
Pieces per case	120	120	72	36	24	9	6	2	1	1
Mortar Length (mm)	300	405	500	600	770	950	1200	1300	1400	1810
Burst Height (m)	50	70	80	100	125	150	200	260	300	320
Burst time after firing (s)	2	2.2	2.4	3	3.4	3.5	4	4.3	5.4	6.6
Effect Duration (s)	3	3.6	4	4.5	5.2	6.5	8	8.5	9.5	13
Effect Diameter (m)	13	15	20	30	45	60	110	130	150	200
Safety Distance Standards:										
German Std. (old) (m)	70	75	75	75	75	75	125	125	125	125
German Std. (new) (m)	75	75	75	80	105	125	170	210	250	300
US-Std. (vertical) (m)	43	43	64	85	105	125	170	210	250	300
US-Std. (vertical) (ft)	140	175	210	280	350	420	560	700	840	1120
US-Std. (angled) (m)	29	29	43	58	70	85	113	140	171	200
US-Std. (angled) (ft)	95	95	140	190	230	280	370	460	560	—
Zenith × 0.8 (m)	40	56	64	80	100	120	160	208	240	256

radius of 75 m (old German standard) and an 85% chance to land within 125 m (new German standard), see Figure 18. For both calibers the risk for a blind shell to leave the safety distance was statistically reduced to one third of the old value by applying the new standard.

In any way, the asymptotic part of the functions shows the necessity to prevent blind shells, since a residual risk continues up to the maximum ballistic trajectory when using that model. Increasing the safety distance to that point would lower the risk of a blind shell to leave that area to zero, but it would be impractical for the shooter. Plus, many years of favorable experience with lower safety distances do not indicate the need for such drastic measures. The reason for that is the good reliability of today's shells. Given a blind shell rate of 0.01% and a safety distance allowing five percent of all blind shells to leave the safety radius, only one shell per 200,000 shots would fall back as a blind shell and outside the safety radius.

Even a blind shell leaving the safety radius does not mean an accident in most cases. Taking this into account, we would get a probability that is a fraction of a million for an accident per shot shell. This proportion has to be considered low enough to be comparable to other risks in life and serve as a basis for actuarial calculations.

Since the probability of coincidence of both a blind shell and long drift distance seems very small, the extrapolation of the linear part of up to 70% impact probability makes sense. One gets values of 75 m safety distance for 5-inch (125-mm) shells and 125 m for 6-inch (150-mm) shells. The first lies far below the NFPA recommendation of 105 m, and the latter matches the NFPA recommendation exactly. It is important to note that both 5- and 6-inch shells were used with a safety distance of 75 m in Germany from WWII until 1998 when the new safety distances were introduced. It is estimated that several million shells up to 6-inch diameter were shot during that period, using 75m safety distance, without any injury or casualty among the audience.

For shells larger than 6-inch, one single accident in 1997 resulted in two people being severely injured. This accident happened when a single-fused 8-inch (205-mm) shell came down 124 m away from the launch point. It could have been prevented if the shooter would have used the new distance table or angled the mortar slightly away from the spectators. From this,

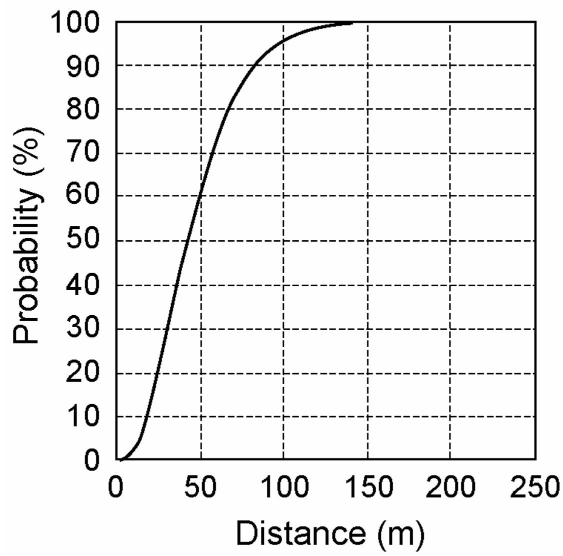

Figure 17. Impact probability for 5-inch (125-mm) shells.

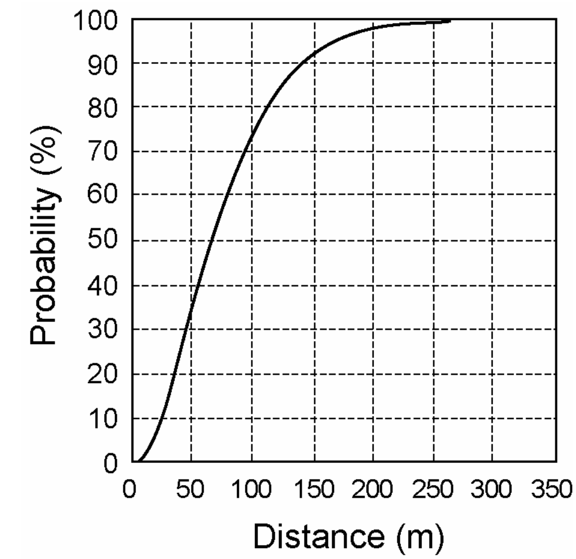

Figure 18. Impact probability for 6-inch (150-mm) shells.

Table 4. Drift Analysis for 5-inch (125-mm) Shells.

Probability (%)	Distance (m)
80	65
90	81
95	96
99	128
99.9	171
99.99	213
[99.999]	[253]

max flight distance (ballistic trajectory): 240 m
(Gamma distribution fit, scale: 15.26, shape: 3.00)

Table 5. Drift Analysis for 6-inch (150-mm) Shells.

Probability (%)	Distance (m)
80	111
90	141
95	169
99	232
[99.9]	[316]

max flight distance (ballistic trajectory): 280 m
(Gamma distribution fit, scale: 31.42, shape: 2.41)

one could deduce that the short car trip to view the fireworks display is statistically much more dangerous than watching a display at the current minimum safety distance.

Conclusions

Taking the shell diameter into account for the required safety distance proved to be correct over the last few years. Since the new safety distances have been used, no severe accidents have happened. Damages caused from fallout declined enormously. Bigger companies reported a decline of 40–50% for that kind of damage, saving some thousand €/$ per year for insurance expenses. Using the distance tables for angled shots and wind drift allows the shooter to ensure maximum safety. Correlation of the erratic drifts to mortar tilt angles allows the display operator to angle the mortars such that no blind shell will fall in the opposite direction of the angle. The necessity for increased safety distances for angled shots is based upon the shell size and angle of the mortar. Finally, the artistic value of display shows is better since the exact position of the effect can be predicted fairly precisely by the numerical model adapted by our tests.

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